W. Sparkin

COLOR TELEVISION

Selections from the Journal of the SMPTE

W. Spurlin

Color Television

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Selections from the Journal of the Society of Motion Picture and Television Engineers

Richard S. O'Brien, *Editor*

Prepared by a special committee, including
the following members of the Society:

Robert W. Byloff
D. Lisle Conway
Richard S. O'Brien
Richard E. Putman
Irving S. Rosner
Rodger J. Ross
James L. Wilson

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Foreword

This book is made up of papers selected from pages of the *Journal* of the Society of Motion Picture and Television Engineers.

The intent has been to make available in one convenient volume, a collection of *Journal* papers covering fundamental aspects of color television technology. Although the coverage inherently has less coherence and balance in emphasis than could be achieved in a book written by a single author, it is felt to offer significant value as both a tutorial and a reference volume. Emphasis has been given to papers covering important principles and concepts which change relatively slowly, if at all, as compared to the rapid evolution of technical equipment.

Supplementing the reprinted papers is a complete index of all other papers on color television which have been published in the *Journal* to date. The coverage is rounded out by the inclusion of pertinent SMPTE-sponsored United States Standards and SMPTE Recommended Practices, together with an index of all current Standards and Recommended Practices.

It is evident that, as time goes on, an even more comprehensive selection of papers will become available for a volume assembled in this manner. It is quite possible that a revision of this volume or a supplement to it will be required in a few years. However, with the North American television broadcasting industry over its initial colorization hurdle, and with color conversion well along in other parts of the world, the time is appropriate for many of the design, maintenance and operations engineers, who have been deeply involved in this process, to take a new look at the basics of color television. This book is intended to be helpful in undertaking this renewal process.

1

Basic Color

ABC's of Color Television

By J. M. BARSTOW

Television programs in color are now being produced regularly by major broadcasting companies, and the corresponding signals are being transmitted over both the local and intercity facilities of the Bell System to color TV transmitters. Although much publicity has been given to the advent of this rather astonishing new development, most of the articles have been either highly technical or intended for the newspapers. They have not provided an understanding of the system for intelligent engineers who are not able to devote sufficient time to the subject to master the more obscure technical details. This article is intended to fill a need felt in many quarters to answer a number of questions which have arisen concerning the generation of the signals and the manner in which they are used to produce a color picture.

It will be assumed that the reader has some knowledge of how a black-and-white TV picture signal is generated and displayed; i.e., the picture is "painted" on the TV tube by the modulated intensity of a spot which is swept repeatedly across the face of the tube from left to right, each sweep taking about 1/15,750 sec, the spot descending gradually from top to bottom of the tube in about 1/60 of a second. This cycle of events occurs over and over again, giving rise to the illusion of continuous motion in any televised scene.

With this background in mind, curious engineers generally have several simple questions in mind when they are told that by a modified, but compatible, system, a color picture can be painted on the tube face. Some of these questions are: (1) how does the system work in simple terms? (2) how is color (hue) produced on the picture tube of a color receiver? (3) how can color TV signals and monochrome TV signals be "compatible"; i.e., what does a monochrome receiver do with the color information signals (which it does not need and cannot use), and how can a color receiver do without color information? In an attempt to answer these questions in

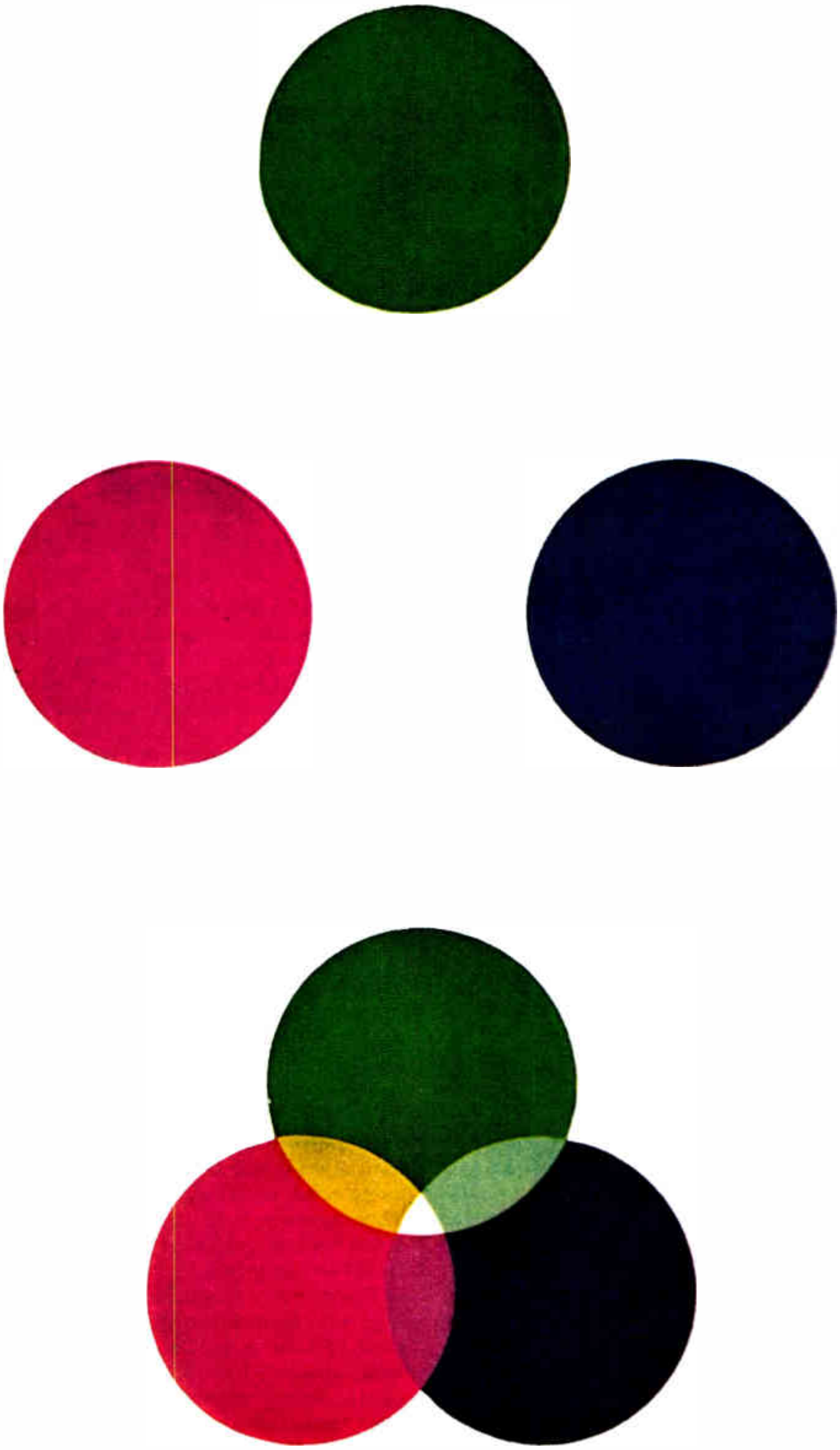
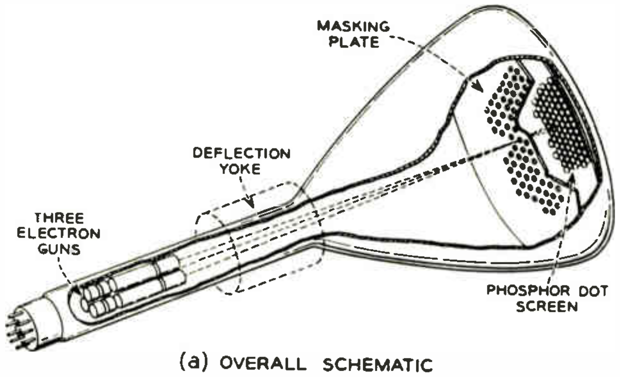
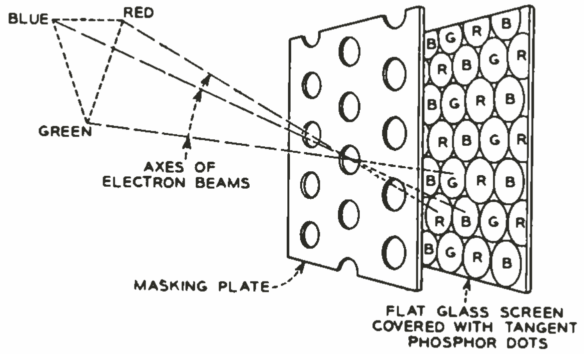


Fig. 1. Primary colors of the additive system: above, shown separately; below, shown partially merged.

This article by J. M. Barstow, Bell Telephone Laboratories, 463 West St., New York 14, is reprinted here through the cooperation of E. K. Gannett, Managing Editor, The Institute of Radio Engineers. It first appeared as "Color TV — How It Works," in the Sept. 1955 IRE Student Quarterly, pp. 11–16.



(a) OVERALL SCHEMATIC



(b) ENLARGED SECTION SHOWING GEOMETRICAL RELATIONS

Fig. 2. Structure of tri-colored television tube. (Courtesy of RCA.)

easily understandable terms, a description will be given in the following paragraphs and associated figures of the general plan employed, without going into details as to how the plan is carried out.

Colorimetry and the Color Picture Tube

A few rudimentary principles of colorimetry must first be understood; i.e., those having to do with the reaction of human vision to lights of differing color. The necessary principles may best be understood by describing an experiment with colored lights. Suppose, for example, in a darkened room, a white reflecting surface is illuminated in three different spots with light from three different projection lanterns. In the path of the light from one lantern, a filter will be placed which will allow green light to pass through, but no other color. Similarly, in the paths of the beams from the other lanterns, red and blue filters will be placed respectively, so that to an observer with good color vision, the spots will appear to be green, red and blue. Now suppose the projection lanterns are oriented so that the three spots partially merge. The area on which all three lights fall simultaneously will appear white. The area on which green and red light falls will appear yellow; the area on which red and blue light falls will appear as lavender or magenta; and the area on which the blue and green light falls will appear blue-green or cyan. These results are shown on Fig. 1 and the results of the experiment illustrate the additive properties of colors (not to be confused with the subtractive properties of color when different color pigments are mixed).

The additive properties of colored lights are employed in color television. When the eye can see separate areas (i.e., areas large enough to be resolved by human vision) illuminated by different colored lights, it will recognize the different colors, but when the colors merge, or the areas become so small and so close together that the eye sees them as if they were in the same place, the individual colors no longer are recognized. In the experiment described above, if the dots were each reduced in size to about that of a pinhead, and then so located on the white surface that they did not merge but were tangent to each other, the area which they effectively cover would appear white from a distance of about 15 ft. At a distance of a few inches, the three separate colors would be recognized.

The structure of a color television picture tube is shown in Fig. 2. Phosphor plate of tube is a glass screen covered with about 1,070,000 phosphor dots (21-in. tube), one-third of which will glow green under the influence of a beam of electrons; one-third, red; and one-third, blue. The dots are placed on the phosphor plate of the tube in clusters of three: one green, one red, and one blue, so that there are about 350,000 clusters of three dots each, uniformly distributed over the active area of the tube. The neck of the tube contains three electron guns, the first, for emitting a beam intended for the green glowing dots, the second, for emitting a beam for the red glowing dots, and the third, a beam for the blue glowing dots. Between the electron guns and the phosphor plate, but only about one-half inch from the phosphor, is a masking plate which has 350,000 small holes in it, each hole being placed approximately over the center of a cluster of three phosphor dots. Under the influence of focusing coils and magnets, the three beams from the three guns are made to converge at the masking plate, and hence, they diverge slightly beyond the masking plate. This slight divergence is sufficient so that the beam from the green gun strikes only the green glowing dots and similarly, the beams from the red and blue guns strike only the red and blue glowing dots, respectively. A cluster of three phosphor dots is so small that one dot cannot be resolved from another at distances greater than a few feet. Therefore, at distances of four times picture height or greater, a wide range of colors can be produced (including white) by controlling the magnitudes of the beams from the three guns. The apparent sharpness of the picture is reduced very little. When the beams from the three guns are strong, and correctly proportioned in magnitude, white is produced. If they remain in the same proportions, but are gradually reduced in magnitude to near zero, the white is correspondingly reduced in intensity through shades of gray to black. If the beam from the green gun is strong and the others near zero, the color produced is green (the red and blue glowing dots do not glow). Similarly, any color can be produced that is within the range of colors that can be synthesized from green, red and blue. This range embraces nearly all those seen in nature or employed by human beings for decorative purposes.

As the tube is scanned from left to right and from top to bottom by the three beams in unison, the convergence of the beams at the masking plate is maintained within close limits.

The remaining features of the system are concerned with the production and transmission over one 4.2-mc circuit of the signals applied to the three guns of the picture tube.

Color Signal Generation

Color signals are generated in a manner shown in Fig. 3 below. Three cameras are used effectively with light filters so that the output of one camera is due to the green light obtained from the object being televised, the output of the second, due to red light, and that of the third, due to blue light. The horizontal and vertical sweep voltages and associated pulses are provided by the camera equipment which converts the light signal to electrical potentials E_{Red}, E_{Green} and E_{Blue}. The gamma unit contains a set of nonlinear amplifiers through which the electrical signals are passed. The unit is used at the early stage of signal generation to anticipate and correct for a characteristic of picture tubes used in receiving sets. The light output of a phosphor in a picture tube is directly proportional to the beam current striking it, but the beam current is proportional to about the 2.2 power of the voltage applied to the picture tube grid. Hence, in the gamma unit, the nonlinear amplifiers whose outputs are proportional to approximately the 1/2.2 power of the inputs, are correct for the opposite kind of nonlinearity in the picture tube. Between the outputs of the gamma unit and the picture tube grids, the system is intended to be linear.

The three outputs of the gamma unit are usually adjusted to be equal when a white area is being televised. They are then fed into a matrix unit which derives three signals: one to be used as a brightness or luminance signal similar in every respect to a monochrome signal, and the other two to be used as color information signals. In Fig. 3, the brightness signal is labeled E'_y, and is formed by adding .59 of the green signal, .3 of the red signal, and .11 of the blue signal. These fractions of the individual color signals are combined because it has been determined subjectively that the three colors contribute to the total brightness of a scene in these proportions. The brightness of a given area in a televised scene corresponds to the "lightness" of the area, or the inverse of the "darkness" of the area, irrespective of "hue."

The two color information signals are formed as indicated on the figure. These signals are going to be used to modulate two single frequencies (color subcarriers) which are identical except for a 90° phase difference. Therefore, the proportions of each color output used are selected so that, if the different hues are considered as located along a circle, as indicated in Fig. 4, their projections on E'_i and E'_Q axes will result in the correct magnitudes of modulating voltages. Before projecting the primary color voltages onto the E'_i (in phase) and E'_Q (quadrature phase) axes, two other magnitude adjustments are made. One governs the relative magnitude of chrominance and luminance signals, and the other adjusts the three primary color magnitudes so that when a white or gray area is televised (corresponding to equal gamma corrected color voltage outputs in each of the three colors), the color voltages projected onto the E'_i and E'_Q axes will sum to zero. Hence, the modulators will have zero output. These two adjustments in the color signal voltage magnitudes produce levels of $E'_G = .593$, $E'_R = .632$, and $E'_B = .447$ before projection on the E'_i and E'_Q axes. When these color voltages are projected onto the E'_i and E'_Q axes, the results are as shown on Fig. 3. It will be noticed in this figure that the coefficients of the color voltages sum algebraically to zero, indicating that when the original gamma corrected output color voltages are equal, both the E'_i and E'_Q modulating voltages reduce to zero. It is obvious from the signs of the coefficients of the color signals emerging from the matrix unit that this unit must contain phase inverters as well as attenuators, amplifiers and mixing circuits.

Figure 4 shows the magnitudes and the angles of both the primary colors, red, blue and green, and the complementary colors, yellow, cyan and magenta. The magnitudes and angles of the complementary colors are the vector resultants of the adjacent primary colors; i.e., yellow .447 at 167° is the vector resultant of red and green; similarly, cyan is the resultant of green and blue, and magenta the resultant of blue and red.

The two modulated subcarrier outputs are combined as indicated in Fig. 3. Since each output consists of an amplitude-modulated color subcarrier, the combination will also be an amplitude-modulated color subcarrier. Since the two components differ in phase by 90°, their vector sum will have an angle which is determined by the relative magnitudes of each component and thus will be phase modulated also. It should be noted that each component output may have reversed phase (i.e., 180° from normal), as when the modulating voltage changes sign from positive to negative. The arrangement, therefore, provides that the color information is contained in an amplitude-modulated subcarrier whose angle, referred to an arbitrary reference, may have any value from 0 to 360°.

The color signal is then combined with the luminance signal as shown schematically in Fig. 3. Since the color subcarrier has been chosen to be an odd multiple of half-line frequency (455×half-line fre-

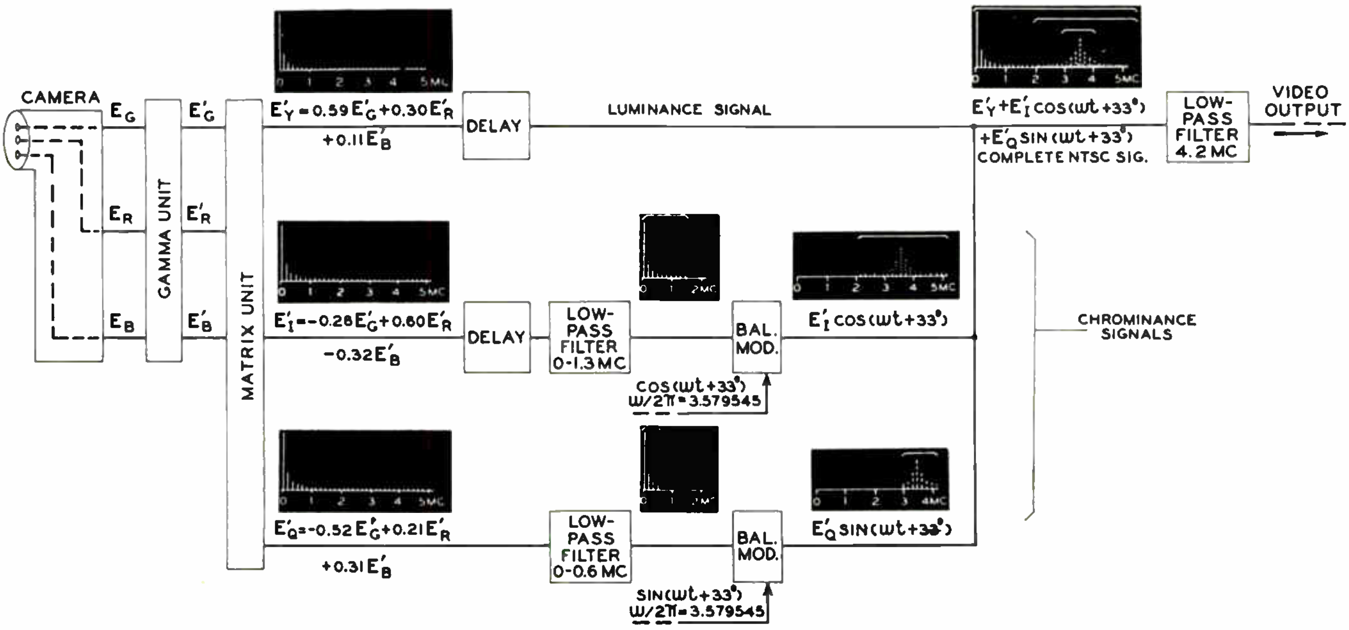


Fig. 3. Schematic of equipment component functions for generating NTSC color video signals.

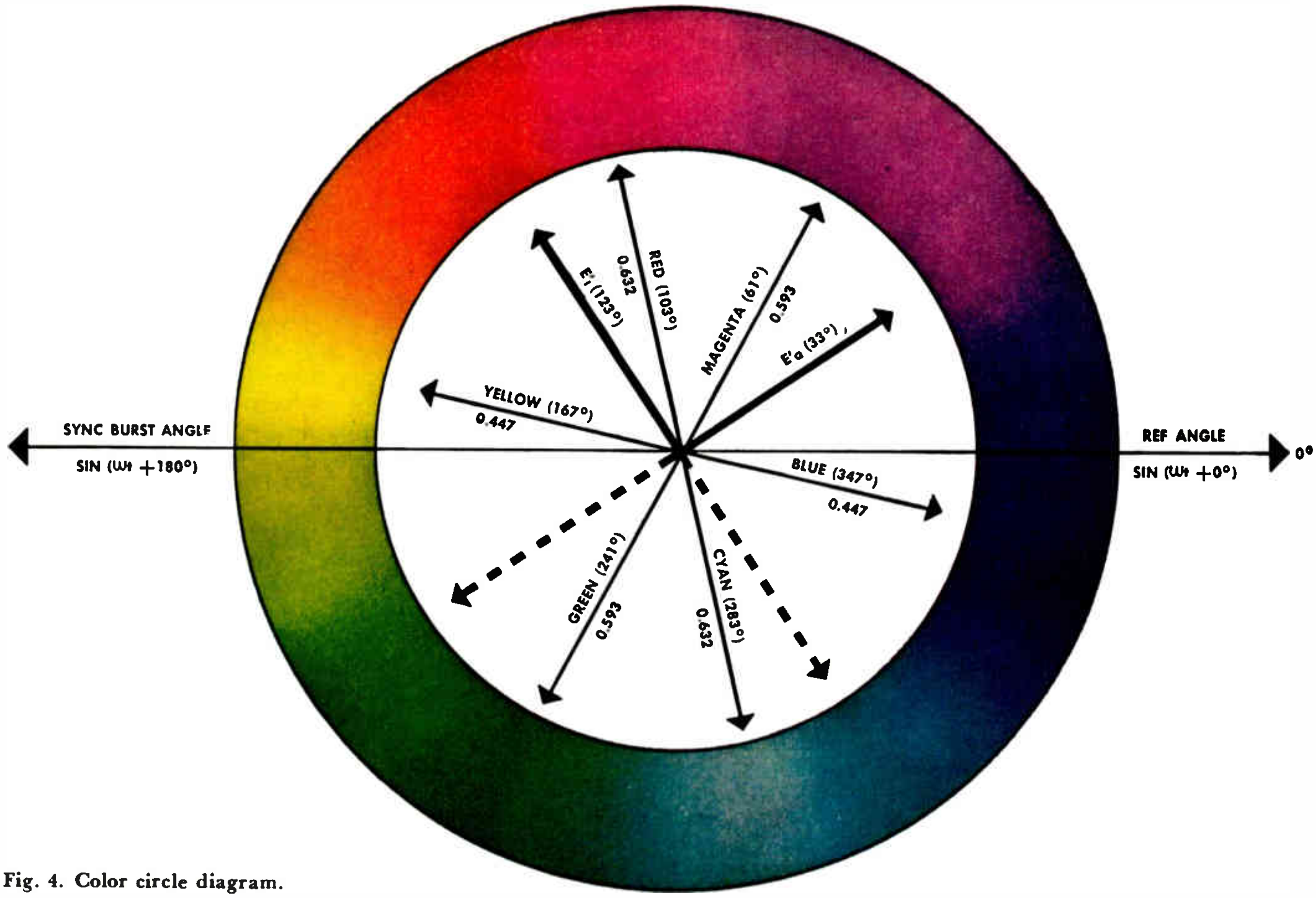


Fig. 4. Color circle diagram.

quency), the color signal interleaves with the luminance signal as shown in the small bandwidth illustration near the line schematically representing the output signal. This is the video signal which is transmitted. A somewhat more detailed illustration is given in Fig. 5. The solid vertical lines indicating frequency components comprise the luminance signal, and the dotted lines, the chrominance signal. Only one-tenth of the number of components are plotted for clarity of illustration. In this signal, the components of the luminance signal are separated by line frequency (approximately 15.75 kc), as are those of the chrominance signal. It should be remembered that the luminance signals are present at all times during the transmission of a picture, although the levels of the higher frequency components vary considerably, depending on picture content. On the other hand, the chrominance components will disappear entirely when black and white objects are being televised.

Figure 6(a) shows a color bar pattern as it would appear on the screen of a color television set and Fig. 6(b) shows the corresponding video signal waveform in one-line interval. The scale at the left of Fig. 6(b) may be considered as a video voltage scale in one-hundredth volt units. The first negative pulse is the line-synchronizing pulse which is used to send the three converging color beams back to the left side of the raster. The next short burst, at a low-voltage level corresponding to black or at least a dark level, is the color subcarrier synchronizing burst, and is used to control the frequency and phase of the demodulating oscillator in the receiver. The phase of this burst is always 180° away from reference phase, as indicated in Fig. 4. The next burst of frequencies corresponds to fully saturated green, having a peak-to-peak amplitude of 2 × .593 = 1.186 and an axis level equal to green brightness or .59 (brightness indicated by light dotted lines). The next burst corresponds to saturated yellow and has a peak-to-peak amplitude of twice the resultant of maximum red and green (see Fig. 4), or 2 × .447 = .894 with an axis level equal to yellow brightness (green brightness plus red brightness), or .59 + .30 = .89. The next burst corresponds to saturated red with an amplitude of 2 × .632 or 1.264, with an axis level at red brightness or .30. The other bursts and the corresponding colors can be seen and the amplitudes and levels of axes computed in a like manner. The factor of 2 in all these computations is used to obtain the peak-to-peak magnitudes from zero-to-peak magnitudes commonly used in electrical engineering as an expression for the maximum amplitude of a sinusoidal wave form.

The phases of the different groups of waves correspond to those shown in Fig. 4, although this cannot be well illustrated in the figure.

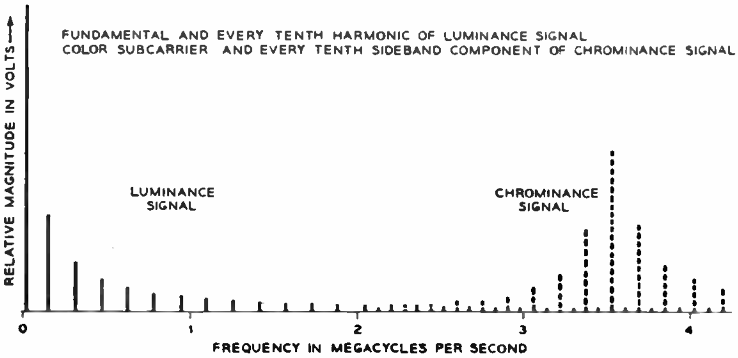


Fig. 5. Frequency composition of typical NTSC color TV signal.

In review of what is shown in Fig. 6, three principles should be stated:

1. Level of zero axis of a group of waves representing a single color represents brightness of the color. [E.g., yellow and cyan have highest and next-highest brightnesses in Fig. 6(b) and are brightest of the six portrayed on color bar pattern, Fig. 6(a)].

2. At any brightness level, the amplitude of a group of waves representing a color corresponds to the saturation of the color. The word "purity" has been applied to this characteristic and it indicates the extent to which the color approaches that of light of a single wavelength. Low purity (amplitude) would indicate dilution with other colors, tending to make the resultant move toward some shade between black and white.

3. The phase of the group of waves representing a single color determines the hue of the color.

Figure 6 also shows the signal corresponding to black-and-white. When the spot formed by the three converging beams passes over the lower half of the image (corresponding to the black-and-white portion of the subject material), the gamma corrected color outputs are equal; they are equal to approximately zero for the left part of the lower half of the picture. They remain equal, but assume high values (unity) for the white area shown at the lower right. The video waveform signal corresponding to this lower picture area is indicated by the heavy solid line at the zero potential level and at the 100 level.

Signal Reception

Once the general scheme for producing the signal is understood, the method of demodulating it to provide signals for each of the three guns in the color tube is rather easily followed. The method is indicated schematically in Fig. 7.

There is no attempt made to separate out the chrominance signal from the luminance signal by toothed, or comb, filters. The complete signal is used for a luminance signal as indicated, although the chrominance information in it is unwanted. This unwanted signal, however, has such a frequency composition as to greatly reduce its visibility in the picture. This is because the error it produces in the picture effectively phases out in the succession of lines and fields by means of which the picture is presented. Specifically, if the chrominance signals produce a brightness error at one spot on the picture, as this spot is traversed by the resultant beam from the three guns, an error of opposite sign will be produced

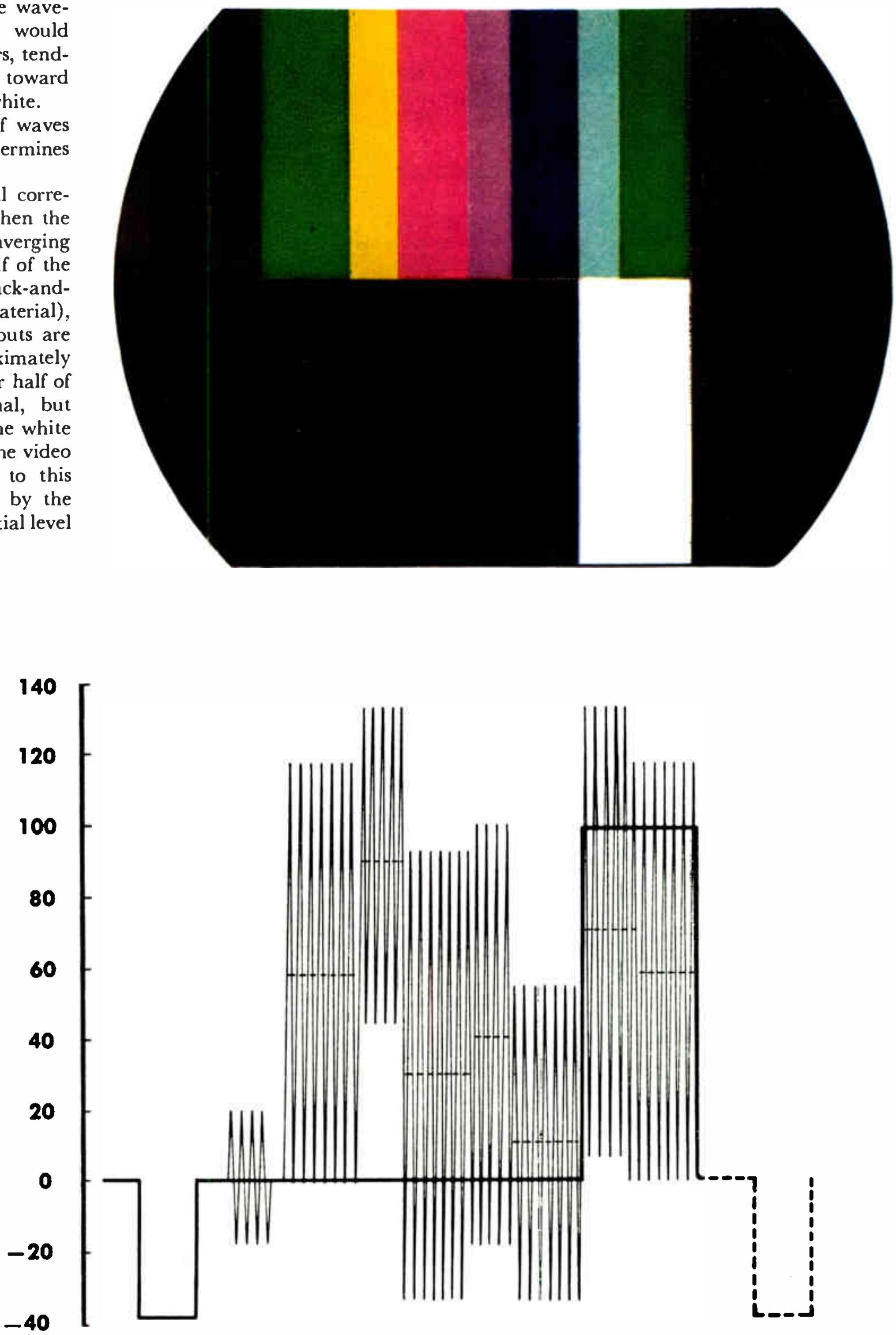


Fig. 6. Color bar pattern and corresponding color video signal: (a) color bar pattern; (b) color video signal.

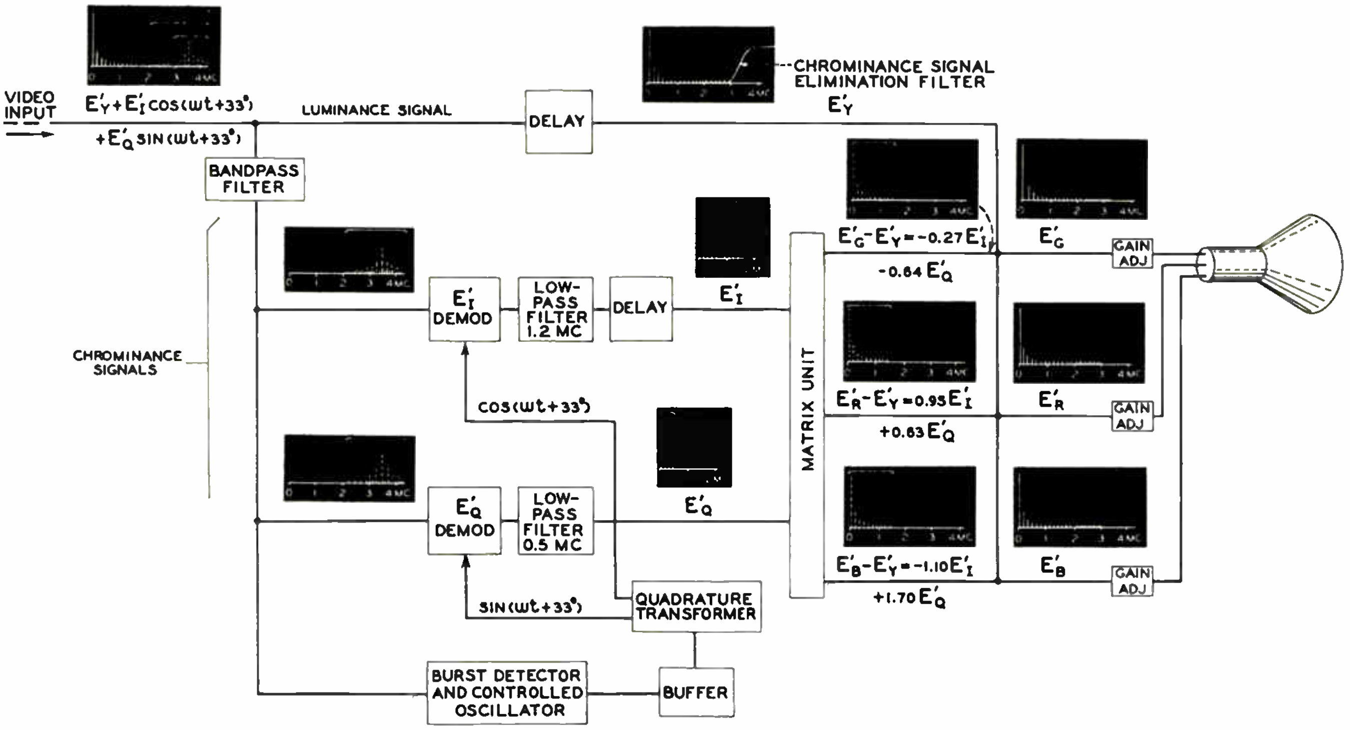


Fig. 7. Schematic of equipment component functions for receiving NTSC Color Video signals.

at this location in the horizontal motion of the spot on the next line in that field. That is, if the error due to chrominance is too bright a spot in the first line referred to above, the corresponding spot will be too dark on the next traverse of the beam across the picture. These errors are therefore close together on the picture; they are of opposite sign and occur rapidly. These three factors tend to reduce their visibility. Also, when the subject material is black-and-white (or any shade of gray in between), the error disappears altogether because the color subcarrier disappears. As a further safeguard against brightness error due to chrominance signal, manufacturers of color sets are using a low-pass filter to cut off the luminance signal at about 3 mc, cutting off also the chrominance signal, which is an error signal so far as luminance is concerned. The philosophy is that a 3-mc luminance signal *without* the chrominance error signal is better than a 4.2-mc luminance signal *with* the chrominance error signal. This is indicated in Fig. 7 by the chrominance signal elimination filter characteristic applied to the luminance signal.

As indicated in Fig. 7, a bandpass filter is used in the chrominance branch to remove the low-frequency luminance signal. The chrominance signals are demodulated with a synchronous demodulator and the E'_i and E'_Q components are derived. The error in the chrominance signal due to the high-frequency luminance signal is small because (1) the error signal components are small; (2) synchronous detection plus low-pass filtering are used so that the high-frequency positive and negative errors are effectively eliminated.

It is more convenient at the receiver to derive the "color difference" signals first from the chrominance signals. This can be done by combining different fractions of the E'_i and E'_q as follows:

$$E'_G - E'_y = -0.27E'_i - 0.64E'_q$$
$$E'_R - E'_y = 0.95E'_i + 0.63F'_q$$
$$E'_B - E'_y = -1.10E'_i + 1.70E'_q$$

These equations follow directly from the equations shown on Fig. 3.

The luminance signal is then added to each of the three color difference signals, thus forming the three primary color signals.

$$(E'_G - E'_y) + E'_y = E'_G$$
$$(E'_R - E'_y) + E'_y = E'_R$$
$$(E'_B - E'_y) + E'_y = E'_B$$

These three signals correspond exactly (except for the errors discussed above) to the gamma-corrected color signals put out by the camera, and are applied through separate gain-adjusting networks to the three guns of the color tube. The gain adjustments are for the purpose of proportioning the beam currents to produce radiations from the phosphors which will produce white (or shades of gray to black) when equal voltages are applied to inputs of gain-adjusting networks. The manner in which the color tube uses these signals has been explained.

Transmission of the Color Signal

The color signal which must be transmitted has been described here in two ways: (1) amplitude vs. frequency (Fig. 5), and (2) amplitude vs. time (Fig. 6(b)). It will be apparent from Fig. 5 that since the color is carried by a frequency of 3.58 mc and sidebands, it is important that this frequency region be transmitted with high fidelity. Subjective tests indicate that a 1-db change in the response of the circuit at 3.58 mc can be easily detected, and a loss of 3 db in this region, compared to the transmission at low frequencies (luminance transmission) begins to be objectionable. In other words, transmission at 3.58 mc is as important for chrominance as is transmission at low frepuencies (below 1 mc) for luminance. This added requirement for color signal transmission necessitates more exacting maintenance of circuit response.

The second requirement which makes color TV transmission more difficult is the delay requirements. In this case, the delay characteristic of most importance is the differential delay characteristic at the color subcarrier frequency; i.e., variation in delay with the various voltage positions the subcarrier may occupy in transmission, rather than the delay characteristic most frequently referred to in wide-band transmission, which is delay vs. frequency. This latter delay must also be maintained constant over the whole frequency band within rather narrow tolerances.

Figure 6 shows that different colors are transmitted at different potential levels through the transmission systems. For example, the axis of the synchronizing burst is at a zero level in the figure, while that of the group of waves transmitting the yellow signal is at a level of 0.89. Since, in the receiving set, the hue of the color is determined by the relationship of the phase of the synchronizing burst and that of the group of waves carrying the color information, it is necessary that the relationship between the phases of these groups of waves be preserved with great fidelity from the point of signal generation to the point where the signal is used. In the example cited, if the group of waves carrying the yellow color information is shifted in phase by as much as 5° with respect to the phase of the waves in the synchronizing burst, a change in hue will be noticed in the picture. If the phase of the yellow color-carrying group of waves is advanced, the yellow color in the picture will become slightly greenish; if the phase is retarded, it will move slightly toward the orange (see Fig. 4). Hence, a differential phase requirement is born, which was not given serious consideration before the advent of color TV. It was considered necessary in overall transmission to maintain differential phase shift within about ±5° limits at color subcarrier frequency.

In regard to compatibility, when a monochrome receiver is fed color signals, only the luminance signal is required. Referring to Fig. 7, the circuitry for selecting the high-frequency chrominance components and demodulating them into color difference signals is not present, and the one gun in the monochrome tube is supplied with the luminance signal, plus the interleaved chrominance signal. As was explained above, the frequency composition of the chrominance signal, which is an error signal so far as luminance is concerned, is of such a nature that its visibility is reduced. In a given small area in a picture, plus- and minus-errors will occur in rapid succession and human vision tends to average them out. Hence, it may be said that the signal is so designed that when received by a monochrome receiver, the visibility of the chrominance portion of the signal in the picture area is materially reduced.

When a color receiver is fed a monochrome signal, the outputs of the synchronous demodulators equal zero; the color difference signals are zero; and therefore, the signal supplied to the gain-adjusting network associated with each gun is the same, namely, the E'_y signal. With equal inputs at these points the beams are of the proper relative strength to produce black-and-white.

Conclusion

It is beyond the scope of this article to go into further detail in regard to how the severe requirements of television transmission are met. It will be sufficient to say that in spite of bandwidths about one thousand times as great as those used for single telephone channels, more severe transmission requirements than those used for telephone transmission are necessary for monochrome TV transmission. More severe requirements must be applied for color television signals, primarily due to the necessity for maintaining amplitude responses constant over the whole 4-mc band, and to the differential delay requirement. Steps are being taken to satisfy these needs, and it is expected that in the reasonably near future, regular color transmissions will be achieved with only moderately increased difficulty over that encountered in the past for monochrome transmissions.

Information on the formation of color TV signals was obtained largely from the reports of Panels 12 and 13 of the National Television Systems Committee. A short bibliography of particular articles of interest is given for the benefit of readers who would like to learn more of the details of the NTSC color system.

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Color Perception and Color Television

By C. J. BARTLESON

An important part of the complete television system is the viewer. His conscious response is the ultimate output of the total system. A summary is made of some of what is currently known of the way in which his responses are formed. This knowledge of the process of color perception is related to the characteristics of color television images.

Introduction

A red light flashes. A director points to an actor. He begins to speak as millions of electrons are emitted amongst a vast complex of interconnected thermionic tubes. The phase, frequency, and amplitudes of narrow bands of electromagnetic energy are purposefully modulated and propagated throughout the atmosphere. Almost instantly, resonance occurs within excited phosphor crystals and the face of a cathode-ray tube lights up to provide an intricate spatial array of emitted photons vibrating at various frequencies and amplitudes. The *first half* of a color television system is operating. This is the "tele-" half of television.

It is an enormously complex half to be sure, but its complexity pales in comparison with that of the other half of the system: *the viewer*, who supplies the "vision." The television system is not complete without a sensing human observer to perceive the image on the face of the cathode-ray tube. He provides the perceptual mechanism that is the *raison d'être* for this complicated transfer of physical information.

Perceptual mechanisms are systems incorporating feedback that are sensitive to certain kinds of energy and are capable of delivering messages to modify the device's output. In other words, a perceptual mechanism is a system for meaningfully relating output to input.

The process of visual perception operates upon chemical and electrical responses to light energy (the input) to produce a conscious response (output) in the brain. It is largely a process of abstraction. The input is encoded into complex but efficient electrical pulse-trains. Information which is significant is enhanced at the expense of that which is less significant. The resultant schema is decoded and processed in the brain where it is compared with stored remnants of past experience in order to form an interpretive perception. This is the process of vision. It is really only in the brain that we "see" anything, including colors.

It is for this reason that psychologists and students of sensory processes prefer to define "color" as an aspect of conscious response. It may be affected by, but is not itself a property of, objects or of lights. Those things are called "stimuli," for they serve to stimulate the perceptual process. The ultimate response is (in part) color.

The process by which this output derives from the stimulation of light energy is one which has long intrigued and puzzled man. It still remains largely an enigma. However, the umbra of ignorance which shrouds the mechanisms of visual perception is yielding gradually to the light of scientific investigation. Such is the pace of this investigation that immensely more of the process is understood today than was the case a mere five years ago.

In order to attempt to understand better the *complete* television system, it would be helpful to examine some of what is known of this process of color perception. It should then be possible to relate that knowledge to the characteristics, both desirable and undesirable, of color television images. The remainder of this paper will be devoted to these two issues.

Theories of Color Vision

How is vision mediated? This is a question which has been asked for probably thousands of years. The Greeks, the Arabs, Renaissance Italians, and more northerly Europeans all addressed themselves repeatedly to the problem.[1,2,3] However, it was not until Newton discovered the refractibility and dispersion of light (described in his famous *Opticks* of 1704) that the physical basis for a reasonable solution was made available. Newton thought that the eye must contain many receptors, each sensitive to a different frequency of light. Just about 100 years later, Thomas Young debunked Newton's idea in four short paragraphs. He argued that it would not be possible for each point on the image plane of the eye to transmit unchanged an infinitude of vibrations. The visual mechanism must be more parsimonious. There must be, he reasoned, an interposed receptor-encoder between the light stimuli and the brain. In particular, he postulated a triad of receptor types. Young thought that each of these was sensitive to a large band of frequencies of light energy. He first suggested they be sensitive to "red," "yellow" and "blue," but a year later (in 1802) he proposed "red," "green" and "blue" sensitivities.

About half a century later, the Scottish physicist James Clerk Maxwell became interested in the problem of color vision. He agreed with Young's hypothesis and in support of it gave (quite by accident[4]) a successful demonstration of the synthesis of a full color image from three additive primaries: the "red," "green" and "blue" of Young's postulate. At the same time the German physicist Hermann von Helmholtz adopted and slightly modified Young's hypothesis.[5] His contributions in experimentation and reduction to scientific description were so great that the idea has become known as the Young-Helmholtz theory of color vision.[6] Basically, this theory postulates two things: (1) the eye contains three kinds of receptors, each kind being principally sensitive to a different band of frequencies of light energy (generally regarded as those which normally evoke "red," "green" and "blue" sensations), and (2) that the responses of these receptors are transmitted directly to the brain where the information is assimilated to form a color perception. The Young-Helmholtz theory is, thus, rather strongly oriented toward considerations of the stimulus or physical aspects of color.

Not all scientists and philosophers were thinking of color in terms of physics, however. The poet Goethe published his thoughts on the matter in a scientifically atrocious work called *Zur Farbenlehre* in 1810. It represented a very different approach to color from that adopted by Newton and his followers. Goethe's idea was to employ observation and intuition; to try to describe color vision in terms of what is actually seen and experienced. The most famous proponent of this response-oriented approach to color vision was another German, the physiologist Ewald Hering. Based on the fact that we perceive only six *unique* colors (black, white, red, yellow, green and blue), he suggested that the eye contains three chemically different substances (*Empfangstoffen*) which absorb light and interact with a receptor mechanism (*Sehsubstanz*) to yield three kinds of opponent responses: white-black, red-green, and

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A contribution from the Kodak Research Laboratories, presented on September 19, 1967, at the Society's Technical Conference in Chicago by C. J. Bartleson, then of the Research Laboratories, Eastman Kodak Co., Rochester, N.Y. 14650. The author is now at Macbeth Research Laboratory, Macbeth Corp., Newburgh, N.Y. 12550.
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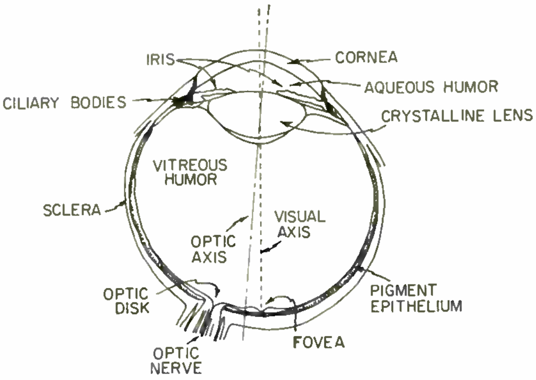

Fig. 1. Cross section of a right human eye.

blue-yellow.[7,8] He observed that we do not see in the same image point *at the same time* both yellow and blue, both red and green, or both white and black. Our responses are of the "either-or" kind.

A number of workers have adopted this response-oriented opponent-colors theory of vision. In recent years, Hurvich and Jameson[9–12] have contributed significantly to it by providing a wide variety of experimental results that have been used to verify much of Hering's basic proposal.

These are the two theories of color vision that have been most generally accepted: Young-Helmholtz and Hering. A number of modifications and variations have been proposed over the years, but they reduce basically to one or the other of these two theoretical structures. In keeping with the interests of their originators, workers whose principal forte lies in the realm of physics have preferred the stimulus-oriented Young-Helmholtz theory and those who concern themselves mainly with organisms and their responses have tended to embrace the response-oriented Hering theory.

Which is correct? If we are to interpret the results of experimental visual research and to apply this knowledge to the practical problems of color television, it would be well to seek an answer to this question. To find it, we must turn to that area of visual science which has been most dynamic in recent years: physiology.

Mechanism for Color Vision

The normal stimulus for vision is light energy formed as an image within the optical system of the eye. That optical system consists of several main parts (Fig. 1). First is the lens system. The outermost element of the lens system is the cornea which is a clear, protuberant, frontal extension of the covering structure of the eyeball. Light is transmitted from the cornea through a watery fluid called the *aqueous humor*. The iris is located within the aqueous humor and merges with a muscle complex which controls the diameter of the central, circular, aperture of the iris. This aperture is called the *pupil*. It serves as the aperture stop of the eye. Its diameter can be varied from about 2 to 8 mm, depending principally upon the level of illumination. In addition to varying the pupil diameter, the muscles of the ciliary bodies change the form of the crystalline lens (behind the pupil) to vary its effective focal length over a range of about 20 per cent in order to accommodate for changes in viewing distance. Finally, after passing through a viscous fluid called the *vitreous humor*, light is imaged on the retina.

The retina covers very nearly two-thirds of the rear of the eye. It consists of several parts, chief among which are the receptors. These are the approximately 150 million rods and 7 million cones. The rods are slender, elongated cells ranging from about 1 to 2.5 μm in diameter. They are found only outside the central or foveal area of the retina. They are unevenly distributed throughout an angle of about ±80° from the fovea. The cones, on the other hand, are virtually all located within an angle of less than about ±20° of the fovea. They are each about 1.5 to 4.5 μm in diameter and are very closely packed within the fovea. Immediately behind these receptors is a dark layer called the *pigment epithelium* which acts something like an antihalation layer. Immediately in front of the receptors lie several layers of neural cells through which light must pass before it reaches the rods and cones. These neural connections relay the receptor signals to the brain through the optic nerve which passes out of the rear of the eye through a small hole called the *optic disc*. We know it as the "blind spot," for it contains no light-sensitive receptors[13] but merely a sheath of nerve fibers which lead, eventually, to the occipital cortex or visual center of the brain. It is significant that, although there are perhaps a total of 157 million receptors, there are only about 1 million fibers in this optic nerve bundle. Obviously, some sharing or encoding must go on. Certainly each receptor cannot have its own private pathway to the brain.

So far, this description of the eye resembles that of a camera. There is a lens which forms a light-image on a photosensitive surface which, in turn, reacts to that energy. Although this may be a common simple analogy, it is a deceptive one. The optical systems and particularly the photosensitive mechanisms are very different in the two cases. As complex as a photographic emulsion is, the retina is immensely more complex.

The retina is considered to have about 10 principal layers.[14] These are illustrated very simply and schematically in Fig. 2. It will aid in understanding the visual process to trace the path of events resulting from stimulation by light through these various retinal layers.

First, the light passes through eight of the layers to the bacillary or receptor

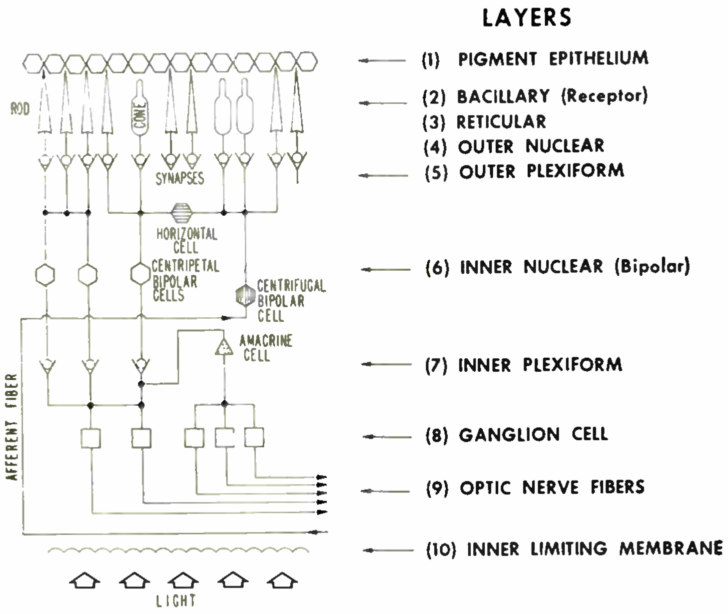

Fig. 2. Schematic representation of a human retina.

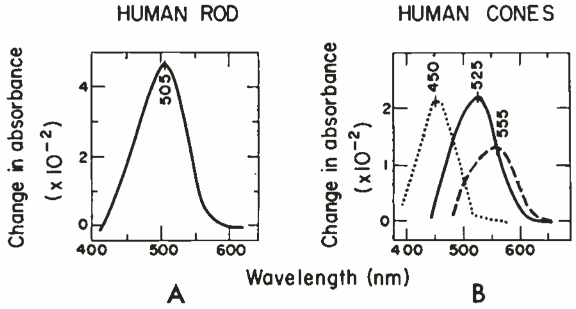

Fig. 3. Difference spectrum of rhodopsin in a human rod (A). Difference spectra of cyanolabe, chlorolabe and erythrolabe from human cones (B).

layer. There it is partially absorbed. In the process, the receptors are stimulated. Light-stimulation in all living organisms is mediated through photosensitive pigments within photoreceptor structures. The light is absorbed by the pigment whose structure is altered to provide an excitatory product affecting the receptor. The human retina is no exception to this general rule. Each receptor contains one of four different photopigments that may be bleached by the action of light and rejuvenated in the absence of light.

The first of these photopigments to be discovered (and for many years the only one known to exist) is a substance called *rhodopsin* or sometimes referred to as *visual purple*. It was first called "sehrot" in 1877 by its discoverer Franz Boll, but later Willy Kühne coined the appelations "Sehpurpur" and "rhodopsin" which are still used. The rhodopsin molecule is made up of opsin and 11-*cis* retinene. When light is absorbed, apparently only the retinene is isomerized, producing intermediate products. When enough light is absorbed to hydrolyze the molecule completely, the retinene breaks down into vitamin A, then wanders into the pigment epithelium which provides a supply of isomers that may be used to rebuild rhodopsin molecules.[15,16]

It was long suspected and finally proved that rhodopsin is the visual pigment of the rod receptors. Rhodopsin has been extracted from human eyes and its spectral transmittances have been measured. However, no one could be quite sure that the extracted substance was exactly the same as it had been *in vivo*. The question was finally answered through a recently developed technique for measuring the spectral transmittances of substances in the intact, living eye. This method of "retinal densitometry" relies on the fact that some of the light entering the eye is reflected back out again. The reflected light is partially absorbed by the various media of the eye. However, the photopigment may be bleached by sufficient quantities of light. Therefore, spectral reflectance measurements made before and after bleaching will differ according to the absorptive action of the photopigment. Such action spectra or *difference spectra* as they are called, show, for measurements in the periphery of the eye, a spectral distribution that closely parallels the distribution of spectral sensitivity for night vision (i.e., the psychophysically determined scotopic luminosity function).[17,18]

Similarity is not proof, however. The latter came in two ways. First, Campbell and Rushton[19] showed that the concentration of rhodopsin in the human retina varied according to a spatial distribution that was the same as the spatial distribution of the density of rods. Secondly, Brown and Wald[20] developed a microspectrophotometer so fine that it could be used to measure the difference spectra of individual rods in a living eye. Those results have been redrawn in Fig. 3A. The peak of the function occurs at 505 nm. This is very nearly the same as the 507-nm peak for the scotopic (night vision) luminosity curves derived by psychophysicists from heterochromatic brightness matching. Indeed, the entire curve is quite similar to the scotopic luminosity function.

Rhodopsin, then, is the rod pigment. But rods are not directly important for color vision or the perception of detail. They occur in parts of the retina that are not used for seeing detail and in which it has been shown that there is little or no color vision.[11,19,21] What, then, of the pigments for color vision?

These have been much more difficult to isolate. Work on lower forms of animals (fish, turtles, monkeys, etc.) eventually gave support to the idea that there *were* three other pigments besides rhodopsin in the retina. Improved biochemical techniques led to the isolation of two pigments: one absorbing frequencies of energy that we normally call "green," the other absorbing 'yellow-" or "orange-" appearing light. Similarly, the development of microspectrophotometric techniques for measuring difference spectra *in vivo* first indicated the presence in the human retina of two pigments other than rhodopsin.

It would be tempting to suppose that rhodopsin itself might be the third necessary pigment. But an ingenious psychophysical experiment carried out by Stiles in 1939 showed that this could not be the case.[22] He proved that the blue receptors, whatever they might be, exhibit a directional sensitivity to light known as the Stiles-Crawford effect.[23] Rods do not show this effect. As we have seen,[18,19] rhodopsin is associated with rods. Hence, rhodopsin cannot be the missing pigment for color vision.

Perseverance finally led to the "blue-" absorbing pigment in spite of its minute concentration levels.[24-30] The difference spectra of the three color vision pigments found in man are depicted in Fig. 3B. There is still some question about the precise shapes of the spectral absorptance curves of these pigments, but the distributions shown in Fig. 3B are representative of recent measurements. Rushton,[31] who is largely responsible for the retinal densitometry technique that led to the isolation of these pigments in man, has called them *erythrolabe*, *chlorolabe* and *cyanolabe* for those pigments having peaks at about 555 nm, 525 nm and 450 nm, respectively. They are definitely associated with cones which have long been known to be the receptors responsible for color vision. They are probably similar in structure to rhodopsin. Since a vitamin A deficiency results in a loss of both rod and cone function, it seems likely that all the photopigments of the retina have the same retinenes but different opsins.[20] Their concentrations are very low and the changes with light-bleaching very small. The manner in which they induce a response in the receptors is not yet well understood. However, there is a three-receptor basis for color vision, as postulated by the Young-Helmholtz theory.

Unfortunately for the staunch supporters of that theory, the photopigments are not simply "red-," "green-" and "blue-" absorbing elements. Figure 3B shows clearly that the spectral absorption of the erythrolabe pigment overlaps that of the chlorolabe to a large extent. The peaks are much closer together than psychophysical color-matching functions interpreted in terms of the Young-Helmholtz theory might suggest. There is, to be sure, differential spectral absorptance involved. But it is of such a nature as virtually to require that some sort of encoding be performed in order to extract "red," "green" and "blue" information. The signals could not pass directly to the brain as R, G, B information, even if there were a sufficient number of fibers in the optic nerve.

If we now return to the schematic representation of the retina in Fig. 2, we may see that encoding does, in fact, take place. Actually, the receptors (in layer 2) converge through nerve endings called *synapses* in the outer plexiform layer (5) onto the bipolar cells of the inner nuclear layer (6). There are basically three types of these bipolar cells. The centripetal bipolar cells are essentially amplifier-mixers that gather signals from a number of receptors and pass them on to a higher neural level. There may be some centri-

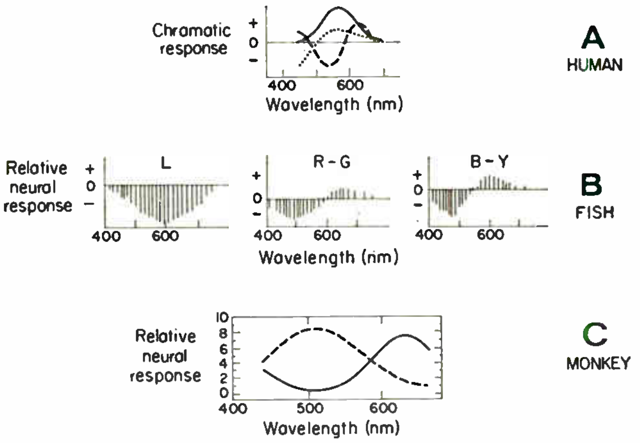

Fig. 4. Psychophysical determinations of human chromatic response as a function of wavelength of stimulation (A). Measured electrophysiological responses of a goldfish outer plexiform layer as a function of wavelength of stimulation (B). Distribution of amplitudes of electrophysiological responses of the lateral geniculate bodies of a macaque monkey as a function of wavelength of stimulation (C).

petal bipolars connected to single receptors in the central foveal pit of the retina, but generally the connections are more diffuse. In the periphery, for example, as many as 100 rods may converge on 17 bipolar cells.[32] In addition to these convergence interconnections, there are receptor interrelations through horizontal bipolar cells. Finally, the centrifugal bipolar cells provide feedback directly from higher brain centers carried through afferent fibers. The inner nuclear layer therefore provides for mixing, amplification, and feedback.

These signals from the bipolar cells pass on through the synapses of the inner plexiform layer (7) to the ganglion cells (layer 8). Here, again, there is convergence. Those 100 rods converging on 17 bipolar cells may finally converge on a single ganglion cell.[32] Several of these ganglia may be interconnected through a feedback loop, including an amacrine cell. Finally, the output of the ganglion layer passes out of the retina through the optic nerve fiber (layer 9) on to the geniculate bodies, optic radiations, and eventually to the occipital cortex of the brain.

The organization of the retina is, then, both chemically and electrically complex. There are several stages of interconnection, of feedback, and of amplification. There are interconnections among dissimilar receptors. Rods and cones interact.[21,33,34] Dissimilar cones interact.[29,30,35] There is also evidence that similar cones interact.[36] These interactions are both inhibitory and excitatory. The electrical system is nonlinear as well as complex. Although the amplitude of the early potential may be linearly proportional to the number of photopigment molecules broken down,[37] this linearity is lost by the time the bipolars are activated.

Many aspects of these signals have been measured. In lower organisms (and even in cats and monkeys), measurements have been made at various levels within the retina and throughout the neural pathways. The most striking aspect of these measurements is their polarity-opponent-response nature. In Fig. 4B the neural pulses elicited as a function of wavelength in a goldfish outer plexiform are depicted. Three kinds of discharge patterns have been noted. These appear to form a "brightness" signal, a "red-green" signal, and a "blue-yellow" signal.[38] The same kind of opponent-response patterns appear in primates also.[39] Figure 4C illustrates the general scheme of differentially polarized neural responses found in the lateral geniculate bodies of macaque monkeys.

Measurements of this kind bear an impressive similarity to the chromatic response characteristics of human observers (Fig. 4A), as measured psychophysically by Hurvich and Jameson.[40–46] Their response measurements provide experimental support for the opponent process postulated by Hering. The neurophysiological measurements, which are so similar, also support this aspect of Hering's theory of color vision.

Which theory is correct, then? Physiological data have shown that there is both a trichromatic and an opponent-response basis for color vision. It would be simple to say that both theories are correct. It would also be inaccurate. The three-receptor pigment system suggested by the Young-Helmholtz theory does exist. But it is not quite of the form postulated by that theory. Also, its output certainly is not transmitted unaltered to the brain. Color perception is not based on a comparison of R, G, B information. Similarly, the opponent-response mechanism postulated by Hering does exist at the neural level. But even though Hering was conservative in postulating mechanisms by which such responses derive, he did suggest a receptor mechanism (the neural "Sehsubstanz" as distinct from the photosensitive "Empfangstoffe") to yield white-black as well as red-green and blue-yellow responses. Although there is no doubt that such a scheme exists at the perceptual level, the physiological evidence for the white-black mechanism is not as clear cut as in the case of the opponent chromatic responses. There is both temporal and lateral spatial inhibition of excitatory responses at the neural level.[47,48] In the foveal region of the retina, however, the excitatory response may itself be a combination of responses from the trichromatic receptor mechanisms.[25]

In one sense, then, both theories are correct and in another sense both are wrong. The amazing fact is that they are both so close to parts of the truth. The earliest levels, at which the system's sensitivity is set, shows interconnection between similar receptors. Later stages involve interactions among dissimilar receptor-signals. Two principal kinds of information channels appear to exist: an opponent channel and a nonopponent kind. The latter involves spectrally nonopponent connections of receptors that all have the same type of effect; all excitatory or all inhibitory. Perceived brightness is probably related to the extent to which these cells are activated. Overlaid upon this is a spatial organization in which different areas show a *spatially opponent* response in a spectrally nonopponent manner.[11,49] The other kind of information channel involves both similar and dissimilar, and excitatory and inhibitory effects arranged in a spectrally opponent manner. Hue perceptions appear to be related to the response characteristics of these cells rather than to the spectral absorption characteristics of the cone pigments. Saturation is probably a function of the relative extent to which opponent and nonopponent cells are activated. The entire mechanism involves nonlinear gain, response attenuation, and feedback gain control.

Adaptation

As we have seen, the process of visual perception begins with the absorption of light causing a change in the spatial arrangement of a retinene molecule; what a stereochemist would describe as isomerization from an 11-*cis* to an all-*trans* configuration. Everything else proceeds from here. Further chemical activity, neural excitation, perception itself follows from this stage of molecular rearrangement.

Adaptation has been defined as sensitivity, i.e., the ability to respond. Is adaptation determined, then, at the level of these photochemical reactions? Although this was thought to be true for many years, the answer apparently is no.

First of all, the concentrations of photo-

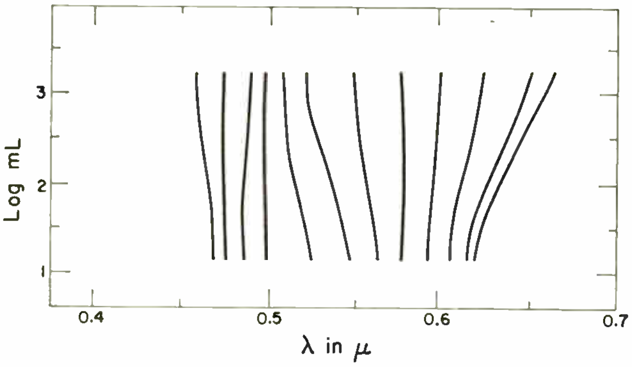

Fig. 5. Isohue contours, showing wavelengths of light energy required to maintain constant hue perception as a function of luminance (shown on the ordinate).

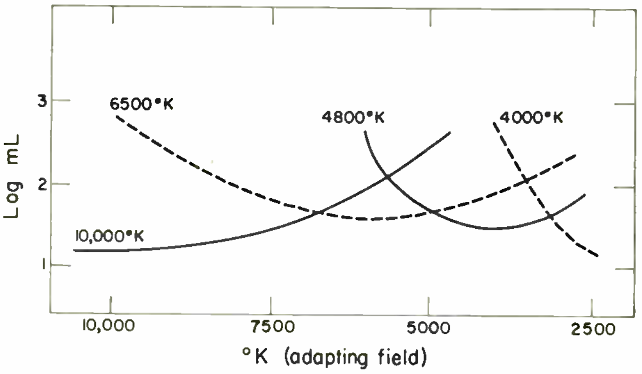

Fig. 6. Log luminance (in mL) required to evoke a white sensation in a 1-s presentation of an 11.7° target of either 4,000, 4,800, 6,500, or 10,000 K as a function of the color temperature of a 15-mL adaptation illuminant.

pigments are quite low. Rushton has estimated that the optical density of the chlorolabe and erythrolabe pigments is not more than about 0.2[26] and that of cyanolabe is much lower, probably only one-sixth of this level.[25] The change in optical density with bleaching is only of the order of 0.01 to 0.03.[20] Tremendous changes in capacity to respond would have to be represented by minute changes in photopigment concentrations. More important, however, the visual system is nonlinear beyond the level of the photochemical reactions. Psychophysical research shows that adaptation changes also are nonlinear. The interconnections and feedback required for such nonlinear gain control do not occur until the inner nuclear layer of the retina. Although sensitivity changes are initiated by photochemical action, the sensitivity itself must be adjusted at a low neural level. Adaptation is not simply a result of bleaching photopigments and certainly it is not merely the slow process of change to durative stimulation that many of the earliest workers thought it to be. Adaptation is a dynamic process (apparently with several time constants) by which the visual mechanism is coupled to the changing input presented to it.

Adaptation is not complete, however. The feedback control does not provide complete correction, i.e., it is not the equivalent of ac-coupling. Complete adaptation is not necessarily in the best interests of the organism. Although we are capable of responding over wide ranges of luminance and chromatic differences, it is helpful to retain some capacity to perceive differences in level and quality of illumination.

This residual lack of adaptation has practical implications for color television. It influences, for example, the appropriate choice of correlated color temperature in receivers and monitors. One of the assumed aims of the system is the capability for producing "white." Although the term "white" has been used to refer to properties of objects and of lights, what we really mean by its use is that we *perceive* something as bright with no trace of hue. In other words, the red-green and yellow-blue signals should both be zero. But if adaptation is not complete, how can we choose a color temperature that will elicit such a response? It would seem that only one quality of energy could be perceived as white. Fortunately, the nonlinearities of the visual mechanism tend to alleviate our problems.

The nonlinearities and gains of the white-black, red-green and yellow-blue channels are not all identical. A manifestation of this fact has long been known as the Bezold-Brücke effect (Fig. 5) where the wavelength of a spectral stimulus must be varied to maintain the same hue perception when the intensity of stimulation is varied. This result can be predicted quantitatively as a result of differences in gain or linearity of the visual "chrominance" channels.[50] Similarly, the fact that even spectral stimuli may appear white at high enough luminances is explicable in such terms or in terms of differences in white-black and chrominance thresholds.[51] In other words, even though the ratio of photochemical reactions remains the same, the ratio of neural chrominance responses differs somewhat with the magnitude of reaction. It is not surprising, therefore, that Hurvich and Jameson, in a series of psychophysical studies of white,[51–53] found that over a wide range almost any color temperature may elicit a white sensation, depending upon the luminance of the stimulus. Their results also show that viewing time, size, and the level and quality of ambient adaptation illuminants are also important in determining the amount of energy of a given color temperature that is needed to elicit a white sensation.

This is illustrated in Fig. 6, where some of the data from one of Hurvich and Jameson's observers have been smoothed and replotted. That graph shows the luminance (in log millilamberts) required to evoke a white sensation for a 1-s exposure to an 11.7° test field at each of four different color temperatures as a function of the color temperature of a 15-mL adaptation luminance. If adaptation may proceed from any reasonable level of color temperature (2,500 K to about 10,000 K, say), it is apparent that a medium color temperature (perhaps about 6,500 K) would be preferable to either a low or a high color temperature. Although low or high color temperatures could be used to produce a white sensation, they would require more luminance than a medium color-temperature stimulus. Stimuli in the neighborhood of 6,500 K are more efficient in terms of "white-producing" capacity, given a reasonable range of qualities of adapting illuminants.

This fact is significant for color television where the maximum screen luminance that may be achieved at present is in the neighborhood of 25 mL. A 6,500 K color temperature is well within the region of most frequently observed daylight correlated color temperatures[54] (about 5,500 K to 6,800 K). It is interesting to note, incidentally, that the locus of chromaticities for the various phases of daylight differs from the locus corresponding to Planckian radiators (i.e., blackbodies) in precisely the same manner as does the locus for light sources that have been found over the years to be preferred.[55] The implication is that a daylight 6,500 K source would be a better aimpoint for color television than a 6,500 K Planckian radiator. All these results suggest that the ecology of the human organism with its environment is, indeed, highly developed.

This is apparent also from the fact that we may respond to levels of illumination over a ten-billion to one range; from about 10^{-5} to 10^5 mL. The adaptation mechanism of our visual system allows us to discriminate among brightnesses over a range of about one thousand to one virtually anywhere within this 10^{10} overall range.

Overlaid on this capacity to respond is our ability to organize perceptions in terms of experience. For example, when we go from the high luminance and high color temperature of daylight to the low luminance and low color temperature of tungsten light, the same white paper appears "white" in both situations. If we look carefully or analytically, we may note that it is bright blue in daylight and darker yellow in tungsten, but we are not normally analytical about our perceptions. We use them mainly to tell us things about objects; as a guide to the world about us. We tend to see the same objects in much the same way unless our perceptions are so unusual that we cannot discount minor variations in them. This process of "seeing" things in much the same way under different conditions is not one which requires deliberation. It is essentially an automatic reaction or maximizing of the information-retrieval process that is part of our perceptual capabilities. Some have called this a sort of *cerebral adaptation*. What we expect to see influences what we do see.

A dramatic illustration of the influence of expectation on perception has been shown in experiments where the perceived colors of stimuli in the shapes of familiar objects have been compared with the colors perceived for those same stimuli presented in meaningless shapes.[56–58] For example, two targets fashioned from the same piece of green cloth, one in the shape of a donkey and the other shaped as a leaf, led to two different color perceptions under exactly the same viewing conditions. The leaf was perceived as more green than the donkey simply because we expect leaves to be green but know that donkeys should be gray. What we remember about an object can influence the way it appears to us. These remembered color attributes have been called *memory colors*.[59,60] Experiments have shown that people's memory colors for familiar objects are quite consistent.[61] There is a tendency for people to remember what is perhaps the most striking attribute of the appearance of an object[62,63]; a process which is distinctly different from the general ability to remember colors.[64]

These memory colors influence the preferred reproduction characteristics of objects. That is, we prefer to see an image in which the color appearance of a familiar object agrees with our memory of it rather than with the actual colorimetric nature of the original object.[65–67] Even our color preferences for natural objects differ from the average colorimetric values of those objects[68] if they are sufficiently familiar to have enabled us to form definite opinions about them. Exact colorimetric reproduction of flesh, for example, is not acceptable in a color picture. To be acceptable, flesh reproductions must be somewhat more saturated and yellower than natural flesh. They must match the memory color for flesh. Such a paradox may be familiar to those who have worked meticulously to produce a commercial in which the colorimetric values of a product package are faithfully reproduced, only to have the film rejected by a sponsor because "it isn't the proper color." The sponsor knows what the package should look like; his memory may not be accurate but it is firmly implanted in the memory cores of his brain. What needs to be done is to match that memory color; to make the small image on the screen elicit the appearance that is associated with the product. Obviously, then, the objective of a color television system cannot be simply to reproduce the colorimetric values of objects.

But if that is not the object, then what is? Are we faced with anarchy, or is there some rational system to the requirements for optimum color reproduction? Recent work in these Laboratories, work which has related people's preferences for images to the ways in which they respond to the stimulus elements of those images, suggests that there is a system. The system involves not reproduction of energy characteristics but, rather, reproduction of *responses*. Accordingly, the quality and objective of a reproduction system can be predicted if the viewer's responses can be predicted successfully. Therefore, response prediction is very much germane to color television.

Response Magnitudes

Let us assume that we have a small circle of light to which we add some more light. In particular, let us add a very small amount of light. Sometimes we will see an increase in brightness if we add enough light. Sometimes we will not perceive any change in brightness. If this process is repeated many times with a large series of increasing luminances added to the original circle, we shall find that at some level of incremental luminance the probability of perceiving a just-noticeable increase in brightness is about 50%. This level of incremental luminance is called the *differential threshold* or *limen*. It has also been called the level of *just-noticeable difference* (JND). As far back as 1760, Bouguer found that the required luminance increment (ΔL) for a JND was very nearly proportional to the original luminance level (L) of the spot.[69,70] In other words, $\Delta L/L = k$; a constant. In 1834 Weber extended this proportionality to other senses and it has become known as Weber's law. This law holds over a wide range of luminances but fails at high and low levels. Fechner, however, assumed that if a constant were added to account for the fact that we do not see "black" in the absence of light, then Weber's law would be strictly true. He went one step further. He proposed that a difference in perceived brightness (ΔB) was proportional to $\Delta L/L$, i.e., $\Delta L/L = k(\Delta B)$. He then reasoned that the small difference (Δ) could be replaced by a differential and the equation could be integrated to represent the manner in which brightness increases as a function of luminance. Such an integration yields the equation:

$$B = a \log L \tag{1}$$

According to Fechner, then, perceived brightness *differences* are proportional to luminance *ratios*. Plateau,[71] on the other hand, argued that not differences but brightness *ratios* were proportional to luminance *ratios*. Brentano[71] agreed with this, in effect, when he proposed that Weber's law held for both the stimulus and the response. Thus, according to Plateau and Brentano, $\Delta L/L = k(\Delta B/B)$. When this expression is integrated, we have the equation:

$$\log B = a \log L \cdot \tag{2}$$

Equations (1) and (2) represent a dichotomy of conceptual approaches that exists to this day. Equation (1) states that brightness increases as the logarithm of luminance. Equation 2 describes brightness as a power function of luminance. Both cannot be true at the same time.

It is important to remember that Eqs. (1) and (2) are the results of integration after certain assumptions have been made about data that relate to *very small* differences in brightness. Those data may be perfectly applicable to such small differences, but their integration or summation may not be wholly justified.

Various attempts have been made to provide a theoretical framework for brightness discrimination which could shed some light on this question. Basically, three kinds of theoretical formulations have been proposed. These have been categorized as photochemical, statistical and quantal theories.[11] The photochemical theories generally assume that a constant perceptual difference results from either a critical difference in concentration of bleaching products of the photopigments or a critical increase in the rate of change of these products. The statistical theories involve basically the assumption that the sensory effect is related to log L by a normal probability integral. Thus, the basis for discrimination lies in the comparison of the statistical effects of two luminances. The quantal theories are somewhat similar except that account is made of the probabilistic nature of the stimulus itself. None of these approaches at present provides a satisfactory theory of brightness discrimination. The basis for relations between threshold differences in brightness and suprathreshold differences remains uncertain. Hunt[72] has pointed out that noise at the differential threshold may make it impossible to extend satisfactorily JND information to account for larger differences in brightness.

In fact, experiments have shown that large brightness differences are not very well predicted by summing JND's. When we look at two stimuli that differ only slightly, there is a tendency to adapt to some function of their average value. When so adapted, the perceived difference between them will tend to be larger than if we were adapted in some other way. This fact is basic to a theory of perception that has been developed by Helson,[73] who emphasizes the importance of taking the level of adaptation into consideration. Responses are then accounted for as negative and positive deviations from the adaptation level (in a manner somewhat reminiscent of Hering's approach to perception). This process, a sort of perceptual homeostasis, finds much support in experimental evidence. Hurvich and Jameson,[48,74] for example, point out that the brightness of the same point in an image may either increase or decrease as the illumination is increased. The telephone becomes blacker just as a paper becomes whiter when the room lights are turned on. Now, if brightness were simply proportional to the logarithm of luminance, this could not be so. Equation (1) requires an additive constant (which is a quite permissible operation) as well as the multiplicative constant, both of which must be varied with illumination level to account for such results. Similarly, Eq. (2) also requires two variable constants to account for such effects. There is, then, no *a priori* reason or theoretical basis for deciding whether luminance ratios bear a proportional relation to brightness differences or to brightness ratios.

If we therefore disregard the relation between threshold and suprathreshold differences and concentrate upon direct estimation of large differences, we are faced with the choice of treating response data as differences or as ratios. Stevens,[75,76] who is the leading proponent of the power function for describing the relation between stimulation and response, points out that many of the difference scales are simply extensions of the magnitudes of errors in response, not the magnitudes of the responses themselves. When two stimuli (let us call them A and B) are very similar, they will appear to stand in different relations to each other at different times. Sometimes they will appear equal. Sometimes A will appear larger than B and sometimes smaller than B. Thurstone[77–79] pointed out that the broadness of the distributions of such responses may be taken as a measure of the extent to which the stimuli appear similar or different. His "law of comparative judgment" is used extensively in determinations of differences among responses to stimuli. A related "law of categorical judgments,"[79] where similarity is measured by placing like stimuli in the same category, is also used frequently. However, both schemes operate upon the dispersion of responses, not upon the responses themselves. A common example in color television would be the expression of a "color" difference in terms of multiples of the chromaticity differences indicated by the MacAdam[80] ellipses. These ellipses represent the standard errors of color matching. A scale of differences built upon them is what Stevens[71] has called an "error" scale.

Instead, Stevens would attack the problem head-on by estimating the magnitude of response directly. He finds that when this is done, the average observer provides data that relate his estimates of his own responses to stimulus magnitudes in a manner that may be described by a power function.[81] He has argued that, since a power function also describes the results of observers matching responses on one sensory continuum to their responses on another sensory continuum (e.g., loudness *vs.* brightness, etc.), the power function is correct. That is, people respond in ratio terms to stimulus ratios not in difference terms. However, this argument is a necessary but not sufficient condition for determining correctness (see Appendix). The question of differences or ratios remains open. Nonetheless, such direct magnitude estimates have yielded power functions for a wide variety of attributes, including brightness, saturation and hue.[82–86]

The power function is represented by a straight line when plotted in log log coordinates (e.g., log brightness *vs.* log luminance). Hurvich and Jameson[47] have pointed out that response interactions beyond the level at which sensitivity is set would be expected to result in a nonlinear response function in log log coordinates when spatially complex images are viewed. Just such a result has been found by Bartleson and Breneman[87] for brightnesses in complex scenes such as photographic prints and transparencies. They found that brightness estimates under such conditions could be represented by a power function plus an exponential departure term:

$$\log B = \alpha + \beta \log L - \gamma [\exp(\delta \log L)] \quad (3)$$

where α, β, γ, and δ are parametric constants relating to adaptation and induction conditions.

These data have been used to analyze the reproduction characteristics of optimum images.[88] Such studies show that optimum reflection prints, projected transparencies, and monochrome television all have one thing in common. Each, under its viewing conditions, provides 1:1 reproduction of brightnesses relative to a reference white. That is, B_i/B_w (where the subscripts w and i refer respectively to the reference white and any other scene element) is the significant appearance attribute. Absolute brightness reproduction influences absolute quality, but for any one set of physical limitations (e.g., inability to provide adequate screen luminance) that image which permits reproduction of relative brightnesses is considered best.

The transfer function of the physical system that produces this optimum image is related to the differences among brightness perception functions for the viewing conditions used in evaluating the image compared with that corresponding to our remembered reference for daylight illumination. The optimum tone-reproduction gradient (i.e., the function relating the logarithms of original or input luminances to output luminances) for reflection prints was found to be about 1.0. Here, both original and reproduction are viewed with an illuminated surround. Projected transparencies (with a dark surround) are optimum when the tone-reproduction gradient is about 1.5. The gradient of the optimum transfer characteristic from original scene to final image for television (with its typically dim surround) was found to be about 1.2.

Such transfer functions, under appropriate viewing conditions, lead to the reproduction of relative brightnesses. That appears to be the criterion for optimum tone reproduction. This is substantiated by the fact that departures from that condition (measured as brightness deviations from the relative brightness aim) can be used successfully to predict decrements in quality.[89] Thus, the objective of a tone-reproduction system is completely explicable in terms of *responses* and considerations of memory references. Regardless of the kind of imaging system involved, the object is simply to provide reproduction of relative brightness responses.

This work has not yet been extended to chromatic reproduction. However, the relativity principle involved in tone reproduction is reminiscent of Evans's "consistency principle,"[90] which states that a primary requirement for good color reproduction is that the fidelity with which all colors are reproduced be approximately the same. This has been paraphrased to say that all colors should be about equally good or equally poor representations of those in the original scene. It might better be called a *relativity principle*. The elements perceived within an image need not be absolute matches for the perceptions that would obtain in the original but, rather, must satisfy the need for relative congruence with the observer's remembered frame of reference. It seems quite likely that chromatic reproduction may also be found to involve such a relativity requirement.

In any event, tone reproduction is a very important aspect of color images. Bartleson[91,92] has shown that the quality of color transparencies depends heavily upon screen luminance. As the luminance is increased to the point where brightness reproduction obtains, quality reaches a maximum. Similarly, with reflection prints[93–95] and with large transparencies on an illuminator[96,97] (a situation that more closely simulates color television), brightness plays a highly significant role in the quality of color reproduction.

All these situations involve quite different conditions of viewing. Viewing conditions have been found to influence critically reproduction quality.[87,88,95,97] Not only the amount and kind of illumination provided for the image but, also, the amount and kind of ambient illumination are important. Both may influence the sensitivity of the visual mechanism. The surround also plays a significant role by virtue of its ability to induce response interactions throughout the visual pathways.

Visual Induction

The lateral interconnections depicted schematically in Fig. 2 indicate that the response in one area of the retina will be influenced by the response in surrounding areas. The visual effect of this phenomenon is familiar to all. A gray paper viewed against a white surround will appear darker than when it is surrounded by black velvet. This has often been called *contrast*, but it is more properly referred to as *induction*.

In recent years, a great deal of interest has been exhibited in induction studies, particularly in connection with induction over small areas. Considerable investigation has been devoted to the study of fine detail or microreproduction. Much of this work has been stimulated by the success of modulation transfer analyses of physical optical systems. Attempts have been made to determine "the spread function" of the entire visual mechanism, as distinct from the optical spread-function of the eye alone. The line spread-function (i.e., the effective spatial distribution of response along a cross section of stimulation by an infinitely narrow line), when convoluted with the spatial distribution of stimulus energy, should yield a spatial distribution of responses. The Fourier transform of the spread function results in a spatial frequency weighting function which is, effectively, the spatial frequency response of the system to sinusoidal stimulus variations of a given modulation ratio. Typically, this kind of information has been deduced for the visual mechanism from psychophysical studies of either modulation thresholds or luminances corresponding to response matches across stimulus gradients.[98–101] It is important to note that neither technique describes responses as such. The resultant "spread functions" show a variety of negative lobes associated with positive functions, depending upon the target and viewing conditions involved in the experiments. The effect of such a function when convoluted with a change in luminance gradient (as in Fig. 7A) is to provide "overshoots" or damped oscillations similar to the effect of physical "crispening" in television images. Indeed, light or dark borders may be seen in the image, depending upon the sign of the second derivative of the spatial luminance distribution.[102] Even though the luminance along a line continues to increase, it is possible to perceive a decrease in brightness as a result of spatial interactions among positive and negative neural events.

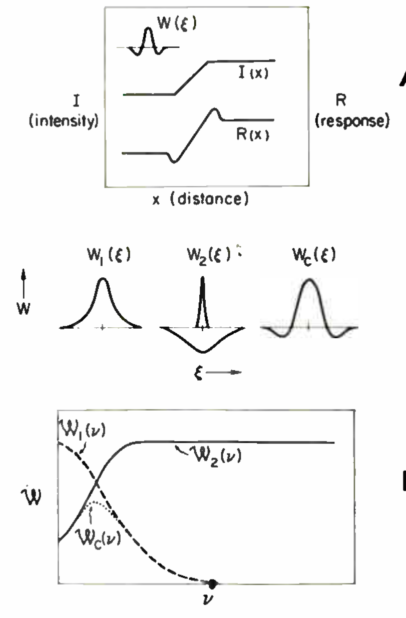

Fig. 7. Spatial distribution of responses [$R(x)$] to spatial distribution of stimulus energy [$I(x)$] as a result of convolution of $I(x)$ with spread function $W(\xi)$ (shown in A). B shows, at the top, the optical spread-function of the eyeball [$W_1(\xi)$], an effective retinal-neural function [$W_2(\xi)$] with both positive and negative portions, and the composite function [$W_c(\xi)$] of $W_1(\xi)$ and $W_2(\xi)$. The lower portion of B illustrates the corresponding spatial frequency weighting functions [$\mathcal{W}_i(\xi)$].

As early as 1865, Ernst Mach attempted to describe mathematically the interplay of excitatory and inhibitory neural responses.[103] He postulated a narrow spatial distribution of excitatory response (the response of a single receptor element) and a broader distribution of negative inhibitory responses (the opposing interaction of neighboring receptor elements). This is illustrated in Fig. 7B. These opposing negative and positive responses were, he suggested, integrated to yield a pattern of complex responses throughout the visual field. Mach proposed a nonlinear model to describe the stimulus-dependent integration of responses,[103] as did Fry in 1948.[104] Other stimulus-dependent models have used linear equations[105,106] and at least two proposals have been made for response-dependent models with simultaneous linear equations.[107,108] The latter approach more closely parallels considerations of other opponent-response mechanisms of vision.[109] Account should be taken of the fact that incremental opponent induction effects are reciprocal. An influence of the focal area on the surround must be assumed as well as the effect of the surround response on that of the focal area.

Since these responses are related to the stimuli in nonlinear and complex ways (indeed, spatial interactions may not even be isotropic[110]), it is difficult to evaluate the so-called "spread functions" derived from modulation transfer data. The Fourier transformation presupposes a linear system or a unique spread function. As we have seen, the visual mechanism is not linear. There is no single "spread function" for the *in toto* mechanism. The whole concept of modulation transfer may not even be applicable to the total visual mechanism or, if it is, it will only be applied satisfactorily after such time as the nature of the nonlinearities, interactions, and functional variations are themselves understood to the extent that they may be subject to computational transformations that provide the needed linearity.

Although it may not be possible to describe mathematically the dynamics of frequency response and interaction, we can examine empirical evidence. There is ample evidence of the influence of detail characteristics on the appearances of images. A sharp image will appear to have higher contrast than a less sharp image. Conversely, a high-contrast image will appear sharper than a low-contrast one.[111] These facts have been used to derive an operationally useful equation which predicts, reasonably well, the apparent contrast of an image as a function of its tone-reproduction and spatial frequency characteristics.[112]

The fineness of detail reproduction also influences the color saturations perceived in an image.[113–117] The less sharp the border of an area, the lower will be its perceived saturation. This is true even though the colorimetric purity may remain constant.

These are facts that have important implications for color television. The relatively unsharp image of the television screen will appear lower in contrast and have less chromatic saturation than an equivalent photographic image, for example. The luminance and purity gain must be higher in a television system if it is to provide the same level of contrast and saturation as a sharper imaging system. The penalty for this is reduced signal-to-noise ratios.

At the same time that the lack of sharpness penalizes the television system, the structure of the raster lines that comprise the image also works to the detriment of image quality. Earlier it was pointed out that similar as well as dissimilar signals may be combined at the neural response level of the visual mechanism. The relatively fine line structure of the raster image provides a spatial situation in which similar signals can be averaged to reduce further contrast and saturation and to decrease hue differences. This kind of phenomenon is known as *assimilation* or as the *von Bezold spreading effect*, after the German scientist who first reported it in 1874.[118]

Recently, Helson and Rohles[119] have studied assimilation systematically and have found that the reduction of appearance differences between adjacent stimulus elements is greatest when the line elements are separated by the smallest distances. This might be in part attributable to stray light in the eye[120] but it appears to involve considerably more than that alone.

In considering alternate light and dark lines, Hurvich and Jameson have summarized the general mechanism for assimilation as follows[118]:

> "Here too, we have evidence that light stimulation of a given part of the retina is associated with an action (*excitatory*) process and that it also brings about a reaction (*inhibition*) in adjacent parts of the visual field . . . With spatial differences in stimulation, the interplay between these two processes across small spatial extents may be such that the action . . .of each stimulus is greater throughout a limited spatial extent, and then as the different stimuli are further separated, the reaction process . . . from the stronger stimulus takes over. Thus the net effect on apparent brightness of spatial stimulus increments is a brightening for very small spatial extents, through averaging for slightly larger ones into darkening contrast . . . Clearly, there is a continuum of effects that depend upon the precise balance between processes of complementation and opposition, and this balance depends very critically on the spatial stimulus parameters." (*italicized words added*)

These small-area induction effects tend to operate to the detriment of the television system because of the physical characteristics peculiar to its image. However, there are other equally significant large-area induction effects that may either degrade or enhance television quality, depending upon the conditions of viewing.

In general, the juxtaposition of stimulus areas that differ significantly tends to enhance appearance differences.[121] Areas which evoke high and low brightness will, when juxtaposed, appear respectively brighter and darker than when viewed in isolation. Similarly, differences in saturation and hue will be enhanced when stimuli are juxtaposed. Recently,[122] it has been shown that the extent of enhancement is a predictable function of both the chromatic differences and degree of juxtaposition of stimulus elements within the visual field. When more than a single inducing element exists, the effects involve interactions among inducing elements themselves as well as between focal and inducing areas.

The complexities of relations between physical characteristics of stimuli and the responses they elicit under complex-field induction conditions was illustrated dramatically by Evans[123] in 1943 and more recently by Land.[124] These demonstrations illustrated the long-known fact that a wide variety of hues can be perceived in a suitably complex image with only two (rather than three) additive primaries. Although Land has claimed that this illustrates novel aspects of his unorthodox theory of color vision,[8] others have pointed out that what is involved are merely striking demonstrations of induction and adaptation effects.[109,125–128]

These effects illustrate again the opponent nature of our responses. The enhancement of color differences brought about under such conditions points to an underlying mechanism for opposition. As Helson's and Judd's work[73,129–133] has shown some years ago, this makes it possible even to perceive a limited gamut of hues throughout a *gray scale* if the viewing conditions are appropriate. In one of their experiments they illuminated a scale of neutrals, presented against a neutral background, with chromatic illumination. They found that those "grays" that were brighter than the surround did not appear gray but, rather, evoked the color of the illuminant. Conversely, those elements that were darker than the background appeared in a hue complementary or opposite to that of the illuminant. Only those areas with the same reflectance as the background appeared to be without hue, i.e., truly gray. This is an illustration of the fact that a variety of hues can be produced with only a *single* primary, provided the image and viewing conditions are appropriate.

Induction effects are spatially and chromatically complex, then. They depend upon the sizes of elements in the image, the relation of the image to its surround, and the brightness and chromatic relations within the image and with respect to the surround as well.

These facts are important to television reproduction. It has been shown that it is the *appearance* of the image (not the colorimetric character) that is important to reproduction quality in the face of chromatic induction. The chromaticity required for optimum simulation of flesh colors, for example, is different, depending upon whether a face is surrounded by red, green, blue or neutral areas. In all cases, the chromaticity required is such as to provide a perceptual match to the memory color for flesh when account is taken of the induction effect provided by the immediate surround.[134]

Induction between image and surround also affects the appearance and quality of reproduction.[87,88,97] Color television images are viewed in a variety of ways. The distances at which they are viewed vary significantly and this influences their appearances. The brightnesses and saturations perceived in the image depend, in part, upon the visual angle it subtends.[135,136] Since apparent sharpness and detail perception also depend upon viewing angle, the opposition and complementation arising from microreproduction characteristics also will differ with viewing distance. The luminance and chromaticity of surrounding areas exert their influence too, and this also will vary with viewing distance. When the surround is bright, the contrast of the image will be higher and its overall brightness lower than when the surround is dark. The difference in color temperature between image and surround will have a variable effect on the image, depending upon both the magnitude of difference in chromatic quality and the difference in average luminances.

In short, the same physical television image may have any of a number of different appearances, depending upon the conditions of viewing. This very important fact seems to have received little consideration in the television industry. It warrants much more careful study.

Conclusions

This superficial examination of the process of color perception has shown that the viewer is an important and extremely complex part of the television system. We see that he must be considered carefully in making the choice of every physical parameter in the total system. The entire chain will succeed or fail upon what he sees. What he sees or perceives depends in a complicated manner upon many factors.

The viewer almost never compares a color television reproduction with the original. Instead, he must rely upon his memory of the original or similar scenes whenever he evaluates the reproduced image. It has often been assumed that one of the objectives of a color television process should be to reproduce exactly the colorimetric properties of the objects televised. However, it is now generally recognized that this requirement need not be met in order to produce an excellent color picture. Indeed, there is considerable doubt that such exact colorimetric reproduction is even desirable. After all, color television pictures are in no way "reproductions" of original objects or assemblages of objects. The purpose of a color television picture is to *suggest* the appearance of the original scene in such a way as to please the viewer. This distinction between reproduction and simulation is an important one for television.

In recognizing that a color television image can never be physically more than a two-dimensional representation of a three-dimensional scene, we accept the inevitable fact that we cannot duplicate the appearance of the original by attempting merely to produce exactly the same tristimulus values at any point throughout the reproduction as existed in corresponding points throughout the original. The color television image is two-dimensional. It occupies a different visual angle than did the corresponding portion of the original scene and it is surrounded by environmental stimuli of different character than was the case with the original. Also, it is viewed with different illumination and under different conditions of adaptation and of attitude than in the original. All of these factors influence the appearance of the image, as we have seen. Finally, the color television image is recognized as a separate entity or object in its own right. It should be no surprise, therefore, that exact colorimetric reproduction is of little avail in attempting to produce a true reproduction.

The point here is that we should not be overly concerned with colorimetric reproduction. It is enough that a color television picture be believable; that it present images that are pleasing to the viewer. It is not ordinarily within the domain of the technician to treat matters of aesthetics. However, he can and should address himself to the problem of providing technically pleasing images. He can best do this by considering the television image as a separate entity. He should forget about the exact colorimetric or physical character of the original scene, and try, instead, to produce an image that conveys to the observer, through his perceptions, the essential nature of the original.

To do this, it is necessary to take cognizance of the ways in which these perceptions are formed. We must be aware of the effects of the sharpness limitations of the television image. We should note that what an observer prefers to see in the image is something that is only proportionally relative to what he might have seen in the original scene and that his memory plays a significant role in his evaluation of the image. Care should be taken not to jolt that expectation. The problems of determining the viewer's preferences admittedly are many and complex. But continuing research indicates that some underlying system is involved. We cannot afford to ignore these problems merely because they are complex. It is the responsibility of the scientist and technician to search for the relations between image quality and perceptions in order that color television may be most effectively presented to the viewer and, indeed, that its technical quality may be improved.

We have not considered here either the physical limitations of the television system in any detail or the complex influence of temporal effects on the appearances of images. Even so, it is obvious that large differences in appearance may exist among television images, depending upon a number of factors. One of the most important of these factors, the conditions of viewing, has received little attention in the design and operation of color television systems. At the very least it appears desirable to establish standard conditions for viewing monitors and for previewing. It is hoped that the information presented here will be useful in other areas of design and operation as well. These visual factors should be considered as an integral part of the system's structure. Careful evaluation of them as a part of the complete television chain should be helpful in answering many perplexing problems and in helping to avoid problems that might otherwise be introduced through failure to account for the response characteristics of the system's final output stage: the viewer.

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APPENDIX

Equation (1) states that brightness is proportional to log luminance. In other words, brightness differences are related to luminance ratios. Equation (2) states that log brightness is proportional to log luminance. That is to say, brightness ratios are related to luminance ratios. The latter relationship has been suggested as correct since intersensory matches yield power relations between the sense modalities. However, it can be shown that either Eq. (1) or Eq. (2) could be expected to lead to intersensory power relations. This is illustrated in the following examples:

Let R_1 and R_2 = responses on different sensory continua 1 and 2,
S_1 and S_2 = stimulus quantities on different corresponding physical continua 1 and 2.

I. Assume that response is related to stimulation by a power function.

(1) Then, $R_1 = a_1S_1^{b_1}$ and $R_2 = a_2S_2^{b_2}$,
(2) when the responses are matched, $R_1 = R_2$;

therefore, $a_1S_1^{b_1} = a_2S_2^{b_2}$

or, $\log a_1 + b_1 \log S_1 = \log a_2 + b_2 \log S_2$

and, $\log S_1 = (1/b_1)(b_2 \log S_2 + \log a_2 - \log a_1)$.

(3) If we let $B = b_2/b_1$,
$\log K = (\log a_2 - \log a_1)/b_1$;

(4) then, $\log S_1 = B \log S_2 + \log K$,
or $S_1 = K\,S_2^B$.

In other words, a power relation obtains between the sense modalities.

II. If we now assume that response is related to stimulation by a logarithmic function,

(1) then, $R_1 = a_1 \log S_1 + b_1$ and $R_2 = a_2 \log S_2 + b_2$;
(2) when responses are matched, $R_1 = R_2$;

therefore, $a_1 \log S_1 + b_1 = a_2 \log S_2 + b_2$
and $\log S_1 = (1/a_1)(a_2 \log S_2 + b_2 - b_1)$.

(3) If we let $B = a_2/a_1$,
$\log K = (b_2 - b_1)/a_1$;
(4) then, $\log S_1 = B \log S_2 + \log K$,
or $S_1 = KS_2^B$.

In other words, a power relation obtains between the sense modalities.

Since either Eq. (1) or Eq. (2) can be used to show that intersensory matches yield a power relation, then evidence for intersensory power relations is not a sufficient condition for determining the validity of either equation.

Discussion

Daan Zwick (Eastman Kodak Co.): One of the controversies that go on periodically in the television committee and I'm sure in the industry is the question of the color temperature of studio monitors relative to the color temperature of the sets in the home. Would you comment on the implications of your illustrations to the statement that is usually made, "Well, we want to have something in the studio that will look like what the customer is seeing, yet we don't really know how the customer is viewing his set"?

Mr. Bartleson: Yes, I'd like to try to separate what I consider to be fact from what is my opinion, and I address myself therefore first to the fact. The facts of the matter are, as I tried to point out on the screen that the choice of correlated color temperature — the choice of the energy characteristics of the screen white —

is not an arbitrary one that is open to legislation. It is one in which a proper answer may be found on the basis of technical considerations stemming from experimental work that has been in existence for nearly two decades. So, the question of what correlated color temperature should be used on a television receiver, and by this I mean to include a monitor too, is one that can be answered on a sound, technical basis.

The next question is, what are the characteristics of the environment? That is, what are the viewing conditions other than the color temperature of the screen itself which would be desirable to use in the studio in order to attend to the monitors, indeed to monitor the quality to see what kind of transmission is going on. I think it is in this area where the greatest amount of work needs to be done. To the best of my knowledge, no one has studied thoroughly and carefully enough the conditions that obtain in the home, and the relationship between various standard viewing conditions that may be used in studios and proving rooms to the kinds of conditions for which the transmission is intended. In other words, I think there's a considerable area of research that still needs to be done on evaluating viewing conditions that affect final image characteristics. I think the television industry has perhaps been sorely remiss in not paying enough attention to where their receivers and their monitors are placed at the expense of some of the quality characteristics that could be obtained from the present system itself.

Observer Adaptation Requirements in Color Photography and Color Television

By RALPH M. EVANS
and W. LYLE BREWER

Observer reactions are the final criteria in determining if a color photograph adequately reproduces a scene. These reactions indicate that ordinary colorimetric measurements cannot serve as the sole indication of reproduction quality. Dependence of the state of observer eye adaptation on viewing conditions has been found to overshadow simple colorimetric considerations. Adaptation requirements in color photography have been met through application of the so-called "first and second black conditions." It will be found essential also in color television that the two black conditions be applied. In both color photography and color television, particularly the latter, a new interpretation of the two black conditions should further improve the color quality of reproduced scenes.

Color mixture laws, which serve to indicate the types of radiant-energy distributions which will match each other, are embodied in the science of colorimetry. This science is well established and well understood. Colorimetry tells us that any two colors, or radiant-energy stimuli, having the same tristimulus values will match each other. Two stimuli having the same tristimulus values but different spectral compositions are called metamers. Except for pure spectrum colors, any color has many metameric forms. These metameric forms exist in such variety that given any one of a number of possible sets of three primary-color stimuli, all colors except those of exceedingly high saturations can be matched. This is indeed fortunate because on it depend all the important color-reproduction systems, including color photography and color television.

Instruments and computing procedures are available which enable us to determine the tristimulus values of any radiant-energy stimulus. This means that given any group of colors in a scene to be photographed or televised, we can determine the nature of the stimulus which must come from the photograph or the television receiver in order that the colors of the original scene be matched. Thus, it would seem, the requirements for the exact reproduction of a scene on either film or color television may be established with high precision.

In actual practice, however, it is found that the problem of matching color stimuli and the problem of obtaining a satisfactory reproduction of a scene are two different matters. The problem of reproducing a scene is that of obtaining color stimuli from the reproducing apparatus which "look like" those of the original scene. This is metamerism of a sort, but not what is usually meant by the term. The distinction between what we mean when we say that colors match and that they look alike can be illustrated by descriptions of two types of color-matching experiments.

Color Matching and Adaptation

In Fig. 1 are illustrated the viewing fields of the type of colorimeter in which color-matching data normally are obtained. By means of filters, or in some other way, the test field is illuminated with light of a certain spectral composition. The matching field is illuminated with a mixture of red, green and blue lights, the amounts of which may be varied. These amounts are varied until the matching and test fields do not differ in appearance. The test and matching fields are enclosed by a surround or adapting field. In establishing the visual characteristics of the CIE standard observer, a completely dark surround was used. Except for precision differences, however, matching results are not influenced by the surround providing that it encloses both the test and matching fields. On the other hand, if the surrounding field is changed, the appearance of both test patches will change. Furthermore, if two patches are matched with like surrounds, they will no longer match if the surrounds are changed so that the two patches are separately encompassed by surrounds differing in appearance.

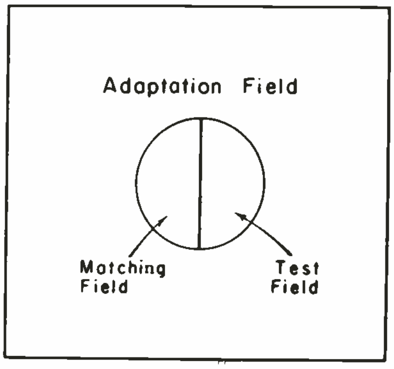

Fig. 1. Schematic diagram of the viewing fields of the type of colorimeter normally used in obtaining color-matching data.

The adapting conditions prevailing for viewing photographic film or television are seldom the same as those for the original scene. Furthermore, the adaptation conditions for any individual scene in a sequence of original scenes may be quite different from those of the scene before it or of the scene which follows. To be satisfactory, the colors of the reproduced scene must conform to those required by the adaptation conditions prevailing for the reproduction.

The Two Black Conditions

Color adaptation requirements as they apply to color photography appear to have been stated first in terms of the two black conditions. McDonough[1] recognized the first black condition in connection with his work on screen-plate processes. In a more complete analysis of screen-plate processes Mees and Pledge restated the first black condition and added the second black condition. As given by Mees and Pledge the two conditions are:[2]

First Black Condition: "In order that whites should be rendered untinged by colour, it is necessary that the screen itself when examined should appear to be free of colours, i.e., of a neutral shade."

Second Black Condition: ". . . · it is necessary that a grey, to be correctly rendered, should produce an equal deposit [of silver] under each of the three filter units."

According to the first black condition the screen elements of a screen-plate process should be combined together to form a neutral. The term neutral applies to an object which does not alter the chromatic characteristics of the illumination incident upon it. The object may be spectrally selective or nonselective but to be neutral its chromaticity must be the same as that of the illumination. To satisfy the first black condition, therefore, the integrated effect of the combination of red, green and blue

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Presented on October 8, 1953, at the Society's Convention at New York by Ralph M. Evans and W. Lyle Brewer (who read the paper), Color Technology Div., Eastman Kodak Co., Rochester 4, N.Y.
(This paper was first received on Oct. 16, 1953, and in revised form on Apr. 9, 1954.)

filter elements of the screen plate should be such as not to alter the chromaticity of the light transmitted by the screen plate.

The second black condition states that a gray of the original scene should result in equal deposits under the three colored filter elements of the photograph. The term gray applies to any one of a series of colors, varying in brightness, between the limits of white to black. It may be applied to an object or to the light stimulus coming from the object. Studies to determine the nature of the light stimulus which will appear as gray or white have usually been confined to stimuli along the black-body locus. The color temperature of the light which, on the average, appears to be most acceptable as white is about 5200 K.[3] Much depends, however, on the particular observer, the state of adaptation, and the intensity of the stimulus.[4] Light from any illuminant in the color-temperature range of about 2800 K to 10,000 K will be acceptable as white if it is of reasonably high intensity and, particularly, if this light is the primary factor in controlling adaptation. Thus, if the major source of illumination for a scene is a tungsten lamp of relatively low color temperature or any one of a number of different forms of daylight of relatively high color temperature, the light from this source may be considered achromatic.

In a scene illuminated by light which, as just described, is achromatic, the application of the terms white and gray to objects is apparent. A white object has high reflectance and high diffusion and the light it reflects has the same chromaticity as the light incident upon it. A gray object is chromatically like a white object. It differs from a white object in appearing to have a lower reflectance.[5]

Taken together the two black conditions state that a gray object in the original scene should be reproduced as a neutral area in the screen plate photograph. This neutral area, upon projection, should appear as a gray in the photograph. Thus, a gray should be reproduced as a gray. The chromaticities of the two grays will not necessarily be the same, however. The chromaticity of the gray in the original scene will be that of the prevailing illumination in the original scene; the chromaticity of the gray in the photograph will be that of the projection illumination. Similarly, a white of the original scene should be reproduced as a white in the photograph

Subtractive Photography and Television

The two black conditions as originally given refer only to screen-plate processes but they can be generalized to include subtractive color photographic processes and color television. For subtractive color photographs the black conditions indicate that a neutral combination of dyes in the photograph should be obtained for any object which is gray or white in the original scene. Red, green and blue exposures which give a neutral combination of dyes are considered equal to each other. Gray and white objects should therefore give equal red, green and blue exposures.

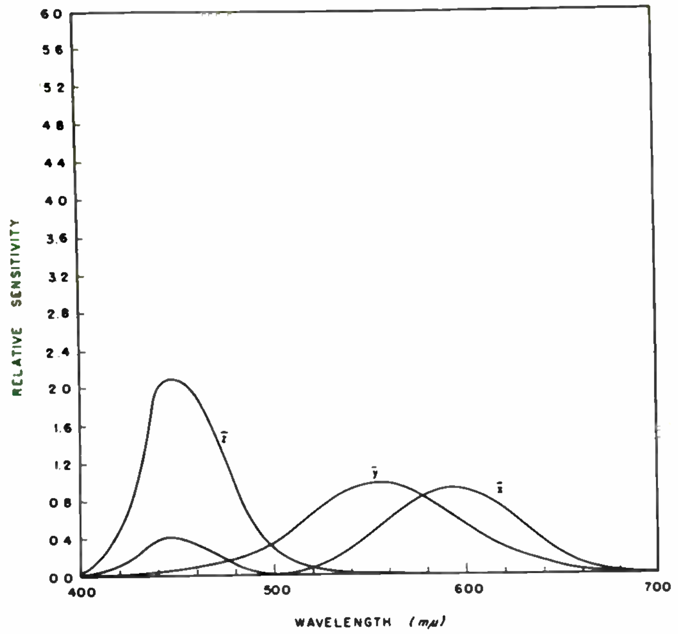

Fig. 2. Required effective relative spectral sensitivities of receptors of television camera conforming to CIE distribution coefficients, x̄, ȳ and z̄, balanced for artificial daylight, CIE standard Source C.

For each family of film products there is normally one type of film for daylight and one type for incandescent tungsten light. The tungsten-light film is usually identified in terms of the particular color temperature for which it is designed. Each type of film is "balanced" so that approximately equal red, green and blue exposures are obtained for light of the spectral quality of its illuminant. At best, the different types of film can be balanced for only a few of the "average" illumination conditions. Additional types would provide for better color balances in the photographs but would necessarily be less convenient and more expensive. Filters over the camera lens can, of course, provide balancing for a wider variety of illuminations.

As applied to color television, the implication of the first black condition is that (1) each television receiver should be capable of giving a white at a luminance equal to or higher than that for any other color, and (2) the white should be fixed in chromaticity, regardless of the scene from which it is derived. Grays should be of this same chromaticity, differing only in luminance.

The second black condition implies that the R, G and B television signals corresponding to those which ultimately control the red, green and blue phosphor excitations should all be equal to each other for a gray of the original scene. It is convenient to normalize the R, G and B signal values so that each equals 1.00 for the highest luminance white. For a gray R, G and B would have smaller values, but would be equal to each other.

The requirements of the second black condition can probably be more easily and more fully met in color television than in color photography. Periodically a white or gray object should be placed in front of the camera and illuminated by the prevailing illumination. If there is more than one type of illumination, the chosen illumination should be that which is considered predominant. The voltage outputs of the three signal channels should then be balanced to equal each other. In going from daylight to artificial light, marked changes will be required. In televising an outdoor event, such as a football or baseball game, it will be desirable to rebalance periodically as the azimuth of the sun changes or as cloud formations result in greater or lesser effective contributions of skylight to the illumination.

The general order of magnitude of the changes is illustrated in Figs. 2 and 3. For purposes of illustration it is assumed that the effective relative-sensitivity distributions of the three camera receptors are the same as the distribution coefficients, x̄, ȳ and z̄, of the CIE observer. The sensitivities are balanced for CIE Source C, which conforms reasonably well with average daylight. The areas under the curves in Fig. 2,

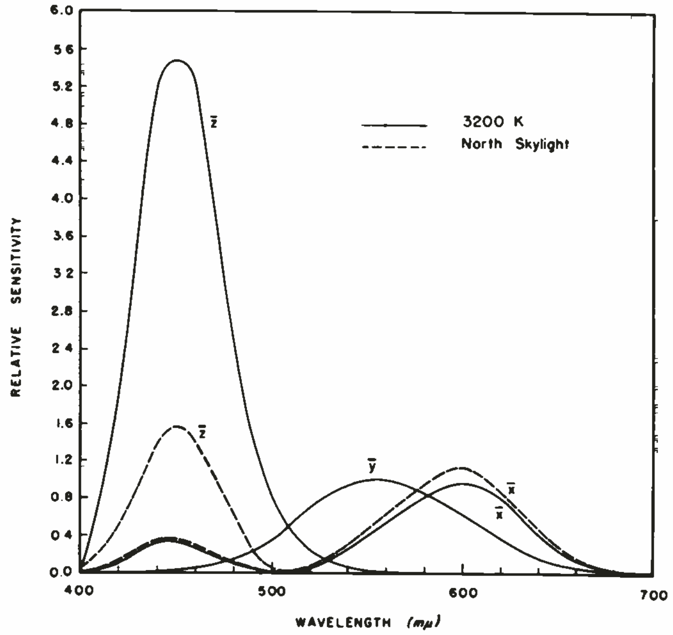

Fig. 3. Required effective relative spectral sensitivities of receptors of television camera conforming to CIE distribution coefficients, $\bar{x}$, $\bar{y}$ and $\bar{z}$, balanced for an illumination of 3200 K (——), and balanced for north skylight (---).

weighted by the spectral energy distribution of Source C, all equal each other. The $\bar{y}$ curve in Fig. 3 is the same as in Fig. 2. The other two curves have been multiplied by constants such that the three are then balanced for 3200 K. This illumination corresponds fairly well to normal tungsten illumination. Balance for a type of skylight[6] is illustrated by the broken-line curves in the same figure.

The changes in effective sensitivities illustrated for three illuminants in Figs. 2 and 3 are indicative of those necessary for conformance to the second black condition. Changes of this order of magnitude will be found necessary (for the illuminants illustrated) and, if made, will probably be found to give satisfactory results.

Adaptation and Fundamental Response Functions

As originally stated, generally interpreted, and as illustrated here, the two black conditions have specific reference only to achromatic colors. To develop more general principles which take chromatic as well as achromatic colors into account it is necessary to study pairs of color stimuli which match each other when the two members of each pair are seen under different states of observer adaptation. One means of doing this is through binocular matching experiments. The type of experiment is illustrated in Fig. 4. One color field, which may be considered as the test field, is viewed by the right eye, and the matching field is viewed by the left eye. The test and matching fields are so arranged that they appear juxtaposed. Separately controlled adaptation fields surround the two fields. Suppose that initially the two adapting fields are made the same and the matching field is adjusted to match some given stimulus in the test field. Except for differences in the characteristics of the two eyes, the results obtained in this type of matching experiment are the same as for normal color matching. If the surround for the left eye is then altered in color, the match will no longer hold. By readjustments in the matching field a new match can be obtained. If the differences in the adapting fields are fairly large, the change in the matching field necessary to obtain the new match is also apt to be large.

The validity of the binocular matching technique has been attested by Wright.[7] His findings indicate that if artificial pupils are used in the colorimeter the adaptation interaction effects between the two eyes are sufficiently small to be neglected.

In a series of color binocular matching experiments Burnham, Evans and Newhall[8] determined a number of pairs of stimuli which would match where one member of each pair was seen under Illuminant A and the other under Illuminant C. By means of a computing procedure described by Brewer,[9] curves were obtained which, within the limits of precision of the original data, correspond to the fundamental response functions of the eye. The curves so determined are shown in Fig. 5. Although high accuracy for these curves cannot be claimed, it is possible by means of them to indicate the nature of the sensitivity changes required in film and in television cameras to fulfill adaptation requirements.

For example, suppose initially a television system is balanced for taking and viewing with adaptation to CIE Source C. Assume also that the effective spectral response characteristics of the camera conform to those of the CIE X, Y, Z system. A change in scene to one giving adaptation to 3000 K would then require camera spectral sensitivities conforming to those of the solid lines of Fig. 6. A mere rebalance of camera sensitivities, keeping the same relative distributions as the standard observer distribution curves, would give the broken-line curves. Differences between the two sets of curves arise because the rebalance in sensitivity distributions for the solid-line curves was taken by reference to the curves shown in the preceding figure, Fig. 5. This is equivalent to stating that color adaptation may elevate or depress each of the fundamental response curves, but cannot change its relative spectral distribution.

The areas under the solid-line curves of Fig. 6, when weighted by the spectral distribution of the 3000 K illuminant, are equal to each other. The same is true for the broken-line curves. In this sense the two are equivalent; both fulfill the requirements of the second black condition. They differ in that the solid-line curves are designed to take into account the phenomena of color adaptation as they apply to a wide variety of colors.

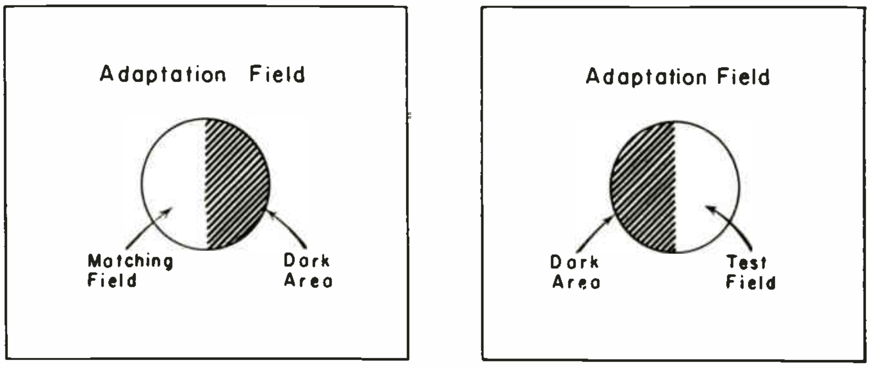

Fig. 4. Schematic diagram of the viewing fields of a binocular colorimeter in which the two eyes can be differently adapted. Left: left eye; right: right eye.

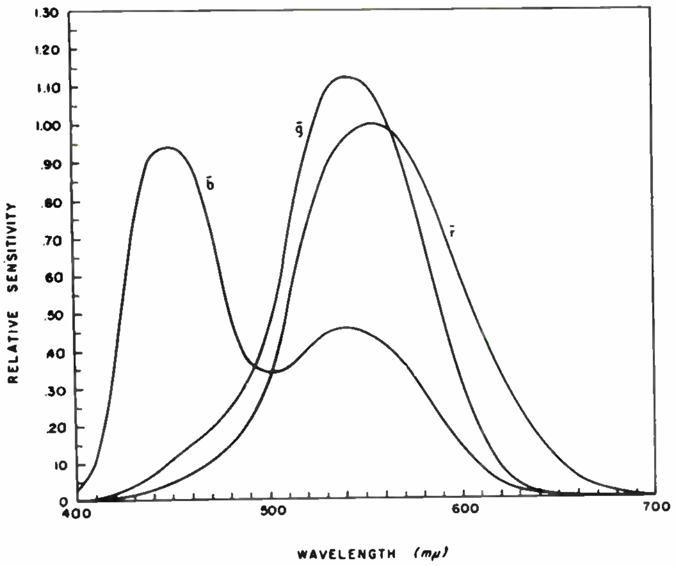

Fig. 5. Fundamental response curves of the eye as determined from a binocular color-matching experiment.

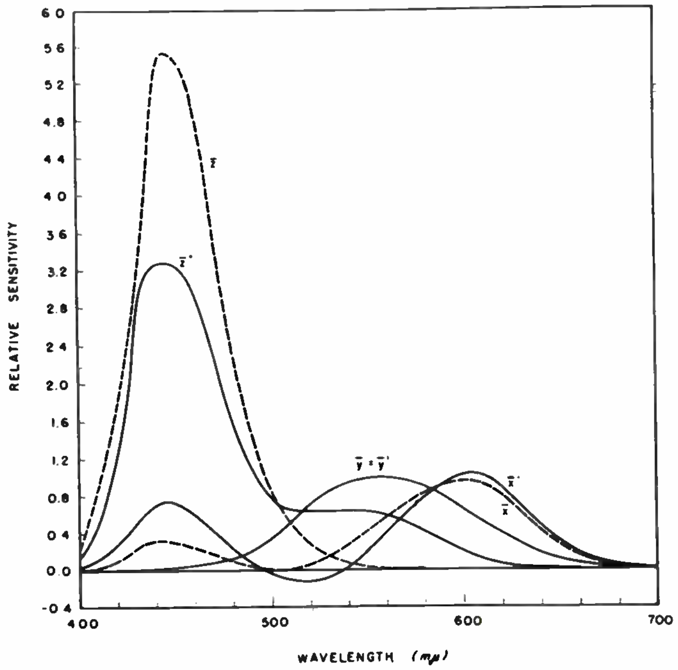

Fig. 6. Camera-sensitivity distributions expressed in terms of CIE *X*, *Y*, *Z* primaries which (solid line curves) are balanced in terms of fundamental response functions for 3000 K, and (broken line curves) are balanced directly in terms of $\bar{x}$, $\bar{y}$ and $\bar{z}$ CIE distributions.

The broken-line curves correct properly for the scale of neutral colors but are less satisfactory than the solid-line curves for other colors. Receptors with sensitivities conforming to the solid-line curves should therefore provide for closer agreement in appearance between colors of the original scene and those of the reproduction.

Results equivalent to those obtained by altering the effective sensitivities may also be obtained without altering the actual receptor sensitivities provided that the signals from the receptors are suitably modified. For example, the effect of multiplying any camera-sensitivity distribution by a constant can be obtained by leaving the actual sensitivity unchanged and adjusting the gain on the signal output according to the value of the constant. Similarly, the more complete corrections indicated by the solid-line curves of Fig. 6 can be obtained by linear matrixing. Let X, Y and Z denote the signals as they would be obtained for balance to CIE Source C. If a change in adaptation illuminant is made to 3000 K, the same camera sensitivities could be used, but the signals going through the remainder of the system should be modified to X′, Y′ and Z′ where:

$$\begin{aligned} X' &= 1.13\,X - 0.31\,Y + 0.17\,Z \\ Y' &= 0.01\,X + 1.00\,Y - 0.01\,Z \\ Z' &= -0.23\,X + 0.69\,Y + 1.89\,Z \end{aligned} \qquad (1)$$

Equations (1) and the curves of Fig. 6 illustrate means of conforming to the two black conditions in such a way as to take adaptation phenomena into account. They are based upon the fundamental response functions as determined from one particular investigation. The true response functions may prove to be different from those illustrated and, if so, the curves and the equations would be different. As a first approximation, however, those given are probably reasonably correct. The curves and equations given also apply to only one pair of adapting illuminants and are expressed in terms of a particular set of primaries. Given the set of fundamental response functions, however, corresponding curves and equations can easily be determined for any pairs of illuminants and for any system of primaries.

Summary and Conclusions

Successful operation of any color-reproduction system such as in photography or television is dependent upon conformance to the two black conditions. Adequate conformance can probably be obtained by adjusting the three effective film or television-camera sensitivities for balance to the prevailing illumination, with a single form for each of the spectral sensitivity curves. The two black conditions are necessary because of observer visual characteristics which are associated with color-adaptation phenomena. Conformance to the two black conditions in such a way as to best take into account color adaptation would require that all rebalancing for adaptation-controlling illuminants be made with reference to the fundamental response functions.

Increased fidelity of reproduction through reference to the fundamental response functions is obtainable only at the expense of greater complications in the reproduction system. The necessary corrections in color television could probably best be obtained through replaceable or continuously changeable matrix units. The gains possible by means of these more complicated systems would probably be worth while only for a reproducing system which is in excellent adjustment and where high fidelity of reproduction is believed to be very desirable. Either in this fashion or by the simple means of relative readjustment of the three signal components, however, conformance to the two black conditions is essential.

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Discussion

Peter Krause (*Ansco*): Could you tell us if the data that you plotted were obtained from binocular matching?

Dr. Brewer: The data from which the curves were derived were obtained from binocular matching.

Mr. Krause: What was the aperture of the instrument, that is, the exit pupil of the binocular instrument that was used in making the observations?

Dr. Brewer: A description of the instrument has been given by Burnham, Evans and Newhall in the Journal of the Optical Society of America, vol. 42, pp. 598–600 (1952). The test and matching fields were each 1 × 2 degrees in subtense. The surrounding adapting fields subtended about 40 degrees.

Mr. Krause: Would you know how many observers were involved in obtaining the data?

Dr. Brewer: A number of observers were involved in the binocular matching experiments. This particular set of data was based upon a single observer. The matching experiments are being repeated with different sets of adapting illuminants in the hope of obtaining more extensive and precise data.

R. P. Burr (*Hazeltine Corp.*): My understanding is that this analysis relates to a television system which is considered to be linear in terms of brightness from input to output. How would you evaluate this analysis in terms of the fact that most reproductions which people consider to be pleasing pictures generally deviate very substantially from a linear transfer characteristic and frequently have an S-shaped transfer characteristic? The question is asked because this sort of work bears on the final specification of gamma correction or the nonlinearity correction in the television system.

Dr. Brewer: I would not agree with your starting premise that our analysis is based upon an assumed linear system. The main thing is that the three H or D or transfer characteristic curves match each other. If one of them is straight, the other two should be straight; if one of them is curved, the other two should be curved in exactly the same fashion. In practice these curves are not linear for screen plate photographic processes, for subtractive photographic processes, or for color television. Linearity is neither obtainable nor necessarily desirable. The requirement is that, regardless of the shape, the three curves be as closely matched as possible.

Mr. Burr: That pretty much answers the question. I believe that what you have said in effect is that if you could do what you described for color photography you would be very happy.

2

Color Television Systems

Color Television vs. Color Motion Pictures

By DONALD G. FINK

The technical capabilities and limitations of color television and color photography are compared in five categories: (1) the viewing situation, (2) image photometry, (3) image colorimetry, (4) image structure and (5) image continuity. The results of a detailed survey of the practices of motion-picture theaters and the 8mm and 16mm motion-picture systems are compared with the current performance obtained by 21-in. color-television receivers. Tables comparing these systems are presented. The avenues open to television and photographic engineers to improve the respective systems are pointed out.

Color television and color photography today occupy an anomalous relationship. As industries they are sharp competitors, but as techniques they are partners. The competition stems from the struggle of television broadcasting and the motion-picture industry to acquire public following at each other's expense. Since neither side has any prospect of a permanent monopoly of good actors, directors or writers, the leaders of the two industries are paying a great deal of attention to technical methods, in the hope that by exploiting their respective media to the utmost they may acquire a competitive advantage. The wide screen, the increasing use of color, and the substantial effort to improve color film and processing are evidence that Hollywood is taking its techniques almost as seriously as its talent. In fact, in many of the late lamented experiments in 3-D production, the factor talent was almost ignored.

The partnership between the two media lies, first, in the fact that television broadcasters use a great deal of film produced specially for network programs. This film must be adapted to the viewing conditions of the home, and its producers must reckon with the resolution, contrast and tonal gradation of the typical television image. A second activity of the partnership is film recording of video programs. This is a highly exacting art, the successful practice of which demands intimate knowledge of the two media.

Thus far, these efforts have been largely confined to monochrome productions. But it seems clear that the *ultimate* destiny of television and motion pictures is color, and we can probably take "ultimate" to mean not later than the end of the next decade. It seems appropriate, therefore, to examine the technical roots of the systems of color reproduction, and to locate the areas where expert attention is needed to sharpen the competition or to cement the partnership. For this paper, we have elected to compare three color systems: the NTSC-FCC compatible color-television system, the amateur color motion-picture system (8mm and 16mm film) and professional motion pictures (35mm film). The categories of comparison are:

1. *The viewing situation.* This includes the comfort and convenience of attending the performance, the choice of available positions with respect to the screen, the aspect ratio and the viewing angle presented by the screen and the effect of the surroundings.

2. *Image photometry.* This includes image brightness, contrast, tonal gradation and the errors of brightness transfer introduced by the system.

3. *Image colorimetry.* This includes the gamut of reproducible hues and saturations, transfer of chromaticity values, flat-field uniformity, reference-white considerations and errors of chromaticity transfer introduced by the system.

4. *Image structure.* Resolution, sharpness and texture, and the degradations therein due to noise and graininess, geometric distortion, misregistration of primary images, errors of scanning and interlace.

5. *Image continuity.* Here the factors are fusion of motion, flicker, frame or raster stability and color break-up.

This list is by no means exhaustive, but it includes the important areas in which technical advances can be expected to occur. Let us start, then, with the first category.

The Viewing Situation

The technical effort expended on a system of visual entertainment is wholly wasted if the customers do not elect to sit down and be entertained. We therefore consider the initial question confronting the customer: The choice of viewing position—how to find a good seat.

There is little doubt that television presents less difficulty than all the motion-picture systems in this respect. Living rooms today are arranged around the television set, so much so that it is hardly necessary to move the chairs or lower lights in preparation for the show. Tuning and adjusting the receiver are simple matters.

Home motion pictures are much more of a special event, not to say a chore. The apparatus must be assembled, projector and screen set up, film threaded and rewound for each reel, lights lowered or turned out altogether, and at the conclusion of the show the equipment must be carried back to the closet. Even an enthusiast seldom gets up the energy for this more than once a week, even if he has plenty of interesting film and an eager audience.

Taking in a show at a theater is also an event, albeit different in detail. Here the deterrents are transportation to and from the theater, providing a baby-sitter and the admission costs. The better the show, the less chance there is of sitting in a good seat. Once settled in the theater, the customer finds himself confined in many ways. He no longer has easy access to the refrigerator and the other standard accessories of the home, nor does he feel so free to express audibly his opinion of the show. Taken all in all, television has an overpowering initial advantage in the convenience and comfort it provides the viewer.

The second factor in the viewing situation is the range of available viewing positions. Here the appropriate psychophysical common denominator for comparing the systems is the vertical viewing angle, that is, the angle subtended by the height of the screen at the viewer's eye. It is evident that so long as the height of the screen is chosen in proportion to the depth of the room or theater, the range of available viewing angles is the same in all the systems.

Presented on April 20, 1955, at the Society's Convention at Chicago by A. G. Jensen who read the paper for the author, Donald G. Fink, Philco Corp., Tioga and C Sts., Philadelphia 34, Pa. (This paper was received on March 8, 1954.)

Table I. Theater Viewing Conditions.

Name and location	Seating capacity	Vertical viewing angle, degrees			Screen dimensions, feet	Aspect ratio	Highlight brightness, ft-L
		Rear	Middle	Front			
Arcadia Theater, Philadelphia	625	9	16	60	27×18	1.5	7
Commodore Theater, Philadelphia	1105	6	11	55	33×15 27×15	2.2* 1.8	7
Erlen Theater, Philadelphia	1500	10	17	63	55×22	2.5*	6
Fox Theater, Philadelphia	2422	11	18	70	52×22	2.4*	7
Green Hill Theater, Philadelphia	706	9	22	42	22.5×16	1.4†	5
HiWay Theater, Jenkintown	540	9.5	22	75	36×18	2.0*	15
Lane Theater, Philadelphia	1000	8	16	60	33×22	1.5	12
Logan Theater, Philadelphia	1862	9	17	70	40×18	2.2*	10
Mastbaum Theater, Philadelphia	4387	10	17	57	60×25	2.4*	7
Stanley Theater, Philadelphia	3000	12	18	45	38×22	1.7	6
Stanton Theater Philadelphia	1375	10	16	53	30×20	1.5	10
Viking Theater, Philadelphia	1012	10	19	50	46×18	2.5*	6
Yorktown Theater, Elkins Park, Pa.	875	9.5	17	60	32×18	1.8	10
AVERAGE VALUES		9.5	17.5	58		1.96	8.3

* For CinemaScope. † Foreign films.

The height of the image on the 21-in. color television tube now emerging as standard is about 14 in. An image of this size is customarily viewed from across the short dimension of the room, or from the center of the room if the receiver is placed against the narrow wall. The typical viewing distance is then about 8 ft (96 in.). The maximum viewing distance is set by the long dimension of the room, which is seldom greater than 240 in. The minimum distance, aside from those chosen by the very young, is about 48 in. The range of vertical viewing angles available with a 21-in. television set thus ranges from 3° upward to about 16° with a typical median value of 8°.

Home motion-picture screens, according to the latest issue of the Sears, Roebuck catalog, vary in height from 18 to 52 in. Since the whole area of the screen is not always occupied by the image, a better index of the viewing angle is the vertical projection angle of the projection lens. The most popular types are the 1-in. lens for 8mm film and the 2-in. lens for 16mm. The vertical projection angle of these lenses is, interestingly enough, equal to the typical television viewing angle, that is 8°. This means that the projectionist sits at a distance equal to 7 times the picture height. Other members of the family tend to line up on the optic axis of the system to get the maximum benefit of the directional properties of the screen. Unless the family group is large, the projectionist occupies the rear position. Accordingly, the range of vertical viewing angles is from about 8° upward. The minimum value of 3° encountered in television is rare in home motion pictures.

The range of viewing angles in theaters is not markedly different. A survey of 13 theaters in and near Philadelphia reveals the data listed in Table I. This shows that the minimum angle, in the rearmost seats, varies from 6 to 12°, with an average of 9.5°. The most popular seats, those chosen by the first patrons to enter the theater, are those just behind the center of the hall, from which the screen height subtends an angle of from 11 to 22°, an average of 17.5°. The maximum angle, from the front seats of the theaters surveyed, ranges from 42 to 75°, the latter figure corresponding to viewing a 21-in. television screen at a distance of less than 1 ft. Here again the minimum viewing angles tend to be larger than those used with a 21-in. television screen.

Since motion pictures employ larger viewing angles than television, it may well be argued that color television needs a larger screen than the 21-in. variety. The increasing popularity of the 24-in. screen in monochrome sets bears this out. The limit is reached when the cabinets fail to pass through standard-size doors. For this reason, progress toward larger color tubes must be accompanied by an increase in the deflection angle from its present maximum value of about 70° to 90°, as has occurred in monochrome practice. Once these techniques have been worked out, the size of color television images can be expected to increase moderately, to an upper limit set by the length of the average living room, perhaps to an image diagonal of 27 in. Work toward such a tube seems justified by the data just presented.

The third factor in the viewing situation is the ratio of the screen width to height (aspect ratio). Here professional motion pictures have recently proved that they are much more flexible than television and home motion pictures. The 4:3 aspect ratio of television was derived from the prewar standard for motion pictures. Now that there are 35,000,000 receivers in use, with picture tubes, mounts and cabinets geared to this ratio, there is a vanishingly small chance of changing it. Even if compatibility did not prevent such a change, there is some doubt that a wider screen would benefit television productions since the reduction in horizontal resolution might seriously degrade the image. A wide-screen system for 8mm home motion pictures is doubtful for the same reason.

A wide-screen system for home motion pictures is perhaps warranted with 16mm film and can be achieved without basic changes in equipment. Wide-screen images can be achieved by using wide-angle lenses in camera and projector, by cutting off the top and bottom of the image in the projector and by confining the objects of interest to the corresponding area in the camera viewfinder. This procedure reduces the resolution substantially below normal for the 16mm system but not below that of the 8mm system. In fact, if the twice-normal aspect ratio of CinemaScope is used, the result is two 8mm pictures side by side.

Motion-picture theaters are becoming increasingly committed to the wide screen. None of the 13 theaters surveyed had an aspect ratio smaller than 1.5 (except those exhibiting foreign films) and the average was 1.96. The projection of standard 1.33 ratio film on such wide screens leaves much to be desired and there are those who will argue that the wide screen is a temporary manifestation. Resolution is indeed a problem, but there appears to be sufficient reserve in the 35mm system to satisfy most of the customers most of the time in this respect. And there is little doubt that the wide screen offers a wider scope of action and hence the display produces a greater degree of realism in productions made especially for the larger aspect ratios. My guess is that some form of the wide screen for motion pictures is here to stay.

Here we have the first example of a major weapon on the side of professional as well as amateur motion pictures: flexibility in system standards. Producers and exhibitors have found it feasible to equip cameras and projectors with anamorphic optical attachments, at trifling cost compared with the costs of talent and theater operation in general. Stereoscopic presentations can also be arranged, although it is now abundantly clear that the customers will not cooperate by wearing cardboard spectacles. When a system requiring no such cooperation is invented, there will be no fundamental bar to its introduction in theaters. Television in contrast has proved many times that, for reasons of compatibility, its standards are inviolate. They may be added to, as in compatible color, but they may not be changed.

The final item of comparison in the general viewing situation is the effect of ambient light and the screen surround. The control of ambient light in theaters has the advantage in that it makes possible presentations of high contrast, with a minimum of distraction from the surroundings. But, according to lighting experts, the ambient lighting in most theaters is too low in relation to the brightness of the screen (Table I). Higher levels of general illumination are needed not only to make it easier for patrons to move about but also to minimize the fatigue caused by too great a difference in brightness between the screen and its surround. When the surround brightness is not less than one tenth the average image brightness, eyestrain from this cause is avoided. The effect of the ambient on image contrast can be controlled by so arranging the lighting that it does not directly illuminate the screen but does brighten the surround to the desired degree.

In television viewing, high levels of ambient light are the rule in most household. To maintain contrast under these conditions, neutral density filters are used. In recent months, two such filters have become standard equipment in de-luxe black-and-white receivers, one built into the tube faceplate (about 70% transmission) and the other in the safety glass (about 50% transmission). To maintain brightness when two such filters are introduced, the initial brightness of the phosphor image must be increased by a factor of 2.8. In exchange for this increase, the reflected ambient light is reduced to 12% of the value it would have in the absence of the filters, and the overall effect is a potential increase in contrast range of about eight times. With such an arrangement, the televiewer can be just as lazy as he likes about drawing the blinds or lowering the lights. He gets good solid blacks under any reasonable condition of ambient light. But this is possible only because the monochrome set designer has light to throw away.

In color-television receivers, image brightness is so costly that only one neutral filter is used; this is a 70% transmission faceplate. Control of ambient lighting is thus a more serious matter with a color receiver. Brighter images, by a factor of about three times, are needed before color sets can be said to be on a par in this respect with monochrome television practice.

Photometric Properties

The next category includes the photometric properties of brightness, contrast and gradation. The brightness levels achieved in the three systems are shown in Table I which gives actual measurements of highlight brightness in the theaters surveyed, and in Table II which compares the performance of color television and color motion pictures.

Table II. Characteristics of Color Television and Motion-Picture Systems.

	Color television (Note 1)	8mm home motion pictures (Note 2)	16mm home motion pictures (Note 3)	35mm motion pictures (Note 4)
Vertical viewing angle:				
Minimum	3°	8°	8°	9°
Median	8°	15°	15°	17°
Maximum	16°	50°	50°	58°
Screen dimensions:	14 by 18.5 in.	13 by 17.5 in.	13 by 17.5 in.	16–25 by 23–60 ft
Aspect ratio:	1.33	1.33	1.33	1.4–2.5
Highlight brightness:	20 ft-L	15 ft-L	27 ft-L	5–15 ft-L
Contrast range:				
Large area	50-to-1	50-to-1	60-to-1	70-to-1
Small area	20-to-1	10-to-1	20-to-1	30-to-1
Resolution:				
Horizontal	280 lines	230 lines	490 lines	1000 lines
Vertical	350 lines	230 lines	490 lines	1000 lines
Product H × V	98,000	52,900	240,000	1,000,000

Notes:

1. Based on receiver employing 21-in. shadow-mask tube, 25-kv ultor voltage, 500 μamp peak beam current.
2. Based on 8mm home projector, 750-w lamp, $f/1.6$ 1-in. coated lens, 21-in. image diagonal, nondirectional screen, 3 projection periods/frame.
3. Based on 16mm home projector, 750-w lamp, $f/1.6$ 2-in. coated lens, 21-in. image diagonal, nondirectional screen, 4 projection periods/frame.
4. Based on data listed in Table I.

It is customary to rate motion-picture projection brightness by measuring the screen with the projector running, but with no film in the gate. The SMPTE standard for theaters states that the screen brightness under these conditions shall be between 9 and 14 ft-L. The optical transmission of color film, in the clear portions corresponding to the highlights, is seldom higher than 60%. The corresponding highlight brightness levels in theaters are, therefore, 5 and 8 ft-L. The measured highlight levels in Table I fall in this range, although one of the smaller theaters reached 15 ft-L. Brightness above about 20 ft-L is undesirable, since flicker begins to appear at this level at the standard motion-picture projection rate.

Home projectors vary widely, according to the wattage of the projection lamp, the $f/$ number of the projection lens, the size of the image and the directive properties of the screen. To make the appropriate comparison with color television, measurements were made with two de luxe projectors having 750-w lamps and $f/1.6$ coated projection lenses, at an image size equal to that of the 21-in. television tube (diagonal 21 in.) projected on a flat-white nondirectional screen. The open-gate brightness of the 8mm machine was found to be 25 ft-L and the corresponding highlight brightness about 15 ft-L. The figures for the 16mm projector were 45 ft-L open-gate and 27 ft-L highlight brightness. The higher figures in the 16mm case reflect the greater opportunity for efficient design in the larger optical system.

Color television, as previously noted, is presently having trouble with highlight brightness. Depending on the second-anode voltage and peak beam current built into the receiver, the highlight brightness of a 21-in. image ranges from 15 to 20 ft-L. This matches the 8mm home projector, but falls short of the 16mm projector. It also falls short of the peak highlight brightness of a typical 21-in. monochrome set employing a 70% transmission, aluminized picture tube, which is typically 50 ft-L without excessive loss of focus. Unless and until color television receivers reach the 50-ft-L level, they cannot be said to meet the requirements imposed by the ambient lighting levels in the average living room. Meanwhile, those possessing color sets must take care to control room lighting.

Consider next the contrast range of color systems, that is, the ratio of the maximum brightness to the minimum brightness that can be present simultaneously in the reproduced image. The upper limit on contrast range in color motion pictures is imposed by the neutral density range of the film. According to Brewer, Ladd and Pinney,* a neutral density range of 3 is attainable in representative color films. Since density is the negative logarithm of transmission, this means that the film proper can provide a contrast range of 1000 to 1. The density range of the color image as presented on the screen is typically 1.85, that is, a contrast range of about 70 to 1. This substantial reduction in the contrast capability of motion pictures is traceable primarily to lens flare in the projector; it emphasizes the importance of keeping the projector lens clean. Ambient light on the screen would further reduce the contrast range.

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* W. Lyle Brewer, John H. Ladd and J. E. Pinney, "Brightness modification proposals for televising film," *Proc. IRE*, *42:* 174–191, Jan. 1954.

Measurements made by the writer in theaters and on home motion-picture screens show that a maximum contrast range between large areas of from 50-to-1 and 100-to-1 is attainable. The contrast between adjacent small areas is not so high, owing to halation and similar effects. At a resolution of 200 lines in the RETMA Resolution Chart, for example, the measured contrast in an image projected from 16mm reversal Kodachrome film in a typical home projector was found to be only 10-to-1.

The contrast attainable in color-television images today is somewhat lower than that of professional motion pictures. Ladd and his colleagues assign a luminous range equivalent to a neutral density of 1.3 to a color-television system employing a shadow-mask tube. This is a contrast range of 20-to-1. The measurements on which this value was based were made in early 1953, and a great deal has happened to color television in the meantime. In particular, higher peak brightnesses have been obtained, without corresponding increases in the shadow brightness, so the attainable contrast has risen appreciably since 1953. Recent measurements on a 21-in. shadow-mask tube show a large-area contrast of 50-to-1 and a small-area contrast of 20-to-1. In other work, large-area contrasts as high as 100-to-1 have been measured in the absence of ambient light.

It thus appears that color television and color photography are not widely dissimilar in their contrast properties, so far as the system apparatus is concerned. The difference lies rather in the degree to which the effects of ambient light are controlled. In motion pictures, the reflecting screen does not distinguish to any great degree between image and ambient, so that control of the ambient light is a prime necessity despite its high cost to the comfort and convenience of the viewer. In television, the image is transmitted rather than reflected to the viewer, so that discrimination against the ambient is possible to any desired degree, subject only to the amount of light the designer can afford to throw away in neutral filters. In the long run, therefore, it appears that color television has the advantage in that it can offer images of high contrast without special measures to darken the room. But, as we have already noted, this desirable state of affairs waits on the development of picture tubes having many times the highlight brightness presently attained.

The third item in image photometry is tonal gradation, that is, the distribution of brightness among the shades of gray in the image, relative to those in the original scene. This is tested by photographing or televising a step tablet, that is, an array of gray patches arranged in increasing steps of luminance. Here we encounter the fact that neither television nor photography can cover the range of brightness inherent in average outdoor scenes. Hence in reproducing such scenes, compression of the highlights or shadows is inevitable if the intermediate grays are reproduced in direct proportion to the original scene values.

Indoor scenes are more amenable to control. In motion-picture studio work, it is customary so to control the illumination that the most brightly lighted part of the set receives no more than four times the light falling on the most dimly lit part. In color-television studios, the illuminance ratio is held to about 2-to-1 wherever possible. These illuminance ratios, combined with the fact that a typical white object has about 20 times the reflectance of a black object, keep the scene contrast within about 80-to-1 in motion-picture work and 40-to-1 in television. Since these contrast ranges can in fact be reproduced on the viewing screen, under properly controlled viewing conditions, strictly proportional portrayal of the gray scale is practical and desirable. This implies an overall transfer gradient (gamma) of the system close to unity.

Some compression does in fact occur, in both color photography and color television, in the darkest parts of the image, with resulting loss of detail and texture in the shadows. But this effect is not prominent in the overall subjective evaluation of the image since shadow detail is commonly degraded in direct vision by the adaptive mechanism of the eye.

When the contrast range of the scene fits the contrast range of the reproducer, we have met only the first condition for correct rendition of tonal values. Another evident requirement is that the luminance of a particular portion of the image shall remain fixed when the luminance of the corresponding portion of the scene is fixed, regardless of what happens to the luminances of the other portions of the scene. In particular, the level of subjective black in the image should not shift to gray merely because an actress wearing a dark dress walks on the scene, nor should shadow detail in the image disappear altogether when the studio lighting is raised from a low value.

These degradations of tonal reproduction occur all too frequently in television. In motion pictures they do not occur because there is actually no mechanism in photography whereby the luminance of one object can be made to shift merely by a change in the luminance of another object. Speaking in electronic terms, it is the nature of the photographic beast to be direct coupled, from scene to negative, negative to print and print to viewing screen. In television, there is unfortunately a substantial opportunity for such luminance shifts to occur. Electrically, the error arises from an incorrect value of the d-c component of the video signal applied to the color television tube.

Most television cameras and all television transmission circuits are capacitively coupled, which means that the *average* ordinate of the signal remains *constant*, regardless of changes in the average illumination of the scene. Special measures must therefore be taken to insert and reinsert the correct average level. The burden first falls on the studio operator, who inserts the d-c component manually, by direct observation of the studio in relation to a monitor image. Necessary tolerances in the operation of studio equipment and in the ensuing transmission process over the network require that the system be permitted to err in this determination by as much as 10% of the maximum tonal range of the signal. The burden is taken up, secondly, in the d-c restoration circuits of the receiver. D-c restorer circuits of economical design (diode peak detectors) are not perfect in their action, even with a strong signal, and they fail badly when the noise level is high.

The net result of these impediments is that d-c restoration has been almost entirely abandoned in monochrome-television receivers. This means that the average brightness of the image is controlled *only* by the brightness control knob of the receiver, *not* by the average brightness of the scene. This seriously affects the tonal reproduction of the system as a whole, since every luminance tends to shift so as to keep the average brightness constant. For example, every fade to black at the studio comes out as a fade to an average gray on the receiver screen. Televiewers have learned to live with this sort of reproduction, but if they are critical of such matters, they know every motion-picture performance they ever saw was far ahead of television in this respect.

The situation is somewhat better in color-television receivers. Here, at least up to the time of writing, d-c restorer circuits are included since it is almost impossible to maintain white balance and correct colorimetry in a 3-gun tube without them. How long this advantage will be maintained rests with the future, particularly the future economy of the television manufacturing business. Because d-c restorer circuits cost money, they will very probably be removed from color sets just as soon as their removal can be shown to do no more harm to a color receiver than it does to a monochrome set.

Here again we have a technical advantage on the side of photography. Correct tonal gradation is available without extra cost in motion-picture systems, since it appears as a by-product of correct exposure and processing which are seldom more expensive than incorrect exposure and processing. In television, correct tonal gradation is not to be had without extra cost. Good d-c restoration performance adds perhaps ten dollars to

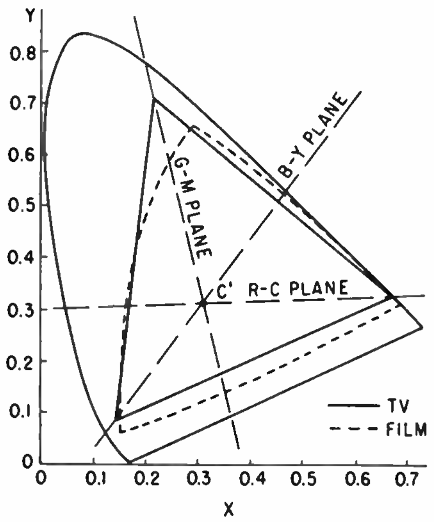

Fig. 1. CIE chromaticity diagram showing representative color gamuts covered by television and film (Courtesy W. Lyle Brewer, John H. Ladd and J. E. Pinney, "Brightness modification proposals for televising film," Proc. IRE, 42: 174–191, Jan. 1954).

the list price of a television receiver, and if the good performance of the circuit is maintained in fringe areas, another five or ten dollars may be added. So its future in color receivers is highly problematical. Once d-c restoration is removed from receivers, the studio operator will realize that he doesn't need to make a special effort to set black level accurate to within a few per cent because the customer cannot tell the difference. The advantage of color motion pictures over color television in tonal reproduction will become, at this stage, a permanent matter.

Colorimetric Properties

Turning now to the colorimetric properties of the color systems, let us consider first the gamut of hues and saturations that can be covered by the dyes used in color motion-picture projection prints compared with that of the phosphors used in color television picture tubes. Hues and saturations are shown conveniently on the CIE chromaticity diagram. Such a diagram appears in Fig. 1, taken from Brewer, Ladd and Pinney, where hues are measured by the angle around the white point C′ and saturation increases radially from that point. The solid-line triangle on this chart shows the gamut covered by the receiver primaries assumed as typical and attainable in the NTSC color signal specification. The broken-line figure bounds the corresponding gamut for a typical dye system used in motion-picture projection prints. The most important fact is that these two figures cover very nearly the same ground. Television can reach more highly saturated greens than can film, film slightly more saturated blues, reds and purples than television. But these are minor differences, especially since the eye is not critical of errors in saturation at these extremes.

Much more important is a difference which the color triangle in Fig. 1 hides, namely the limits on luminance that are imposed by the respective systems in the highly saturated colors. To show the luminance range, it is necessary to consider a 3-dimensional solid in color space, of which Fig. 1 is merely the top view. Three sections taken through this solid are shown in Fig. 2. At the left is a slice through the solid from magenta to green, shown from left to right, and with increasing luminance upward (corresponding to decreasing density upward); the middle slice is from cyan to red; the slice at the right from yellow to blue.

In each case we find that at high levels of luminance, below an equivalent density of about 0.5, the television system is capable of producing more highly saturated colors than is the motion-picture system. This is explained by the fact that each of the film dyes absorbs in regions outside that of its major absorption.

Here is a weapon in the hands of the television engineer. He can make more vivid (more highly saturated) bright colors than can his brother in the photographic art. To show this fact in another way, we can take a horizontal slice through the color solid at the 0.5 level of density, as shown in Fig. 3. Here the inner figures represent the performance of the photographic dyes, the triangle that of the television phosphors.

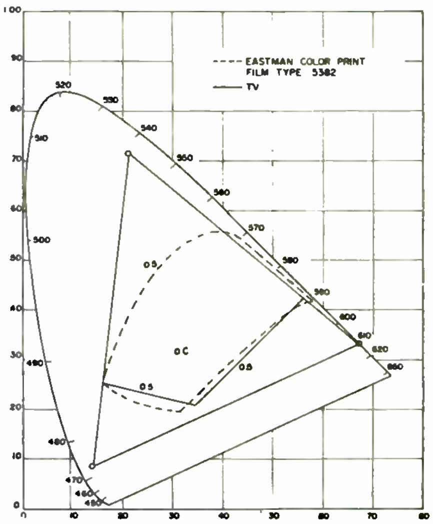

Fig. 3. Color gamuts bounded by a density of 0.5.

It must not be inferred from this that the television system has no trouble in reproducing highly saturated colors at high luminance. Such colors are transmitted by chrominance signals of high amplitude which may not be properly handled in the system. The signal for yellow at maximum luminance, for example, actually exceeds the amplitude range of the transmitter and must be clipped off, resulting in reproduction at lower saturation. Moreover, the demand on the transmitter for high-saturation, high-luminance colors varies widely according to the system of gamma correction adopted, and the gamma-correction standard is at the moment indefinite. Nor must it be inferred that the superior ability of color television to deal with highly saturated bright colors is an overwhelming advantage, since such colors are not prominent in nature and hence are seldom presented to the camera. But, in a side-by-side comparison, it is a fact that television has an advantage over motion pictures in the rendition of bright vivid colors, when use

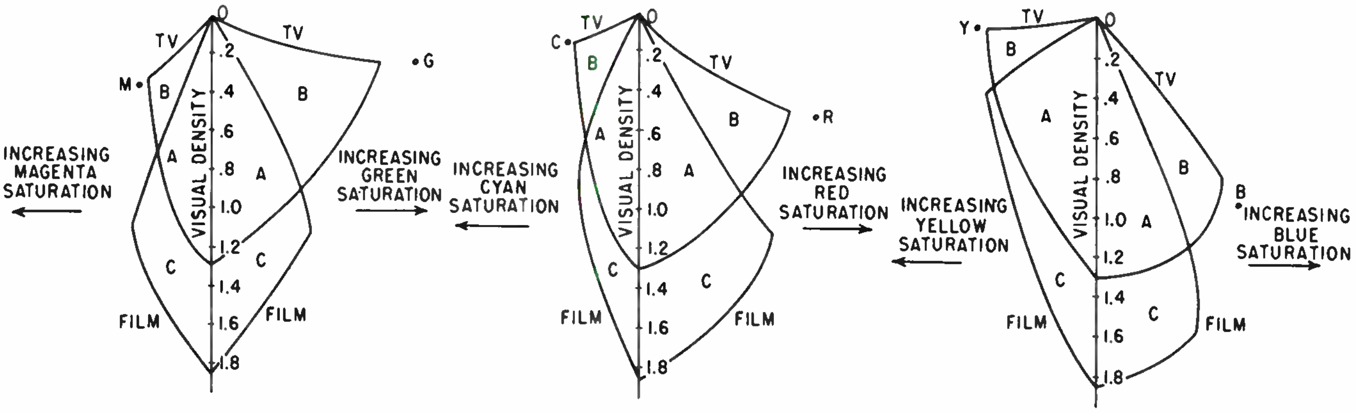

Fig. 2. Three sections of the color solid showing density and saturation. These correspond to the traces shown in Fig. 1.

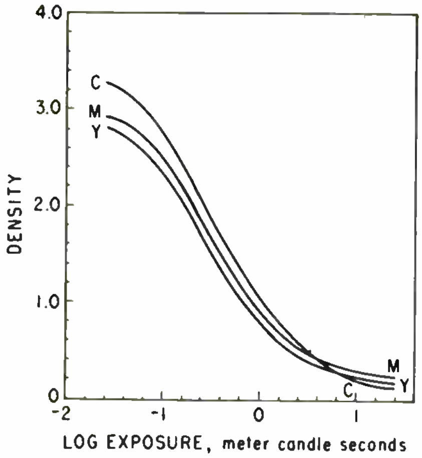

Fig. 4. Relationship between exposure and density in typical reversal color film processes.

is made of the full capabilities of the respective media.

Referring again to Fig. 2, it should be pointed out that the data shown indicate that the motion-picture system has a greater density (contrast) range than television and hence is capable of rendering a higher degree of saturation at low brightness than is the television system. Since recent improvements in the contrast performance of color television tubes have more nearly equalized the contrast range of the two media, the outlines in Fig. 2 are somewhat misleading. In any event, high saturation is of particular importance in the higher luminance ranges, much less so in the shadows. In consequence, the upper regions in Fig. 2 are the significant ones, and they indicate a definite superiority for color television when highly saturated, bright colors are to be reproduced.

The next item in colorimetry is the ability of the systems to reproduce the gray scale without introducing color tints at any of the luminance levels. White and gray are reproduced by mixing definite proportions of the reproduction primary colors, and this proportion must be maintained precisely, at all levels of luminance, if the reproduced gray scale is to be truly neutral in color. Stated differently, the transfer characteristic relating intensity of a primary color before the camera to intensity of the same primary on the receiver screen must have the same shape as that for the other two primaries. To reproduce a tintless gray scale, it is not necessary that the transfer curves be straight lines (gamma unity); but the three curves must have the same shape. (To reproduce a mixture color other than gray, the gamma of the system should be close to unity, in order to preserve the specific proportions of the primary colors at all levels of luminance.)

In this matter of primary-color transfer, the curves shown in Fig. 4 show the relationship between exposure and density in the cyan, magenta and yellow dyes in a typical reversal color film process. The three curves are closely similar in shape. One would expect, therefore, that the gray scale reproduced on such film would display a high degree of neutrality throughout the full range of luminance demanded of the system. This expectation is realized in 16mm Kodachrome shots of the RETMA Resolution Chart.

The color-television receivers now available to the public (as of early 1955) do not perform so well in this respect. The difficulty lies in the fact that the three electron guns of the shadow-mask color tube used in such receivers are operated in dissimilar fashion. The red phosphor is substantially less efficient than the green and blue phosphors, so the red gun is operated at its maximum current capability while the other two guns are backed off to produce the proper white balance. Under these conditions, it is very difficult to secure similarly shaped transfer characteristics for the three primaries. The grid biases of the guns are adjusted to obtain as good a match as possible, but in most color sets a shift in the color of the raster is clearly evident as the brightness control is rotated through its full range. This effect is difficult to avoid when a 3-gun tube is operated so as to attain maximum brightness. Eventually the quality of the televised gray scale will match that of the photographed gray scale, but further development is needed.

Another colorimetric requirement is uniformity of color over the area of the image, commonly referred to as "flat-field" uniformity. This may be tested in photography by exposing the film to a uniform white area and placing optical filters of various colors in succession in front of the lens. (During the oral delivery of this paper a 16mm Kodachrome film was projected to show flat color fields taken in this manner. There was very little evidence of color nonuniformity, either as a function of position over the image area or as a function of time.)

Color shifts with time are, in fact, often detectable during the running of color films in theaters. For example, flesh tone may change from pale to ruddy and back again within a few seconds as a result of minor variations in exposing, printing or processing the corresponding frames of the film. Usually such effects are hidden by the changes in illumination that accompany motion of the subject or camera. Those technicians who enjoy looking for the cue marks at the end of each reel may further amuse themselves looking for such color shifts, particularly between successive reels, during their next visit to the local motion-picture theater. A print that does not show them has been very well printed, even by modern standards.

Color nonuniformity is present to a considerably greater degree in the 3-gun color tube. One cause, which may be built permanently into the color tube, is localized lack of balance in the efficiency of the three sets of phosphor dots. Close inspection of a color tube, illuminated by a blank white raster, will show some of this effect in the form of slight color tints in certain areas of the screen which appear irrespective of other adjustments of the receiver components. Another cause is misadjustment of the color purity coils or magnets, which allows the electrons from one gun to stray onto the phosphor dots assigned to the other two guns. Malfunctioning of the circuits — for example, poor 15-kc response in one of the primary-signal video amplifiers — can produce the effect. Finally, localized unbalance in the photosensitivity of the three camera tubes used in the color camera can, and all too often does, contribute a major share of nonuniformity. Since there are so many possible sources of this difficulty in color television, we must assign the superior position in color uniformity to motion pictures.

Next, consider the reference-white question. The axiom in color studios is: Use film balanced for the white light used in the studio, take care with the flesh tones and trust your luck for the rest. The first step, balance for white, has led to the double inventory problem in vending color film to amateurs. One type of film is balanced for average daylight and is used out of doors; the other (Type A) is balanced for tungsten light and is intended for shots under artificial illumination. The color film enthusiast does not live who has never made a mistake in keeping his film and his illumination straight. Using the wrong film, or the wrong filter, with the illumination actually on hand is, in fact, one of the standard initiatory rites into the sacred precincts of the domestic color motion picture.

Here the amateur motion picture comes off second best, because the color balance has to be built into the film, and only two conditions can be accommodated in the commercial distribution system. Professional motion pictures are somewhat more flexible.

Color television has almost unlimited flexibility in this respect, since manual adjustments in the studio can balance the camera for a wide variety of studio illuminations, assuming proper gamma correction. Strangely enough, not until the NTSC was finished with its deliberations on the compatible color standard was it realized that *permission* to make such adjustments had not been written into the proposed standards. Such rigidity would have had the effect of forcing the broadcaster to use a daylight taking characteristic with tungsten light, which might have been just as disruptive as taking Kodachrome Type A film off the market. The omission was forthwith corrected, and the final standard reads: "The radiated chrominance signal shall vanish on the reference white of the scene." This correction put the technical director of a color-television production back in business. The fact that the color-camera taking characteristics are capable of electrical control is a blessing, but not an unmixed one. The balance knobs are there; but it takes some fortitude to keep one's hands off them, once the white card has been held before the camera and the balance has been set.

Finally, in this discussion of colorimetry, consideration may be given to errors of chromaticity transfer introduced by the respective systems. Here it is difficult to make a precise comparative assessment, except to acknowledge that the motion-picture people have been worrying about this problem for twenty years longer than their television brethren and are therefore presumably in the lead.

Errors of chromaticity are shown by arrows in the CIE chromaticity diagram. One end of the arrow shows the hue and saturation presented to the camera, the other end the corresponding hue and saturation presented to the viewer. So long as these arrows are small compared with the dimensions of MacAdam's ellipses of least perceptible color difference, the system is above reproach from the scientific point of view. But in an artistic medium, such accurate rendition of hues and saturations is often positively undesirable. To create the illusion of reality, or to improve on reality, most producers and directors of professional color motion pictures strive for some sort of controlled distortion of chromaticity transfer. When one tries to assess the validity of the distortion, one quickly finds oneself in an argument with an artist, which is entirely unprofitable. Producers and directors of color television shows have the same problem and attack it in the same way, with the same disregard for Robert's Rules of Order.

The distinction between television and motion pictures is the degree of control available in the distortion of chromaticity. Here photography wins, at least for the time being. The manufacture of film and its processing are much more standardized than are the corresponding processes of signal generation and transmission in color television. For example, the vagaries of electronic gamma correction are real, honest vagaries at present. So the producer of motion pictures more often sees what he wants, in the color values displayed by release prints, than does the producer of color television on the monitor screen. Time will bring the two media closer in this most important matter of pleasing color rendition; but as of now the burden of rapid progress is definitely on the television engineer.

Image Structure

We come now to the differences among the systems in the structure of the images they provide. The first item is resolution, one of the few matters on which reasonably specific numerical comparisons can be made. We shall take as the basis of comparison the standard definition of television resolution, namely, the maximum number of adjacent black and white lines that can be discerned in a distance equal to the height of the image. (This is twice the number of lines as defined in optical measurements.)

Experience abundantly confirms that the resolution of black-and-white television is limited by the system standards to about 350 lines vertically, and to about 320 lines horizontally. In compatible color, assuming that registration of the primary images is not at fault, the corresponding figures are about 350 lines vertically and about 280 lines horizontally. The 12% degradation in horizontal resolution in the color system is imposed by the restricted bandwidth available for the luminance, necessary to accommodate the chrominance signal.

The resolution of a typical amateur home motion-picture system, using Kodachrome reversal film, has been measured by the writer in a manner strictly analogous to the television case by photographing the RETMA Resolution Chart, projecting the processed film and reading the resolution wedges on the resulting image. Care was taken with focus of camera and projector, and it is believed that the results fairly represent the capabilities of the home motion-picture systems. Results: the 16mm system has a resolution of about 490 lines, vertically and horizontally; the 8mm system about 230 lines. We thus find that the color system falls between the film systems, rather nearer the 8mm level than the 16mm. This finding will be subject to argument from many quarters; it is typical rather than definitive. But the writer feels that reading the wedges as one finds them is worth a pound of theory. If the numbers are correct, the directors of color television spectaculars can get much valuable (and sobering) practice by taking up 8mm color motion pictures as a hobby. (The final section of the 16mm film projected at the convention illustrated the resolution capabilities of the system.)

Professional motion pictures using 35mm film with the 4 : 3 aspect ratio are, on the same basis, capable of 1000-line resolution. There is some degradation when, as is usual, the release print is made by the imbibition (Technicolor) process owing to minor losses of resolution in registering the dye images. Further degradation occurs when the image is anamorphically expanded, as in the CinemaScope process, which lowers the horizontal resolution by a factor of approximately two. The VistaVision process of exposing (and, in large theaters, projecting) the 35mm film twice as fast as normal, and thus getting more than twice the area per frame, more than meets the resolution needs of the wide screen. It is perhaps pointless to pursue the matter beyond this point. Professional motion pictures win easily on resolution, compared with the other color systems. The only competition they have is that provided by other professional motion-picture systems.

Closely related to resolution is the rendition of texture. This is not merely the difference between rough and smooth. It includes such subtle distinctions as the sheen of metals, variations in the weave and surface treatment of textiles and impressions conveyed by small highlights. It appears that high resolution is not so important in reproducing texture as is high contrast range in small areas. A color display capable of reproducing the highlights on the eyeballs of an actor, for example, gives an impression of realism lacking when highlight compression is present. Similar contrast distinctions in the shadows are essential to depicting the texture of coarse woven surfaces. Both television and photography have sufficient contrast range for this, but tonal compression is more prominent in television. This fact, coupled with higher resolution, gives the superior position in reproduction of texture to professional motion pictures.

The sharpness of reproduced images is limited fundamentally by the heterogeneous nature of the fine structure of the image. In photography, assuming that no limit has been imposed by the optics of exposure, printing and projection, sharpness is limited by the graininess of the emulsions and dyes used. Photographic graininess is affected by the processing conditions as well as the density of the film. But graininess has at least the simplicity of being a quantity specifically associated with a given type of film stock and its processing.

The corresponding heterogeneous quantity in television, noise, is more involved. If noise were totally absent, the sharpness of television images would be limited by the scanning apertures of camera and picture tube, and by the amplitude and phase responses of the transmission system. Needless to say, television images are never entirely free of noise. For one thing, color cameras require from three to five times as much light as monochrome cameras for the same signal-to-noise ratio. This means that extra lighting has to be installed in converting a studio for color productions. Additional lighting sufficient to overcome camera noise under all conditions is hardly justified, even if it were possible. So close inspection of color monitor images usually shows camera noise at luminance levels below middle gray.

If this were the end of it, there would be little cause for complaint. But at every succeeding stage in the transmission process up to the transmitting antenna, designers of equipment have necessarily contented themselves with noise figures less than perfect. The RETMA standard for noise in transmission amplifiers and relay amplifiers is no help. Neither is the FCC standard on the same subject. Both standards, in fact, are entirely nonexistent. In general, it is considered good if when the picture signal leaves the transmitter, it has a video signal-to-noise ratio, peak white to root-mean-square noise, of better than 40 db (100-to-1 voltage ratio).

Possibly such noise performance is good enough, but its visible effect is substantially greater than that of the grain in the average Technicolor release print, so here again photography wins.

Progress in this line is particularly difficult for television engineers, because a large and increasing segment of the television audience lives more than 20 miles from the transmitter, and/or uses an indoor antenna, and/or is located in a natural or man-made canyon below line of sight—all of which conditions bring into prominence the noise introduced by the television receiver itself.

To serve this segment of the audience, designers of television tuners have been in quest of the lowest possible noise figure. In 1947 figures ranged from 15 to 25 db, but the vhf tuner of today hits better than 10 db, and 6 db is a good bogey figure. On some channels, some tuners actually go to 3 db, which is very, very good (such a tuner adds noise power to the signal passing through it to the extent of only two times the level of thermodynamical perfection). Uhf tuners are worse than the vhf variety, by 6 db in a good tuner, by more like 10 db in the average uhf tuner produced in the past two years.

The general introduction of good noise figures in receivers has meant that a very much larger portion of the audience gets reception uncontaminated by receiver noise, and a great many more square miles within which a recognizable image is receivable are added to the coverage of the station. The television industry is so conscious of this problem that continued effort can be confidently anticipated.

It must be admitted that the noise problem in television is fundamentally different from the grain problem in photography. The home motion-picture addict gets his grain given to him by experts; so does the theater exhibitor. But the owner of a television set finds a layman, himself, in the act. Ignorance of the causes and effects of noise in television reception is widespread. The engineers cannot force the owner in an outlying district to put up a better antenna, or to move in closer to town. Therefore, noisy pictures are all too common in the major part of the area claimed as served by the broadcasters. Fortunately, this part of the area is sparsely populated; the majority of televiewers can get pictures free of receiver noise as long as they confine their attention to local stations. This fact justifies a lot of work on camera and network noise. We in the United States can well afford to adopt the high standard set by the British Broadcasting Corp. in the matter of noise introduced prior to radiation of the signal.

The next topic under image structure is geometric distortion. In photography, the dimensions of the scene, as focused within the camera, are reproduced on the viewing screen in correct proportion unless very special means are taken to prevent it. It is possible to use lenses or shooting angles to distort perspective. But whatever are the shapes of things as the image lands on the negative, just so are the shapes as they fall on the viewing screen.

In television the situation is almost reversed. It is not too strong to state that the shapes of objects on the television viewing screen are not in correct proportion to those focused on the camera tube unless very special means have been employed to make them so. This trouble arises from the necessity of analyzing the image into the vertical and horizontal components of scanning. Unless the velocities of scanning in the receiver match the corresponding velocities in the camera geometric distortion occurs. Result: Circles appear as circles in film reproduction, but they all too often have the shape of an egg in television reproduction.

This problem has been recognized for a long time, and it must be acknowledged that the major stations and networks are taking a great deal more trouble with linearity of camera scanning than they did ten years ago. Friends in the network headquarters assure us that most camera-scanning systems have a positional linearity error under 2% (that is, the position of the picture elements never departs from the correct position by more than that amount, except accidentally and in emergencies).

Receivers do not fare so well. It appears, in fact, that horizontal scanning circuits as presently designed have positional linearity errors on the order of 4% (corresponding to scanning velocity errors of 10% or more). This is not to say that better linearity is not achieved in particular cases; it is to say that the 4% figure is accepted as a design objective. Nor is this designer's choice an arbitrary one. Careful study of the problem has shown that the means to improve horizontal linearity to the level of excellence now offered by the broadcasters are so expensive in components and power consumption that they are not justified in the highly price-competitive atmosphere of the television receiver industry.

These remarks apply to monochrome broadcasting and reception. In color television, since the camera has three camera tubes whose scanning systems must match each other with great precision, adjustments and operating procedures are available for a substantially improved grade of scanning linearity. Moreover, in studios where live color programs are produced, it appears that the standard is high in this respect. In color receivers of the type currently available to the public, however, there is no particular need for extra care in the scanning circuits, and the performance is not noticeably better than that of black-and-white receivers. The conclusions are: Photography inherently preserves the shapes of objects; television tends to distort them, and the burden of correcting this situation lies principally with the designer of the receiver scanning circuits.

Consider next the principal color error in the structure of the image, that is, misregistration of the primary colors. In monopack film, there is no chance for this error to occur, so the typical amateur color motion picture is distinguished by substantially perfect registration. Professional motion pictures taken by color separation negatives offer an opportunity for misregistration; so also do release prints made by the imbibition process. But the fact is that the registration problem in these processes has been taken in hand and solved by the designers and operators of the equipment. Prints having such errors simply are not released to the exhibitors, at least to judge by critical examination of the product now showing in theaters.

Registration errors do occur in color television, so much so that the writer has to date never seen a live color broadcast that was completely free of them. The problem at the studio lies in keeping the rasters of the three camera tubes precisely alike in width and horizontal centering, height and vertical centering, angular orientation, vertical linearity and horizontal linearity. Color film televised by the flying-spot method gets around this difficulty, since only one source of light, the scanning spot, is used. A similar correction-in-principle is needed to remove the problem in live cameras; what is needed is a single-gun color camera tube.

In receivers using the shadow-mask color tube, misregistration comes from another cause known as convergence errors. These may be simply described as excessive differences in the angles at which the three beams pass through a given aperture in the shadow mask, which arise from the fact that the three beams do not originate from the same point. Dynamic correction is used to bend the beams so that at the edges of the picture they appear to have originated from the same sources as at the center of the image. As the maximum deflection angle has increased from 50° in the early tubes to about 70° in the latest version, the problem has become worse, and more sophisticated convergence correction methods have become necessary.

When in good adjustment, the convergence correction system keeps misregistration down to a small amount, say about $\frac{1}{32}$ in. in a 21-in. tube. But exact registration, all over the face of the tube, appears to be practically unattainable, as anyone who has wrestled with convergence correction while observing a dot pattern can testify. Misregistration of this amount is readily tolerated when viewing a color image from the normal distance, but it does detract from the overall excellence of the image when black-and-white programs are viewed on the color tube. What is needed to correct the situation is a color tube free, in principle, of convergence errors. Conclusion: On excellence of registration, score one for photography.

The final comment on the relative structure of the color images relates to the simultaneous utilization of the whole area of the motion-picture frame, compared with the sequential nature of television scanning. Since the television image is composed of two sets of lines laid down alternately, two minor defects of image structure are present: virtual pairing of interlace and jagged edges of vertical boundaries. These are visible on close inspection, even if the scanning system is otherwise faultless, whenever the eye moves in following the motion of the image or as any other motion of the head occurs. For example, the difference between scanning and area-type displays is never more evident than when the viewer is eating peanuts. This pastime has little effect on the appearance of a motion-picture image; but the chewing motion moves the head sufficiently to cause the television image to appear to move about, in localized bumps and grinds. If you have never noticed this, try it at the next opportunity. Peanut brittle is an appropriate confection for the purpose.

Image Continuity

We come to the last of our categories, the differences in the apparent continuity of motion and illumination inherent in the frame repetition rates of the three systems. Home motion pictures are exposed at 16 frames/sec., professional motion pictures at 24/sec. and color television at 30/sec. As these numbers suggest, television outperforms the color motion-picture systems, particularly the home motion-picture system, when it comes to fusion of motion. Actually television has a further advantage in that each frame is divided into two fields, which are separately exposed and reproduced, and the motion in the image is thus cut up into 60 segments/sec. Professional motion pictures have only 24 such segments; the shutter action in the projector (which projects each frame twice) is helpful only in removing flicker, not in smoothing out fast motion.

The camera operator in television thus has substantially less stringent limitations in the speed with which he can pan the camera, compared with the motion-picture cameraman. The wide screen adds to the problem because there is correspondingly more ground to be covered in the horizontal direction. In fact, it is my observation that the outstanding technical shortcoming of wide-screen motion-pictures is the jerkiness of motion apparent when an actor moves across the full width of the screen at an above-normal pace. In the older "narrow-screen" productions, panning of the camera would have been used to transfer the jerkiness from actor to background. This camera technique is apparently not popular in wide-screen productions.

Continuity of illumination, that is, control of flicker, is also heavily stacked on the side of television by its high repetition rate. Here the appropriate numbers are 60 fields/sec for television, 48 screen illuminations/sec for professional motion pictures. Since the threshold of flicker is a logarithmic function of brightness, the permissible screen illuminations in the two systems are widely different, typically 180 ft-L for television and 20 ft-L for professional motion pictures. In home projectors, the screen is illuminated three times per frame (typical of 8mm projectors) or four times per frame (used in some 16mm machines), making flicker rates of 48 and 64/sec, respectively, when the film is run at the standard rate of 16 frames/sec. The home projector thus approximates or exceeds professional motion pictures in flicker performance.

These brightness limits of television and motion pictures are closely related to the viewing conditions discussed at the beginning of this paper. Screen brightness less than 20 ft-L is the rule in motion pictures, not only because it is difficult to make large images brighter than this, even with the most powerful light sources, but also because of the flicker problem. Television can handle any image brightness likely to be demanded indoors, without fear of flicker.

Both television and the motion pictures have passed the day when the stability of the frame as a whole was a serious problem. Worn sprocket holes and misadjusted claws are, of course, always a potential source of jitter. Optical misalignment can cause weave in the immobilizer type of projectors used in flying-spot scanners. But ordinary care of film and alignment suffices to produce completely steady projection, even on amateur equipment. In television, raster stability is a function of horizontal and vertical synchronization circuits. These have been so improved during recent years that the raster remains steady even when the signal is so weak that the picture can barely be discerned against the noise. Critical friends who view motion pictures regularly say that film jitter is by no means totally absent and state that television is superior in this respect. Accepting this judgment, we give the edge to television in the matter of frame stability.

The final item under image continuity is color break-up, that is, the appearance of separately colored images when an object is in rapid motion. This effect cannot appear when all three primary images are present simultaneously in camera and image reproducer. So color break-up is no problem in color motion pictures or the simultaneous form of color television cameras, nor is it in televising color film. It can appear when a sequential type of camera is used, such as that used in the Chromacoder type of live pickup chain. But in that case, the color field rate is so high (about 180 fields/sec) that color break-up is visible only when the motion is very rapid, and even then it is likely to be noticed only by those keeping a sharp eye out for it. So we can cross out color break-up as a factor in the present-day systems of photography and television.

Summary

This completes the list of comparisons. A summary has been attempted in Table III. Each of the several areas of comparison mentioned in this paper is listed at the left and the superior system identified.

Study of this table reveals that color motion pictures come off best in most of the technical items, as might well be expected. After all, we are comparing color motion-picture systems which have enjoyed twenty-five years of steady development with a color-television system having less than five years of comparable technical activity. Very few of the distinctions (of which only one, resolution, is a major factor) are fundamentally rooted in system standards. Perhaps the most significant differences arise from the facts that the 35mm motion-picture system is under professional control from start to finish, and that price competition is not a large factor in the design of its equipment.

Two conclusions are unmistakable: First, television engineers have a long way to go to produce a color system that works as well as color motion pictures, and the task is not made easier by the requirement that the receiver perform well in the home where lighting conditions are not under control, and where the knobs are set by laymen. Second, omitting only the resolution limit imposed by the width of the television channel, there is no technical reason why the television engineer cannot meet the competition. In many cases, the needed improvements can be found without hav-

Table III. Summary of Color System Characteristics.

Characteristic	Superior System	Remarks
Viewing situation:		
Choice of viewing position	Television	On basis of viewer comfort and convenience
Viewing angle	Film	At median viewing position
Aspect ratio, flexibility of	Film, 35mm	Wide-screen professional motion pictures
Ambient light and surround	Television	
Image photometry:		
Highlight brightness	Television	
Contrast	Television	In presence of high ambient light
Tonal gradation	Film	
Errors of tonal transfer	Film	
Image colorimetry:		
Gamut of hues and saturations	Television	Particularly at high luminance
Gray scale, neutrality of	Film	
Flat-field uniformity	Film	
Reference white, control of	Television	As applied to camera
Chromaticity transfer distortion	Film	
Image structure:		
Resolution	Film, 16mm & 35mm	
Noise, graininess	Film, 35mm	
Geometric distortion	Film	
Misregistration of primary colors	Film	
Systematic structure errors	Film	Due to sequential nature of scanning
Texture	Film	
Image continuity:		
Fusion of motion	Television	
Flicker	Television	
Frame (raster) stability	Television	All systems highly satisfactory
Color fusion	Film	Not a significant factor

ing to surmount economic barriers. In other cases, the toughest engineering job of all must be faced: finding a better technique at no increase in cost.

We may then terminate the discussion with a question: What are the chances that the needed improvements in color television will be recognized, the needed support for research and development provided and the results put into production? The answer involves, I think, two distinct periods in the years ahead. Initially, the performance of color television receivers may actually be degraded, in certain respects which are acceptable to the buying public, in the process of reaching a price sufficiently low to permit every American family who really wants a color set to own one.

Following this, the television industry will be faced with the situation that has faced the automobile industry in recent months: a highly saturated market with buyers looking for something better, in looks and performance, than they now have. Then, it is to be devoutly hoped, the television industry will respond as the automobile industry has responded, with a steady upgrading of performance, accompanied, if necessary, by a corresponding upgrading of price. In this second phase of development, it is certain that those items of performance in a color receiver that are important to the customer, whether or not they enjoy a similar reputation among engineers, will receive concentrated attention.

During the same period, the motion-picture industry will not be standing still. Enjoying freedom in system standards, this industry will continue its forays into territory not likely to be invaded by a television system bound by the confines of compatibility. Two results seem certain: (1) engineers and physicists who understand color will enjoy steady employment, and (2) the public will enjoy the show.

Acknowledgments

The author acknowledges with gratitude the assistance of the following persons who read the manuscript and offered suggestions: A. G. Jensen, W. T. Wintringham and M. W. Baldwin, Jr., of the Bell Telephone Laboratories; R. E. Shelby of NBC; R. S. O'Brien of CBS; F. J. Bingley, W. P. Boothroyd, R. G. Clapp, J. F. Fisher and J. B. Williams of the Philco Corp.; and W. Lyle Brewer of the Eastman Kodak Co.; and of the managers of the Commodore, Erlen, Fox, Green Hill, Logan, Mastbaum and Viking theaters in Philadelphia for the data in Table I. Thanks are also due to Messrs. Brewer, Ladd and Pinney for the data of Fig. 3 and for permission to reproduce the figures credited to them and their associates in the test.

Supplement

The 16-mm motion-picture film shown with the reading of this paper at the Convention was produced on 16mm Kodachrome Type A using a Cine Special Camera, Model 1. The following notes serve to amplify the preceding text.

Text reference, page 286:

Eastman Kodak reflection gray scale with lens aperture varied from maximum (*f*/1.9) to minimum (*f*/16).

Text reference, page 286:

White paper photographed through the following color filters:

1. Exposed for white at 1200 ft-L, 8 frames, at *f*/5.6.
2. K-2 yellow filter, 8 frames, *f*/4.
3. Wratten F-29 red, 8 frames, *f*/2.7.
4. Wratten N-61 green, 8 frames, *f*/2.7
5. Wratten C-4 blue, 8 frames, *f*/2.7.
6. Through filter for photoflood (light blue), 8 frames, *f*/5.6.
7. Filter for outdoor exposure with Type A Kodachrome, 8 frames, *f*/5.6.

Text reference, page 287:

RETMA Resolution Chart at four levels of exposure. The following are readings of horizontal and vertical resolution: high exposure, 400 lines discernible, 350 lines with good contrast; medium high exposure, 500 lines discernible, 450 lines with good contrast; medium low exposure, 550 lines discernible, 500 lines with good contrast; low exposure, 600 lines discernible, 550 lines with good contrast.

On the Quality of Color-Television Images and the Perception of Color Detail

By OTTO H. SCHADE, Sr.

A theoretical and experimental study of the NTSC color system supported by color photographs shows that contrast range and color saturation obtained with commercial tricolor kinescopes provide a larger color space than provided by color motion pictures. In fine detail more than 60% of full color information is transmitted and reproduced by the NTSC system, because the bandwidth restrictions of the electrical color signals (I, Q) do not affect definition in the vertical dimension and have a smaller effect on the reproduction of horizontal color detail than indicated by earlier evaluations which disregarded the two-dimensional nature of the image.

The detail color reproduction appears adequate to the eye, because the color errors remaining are small although perceptible. This fact is significant because the spatial sine-wave response functions of the color discriminators of the visual system are found to be substantially independent of the color of light and similar to the spatial sine-wave luminance response function of the eye.

CONTENTS

A. ELECTRICAL AND OPTICAL CHARACTERISTICS OF NTSC COLOR TELEVISION SYSTEM

1. General Characteristics of Color Systems

The reproduction of color in a television or photographic system is based upon the trichromatic theory. The analysis of color in a television or photographic camera requires a discriminator mechanism having three different spectral sensitivities, resulting in three integrals or "primary signals" R, G, B* (or any linear transformation thereof, such as the NTSC values Y, I, Q) which are independent two-dimensional intensity functions of the object point coordinates. In the synthesis of a colored image, luminance and color of all image points are restored by letting the primary signals control three properly chosen "primary lights": the reproducing primaries red, green and blue. The reproduction of color by a linear or a nonlinear system must be independent of illumination intensity to conform with the requirements of vision. A stable color balance necessitates a constant ratio of the three signal functions, which requires:

(a) matched transfer characteristics,
(b) matched spatial frequency spectra of the system, and
(c) matched noise-levels

These specifications express a *registry requirement*. The *registry of three transfer characteristics* is an old problem in photography and a new problem in television, demanding high precision in maintaining relative and absolute gain and black-level stability in linear or nonlinear amplifiers as well as in camera tubes and kinescopes, where sensitivity or response within the image area must be highly uniform. *Registry of the spatial frequency spectra* of three color images requires accurate time-delay and phase equalization in electrical channels and a closely matched image geometry in three scanning rasters. *Matched noise levels* become important when the signal-to-noise ratios are low, because unmatched levels result in a mismatch of transfer characteristics.

For the reason of "compatibility" in television, the color information must be transmitted without increase of video bandwidth together with a luminance signal suitable for monochrome receivers. The two additional color-transmission functions (I, Q) are, therefore, restricted to smaller passbands than the luminance function (Y). (See Sect. 5.)

The present analysis does not concern itself with faults of a temporary nature in the operation of a color system, but with the range and purity of colors obtainable, in particular with the unequal passbands of NTSC television signals and with commercially available color kinescopes. The computed colorimetric performance is checked by measurements, supported by visual observations (color photographs), and interpreted with reference to the performance of color photography and the visual system.

2. Color Television System for Measurements and Visual Tests

The color signals are generated by a light-spot slide scanner (see Fig. 1) followed by three gamma-correction amplifiers and band-limiting filters feed-

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* The spectral sensitivities or wavelength functions $f(\lambda)$ should be such that the primary signals are approximately proportional to the tristimulus values of the object, the tristimulus values being those of the receiver primaries.

Presented on October 22, 1958, at the Society's Convention at Detroit by Otto H. Schade, Sr., Electron Tube Div., Radio Corp. of America, 415 S. Fifth St., Harrison, N.J. This paper is also appearing in the December 1958 issue of *RCA Review*.
(This paper, first received on May 9, 1958; received in final form on November 5, 1958.)

ing the cross-mixing network or Matrix I (RCA "colorplexer") for translation of the input signals E_R, E_G and E_B into signals E_Y, E_I and E_Q. The matrix coefficients for the system are given in Table I. After band-limitation by *I*- and *Q*-filters in the colorplexer. the signals are translated back to $E_R'E_G'E_B'$ in the inverse Matrix II. The primes indicate that each signal is now a frequency-dependent mixture of components from three unequal passbands as indicated in Table I and discussed later. These signals are then modified by the transfer characteristics and frequency characteristics of the electron guns of the color kinescope and superimposed on the kinescope screen, where they are converted to light energy. Modulation and demodulation circuits (not shown) can be switched in at point *M* to observe effects introduced by transmission of the multiplexed NTSC signal over a single channel as discussed briefly in Sect. 5.

For measurements of the dynamic transfer characteristic of the system, the light intensity in a fixed small area on the kinescope screen is observed by a multiplier phototube while a calibrated step tablet image is slowly drifting over this area in a vertical direction. The step signal is generated by a color transparency having the characteristics indicated in Fig. 2. The slow vertical drift is generated by synchronizing the vertical oscillator of the light-spot scanner with a stable oscillator differing very slightly in frequency from the field frequency. The screen of the kinescope is thus illuminated continuously in its entire area by the drifting colored test-pattern picture, while the monochrome step intensities are traced on a recorder. The optical step signal is generated in two sections. The main step tablet (a) covers a 70-to-1 range, and a 10-to-1 neutral filter strip (b) extends this range to 700. Measurement of the electrical signal steps at intermediate points of the system furnishes the various transfer characteristics shown in Fig. 3.

3. Picture-Tube Transfer Characteristics

The dynamic transfer characteristic shown in Fig. 3 was measured several years ago on a 21AXP22 metal color kinescope. It follows a power law (close to a square law) with an additive constant B_0, which expresses the black-level illumination or light bias on the screen resulting in a "toe" in the characteristic. The light bias is caused by diffuse electron excitation (secondaries), optical diffusion in the screen and ambient light. It is variable, therefore, and has its lowest value for a dark viewing room and for pictures having a high ratio of peak-to-average luminance. For normal picture material, the range of the transfer characteristic is similar to that measured with the colored test pattern (Fig. 2), i.e., approximately 600 to 1 in a dark room.[*] This range is much higher than that obtained in motion-picture theaters (60 to 100 to 1) where the light bias B_0 is caused by projection lens flare and ambient light; in fact, it is even higher than the contrast range of the color film positive itself,[*] which is in the order of 470 to 1.[†] The large range of the color kinescope cannot be photographed in its entirety on Kodachrome or Ektachrome film, and is further reduced by the color printing process in the various illustrations.

4. Excitation Purity (Color Saturation)

The degree of color saturation obtainable in a color image is determined by the reproducing primaries and the contrast range of the reproducer. The red, green and blue primaries of the color kinescope are located in the CIE diagram as shown in Fig. 4. A straight line drawn through the white point (illuminant C) intersects the spectrum locus at two points. The *excitation purity S* of a

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[*] The reader may compare these values with those given in Ref. 2, showing transfer characteristics of early (1954) color kinescopes covering a range of hardly more than 20 to 1.

[†] Today's color kinescopes (21CYP22) have an even higher contrast because of reduced electron diffusion by secondary emission.

Table I. Voltages in NTSC Color System.

	Transmission primaries (Matrix I)				E′ Components from Matrix II				Sum E′ in freq. range Δf (mc)			Luminance factor for linear system		
Color	E	E_Y	E_I	E_Q	Gun	Y	I	Q	$(Y+I+Q)$ $\Delta f = 0 \to 0.6$	$(Y+I)$ $0.6 \to 1.8$	Y $1.8 \to 4$	$l_{0.6}$	$l_{0.6\to1.8}$	$l_{1.8\to4}$
Red	1.0	.299	.596	.211	Red	.30	.57	.13	1.00	.87	.3	.30	.26	.09
	—				Green	.30	−.16	−.14	0	.14	.3	0	.08	.18
	—				Blue	.30	−.66	.36	0	−.36	.3	0	−.04	.03
												Σ .30	.30	.30
Green	—	.587	−.274	−.523	Red	.59	−.26	−.33	0	.33	.59	0	.10	.18
	1.0				Green	.59	+.07	+.34	1.00	.66	.59	.59	.39	.35
	—				Blue	.59	+.30	−.89	0	.89	.59	.0	.10	.06
												Σ .59	.59	.59
Blue	—	.114	−.322	.312	Red	.11	−.31	+.20	0	−.20	.11	0	−.06	.033
	—				Green	.11	.09	−.20	0	.20	.11	0	.12	.065
	1.0				Blue	.11	.36	.53	1.00	.47	.11	.11	.05	.012
												Σ .11	.11	.11
White	1.0	1.	0	0	Red	1.	0	0	1.0	1.0	1.0	.30	.30	.30
	1.0				Green	1.	0	0	1.0	1.0	1.0	.59	.59	.59
	1.0				Blue	1.	0	0	1.0	1.0	1.0	.11	.11	.11
												Σ1.0	1.0	1.0
Yellow	1.0	.886	.322	−.312	Red	.89	.31	−.20	1.0	1.20	.89	.30	.36	.67
	1.0				Green	.89	−.09	+.20	1.0	.80	.89	.59	.47	.53
	—				Blue	.89	−.36	−.53	0.	.53	.89	0.	.06	.09
												Σ .89	.89	.89
Cyan	—	.701	−.596	−.211	Red	.70	−.57	−.13	0	.13	.70	0	.04	.213
	1.0				Green	.70	.16	.14	1.0	.86	.70	.59	.51	.415
	1.0				Blue	.70	.66	−.36	1.0	1.36	.70	.11	.15	.072
												Σ .70	.70	.70
Magenta	1.0	.913	.274	.523	Red	.41	.26	.33	1.0	.67	.41	.30	.20	.123
	—				Green	.41	−.07	−.34	0.	.34	.41	0.	.20	.245
	1.0				Blue	.41	−.30	.89	1.0	.11	.41	.11	.01	.042
			1				2			3		Σ .41	.41	.41

color located on such a line is by definition[1] the ratio of the distance from the color point to the white point, to the distance from the spectrum locus to the white point. The excitation purity is thus specified by a mixture of a spectral light with white light. The fixed light bias (B_0) caused by ambient or scattered light will be assumed to have the neutral color of illuminant C. The addition of this white light moves all color points toward the white point and decreases the excitation purity of the color from the value S_c computed for $B_0 = 0$ (see Table II) to a smaller value S. The purity reduction by a fixed white-light energy is obviously dependent on the excitation level of the color and its relative stimulus energy, defined as follows:

The maximum luminance $Y_{\max}$ in a color system is that of the white light ($Y_{\max} = Y_{w\ \max}$) obtained when the three primary lights (phosphors) are excited to selected maximum luminance values ($Y_{r\ \max}$, $Y_{g\ \max}$, $Y_{b\ \max}$) giving the specified white light (Illuminant C for color television). The maximum luminance of a color (c) is therefore obtained when at least one of the primary lights reaches the excitation limit established for maximum white-light excitation.

The excitation level of a color is hence specified by the excitation factor

$$k_c = Y_c/Y_{c\ \max} \leqq 1 \qquad (1)$$

The maximum luminance of a color relative to the maximum luminance is expressed by the luminance factor

$$l_c = Y_{c\ \max}/Y_{w\ \max} \qquad (2)$$

and the relative tristimulus energy of a color is given by the product

$$k_c w_c = k_c(X + Y + Z)_{c\ \max}/(X + Y + Z)_{w\ \max} \qquad (3)$$

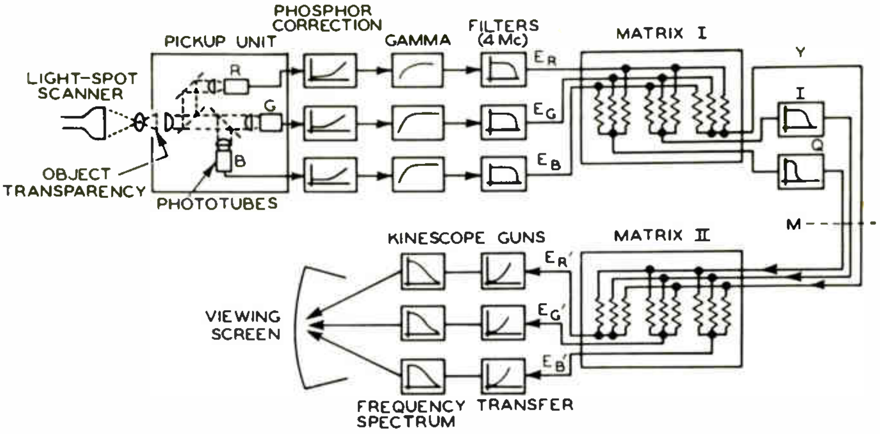

Fig. 1. Block diagram of color system. (Modulator and demodulator system (not shown) can be inserted ahead of Matrix II at point M.)

The tristimulus energy factor w_c can be expressed in terms of trichromatic coefficients (y) and the luminance factor l_c by the simple relation

$$w_c/l_c = y_w/y_c \qquad (4)$$

The tristimulus energy factor w_0 of the light bias is specified by the maximum contrast ratio C,

$$w_0 = w_w/C = 1/C \qquad (5)$$

The mixture ratio $k_c w_c/w_0$ of the relative tristimulus energy of the color to the fixed relative tristimulus energy of the light bias is equal to the distance ratio $S/(S_c - S)$, which gives the desired purity relation

$$S/S_c = k_c w_c/(k_c w_c + w_0) \qquad (6a)$$

and with Eq. (5)

$$S/S_c = k_c w_c/(k_c w_c + 1/C) \qquad (6b)$$

The total relative luminance of the color and light bias energy is the sum

$$Y/Y_{\max} = k_c l_c + 1/C \qquad (7)$$

Inspection of Eq. (6a) shows that only an ideal color reproducer having an absolute black level ($w_0 = 0$) provides a constant excitation purity for all colors, independent of excitation (k_c). A plot of excitation purity (S) as a function of relative luminance ($Y/Y_{\max}$) for all possible colors furnishes a *color space* in which are tan y/x is the vectorial direction of the color from the white point (see Figure 4), excitation purity is the vector length and relative luminance is the elevation.[2] The axis of this space, erected over the white point, represents the gray scale, and vertical sections through this axis furnish *color planes* such as shown in Figs. 5 to 7. The boundaries of these color planes include all possible colors and permit a comparison of different reproducers.

Given the NTSC primaries and constants (Table II) and the contrast range C of the picture tube (see Sect. 3), the

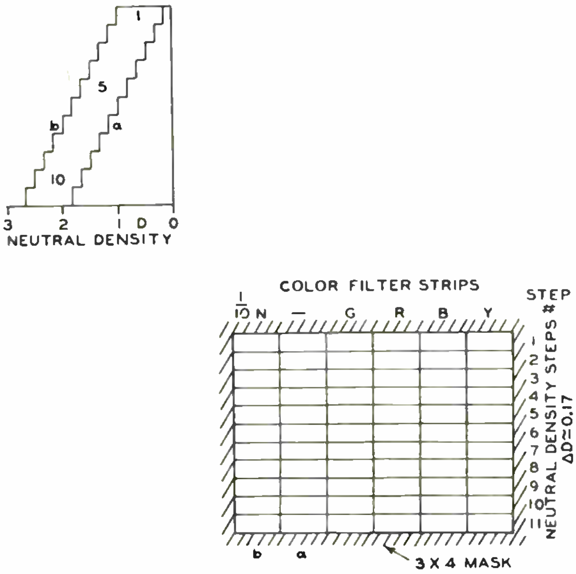

Fig. 2. Test pattern for measuring transfer characteristics.

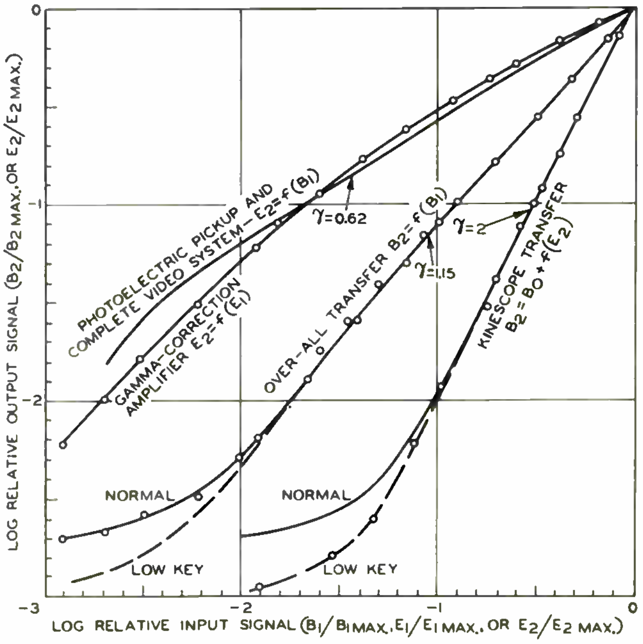

Fig. 3. Transfer characteristics of color system.

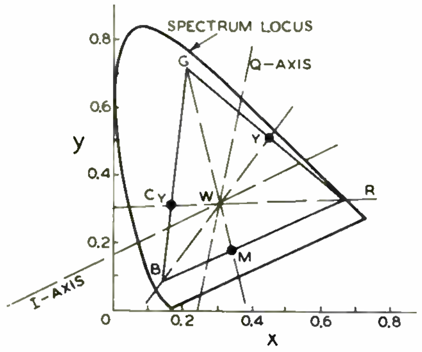

Fig. 4. CIE diagram showing location of television receiver primaries (R, G, B), I- and Q-axes and color planes.

Table II. Tristimulus Energy Factors w_c, Luminance Factors (l_c) and Excitation Purity (S_c), NTSC Standards.

Color	w_c	l_c	Dominant λ (mμ)	S_c	Trichromatic coefficients x	y	z	(See Fig. 4)
White	1.00	1.0	. . .	0	0.31	0.316	0.374	
Red	0.286	0.299	611	1.0	0.67	0.33	0.00	
Green	0.261	0.587	535	0.85	0.21	0.71	0.08	
Blue	0.453	0.114	470	0.88	0.14	0.08	0.78	
Yellow	0.547	0.886	573	0.88	0.45	0.512	0.038	
Magenta	0.739	0.413	535 compl.	0.625	0.345	0.177	0.48	
Cyan	0.714	0.701	490.5	0.52	0.165	0.31	0.525	

Munsell Lightness Value (V) and Luminance (Y)

V	10	9	8	7	6	5	4	3	2	1	0.5	0.2
$Y(0/0)$	102.56	78.66	59.1	43.06	30.05	19.77	12.	6.56	3.126	1.21	0.581	0.237

lower boundary of television color planes is constructed by selecting a color *on* the color triangle (Fig. 4) and computing the coordinates S, $(Y/Y_{\max})$ of points on the boundary curve with Eqs. (6) and (7) by assigning values between zero and one to the parameter k_c.

The computed boundary extends up to the relative luminance $l_c + 1/C$ at full excitation ($k_c = 1$) of the primary color (or two-component mixture). Higher luminance values in the particular color plane can therefore be obtained only by adding light of complementary color which combines with a certain fraction k' of the color energy to a partial white excitation, having the relative stimulus energy $k'w_w$. The remaining relative stimulus energy of the color is $(1 - k')w_c$. The excitation purity is hence determined by the mixture of the remaining color amount $(1 - k')w_c$ with the amounts of white $k'w_w + w_0 = k' + 1/C$, which leads to the expression for the upper boundary of the color space,

$$S/S_c = (1 - k')w_c/[(1 - k')w_c + k' + 1/C] \quad (8)$$

where $k' \leq 1$ (white excitation factor).

The relative luminance is given by

$$Y/Y_{\max} = (1 - k')l_c + k' + 1/C \quad (6)$$

The relative (per cent) luminance scale in Figs. 5 to 7 is distorted, because a better appreciation of the contrast range and color purity of a reproducer is obtained by using the psychophysical *Munsell lightness scale* (V) which divides the dynamic luminance range of the visual system into uniform lightness steps. (The conversion from per cent luminance to lightness (V) is given in Table II.)

A "perfect" color reproduction requires an absolute black level ($C = \infty$) and reproduces all spectrum colors with 100% purity; i.e., the color triangle is replaced by the spectrum locus. The lower boundaries of "perfect" color planes are therefore rectangles, indicated by $C = \infty$ and $S = 1$ up to the relative luminance for the spectral color point as exemplified by the red television primary. The upper boundary of the "perfect" color plane is determined by Eqs. (8) and (9) with $1/C = 0$ and w_c equal to the tristimulus energy factor for the spectral color point. Because their form is not strongly dependent on the contrast C, the upper boundaries of the television color planes R, G, B and Y approach those of the "perfect" color planes for the corresponding spectral color points. It is seen from Fig. 4 that the cyan and magenta regions of the color triangle lie approximately halfway between the spectrum locus and the white point. The corresponding color planes in Figs. 5 and 6 have therefore approximately one-half the width of the corresponding "perfect" color planes. It is further evident that the 600-to-1 contrast range obtained with a color kinescope comes much closer to a "perfect" color reproduction than a motion picture does. The color space boundaries of a color motion picture (broken lines taken from Ref. 2) are by comparison much more restricted and illustrate the basic fact that a subtractive process rapidly loses saturation at higher luminance values, because an increase in film transmission reduces the dye concentration and its color filter action.

To approach the chroma obtainable by the additive color television reproduction, color film could be modified to have a neutral density range of approximately 3.7, to be used with a minimum neutral highlight density near unity to retain a sufficiently high dye concentration. Unfortunately this modification leads to the requirement for ten times more light from the projector coupled with heating and other film problems.

The difference in performance of

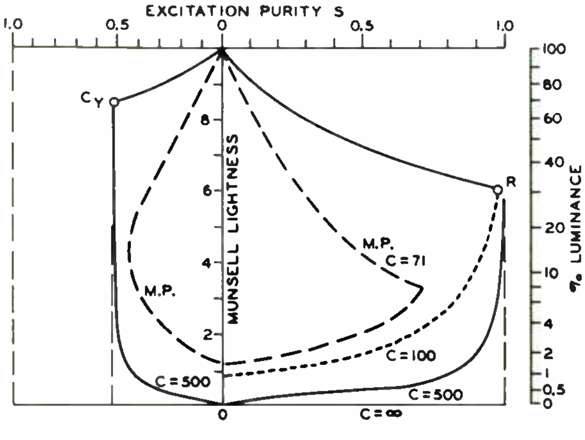

Fig. 5. Red-cyan color plane of additive TV process (Shadow-Mask Kinescope, C = 500), solid lines, and subtractive M.P. process (C = 71), broken lines.[2]

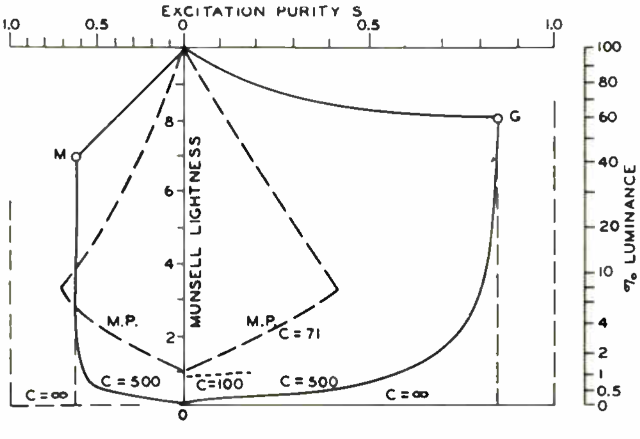

Fig. 6. Green-magenta color plane of additive TV process (Shadow-Mask Kinescope, C = 500), solid lines, and subtractive M.P. process (C = 71), broken lines.[2]

normal color film and color television can be demonstrated strikingly by color photographs of television images having constant luminance (constant *Y*-signal) and various degrees of color saturation, obtained by a progressive increase of *I*- and *Q*-signals (chroma control). Photographs were taken with chroma signals 1, 2 and 3 times normal. The 2 times chroma value produced very high color saturation on the kinescope. The corresponding color photographs, however, taken with *normal exposures*, show only minor increases in chroma, as illustrated by Plates I and II and expected from the color diagrams Figs. 5 to 7, while the denser photographs reproduced in Plates III and IV, taken with one-half normal exposure, give a better reproduction of the kinescope chroma at the expense of a shorter distorted contrast range. Relative chroma values are fairly well reproduced in the prints, although the color purity is lower than in the transparencies and considerably less than in the original kinescope image.

5. Sine-Wave Spectra and Optical Passbands

The transmission of color requires three independent video signals as compared to a single one for a monochrome image. Equal definition in a color image requires thus in theory a transmission system having 3 times the information capacity of a monochrome system. An appraisal of the total information capacity of the NTSC color system can be obtained by comparing its information capacity with that of a color system having three equal independent channels, taking into account a number of nonideal conditions arising in practical systems and deserving particular attention.

The electrical frequency spectrum of a *stationary* monochrome television picture-signal is a line-spectrum of discrete frequency components which are harmonics of the frame frequency (30 cycles). Because of this fact a second line-spectrum, the *color signals* (*I*, *Q*), can be added to the monochrome or *luminance signal* (*Y*) by interleaving its frequency components with those of the *Y*-spectrum. Interleaving is accomplished by modulation of a color carrier frequency (3.579545 mc) which is made an odd multiple of the half-line and half-frame frequencies. To permit separation of color signals by synchronous demodulators in the receiver, one color signal (*Q*) is transmitted with double sidebands. It is, therefore, limited to a 600-kc bandwidth, and a 600-kc filter is required after demodulation to eliminate all higher cross-product frequencies. The other signal (*I*) (also double-sideband up to 600 kc) can have its bandwidth extended by single-sideband transmission. It is restricted to one-half the color carrier frequency, i.e., a bandwidth of 1.8 mc, and a 1.8-mc filter is required after demodulation to eliminate crosstalk.

A perfect separation of the interleaved luminance and chrominance signals can be achieved with interleaved comb-filters when the image is stationary. The inexpensive continuous passband filters used in practical receivers, however, give rise to spurious color signals upon synchronous demodulation in the *I*- and *Q*-channels, caused by high-frequency *Y*-signal components, and the chrominance signal (modulated color carrier) produces periodic errors in the luminance signal. These errors change polarity in successive frames and would cancel out in a linear system when integrated (by the eye) over two frame periods ($\frac{1}{15}$ sec). Practical systems, however, are not linear (all kinescopes are rectifiers), and integration by the eye is incomplete, particularly for bright pictures. The errors, therefore, do not cancel completely even in stationary pictures. They become larger for moving objects and attain full magnitude for random signals such as noise.

The high-frequency crosstalk from the common 2–4-mc region of a "flat" *Y*-spectrum into the color demodulator band causes orange and blue color tinting of horizontal monochrome detail (coloring of resolution wedges in a monochrome test pattern), and normally fine-grained camera noise in this region of the *Y*-channel is heterodyned into rather objectionable coarse color-noise ("streaks") by the demodulators, as indicated by the large values of the broken-line cross-product curves in Fig. 8b.

These undesirable effects can be substantially eliminated by introducing a bandwidth limitation of 3.6 mc and a gradual "roll-off" into the *Y*-channel *before* synthesis of the NTSC signal in the colorplexer of the transmitting station as shown by the solid-line curves in Figs. 8a and 8b. Subsequent re-emphasis (aperture correction) of the *Y*-channel in the receiver (see Fig. 8c) after removal of the color carrier restores a good *Y*-signal response. The various degrees of color crosstalk are illustrated in Plates

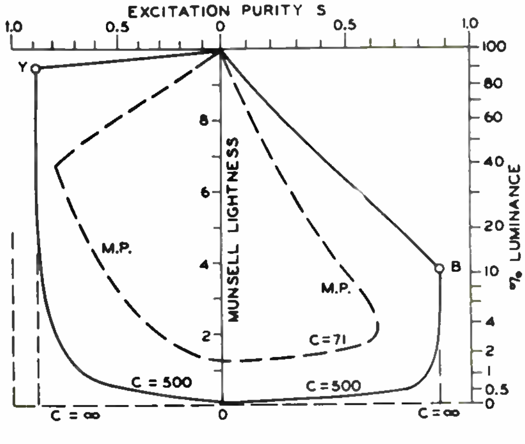

Fig. 7. Yellow-blue color plane of additive TV process (Shadow-Mask Kinescope, C = 500), solid lines, and subtractive M.P. process (C = 71), broken lines.[2]

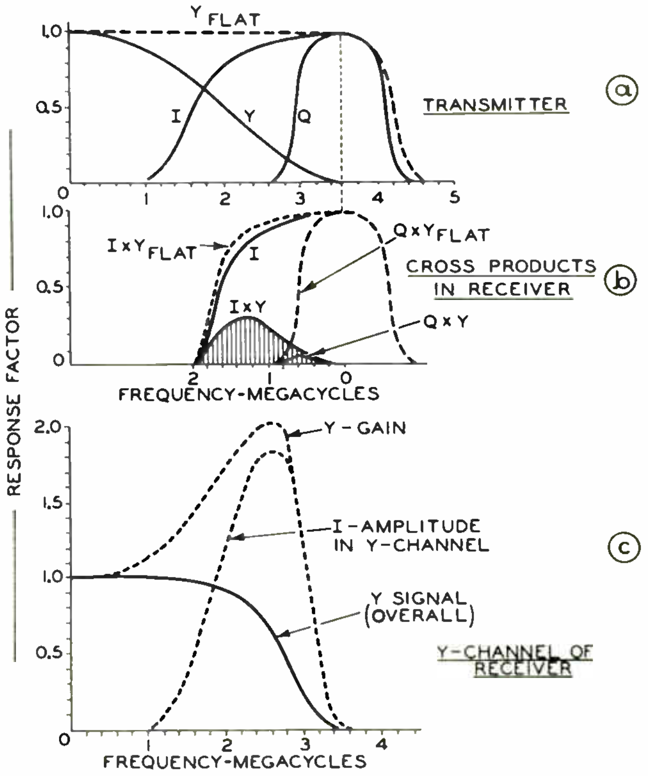

Fig. 8. Filter response and crosstalk in a color system (see text).

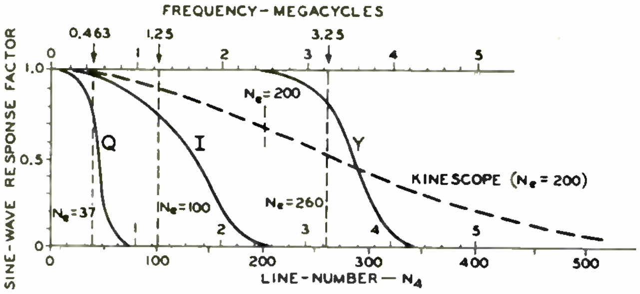

Fig. 9. Sine-wave spectra of horizontal (*Y*, *I* and *Q*) transmission passbands used in the analysis.

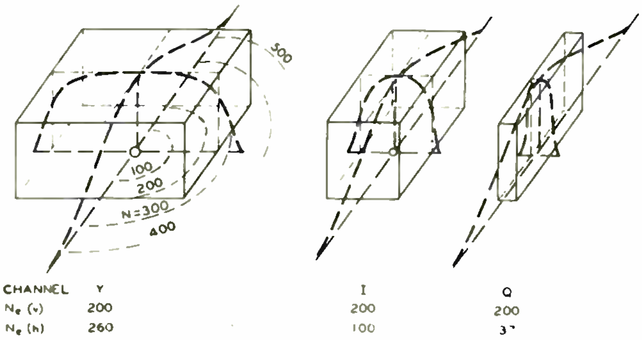

Fig. 10. Two-dimensional sine-wave spectra (*Y*-, *I*- and *Q*-passbands).

V and VI. (The bluish background color of the "white" test pattern photographs resulted from the accidental omission of the ultraviolet filter on the camera lens.) The striking reduction of noise obtained by the bandwidth limitation and roll-off is not reproduced because of integration by the time exposure. Considerable improvement in noise crosstalk is obtained by the bandwidth limitation alone.

The complete elimination of the chrominance signal (modulated color carrier) from the *Y*-signal (in the receiver) is not possible with continuous filters. It is therefore common practice to suppress the color carrier and its lowest sideband frequencies in the receiver by insertion of a filter (trap) which limits the *Y*-channel response to 3.6 mc (see Fig. 8c). The carrier interference is thus completely eliminated in large areas, leaving only beat patterns of reduced amplitude (occurring near sharp vertical edges) from the remaining sideband components (*I*-amplitude in *Y*-channel, Fig. 8c) which generally contain little energy and permit aperture correction of the remaining *Y*-channel at the receiver.*

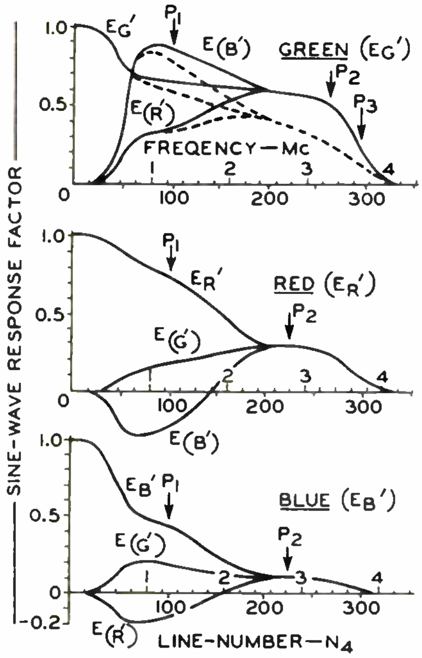

Fig. 11. Horizontal sine-wave-spectrum components at kinescope grid for green, red and blue camera signals.

There are thus available three electrical passbands for the transmission of color signals, which correspond to three two-dimensional optical passbands for the color image. Because of the rectilinear scanning process, the three optical passbands in the "vertical" (*v*) coordinate are alike. They are determined by the raster line number and have the theoretical equivalent passbands:†

$$N_{e(Y)v} = N_{e(I)v} = N_{e(Q)v} = 490 \text{ lines.}$$

The equivalent passbands in the horizontal coordinate (*h*) are unequal and have the theoretical values

$$N_{e(Y)h} = 320 \text{ lines for } \Delta f = 4 \text{ mc}$$
$$N_{e(I)h} = 144 \text{ lines for } \Delta f = 1.8 \text{ mc}$$
$$N_{e(Q)h} = 48 \text{ lines for } \Delta f = 0.6 \text{ mc}$$

The equivalent symmetrical passbands†

$$\overline{N}_e = [(4/\pi)\, N_{e(v)}\, N_{e(h)}]^{1/2} \qquad (10)$$

are hence

$$\overline{N}_{e(Y)} = 446 \text{ lines}$$
$$\overline{N}_{e(I)} = 300 \text{ lines}$$
$$\overline{N}_{e(Q)} = 173 \text{ lines}$$

Their sum, $\Sigma \overline{N}_e$ = 919 lines, is hence 68% of the sum of three equal passbands of 446 lines each. This simple appraisal of total information capacity in such a color system assumes theoretical rectangular frequency spectra having abrupt cutoff which are neither practical nor desirable for image transmission (monochrome or color) because of strong edge transients and spurious signals generated in the signal-separating process.

The sine-wave response characteristics of practical electrical passbands used in the following analysis are shown in Fig. 9. Their equivalent spatial horizontal passbands are $N_{e(Y)h}$ = 260,‡ $N_{e(I)h}$ = 100 and $N_{e(Q)h}$ = 37. The spatial vertical passband is determined by the cascaded value of the camera and kinescope sine-wave spectra and is in the order of $N_{e(v)} \simeq 200$ for each of the three signals. The equivalent spectrum spaces for the *three practical* channels are the rectangular solids illustrated in Fig. 10. The equivalent symmetrical passbands obtained with Eq. (10) form cylindrical spectrum spaces having the radii:

$$\overline{N}_{e(Y)} \simeq 257 \text{ lines}$$
$$\overline{N}_{e(I)} \simeq 160 \text{ lines}$$
$$\overline{N}_{e(Q)} \simeq 97 \text{ lines}$$

Because of the coordinate transformation or cross-mixing processes and unequal passband limitations, the electrical sine-wave spectra ("frequency responses") for different colors are not equal in this system and can be determined as follows. Referring back to Fig. 1, it is seen that the electrical frequency spectra

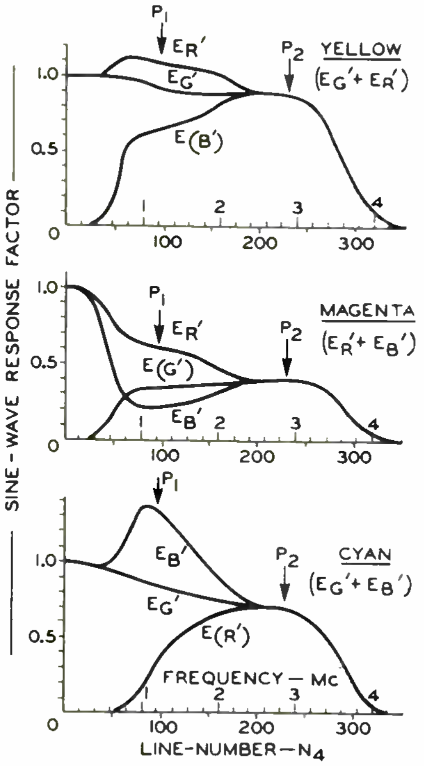

Fig. 12. Horizontal sine-wave spectrum components at kinescope grid for yellow, magenta and cyan camera signals.

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* The aperture correction approximately doubles the chrominance signal amplitude in the *Y* channel.

† See Ref. 3.

‡ This Y channel is somewhat wider than for receiver use (Fig. 8) because it does not contain a trap circuit for the carrier frequency.

of the color signals E_R, E_G, E_B entering Matrix I are alike. The linear cross-mixing process to Y-, I- and Q-signals and back to E_R', E_G', E_B' in the inverse Matrix II does not disturb the signal ratios in the range up to 600 kc where the frequency response in the Y-, I- and Q-channels is alike, i.e., $E_R' = E_R$, $E_G' = E_G$, $E_B' = E_B$. *This range includes the complete electrical frequency spectrum required for transmission of the vertical spatial passbands of the three color functions, which remain therefore unaffected by the cross-mixing processes.* The *horizontal passbands* are normal in the 600-kc range, i.e., a green signal E_G, for example, will result in a green signal E_G' on the "green" kinescope gun and in zero signals on the other two guns as indicated in Table I under the column $\Delta f = 0 \rightarrow 0.6$. In the range from 600 kc to 1.8 mc, however, all Q-coefficients in Matrix II are zero because of the Q-filter cutoff. The matrix is no longer the inverse of Matrix I, and causes signal voltages to appear on all three kinescope grids as shown in Table I. Beyond 1.8 mc, both Q- and I-coefficients are zero, with the result that all three kinescope guns receive equal signals. The last three columns of Table I show that the total luminance would remain constant in all sections of the total passband for a hypothetical *linear* kinescope, although the color or color mixture does not remain constant because of "spurious" signals. The complete video frequency spectra (at the control grids of the kinescope guns) have been plotted in Figs. 11 and 12 for the seven colors listed in Table I. Note that all of them are different, and some of the spurious responses have negative lobes (negative signs of coefficients indicate a phase reversal).

6. Effect of Unequal Passbands on Color Detail

It is a rather widely accepted opinion that the NTSC color transmission provides a three-color presentation for large areas, a two-color presentation for medium-sized areas and a presentation of fine detail without color information. This cannot be true because full color information is transmitted in the *vertical* dimension up to the finest detail (see Section 5 above) which is not affected by the inequality of the electrical passbands. Detail color information is also transmitted in the horizontal dimension, because only the true or "fundamental" color signal components have a normal frequency spectrum including a d-c component, while the frequency spectra of the "spurious" color components contain only horizontal a-c components and represent one-dimensional high-pass filters. It is improper to disregard the difference in d-c components and conclude from Fig. 11, for example, that a vertical line group in a green sine-wave test pattern (for which the blue and red camera signals are zero) would appear in black and white in the fine detail "mixed-high-frequency" region of line numbers $N_h > 200$.

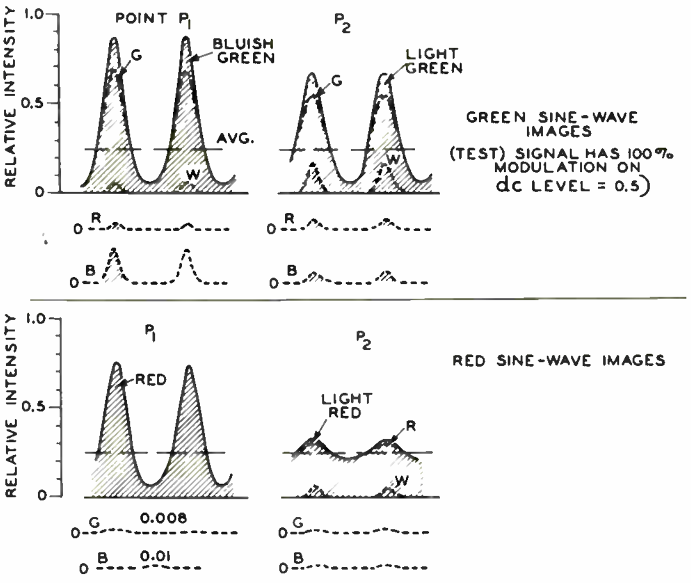


Fig. 13. Intensity function and components (broken lines) of green sine-wave images on the kinescope screen (top), and of red sine-wave images (bottom).

Actually these lines appear green because only the green a-c signal is raised completely above the black level by a d-c component, while the spurious color signals $(E_{(R)}{}'$ and $E_{(B)}{}')$ have an electrical zero-level axis, *are rectified by the kinescope*, and can only produce light of much lower intensity during positive half-cycles. In computations of color mixtures for small areas it must be remembered that the normal Fourier relations between impulse forms, unit functions and their spectra do not hold in systems containing nonlinear elements such as a kinescope.

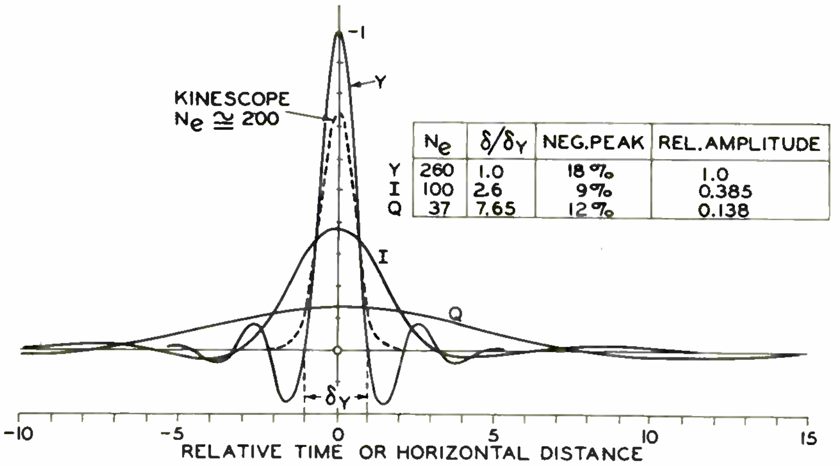
To obtain the correct answer, it is necessary to convert frequencies to intensity functions (waveforms) at the input terminals of nonlinear elements, such as the kinescope guns, project the waveforms over the nonlinear transfer characteristics, pass them through the low-pass filters representing the gun and optical performance, and then combine the light signals to color mixtures as indicated in Fig. 1. The general *effect of the kinescope "spot" size* on fundamental color signals is a reduction of high-frequency components as indicated by broken-line curves in Fig. 11 for small signals. The spurious color signals, however, are rectified by the kinescope, so that each sine-wave frequency is replaced by a series of even-order harmonics which is attenuated more rapidly by the kinescope low-pass spectrum than is indicated by the dotted lines, which lose their meaning as a sine-wave response.

The observed transfer characteristic of the actual kinescope is substantially a square-law characteristic. The intensity function of the fundamental green sine-wave pattern on the kinescope screen (neglecting kinescope spot size) can hence be calculated by squaring the instantaneous sine-wave grid-signal values measured from the current cutoff point, as illustrated in Fig. 13 (top) for two frequencies (points P_1 and P_2 in Fig. 11). Because of the missing d-c component, the squared spurious red and blue a-c signals become very small and only their positive half-waves produce light which adds to the green sine-wave light on the kinescope screen, diluting its chroma as indicated. Similar conditions prevail for test patterns of other saturated colors (see Fig. 13, bottom) as summarized in Table III.

The fine line groups in the "mixed-high-frequency" region retain, therefore, substantially the color of the fundamental signal, although they acquire a spurious tint. Their relative amplitude and luminance are determined largely

Table III. Color of Horizontal Sine-Wave or Periodic Line-Patterns (See Fig. 13)

Object color	P_1	P_2	P_3
Green	Bluish-green (20% blue)	Light green (26% white)	Green
Red	Red (1.5% green)	Light red (17% white)	
Blue	Blue (1.8% green)	Light blue (22% white)	
Yellow	Yellow (5% blue)	Yellow (10% blue)	
Magenta	Magenta (3% green)	Magenta (4% green)	
Cyan	Cyan (2% red)	Cyan (8% red)	



	Ne	δ/δY	NEG.PEAK	REL.AMPLITUDE
Y	260	1.0	18 %	1.0
I	100	2.6	9%	0.385
Q	37	7.65	12 %	0.138

Fig. 14. Unit-pulse forms of *Y*-, *I*- and *Q*-channel from Matrix I and of kinescope.

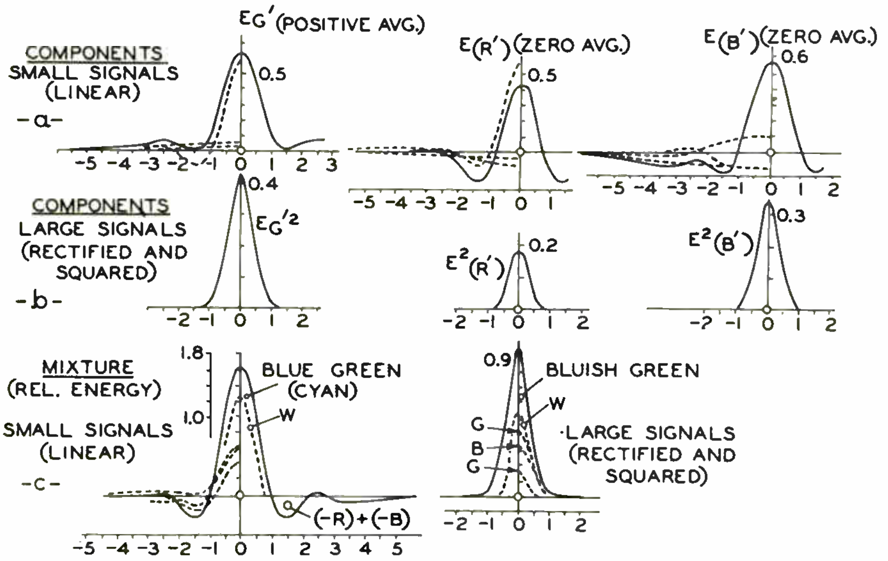


Fig. 15. Relative intensity of impulse components and sums forming the green line-image.

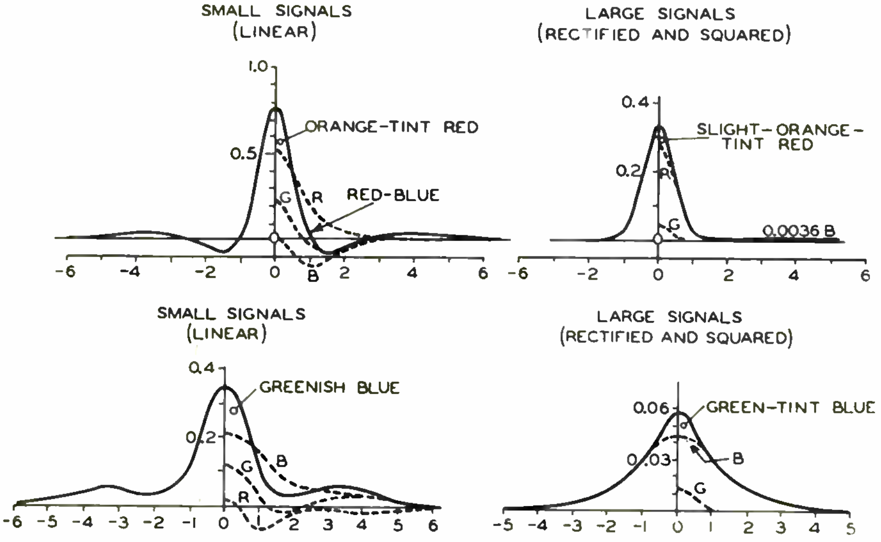


Fig. 16. Relative intensity of red and blue line-images.

by the amplitude of the fundamental color component which is proportional to the *Y*-component of the particular color and therefore lowest for blue (11.4%). These findings are confirmed visually by turning off one or two of the three equal color signals generated by a "white" SMPTE test pattern ahead of Matrix I (see Fig. 1) and comparing the color in the vertical line-wedge reproduc-

Plates I to IV. Ektachrome performance in recording constant luminance images. Plate I, normal chroma, normal exposure; Plate II, 2X chroma, normal exposure; Plate III, normal chroma at ½ exposure; Plate IV, 2X chroma at ½ exposure.

Plates V and VI. Monochrome test pattern reproductions by NTSC system. Plate V, left, 4-mc flat *Y*-channel input, demodulators off (no crosstalk); Plate V, right, 4-mc flat *Y*-channel input, demodulators on; Plate VI, left, 4-mc gradual roll-off *Y*-channel, demodulators on, subsequent re-emphasis; Plate VI, right, 3-mc flat *Y*-channel, demodulators on, normal *Y*-response in receiver.

Plate VII. Samples of three line-object reproductions, 4-mc *Y*-channel and standard NTSC *I*- and *Q*-channels; pure color signals obtained from a white pattern by turning off unwanted color channels in camera.

Plates VIII to XI. Effects of unequal passbands and luminance weighting on kinescope image. Plate VIII, Three independent 4-mc channels (*R*, *G*, *B*); Plate IX, $Y + I + Q$ signals, standard NTSC matrix and filters as in Fig. 1; Plate X, $Y + I + Q$ signals and filters, but *G* and *B* reversed to Matrix I and from Matrix II; Plate XI, $Y + I + Q$ signals and filters, but *R* and *G* reversed to Matrix I and from Matrix II.

Plate XII. Complete NTSC signal with standard matrix and filters, incuding modulators, multiplexing and demodulator circuits.

Plate XIII. Three independent 4-mc channels (*R*, *G*, *B*).

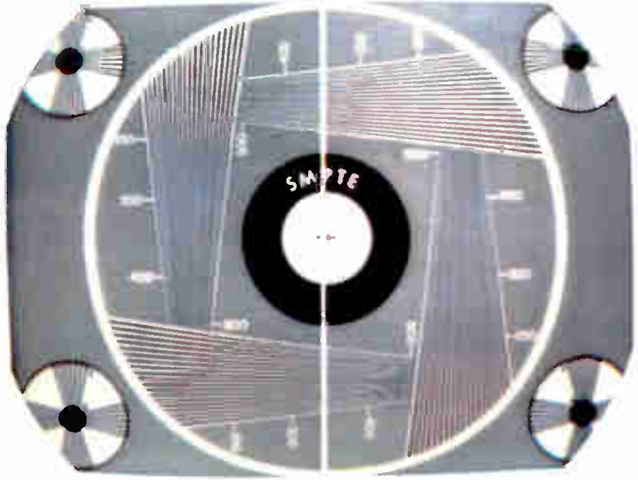
I

II

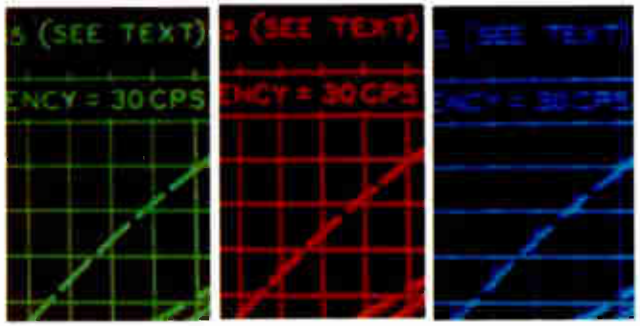
III

IV

V



VI



VII

VIII

IX

X

XI

XII

XIII

of the color signals E_R, E_G, E_B entering Matrix I are alike. The linear cross-mixing process to Y-, I- and Q-signals and back to E_R', E_G', E_B' in the inverse Matrix II does not disturb the signal ratios in the range up to 600 kc where the frequency response in the Y-, I- and Q-channels is alike, i.e., $E_R' = E_R$, $E_G' = E_G$, $E_B' = E_B$. *This range includes the complete electrical frequency spectrum required for transmission of the vertical spatial passbands of the three color functions, which remain therefore unaffected by the cross-mixing processes.* The *horizontal passbands* are normal in the 600-kc range, i.e., a green signal E_G, for example, will result in a green signal E_G' on the "green" kinescope gun and in zero signals on the other two guns as indicated in Table I under the column $\Delta f = 0 \rightarrow 0.6$. In the range from 600 kc to 1.8 mc, however, all Q-coefficients in Matrix II are zero because of the Q-filter cutoff. The matrix is no longer the inverse of Matrix I, and causes signal voltages to appear on all three kinescope grids as shown in Table I. Beyond 1.8 mc, both Q- and I-coefficients are zero, with the result that all three kinescope guns receive equal signals. The last three columns of Table I show that the total luminance would remain constant in all sections of the total passband for a hypothetical *linear* kinescope, although the color or color mixture does not remain constant because of "spurious" signals. The complete video frequency spectra (at the control grids of the kinescope guns) have been plotted in Figs. 11 and 12 for the seven colors listed in Table I. Note that all of them are different, and some of the spurious responses have negative lobes (negative signs of coefficients indicate a phase reversal).

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Color transitions at sharp edges can be synthesized in the same manner from the component step-functions shown in Fig. 18. The results are plotted in Figs. 19 to 23. Inspection shows that both color and waveform distortions vary with color and are again relatively smaller in high-contrast transitions than in low-contrast transitions because of the square-law kinescope characteristic.

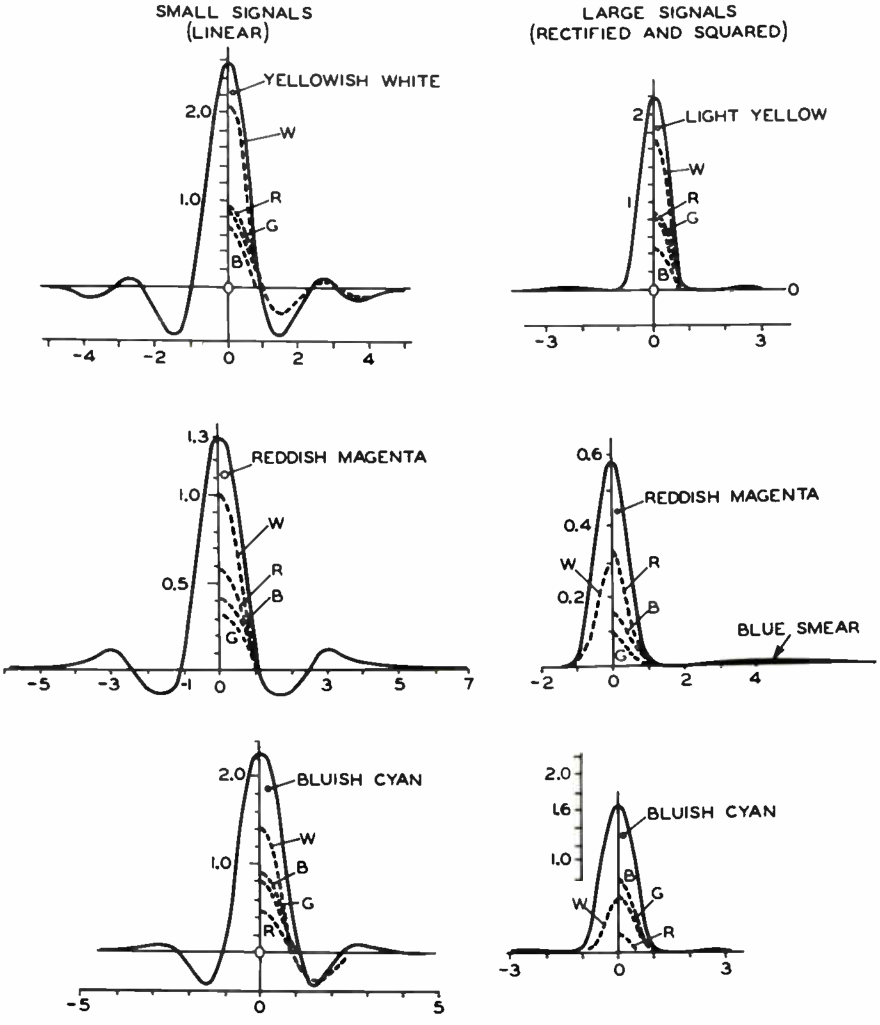

Fig. 17. Relative intensity of yellow, magenta, and cyan line-images.

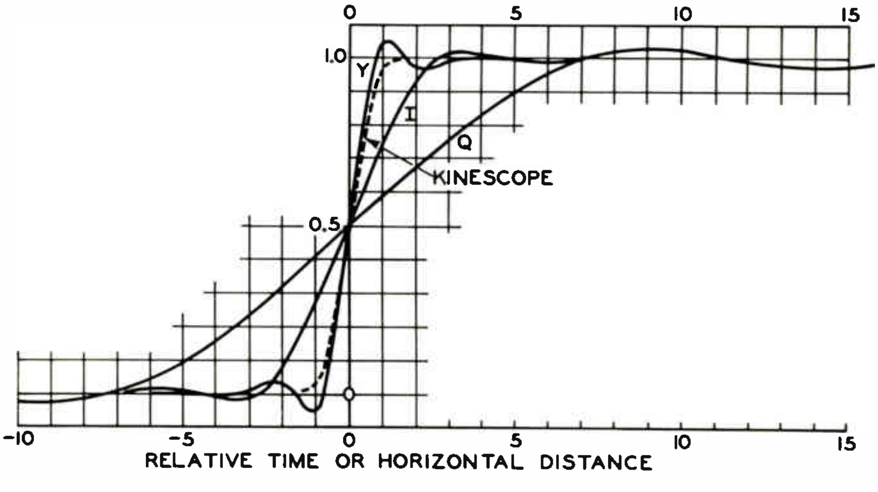

Fig. 18. Unit step-function components from Matrix I and of kinescope.

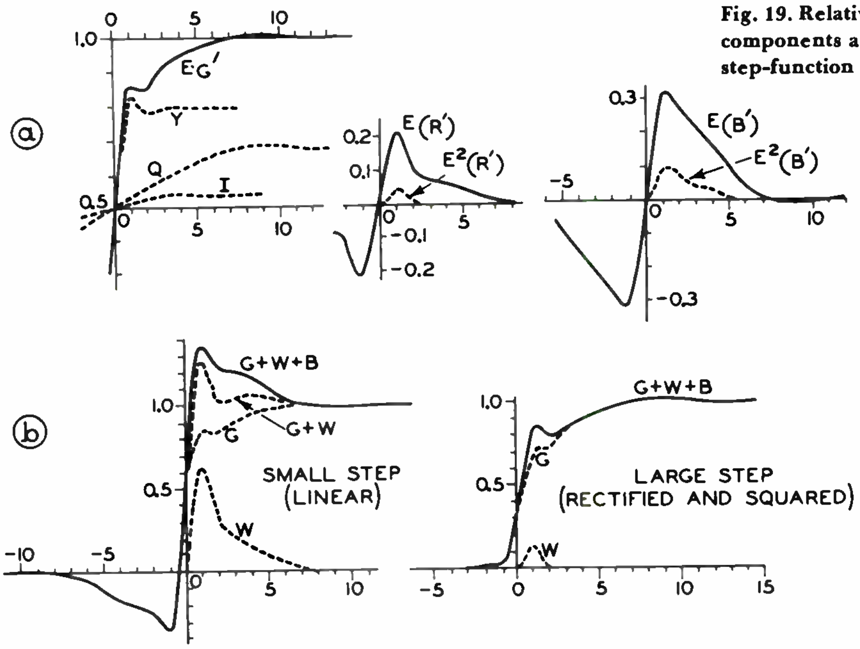

Fig. 19. Relative intensity of step-function components and sums forming the green step-function image.

It should be pointed out that the effect of camera-tube and kinescope-beam sizes and also the $\frac{1}{2}$-power gamma correction for the kinescope have not been included in the line-image and step-function evaluations. The gamma-correction amplifier itself would not change an ideal unit impulse or a step function, but it does round off the low-level corner of the actual S-shaped step-function from the camera relative to its high-level corner, thus making the large signal step-functions more symmetrical and all step-functions less steep with reduced transient ripples. To include the effect of the kinescope beam size, it is necessary to perform a convolution of its line-image or its step-function response with the computed response forms. The finite kinescope beam size broadens the line-images and transitions somewhat more and further reduces high-frequency transients. The visibility of the luminance errors caused by the unequal passbands of the NTSC system can be assessed by computing the visual lightness of horizontal step-functions and line-images for red, green and blue as shown in Fig. 24. Constant-bandwidth vertical step-functions and line-images are shown for comparison and indicate that the errors in the blue are readily visible as confirmed by observation (compare color plate VII).

It can thus be concluded that *considerable color information is transmitted and reproduced even in fine horizontal detail with NTSC color signals and that a high gamma (square-law) kinescope transfer characteristic is a definite asset because it reduces the color distortion introduced by unequal color-transmission channels.* Furthermore, the fact that relatively small color changes can be seen in the fine detail of color television images raises doubts that the eye's color mechanism does not function when observing fine detail, and suggests a reappraisal of the capabilities of the visual system at normal luminance values.

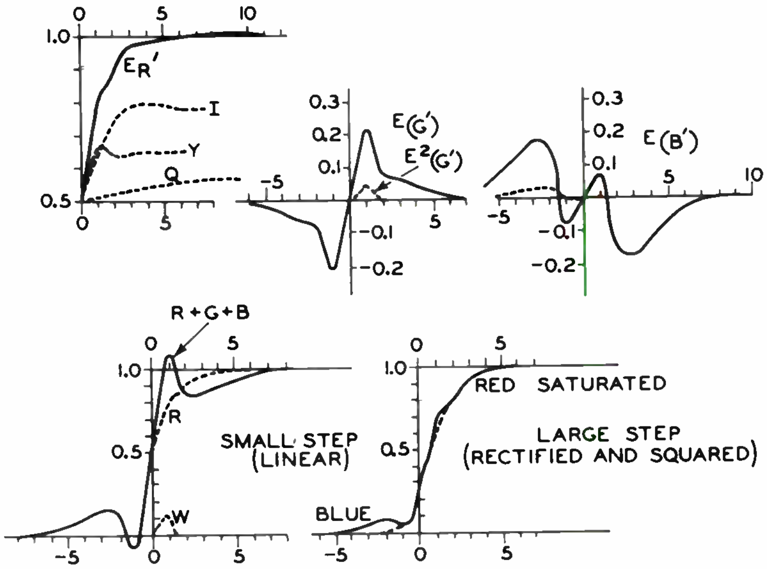

Fig. 20. Relative intensity of step-function components and sums forming the red step-function image.

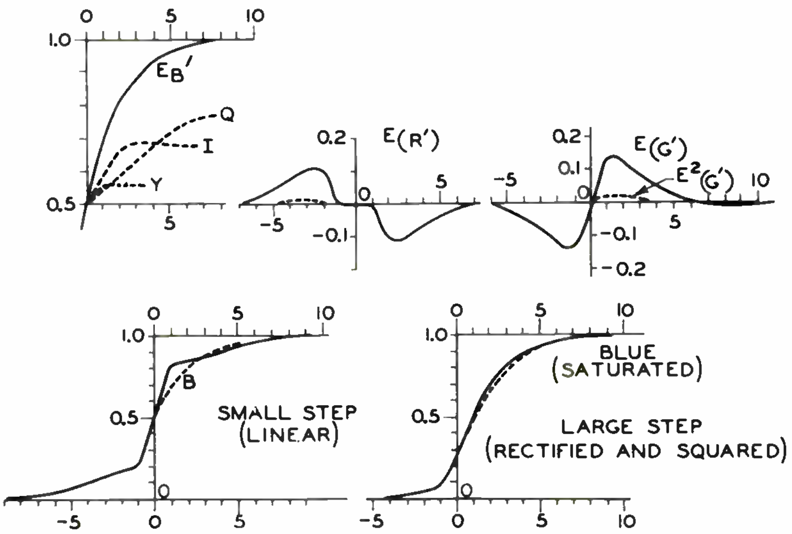

Fig. 21. Relative intensity of step-function components and sums forming the blue step-function image.

Table IV. Horizontal Line-Image Characteristics.

Object color	Incremental impulse (linear) color*	Large-signal impulse (rectified, squared) color*	Rel. brightness	Rel. sharpness
Green	Light blue-green (60% white)	Bluish-green (36% white)	Normal†	Normal‡
Red	Red, orange tint (29% green)	Red, slight orange tint (7% green)	Reduced†	Fair‡
Blue	Greenish-blue (17% green)	Blue, green tint (7% green)	Low†	Blurred‡
Yellow	Yellowish-white (27% blue)	Light yellow (21% blue)	Normal	Normal
Magenta	Reddish-magenta (25% green)	Reddish-magenta (17% green)	Reduced	Fair (blue haze)
Cyan	Bluish-cyan (20% red)	Bluish-cyan (12% red)	Good	Normal
White	White	White	Normal	Normal

*The per cent color admixture refers to the area under the main lobe of the impulse or line. Incremental impulse color refers to the increment, not to the total which depends on the color of the setup level.

†See Fig. 24.

‡See Plate VII.

B. SOME CHARACTERISTICS OF THE VISUAL SYSTEM AND EFFECT ON OVERALL SYSTEM CONCEPT

1. Transfer and Wavelength Functions; Incremental Sensitivity for Luminance and Color

The visual system is a very complex system which terminates in a "computer" (the brain) having random connections, and very little is known about its memory and interpreting processes.* There is ample evidence that the system is nonlinear in many of its sections. It is well known that both hue and lightness of colored objects are functions of the surrounding background, although there is no spectral or colorimetric change. It is also known that the apparent "lightness" of a color mixture does not necessarily agree with the luminance value computed as the linear sum of component luminances. (A bluish-white screen, for example, appears brighter than a screen of equal luminance illuminated by a low-color temperature light source.) Observations made by the author on equiluminous sine-wave mixtures (considered later in this paper) indicate likewise that the fixed relation of lightness and luminance given in Table II does not necessarily apply to incremental amounts of the components in a mixture of primary colors, but that it is strongly dependent on the relative total amounts of the primaries.

As to chromatic sensitivity, it is known that the just-perceptible amounts of pure color added to white are about 1% for red and blue and about 2% for yellow and green.[5] The chromatic sensitivity $f/\Delta f$ or $\lambda/\Delta\lambda$ of the eye for spectral colors[6] has two peaks (less than 3 : 1) at yellow and cyan above a substantially uniform level from red (650 mμ) to blue (430 mμ). From the system analysis point of view, it does not appear likely that the wavelength functions of the eye's color discriminating system are as simply related to the wavelength function of its luminance channel as they

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* An interesting theory on this subject is discussed in Ref. 4.

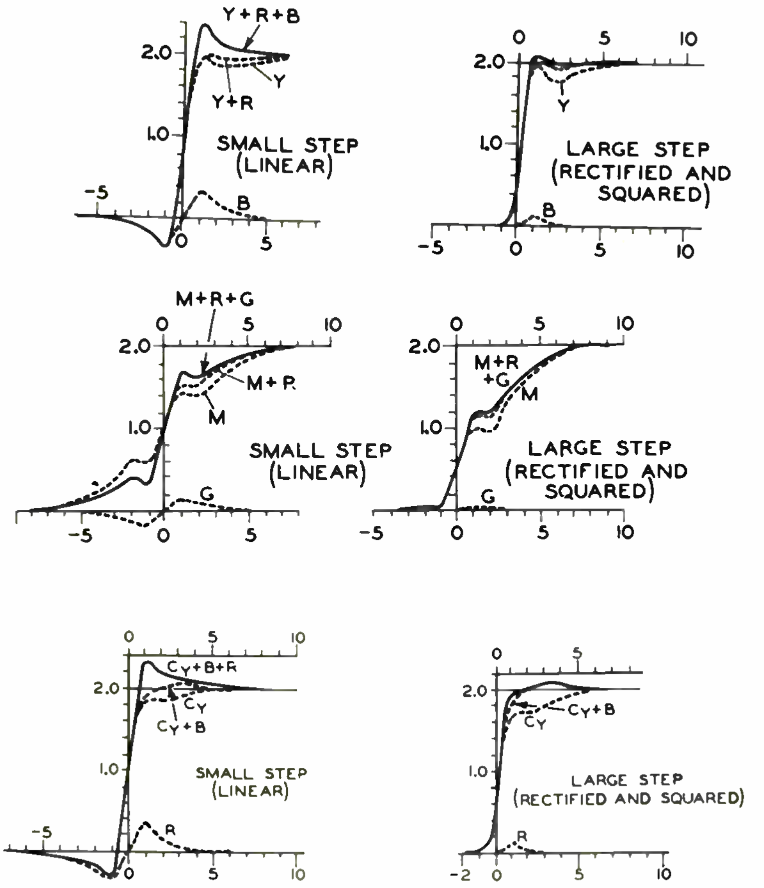


Fig. 22. Relative intensity of yellow, magenta and cyan step-function images.

COLOR SIGNALS		SIGNAL STEP	ΔE
G	Y	0.59 TO -0.41	-0.18
	I	0.07 " -0.07	-0.14
	Q	0.34 " -0.34	-0.68
R	Y	0.59 " 0.41	-0.18
	I	-0.26 " 0.26	0.52
	Q	-0.33 " 0.33	-0.66
B	Y	0.59 " 0.41	-0.18
	I	0.30 " -0.30	-0.60
	Q	-0.89 " 0.89	1.78

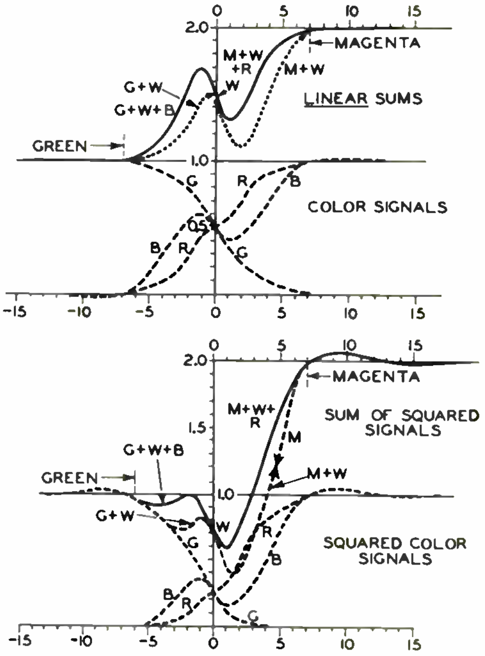


Fig. 23. Relative intensity of green to magenta step-function images.

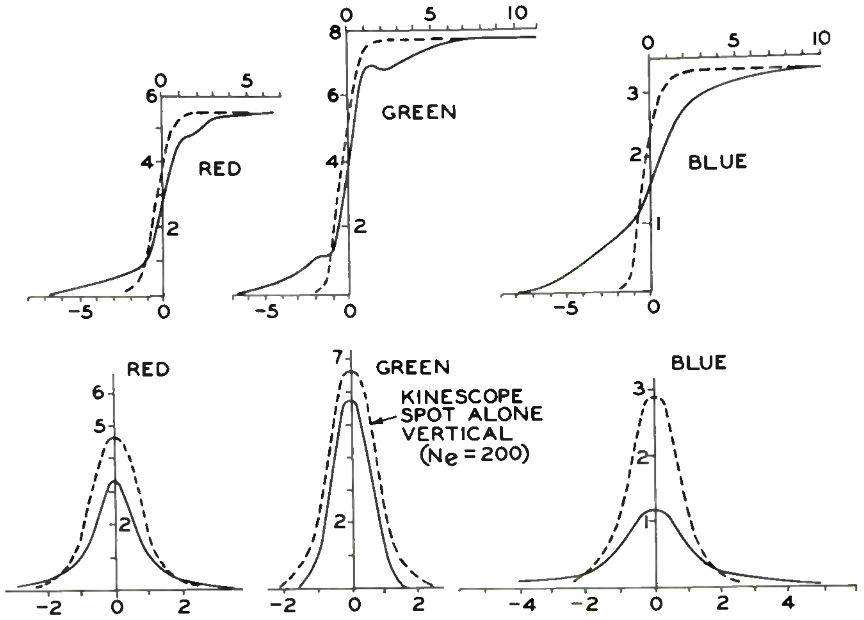
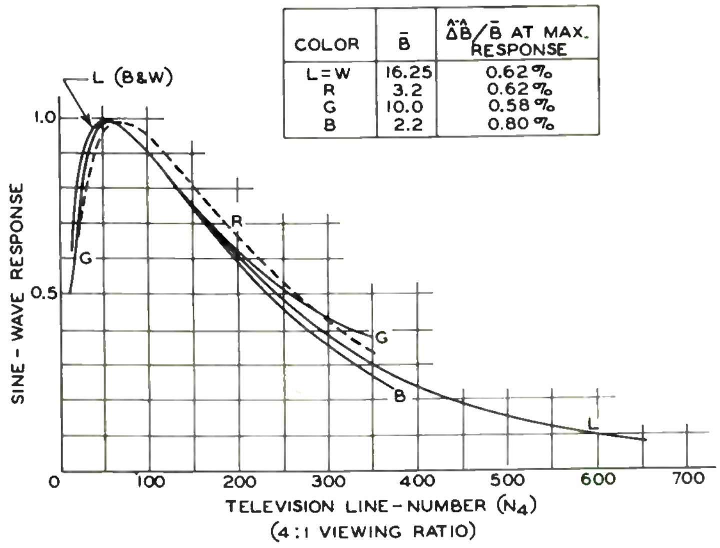


Fig. 24. Step functions and line-images (NTSC) in Munsell lightness values. Solid curves horizontal, broken-line curves vertical coordinate.



COLOR	$\bar{B}$	$\hat{\Delta B}/\bar{B}$ AT MAX. RESPONSE
L=W	16.25	0.62%
R	3.2	0.62%
G	10.0	0.58%
B	2.2	0.80%

Fig. 25. Response of visual system to single-color sine-wave patterns.

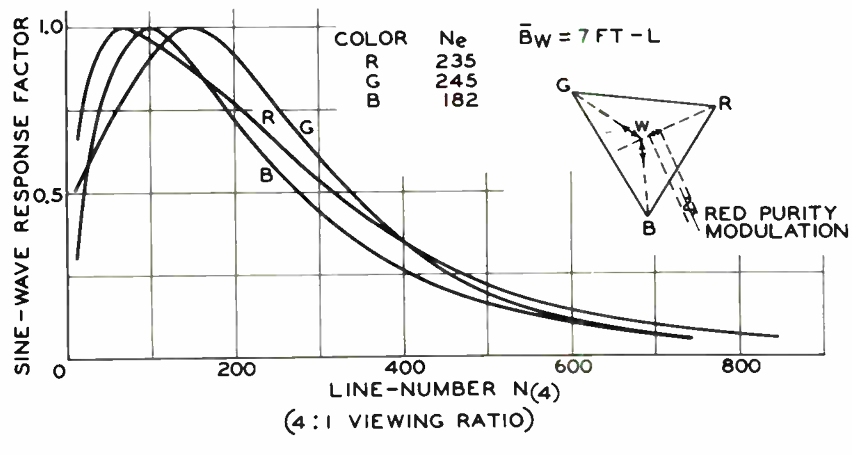


Fig. 26. Response of visual color discriminator system to constant brightness sine-wave patterns (purity modulation).

are in a photographic or color television system, because the eye's luminance system continues to operate at light intensities far below the threshold for color vision.

It has been demonstrated that the eye can see all the calculated defects in the color detail reproduction of the NTSC system, including those in low luminance colors, such as blue, for which the eye's "acuity" is low. It is important to understand clearly that acuity and resolving power are not determined by the spatial sine-wave response alone, because they are strongly dependent on the noise level as well. The remarkable visual constancy of color mixtures over a large part of the photopic range may be taken as an indication that the transfer characteristics, spatial sine-wave response characteristics and noise levels of the eye's color discriminating system are well matched (see Sec. 1 in part A above). Similar noise levels in turn indicate that the "discriminators" receive similar signal levels, or more likely, similar signal differences from the photo receptors in at least three principal regions of the visual spectrum. Their spatial sine-wave response appears to be well matched, because there is no evidence to the contary in their performance (no color fringes, transients or "smears").

It was therefore decided to determine the spatial frequency passbands of the visual color discriminators by sine-wave response measurements, following a procedure previously described for the luminance channel of the eye.[7]

2. Sine-Wave Response Functions

There have been general observations to the effect that resolution and sharpness of images (in microscopy, for example) do not change appreciably with blue, green or red illumination, and that the readability of colored print of equal luminance is fairly independent of color, with red slightly better than green or blue. These observations are not convincing, because they relate to an interpretation of signal combinations (depending on noise level and sine-wave response) from the luminance as well as the color mechanism. The same criticism can be applied in part to the single-color sine-wave response characteristics, Fig. 25, measured by the author on an observer having normal vision. The response of a luminance system can, however, be eliminated by the use of *equi-luminous* sine-wave objects, which provide a sinusoidal variation of excitation purity at constant luminance. A red purity change, for example, is represented in the red color plane (Fig. 5) by a sinusoidal modulation of the radius length (horizontal distance), which can be centered near the white axis (near-white background) or may be moved out toward a higher purity point. The generation of such sine-wave patterns on a color kinescope screen is relatively simple, as discussed in the Appendix.

Sine-wave patterns of constant luminance were set up by measuring the sine-wave luminance distribution with a luminance meter,[*] and adjusting the component intensity for a constant reading. It was observed immediately that luminance does not have a constant relation to visual brightness. The adjustment for constant luminance (by calculation or meter) differed from the incremental brightness, particularly for equiluminous blue purity sine-waves in a near-white background where the increment-component ratio was in error by several hundred per cent. The flicker test for equal brightness was made by reducing the temporal (electrical) sine-wave modulation frequency to 20 or 25 cycles and adjusting, for example, the blue component (see Appendix) for minimum flicker. Because of the possibility of errors arising from the difference in phosphor decay time for different kinescope primaries, the brightness equality of the positive and negative purity half-waves was judged visually at a higher modulation frequency producing a wavelength of about 2 cm on the kinescope screen. It was found to agree with the flicker test. When such a stationary wave-pattern is observed while one component is varied, a sudden phase shift seems to occur in the sine-wave position when constant brightness is reached.

The constant-brightness condition near the white point requires more nearly[†] equal stimulus energy than equiluminance of the components, as is most strikingly evident from blue purity modulation tests. It approaches equiluminance when the operating point (background color) is moved toward the spectrum locus, which is to be expected because the luminosity curve is determined from spectrum colors by brightness equality tests. This observation may well explain observed discrepancies in color noise visibility with the NTSC color system, because *equal luminance increments do not guarantee equal increments in visual brightness.*

At the time of this writing only one set of sine-wave response-measurements taken near the white axis (B_W = 7 ft-L) is available. The designations red, green and blue in Fig. 26 refer to the color plane in which the purity modulation occurs, although the color in the areas of reduced "negative" purity (negative half-cycles of sine-wave) appears to the eye as a complementary color in comparison with the color of adjacent areas of higher "positive" purity, even at a larger distance from the white point. (The negative blue bar appears yellow, negative green appears magenta, etc.) Lacking a luminance change, the bars appear to have a constant purity as if produced by a square-wave rather than a sine-wave modulation.

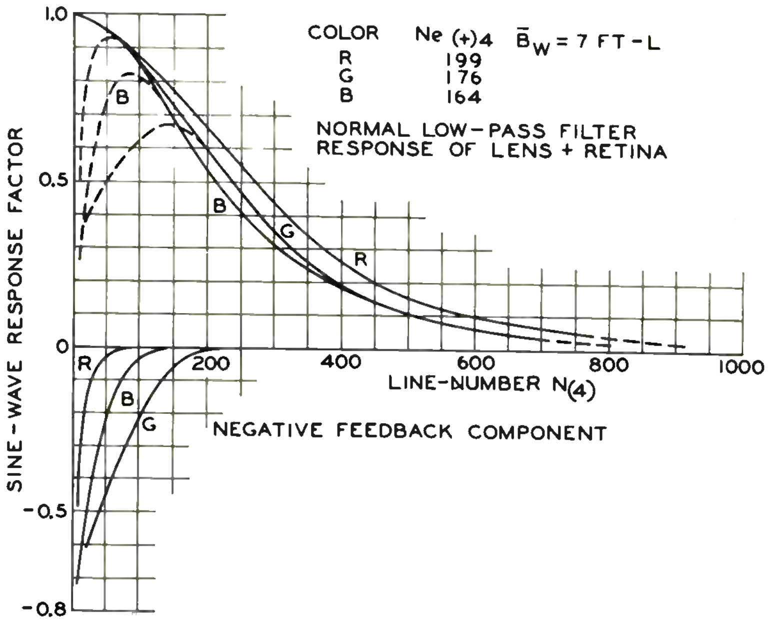


Fig. 27. Positive and negative sine-wave spectrum components of visual color discriminator system.

The measured sine-wave response-functions of the color discriminator elements in the visual system differ from one another by much smaller factors than the "standard" luminance values. All show a loss of low-frequency and d-c response as in the luminance channel. An analog of the visual system[7] contains therefore a high-pass filter or a negative frequency-limited feedback loop which superimposes a negative image of low definition on the normal image, "inhibiting" the normal low-pass filter response by addition of a negative response as reconstructed in Fig. 27 (see Appendix). The feedback is least for red light and largest for green light, with blue intermediate. More data are required to support a more quantitative analysis of the details of these results.

3. Equivalent Passbands and Number of Receptors in Effective Retinal Sampling Areas

The equivalent passbands (N_{e+}) of the main low-pass characteristics give information on the *effective discriminator areas in the retina* and appear to be in general agreement with Polyak's anatomically well-founded deductions[9] that the red end of the color spectrum is signaled over direct "private line" connections between optic nerve fibers and cones and that it has the best detail response, while green and blue signals involve more diffuse matrix networks in the order stated. The effective sampling area a (area of equivalent constant intensity point-image) can be computed from the equivalent passband by $a = 1.16/N_e^2$ (see Ref. 3). It has been shown in Ref. 7 that at a luminance of 7 ft-L the equivalent passband of the eye's lens is $N_{e(L)} = 50$ television lines/mm on the retina. The effective sampling area a_L of the optical point-image produced by the lens of the eye or the retina includes, therefore, 88 2.2-micron cones at this illumination as illustrated in Fig. 28. The normal positive sine-wave response function (Fig. 27) of the visual system is the product of the sine-wave response function of the lens and the sine-wave response function of the color discriminator neuron system. Since the equivalent area of the final point-image in a cascaded system is simply the sum of the equivalent areas of its cascaded components, the equivalent areas a_d of the color discriminator system are obtained as the difference

$$a_d = a_m - a_L$$

where a_d = effective area of discriminator neuron system, $a_m = 1.16/(N_{e(+)4}/4.25)^2$ = equivalent area of entire system[‡]

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[*] Weston Foot-Lambert Meter, New Candle Model 931 with Viscor Filter, corrected for visual response. The meter is designed for kinescope measurements and gave correct luminance readings on the phosphor primaries and their mixtures. The readings agreed with comparative readings taken with a Macbeth Illuminometer.

[†] This might be expected from a discriminator near its neutral point. A more extended quantitative study of incremental luminance and brightness ratios in sine-wave objects would be of value. The author is aware of many publications (in the *Journal* of the Optical Society of America and elsewhere) discussing discrepancies in the total luminance of a color from standard sums.

[‡] The equivalent passband $N_{e(+)4}$ of the overall sine-wave function (Fig. 27) is measured at an object distance equal to four length units (indicated by the index 4); since the effective distance to the retinal image is 17 mm (effective focal length of lens), this length unit corresponds to 17/4 mm = 4.25 mm on the retina, requiring division by 4.25 to obtain lines per millimeter on the retina.

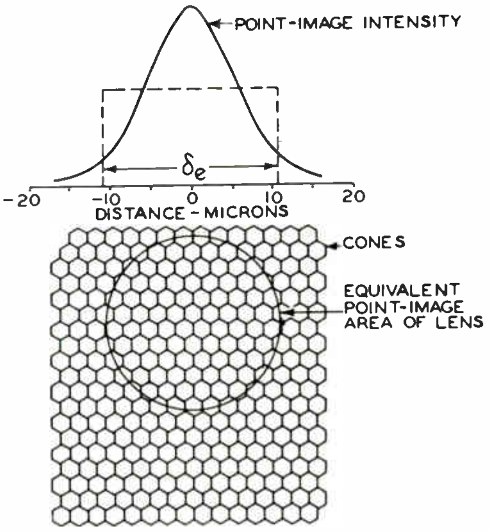

Fig. 28. Diameter δ_e (microns) of equivalent round sampling area of optical point-image and color discriminators of visual system relative to the diameter (2.2 μ) of the photoreceptors (cones).

COLOR DISCRIM.	EQUIV. PASSBAND N_e, (L/MM) OF RETINAL AREA	DIA. δ_e OF EQUIV. AREA (μ)	NUMBER OF 2.2μ CONES
R	135	8.0	12
G	75	14.4	39
B	61	17.7	59
POINT-IMAGE OF LENS: AT $\bar{B}$ = 7 FT-L	50	21.6	88

and $a_L = 1.16/N_{eL}^2 = 1.16/2500$ mm^2 = equivalent sampling area of lens.

The diameters obtained for equivalent circular sampling areas a_d of the color discriminator neuron systems are listed in Fig. 28.* The red discriminator receives signal contributions from approximately 12 cones, while the more diffuse green and blue discriminators collect signals from equivalent areas containing about 39 and 59 cones, respectively. The intensity distribution in the actual point-image of the lens and the chromatic sampling areas is approximately gaussian, as illustrated in Fig. 28, and the actual areas include a larger number of cones with partial signal contributions. The relatively large number of cones associated with a single point-image area does give a logical explanation to the known fact that *the retina contains a much smaller number of matrix units (bipolar and ganglion cells) than cones and that this ratio is adequate to derive color signals from the receptors, with only minor effects on the overall passbands.*

4. System Concepts Unresolved

The complexity of the visual system, much of it unexplained, leaves room for much variety with regard to its possible functioning as a color system, and many different theories can be found in the literature.† The number of possible systems, however, is reduced by the high "quantum efficiency" of the eye[7,11] which does not seem to agree with systems of area-sharing receptors, where each covers only a narrow region of the visible spectrum. Given supersensitive receptors, even slight dissimilarities in three spectral response characteristics similar to a luminosity function are quite sufficient to produce excellent color discriminators by signal subtraction and to retain full luminance sensitivity by addition. Like the eye, such a system will continue to "see" images in monochrome when the scene illumination becomes insufficient for operation of its discriminators.‡

The nonlinearity and the matrix system of the retina allow for variation of amplitudes and weighting of respective gains (negative feedback) in combination with the luminance signal, so that the "computer" (the brain) assigns less importance to signals from dark-colored objects in a bright surrounding than it does to small-component signals in a color mixture, or when the general "lightness" of all colors in the viewing field is more balanced. A similar mechanism is effective for pure neutral-luminance signals, where lower-intensity signals are suppressed near strong ones, to enhance contrast by creating a subjective black-level. In such cases one could replace the low-intensity surrounding of an object by a black surrounding without introduction of error, but this obviously does not permit the omission of all low-intensity signals. For the same reason one cannot replace blue or for that matter any dark-appearing color by a dark neutral or black except under specific conditions.

5. Choice of Color Axes in External Systems Having Unequal Passbands

It follows from the discussion of the visual system that, given three unequal passbands for an external color-reproducing system, a preferred assignment to particular colors cannot be made on the basis of the eye's spatial frequency response, since there are apparently no major inequalities between color and luminance passbands in the visual system. One must look toward other characteristics, such as the chromatic aberration§ of its lens, the lightness weighting and the subjective black-level (or feedback) mechanism, which, in a comparison, cause it to attach less importance to "dark" colors, thereby permitting errors in their reproduction to be noticed less frequently.

In the NTSC system the translation of the camera primaries *R*, *G*, *B* into the transmission primaries *Y*, *I*, *Q* containing a luminance channel (*Y*) was essential to establish compatibility with monochrome receivers. Matrix I also assigns a percentage of the full video passband to each color. In view of the above analysis it appears that a somewhat more panchromatic distribution of these percentages (higher blue content in *Y*) could be of some advantage.

Having assigned the normal wide passband to the luminance channel of the NTSC color system, there will be no inequality of optical passbands in the reproduction of black-and-white objects. The axes for the remaining two theoretically nonluminous‖ color signals (*I*, *Q*) must pass through the white point, and thus affect pairs of complementary colors, such as red and blue-green, orange and cyan, yellow and blue, yellow-green and purple, green and magenta. A balanced psychological weighting condition might be indicated by letting the *Q*-component be larger for high-luminance colors (which have a large wideband *Y*-component), but except for the red and blue-green color-pair, all pairs contain one higher and one lower luminance color. The choice of *I*- and *Q*-axis directions is thus not very critical. The two color axes should include in general a large angle, and the *Q*-axis should not come too close to the low-luminance blue primary on one side and should point toward the high-luminance green region on the other side of the white point. These considerations place the *I*-axis in the orange and cyan region, helping the medium-luminance red. The NTSC system axes have these locations (see Fig. 4).

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*The signal integration computed from the measured sine-wave spectra agrees in order of magnitude with the number of synaptic connections from optic nerves over specialized types of ganglion and bipolar cells to the cones in Ref. 9.

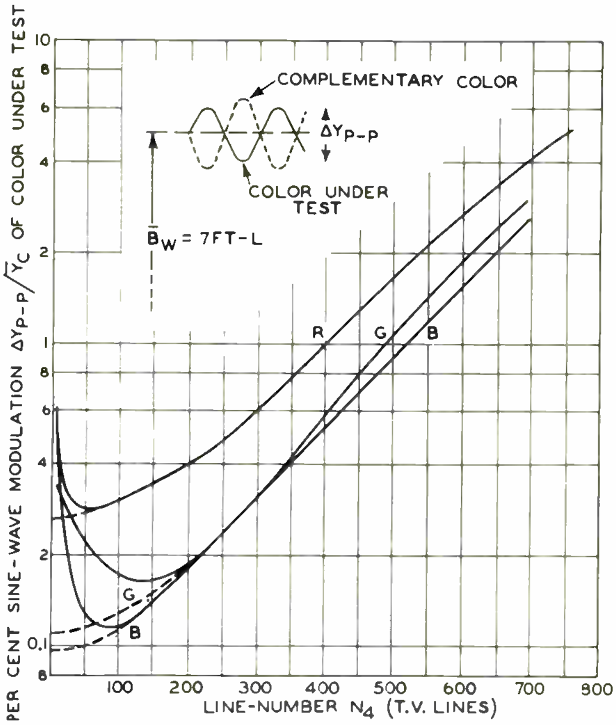
†Excellent discussions are given in Refs. 8 and 10.

‡At still lower illumination (scotopic range), cone vision ceases and only the rod system remains in operation.

§The axial chromatic aberration (*J. Op. Soc. Am.*, *47*, No. 6, 1947) of the human eye is approximately 2 diopters from 400 to 550 mμ and less than 1 diopter from 500 to 700 mμ.

‖Because of the nonlinearity in an actual system, the *I*- and *Q*-signals cause small luminance components.

Fig. 29. Optical modulation intensities required for threshold vision (corrected for kinescope response).



Conclusions

The above analysis as well as visual tests indicate that the bandwidth restriction in the *I*- and *Q*-channels causes small red-colored objects to lose some intensity and blur slightly (relative to white); green- and yellow-colored objects are sharp but lose some saturation, while small blue-colored objects have good saturation but lose intensity and sharpness. Because these effects are smaller in high-luminance colors, disappear toward white, and occur in one (horizontal) direction only, the degradation in a normal two-dimensional color picture transmitted by the NTSC system is relatively small in comparison with a color transmission over three equal independent channels as illustrated by Plates VIII and IX. The relatively uncritical nature of the bandwidth assignments can be appreciated by deliberately disturbing the luminance weighting by an interchange of red, blue or green signal connections at the input to Matrix I, making the corresponding change after Matrix II, and observing the results visually at the kinescope as illustrated by Plates IX to XI. The reversal of luminance weightings for green and blue by interchange of matrix connections (Plate X) can be detected only by the appearance of a transient (following the right-side edge of the hat). The reversal of luminance weightings for red and green by interchange of matrix connections (Plate XI) gives no detectable effect for this subject as compared to the normal reproduction in Plate IX. Critical observation of test-pattern slides reveals that the defects caused by unequal passbands are readily visible and change to different colors when the above interchanges are made, and that there is a preference toward the NTSC choice. In a direct demonstration on a kinescope, most observers (engineers) were unable to recognize the equal bandwidth condition or the interchange of matrix connections when shown a variety of outdoor and indoor color pictures (SMPTE test series and many others).

The analysis has shown that commercial color kinescopes have a color contrast range resulting in a color space which is larger than that of a commercial color motion picture, that color reproduction errors caused by the unequal passbands of the system in fine detail are relatively small, and that they are considerably reduced by rectification in the nonlinear kinescope. It has also been shown that the spurious signals generated in the practical separation of chrominance and luminance signals from the composite (NTSC) signal can be minimized by proper choice of amplitude response in the various band-limiting filters at the transmitter and receiver, and result in a relatively small loss of bandwidth and picture sharpness, as illustrated by Plates XII and XIII. The relative sharpness is well reproduced in the color plates. (Note the slight horizontal edge transients in the NTSC reproduction, Plate XII.) The color saturation, however, is considerably reduced by the printing process.

Regarding the performance of commercially available color receivers, it can be stated that the contrast of the color picture tube is as good as that of the tube used in these tests. Pictures received from commercial color broadcasts can be, and on many occasions have been, as good as those observed in these tests. However, with color even more than with black-and-white reception, performance depends on proper adjustments of the receiver controls and, of course, the ambient light level. The fine-detail monochrome performance should be close to the values given (again assuming correct adjustments), but the horizontal color detail is not quite as good, because it is present practice to use a common intermediate bandwidth for both *I*- and *Q*-channels in the receiver.

APPENDIX

Generation of Equiluminous and Constant-Brightness Sine-Waves

A white background is set up first by adjustment of d-c components. The color gun (or guns) producing the desired hue, red for example, is then modulated with a sine-wave signal to generate a vertical sine-wave field, and the guns producing a complementary signal (white minus red equals blue plus green) are simultaneously modulated by negative sine-wave signals (opposite phase) of the same frequency.* To adjust the proper mixture, all guns are first modulated in phase to produce a "white" sine-wave, after which the red gun signal is reversed in phase and adjusted in amplitude for constant luminance or constant visual brightness of the pattern. It is observed that this adjustment varies with the background color (horizontal distance from the white axis) which is, therefore, adjusted first by change of d-c components.

The adjustment for constant brightness (red sine-wave amplitude) must be made for the actual observer to make his luminance mechanism inoperative, because the values (Y) computed from the CIE "standard observer" curve are in error near the white axis as mentioned in Sec. 7. This error is surprisingly large for blue (seven different observers).

Measurement of Sine-Wave Response Functions and Interpretation of Data

The observer views from a fixed distance a uniformly illuminated field on which an extended sine-wave bar pattern is faded in slowly by a master control ahead of the potential dividers for the component ratios. The pattern becomes visible when the brain receives a just-perceptible signal. A plot of the required optical input signal modulation is shown in Fig. 29. The operating point in the color plane was near the white point and had a total luminance indicated in Fig. 29 by $\bar{B}_W$ = 7 ft-L. Since the modulation is given in relative units of the color

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*A noninterlaced raster of 500 lines is used to obtain a direct proportionality of optical and electrical frequencies (see Ref. 12).

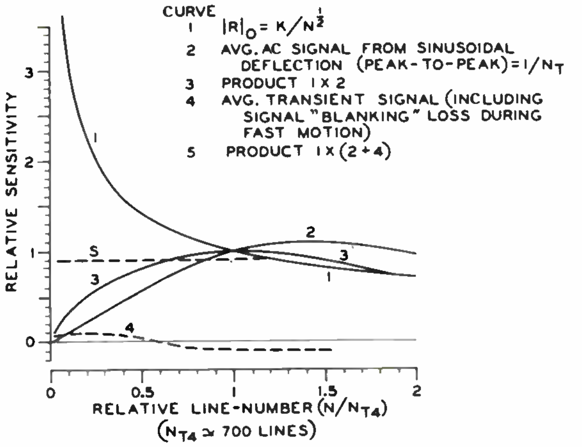

Fig. 30. Effect of signal-to-noise ratio, ocular tremor and transient motion on threshold sensitivity.

under test and relative stimulus values are close to the values, $w_R/w_G/w_B = 1/0.92/1.57$ of the white point, the minimum perceptible stimulus increments of the three colors differ by less than a factor of two from one another at any spatial frequency. The normalized reciprocal values of the sine-wave input signals plotted as a function of spatial frequency f_s or line-number $N = 2f_s$ furnish the sine-wave amplitude response of the visual system (Fig. 26), provided the threshold criterion is independent of frequency. Otherwise a correction is needed. Upon examination, one finds that the visual threshold is noise limited and that detection of any object area requires a certain constant signal-to-noise ratio. Because the area of sine-wave bars of constant length and one-half cycle width decreases in inverse proportion to their line-number, signal-to-noise ratio $(R)_0$ and sensitivity should be proportional to $1/\sqrt{N}$, as illustrated by curve 1 in Fig. 30. It is known, however, that the eye must vibrate (ocular tremor) in order to see detail; i.e., it must generate a-c signals for transmission to the brain (its analog contains a blocking capacitor). The deflection amplitude of the tremor is quite small, 6 μ on the average,[13] which does not degrade the image, but is sufficient to generate strong a-c signals at line numbers where the half-cycle length $1/N$ of the retinal sine-wave image is in the order of the deflection amplitude. The a-c signal, however, decreases toward lower line-numbers and goes to zero at $N = 0$. The average a-c signal developed at different points on the retina due to ocular tremor is therefore a function of line-number, and calculations indicate the function shown by curve 2 in Fig. 30. The deflection amplitude is specified by its reciprocal value, expressed as a television line-number $N_{T(4)}$ for an object distance equal to four length units.*

The action of the tremor counteracts the sensitivity change due to the varying signal-to-noise ratio as shown by the product curve 3, but overcompensates at low frequencies. This deficiency is decreased by a partial d-c response[7] and by the continuous jerky motion of the eyeball when a larger image is observed. One becomes conscious of this motion and its effect in generating a-c signals when a barely visible large object or pattern is viewed, because the pattern fades out when fixed steadily. The signal generation in this case is a series of detached transients (a continuous large deflection would blur the image). A transient image appears after the sudden motion stops, just as in tests where ocular tremor and image motion are prevented artificially and transient vision is obtained after a change of image content. The dashed curves in Fig. 30 show that a constant threshold requires only a relatively small increase in a-c signal at the low-frequency end of the response curve, which is obtainable by intermittent excitation.

In view of these facts, it appears justified to assume a constant threshold criterion in the upper portion of the sine-wave response characteristic of the eye which is thus obtained directly from the measured data. The lower portion is less well defined, but indicates that an analog system contains a high-pass filter in cascade, with the normal low-pass filter representing the optic and retinal structure of the eye. The low-frequency section of the low-pass filter response can be extrapolated by matching the high-frequency section to a possible lens-plus-grain-structure response characteristic (see Fig. 27).

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Discussion

William L. Hughes (Iowa State College): Would you expand your statement on the interchangeability of blue, green and red?

Dr. Schade: I'll be glad to: I have shown you the circuit diagram, Fig. 1, which shows red, blue, and green signals going into Matrix I for conversion to Y, I and Q signals at its output and then through Matrix II back into red, blue, and green signals. The terminal on the matrix, labeled green, leads to a luminance weighting of 59% — the one labeled blue, to 11.4%. By interchanging the input signals, the blue and green weightings are interchanged. To obtain the correct colors on the kinescope, the output terminals blue and green from Matrix II have to be interchanged also. Because of the matrix connections and filters, the blue is now treated like green in terms of its weighting and the green, like blue. The net overall result comes out the same as far as large area colors are concerned but the frequency weighting is reversed. Reversal of red and green connections at the input of Matrix I and at the output of Matrix II similarly interchanges the weighting of the red and green signals.

Dr. Hughes: Would one conclude from this, then, that for the NTSC system they really had many choices for a narrow band and for wide band, that after you've selected your luminance signal, of course, they are really not too important?

Dr. Schade: Yes: It is not very critical what luminance you assign to the color; but as shown by the analysis, a somewhat higher luminance channel percentage of the blue, say 20% instead of only 11%, might be advantageous. It would give a little more even frequency weighting, so that, for example, a blue-lettered label on a box would be less blurred. But in general this defect

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*The reciprocal distance on the retina in television lines per millimeter is given by N/mm = $N_{(4)}/4.25$.

is not very serious and the NTSC choice is in the correct direction as discussed in the paper.

Dr. Hughes: Would you go so far as to say then that in forming the luminance signal one might have taken equal luminance from all three channels and not be very far off?

Dr. Schade: I think the effect would probably hardly be noticed in pictures. There is, however, a compensating effect: the green signal has a high luminance and it is getting a large percentage, 59%, of the 4-mc channel. On the other hand it also gets a high percentage of the narrow-band *Q*-channel, while the blue signal, which gets a low percentage of the 4-mc channel, gets the highest percentage of the medium channel *I*-signal. So it is partly compensated by that choice — you can't just make a flat statement.

J. R. Popkin-Clurman (*Telechrome Mfg. Co.*): Would you now advocate that the luminance channel bandwidth be restricted as a great improvement in picture performance?

Dr. Schade: I assume that you mean from the standpoint of crosstalk. In the studio, the cameras all have wide bandwidths, perhaps 6 or 8 mc wide. This wide-channel signal (and noise) is put directly into the colorplexer without band-limiting filters. On a studio monitor, which shows the black-and-white picture, you therefore see a little more definition. In a normal receiver, however, the wide *Y*-channel causes crosstalk. Now, if you insert a filter into the *Y*-channel after Matrix I to limit its bandwidth to that of the receiver in the home, you eliminate most of the crosstalk; but in the studio the picture won't look quite as good. I advocate as the simplest change to insert a Bode-type filter having a 3½-mc cutoff into the luminance channel at the transmitter, and most of the color noise will disappear in the receiver without loss of definition, because no commercial receiver exceeds this bandwidth.

Mr. Popkin-Clurman: Your curve showed a considerable cut, starting at around 1¾ mc.

Dr. Schade: Yes, one of the curves showed a roll-off requiring aperture correction in the receiver. With that you get very drastic reduction in crosstalk. But the last one of the four color slides I had, illustrated a "flat" channel with a sharp cutoff at 3 mc with no aperture correction in the receiver. No change was made otherwise and you could see that the difference wasn't very large. I have shown many pictures with this arrangement to a number of our engineers and they all liked it because it requires no change in the receiver and no change at the transmitter except for one filter.

Mr. Popkin-Clurman: In respect to the color pictures, in reversing the red for the green, the green for the blue, etc., one of the things, of course, that doesn't show up in these pictures is that the noise gets integrated. Normally we're used to seeing blue noise rather heavily — low-frequency blue noise if you turn up the chroma and you have an excessively noisy system.

Dr. Schade: That is the crosstalk I was talking about.

Mr. Popkin-Clurman: Now what happens when you reverse, say, blue and green? Does the blue noise change to green noise or red noise? Doesn't this become more objectionable from a subjective standpoint than would be apparent from looking at the pictures?

Dr. Schade: The point I'm trying to make here is not that we should reverse the matrix. This is just to show you that the picture in general — forgetting the noise — doesn't change. If you go through forty or fifty different subjects you can divide them into two quality groups and for any condition you get two groups — one judged better, one poorer — which are about equal in size, your choice depending slightly upon the subject. There isn't very much preference. Now with respect to noise, if its visibility was according to luminance, it should not look blue. It does look blue because, particularly near the white point, luminance and apparent brightness increments don't correlate, as discussed in the paper.

Mr. Popkin-Clurman: I believe you stated that in the NTSC system, the color pictures have an added resolution due to resolution in the vertical, even though it may not be present in the horizontal?

Dr. Schade: I'll restate this. In the vertical direction the resolution, or better, the sine-wave response of any television system is determined entirely by the spot size in the camera tube, the number of lines in the raster, and the spot size in the kinescope. In other words, it has nothing to do with the electrical channel, only with the choice of raster line numbers and the size of the spots. Because all the signals in any vertical cross section are transmitted in the lower portion, up to 100 or 200 kc, the video band which is always flat in this range never affects these signals. Since the three color signals, *Y*, *I* and *Q*, are alike up to 600 kc, there is no limitation by the electrical portion of the system at all. We have full vertical definition in all colors. Now, horizontally, you need a wide bandwidth for the higher frequencies to reproduce fine detail and that's where the inequality of the channels comes in.

The Resolving-Power Functions and Quantum Processes of Television Cameras

The extensive paper by O. H. Schade, Sr., (RCA Review, vol. 28, pp. 460-535, September 1967) is summarized. The resolving power of an imaging system is described in terms of a series of "resolving power functions"; these relate the resolution to the exposure as a critical variable. The successive functions vary as a number of other significant parameters are changed. The treatment permits prediction of resolving power performance of TV camera and other imaging systems under a variety of operating conditions. Experimental confirmation of the analysis is mentioned.

By OTTO H. SCHADE, SR.

A Tutorial Summary by PIERRE MERTZ

An EXTENSIVE original paper has been published in the *RCA Review*.[1] The paper is highly detailed and particularly designed to be read by the close specialist in this field. The general philosophy and method of approach expounded in the paper are important to the art; and to enable the reader who is less specialized to obtain the essential gist of it a tutorial summary of the work is presented herewith. No attempt is made even to outline the very large amount of detailed information contained in the original. The summary must simply be taken as an abstract sketching out the main trend of the author's thesis, and indicating the general nature of his principal conclusions.

The work is essentially an analysis of the factors that affect resolving power in television camera systems, to the point where predictions can be made of what performance, in this sense, can be expected of such systems, under different design conditions. The end product of the analysis is a series of functions, which the author calls "resolving power functions," that relate the resolution performance to the exposure, which the author takes as a critical variable. The specific trend of these functions varies with a number of other significant parameters.

The author considers the case where the dominant element of a television system, insofar as resolving power is considered, is the camera system, and envisages the analysis of the remainder of the assemblage as a separate study. He gives some attention to the influence of the scanning-line pattern in terms of line-spread functions, and this leads to a lower limitation on raster-line density for the camera. However when observing the resolving power of the camera he notes that the beam diameter is much larger than the raster-line pitch. This leaves the scanning-line influence relatively negligible. He generalizes the study, at various places, to include the analysis of photographic cameras.

The definition of resolving power used is based on the threshold of visual detection of the lines in a 3-bar test pattern as described in more detail in a previous paper.[2] Specifically, it is the smallest pattern in the group in which the lines can be resolved. In that earlier paper it was found that this threshold of detection occurred, fairly closely, when the "signal-to-noise ratio" in the luminance of the bar pattern was 3.6. In the simple case where the dark bar was black, the "signal" was the light flux coming from the light bar. This was averaged over a number of such bars in preliminary calibrating measurements. The "noise" was the rms deviation of this light flux, in the individual measurements, from the average.

The above relation to signal-to-noise ratio covers the viewing of a fixed single test frame. Where a continuous "live" image is viewed the threshold signal-to-noise ratio for detection was found to be approximately 2.

Under extreme low conditions of scene illumination[3] and consequent low density, on the photosensitive surface, of excited grains or photoelectrons in a photographic or television camera, the signal-to-noise ratio is distinctly a function of exposure (as measured, say, in meter candle seconds). For under these conditions the basic "noise" would be determined by the electron shot noise resulting from the effect of the incident light (measured by E, the exposure). The signal S would be proportional to the product EW^2, where W is the width of the test bar (and therefore W^2 is proportional to the area of the single bright test bar or sampling aperture). The noise interference I, by simple statistical theory, would be proportional to $E^{\frac{1}{2}}W$, and signal-to-noise ratio to S/I or $E^{\frac{1}{2}}W$.

The spatial frequency N (in cycles per mm) on the test pattern is equal to $1/(2W)$. If over a range of exposures one sets a fixed signal-to-noise ratio, at the threshold of spatial frequency resolution, then N is found to be proportional to $E^{\frac{1}{2}}$.

The plot of this straight line, on log-log paper, forms what is called the "absolute photon limit" ***resolving power function***. This is illustrated by curve 1 of Fig. 1* (for image orthicons used in a continuous exposure mode).

The author, however, warns at several points that "a one-to-one correspondence of electrons and exciting photons has yet to be demonstrated." Thus an absolute limit conditioned only by photons is hypothetical. What does happen, however, is that the different photosensitive surfaces used in various camera equipments do show an effective quantum efficiency ϵ less than unity. Thus, if this were the only phenomenon applicable, the excited electron rendering would show a granularity coarser than obtained from the shot noise. If ϵ were constant over the exposure range, it would lead to a straight line parallel to and below curve 1 of Fig. 1 — something like curve 2 (though curve 2 includes additional phenomena).

Dr. Otto H. Schade, Sr., is Research and Development Engineer, Radio Corp. of America, 32 Francisco Ave., Caldwell, N.J. 07006. This summary was received on February 12, 1968, from Dr. Pierre Mertz, Chairman of the SMPTE Board of Editors, 66 Leamington St., Lido, Long Beach, L.I., N.Y. 11561.

* Figures in this summary, numbered Fig. 1 through 6, were, respectively, Figs. 14, 12, 15, 16, 19 and 28 in the author's paper.

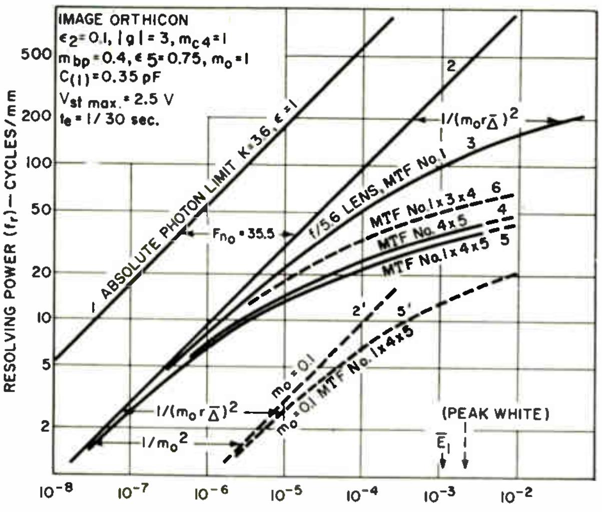


Fig. 1. Quantum limits and resolving power of image orthicons, continuous exposure mode.

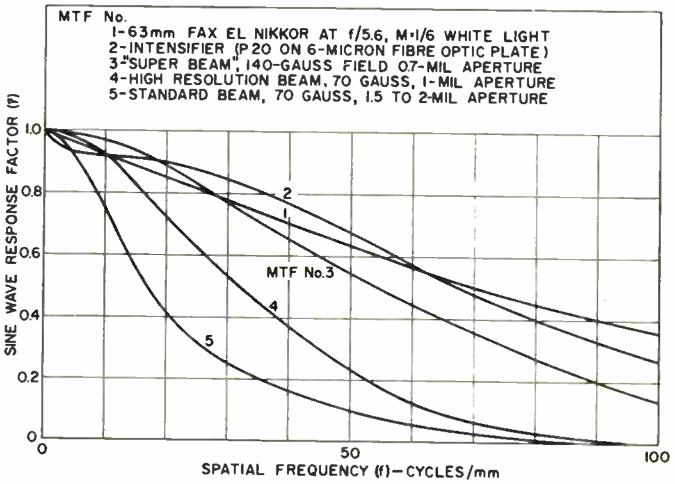


Fig. 2. Sine-wave modulation transfer functions (MTF's) of television cameras.

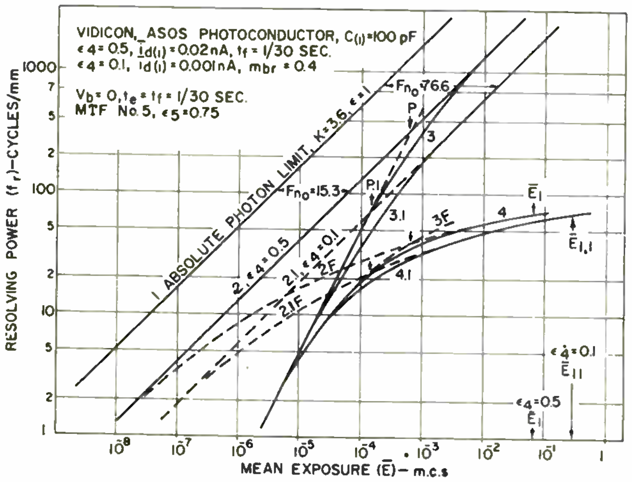


Fig. 3. Quantum limits and resolving power of vidicons, continuous exposure mode.

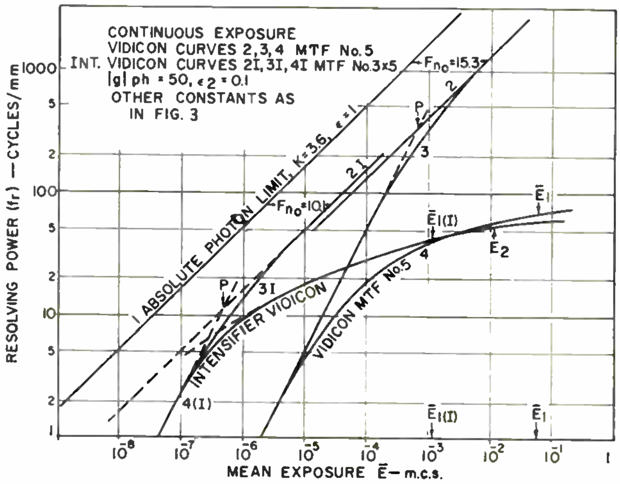


Fig. 4. Quantum limits and resolving power of vidicon (curves 2, 3, 4) and of intensifier vidicons (curves 2I, 3I, 4I).

These additional phenomena are the secondary emission gain of the image-orthicon target and the readout efficiency. Curve 2 is called by the author the *quantum limit*.

The maximum charge potential that can be read out by a low-velocity electron beam is limited to a few volts, because of electron reflection and secondary emission at the storage surface. This means that the tube is limited in the maximum exposure that it can convert into a signal. When translated into meter candle seconds, this is the meaning of the $\bar{E}_1$ shown in the figure at 1.22×10^{-3} mcs. It indicates the maximum mean level exposure and the peak highlight exposure comes at twice this value.

Obviously also the resolving power is limited by the modulation transfer functions (MTFs) that are encountered in the tube operation. The allowance for these is a little tricky because one runs into implicit equations. They can be solved graphically or by methods of successive approximation, as briefly noted by the author. The curves 3 to 5 make allowances for a variety of assumed MTFs, ranging from numbers 1 to 5. These cover lens properties and the properties of various types of electron beams. The MTFs are plotted in Fig. 2. The specific cases covered, referred to by number in Fig. 1, are listed in the legend in Fig. 2.

So far the discussion covers only a test pattern of full contrast. The effects for low-contrast resolving powers are indicated by the curves 2′ and 5′.

The author then discusses the effects of adding an intensifier stage to the image orthicon. These do not appear on the figure, and essentially comprise a small improvement in light sensitivity and a reduced lag at very low light levels, but at the expense of a reduced resolving power.

The curves for vidicons used in the continuous exposure mode are shown in Fig. 3. Here curve 1 represents the absolute photon limit, as labeled, and curve 2 the quantum limit, as discussed for Fig. 1. A new factor, the dark current, now appears. At low exposures, this considerably reduces the resolving power; and it effectively changes the ½ power law to a first power law, between exposure and resolving power. It is illustrated by curve 3 in Fig. 3. At high exposures the effect of the dark current diminishes, and as shown curve 3 merges into curve 2. When typical MTF effects (not specifically identified with those illustrated in Fig. 2) are included with curve 2 they lead to curve 2F. When included with the linear part of curve 3 they lead to curve 3F; and when included with the complete curve 3 that merges with curve 2, they lead to curve 4. The maximum mean level exposure is shown at $\bar{E}_1$. The functions 2.1, 2.1F, 3.1 and 4.1 show the effects of halving the photoconductor efficiency by a reduction of target voltage.

The author shows the effects of adding an intensifier stage to the vidicon in Fig. 4. Here curves 1, 2, 3 and 4 are merely copied from Fig. 3 for comparison. Curves 2I, 3I and 4I illustrate the effects

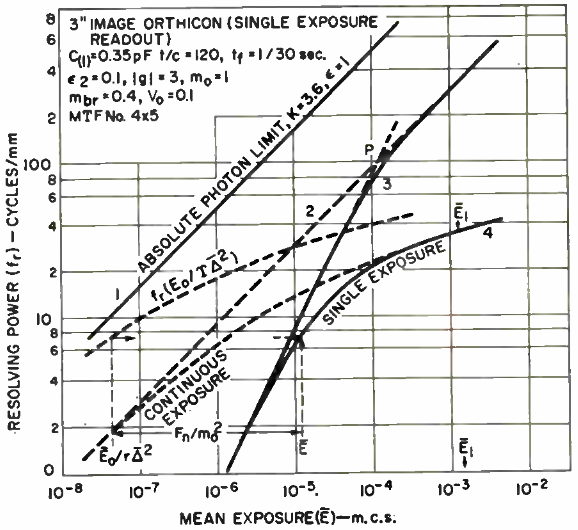


Fig. 5. Resolving power of 3-in. image orthicon, single exposure readout.

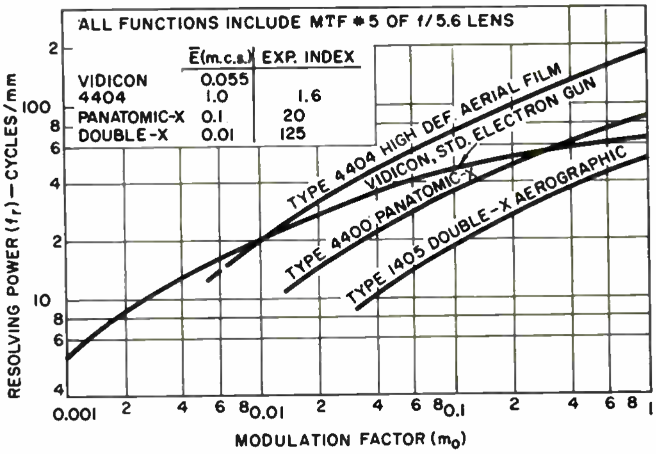


Fig. 6. Resolving power of photographic cameras and a vidicon camera using an identical f/5.6 camera lens.

of the intensifier. Similarly the exposure limit $\bar{E}_1$ is shifted to $\bar{E}_{1(t)}$.

On a number of occasions, such as satellite television, single exposures are utilized, with an erasure clearance between the exposures. For a single image exposure this changes the curves from those of Fig. 1 to Fig. 5. The erasure process leaves a dark current effect, so that curves 3 and 4 for the single exposure resemble those of the vidicon in Fig. 3. Similarly the author considers single exposures for vidicons, which further somewhat complicate Fig. 3.

The author concludes with a plot that compares the resolving powers of a vidicon camera (at its maximum exposure) with various photographic cameras using the same $f/5.6$ camera lenses (at different and presumably optimum exposures in each case). This is illustrated in Fig. 6, which lists the exposures. The abscissa in this plot is the modulation factor m_0 of the test pattern, which is defined as

$$m_0 = (C - 1)/(C + 1)$$

$$\text{where} \quad C = \text{contrast ratio} = \frac{\text{luminance of bright bar}}{\text{luminance of dark bar}}$$

The author describes several experimental verifications of his theories, showing a number of actual measurements of resolving powers, which compare well with the computed predictions. The resulting images are illustrated. They were taken over a complete system which would not sensibly degrade the resolution beyond the camera effects (except possibly, of course, the halftone process reproduction).

References

1. O. H. Schade, Sr., "The resolving-power functions and quantum processes of television cameras," *RCA Review, 28:* 460–535, Sept. 1967.
2. O. H. Schade, Sr., "An evaluation of photographic image quality and resolving power," *Jour. SMPTE, 73:* 81–119, Feb. 1964.
3. A. Rose, "Television pickup tubes and problems of vision," *Advances in Electronics and Electron Physics*, vol. I, ed. by L. Marton, Academic Press, New York 1948.

Recommendations of the National Television System Committee for a Color Television Signal

By A. V. LOUGHREN

I. INTRODUCTION

The work of the National Television System Committee on color television has probably constituted a fundamental and major advance. This report of the NTSC's accomplishments is the author's view, and not an official statement on behalf of that Committee.

To assist in the understanding of the significance of the several elements in the total contribution, a review of some of television's history is useful.

In 1949 the Federal Communications Commission issued a Notice of Proposed Rule Making[1] dealing with color television, and held a hearing on the subject which lasted many months. The Commission appears to have had two purposes in this course of action. First, it certainly wanted to bring about a color-television service to the public at an early date. Second, and perhaps from its point of view, equally important, it wanted to establish whether or not color television would require different treatment in frequency allocation than did monochrome television. It had become apparent before the issue of the notice that the 12 channels then available for television were insufficient to satisfy the Commission's objective of a nationwide and competitive television broadcast service. Additional channels in excess of 50 were going to be required. An uncommitted portion of spectrum known to be reasonably suitable for television broadcasting lay below 1000 mc, sufficient in extent for 70 added channels if 6 mc was sufficient channel width. No other frequency space gave promise of being available within the foreseeable future for television broadcasting. This state of affairs is shown in Fig. 1. The Commission was faced, therefore, with the difficulty "If color television cannot be done in a 6-mc channel, we must either have less channels than needed for a nationwide competitive service or we must postpone color television into the indefinite future"; and there had been evidence, in 1947, that color-television broadcasting of quality comparable to monochrome television would require 12- to 15-mc channels.

The Commission concluded, from the evidence presented in the hearing, that color television could be broadcast in a 6-mc channel, that the field-sequential method of color-television broadcasting was the only method which at that time had been demonstrated both to give pictures with some prospect of viewer acceptance and to be practicable with apparatus then readily available, and the Commission adopted that method.[2,3]

In response to the Commission's notice of the hearing a large number of interested parties in the television broadcasting and television apparatus manufacturing industries established a National Television System Committee to provide a means for the industry to assist the Federal Communications Commission by making information available to it in the course of the hearing. Before, during, and following the hearing, some of the members of this committee had made substantial progress with both the theoretical and practical aspects of a method of color-television broadcasting quite different from the field-sequential method. In the fall of 1950 the NTSC set up a six-member Ad Hoc Committee to investigate the progress of these developments and to report back a recommendation as to whether or not NTSC should work actively toward the completion and experimental verification of a color-television signal based on all of these developments. In the spring of 1951 the Ad Hoc Committee turned in its report. The committee found that the developments had indeed reached the point where it seemed highly likely that further work would lead to a most advantageous form of color-television broadcast signal. The committee's report recommended that the NTSC proceed actively to study the signal, to arrange for such tests as were necessary to select the signal characteristics,

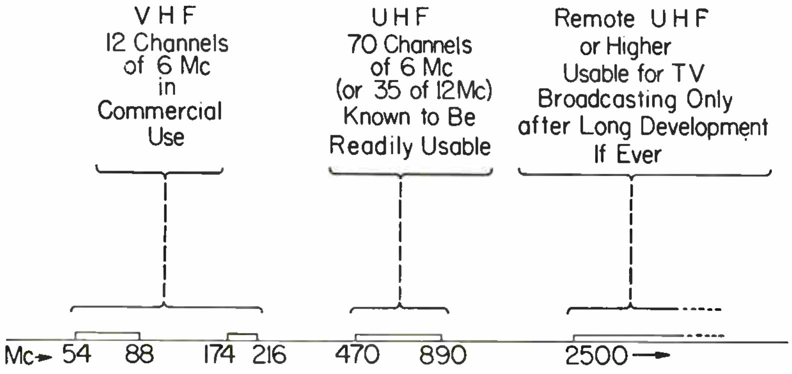


Fig. 1. Existing and potential television allocations, as of 1949; immediate need, 70 or more channels.

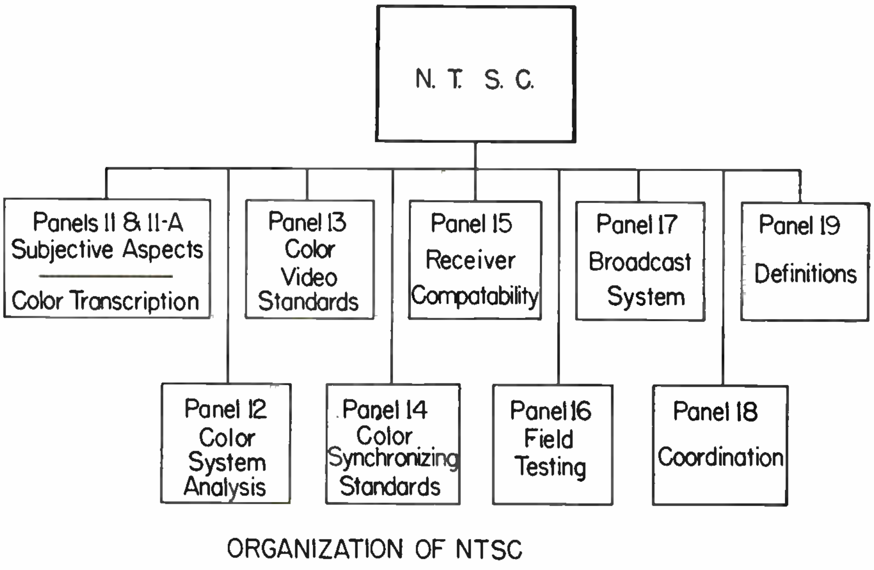


Fig. 2. Organization of National Television System Committee.

Presented on October 6, 1952, at the Society's Convention at Washington, D.C., by A. V. Loughren, Hazeltine Corp., Little Neck, L.I., N.Y. The author has reviewed the entire Convention transcript and brought salient points from the oral discussion into this presentation, brought up to date for the *Journal*.

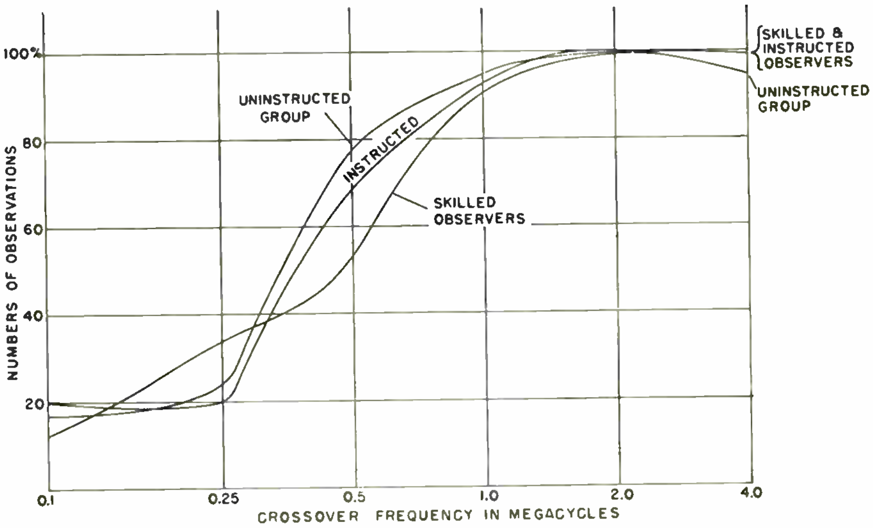


Fig. 3. Comparison of "Satisfactory Picture" curves for various skills.
Courtesy, *Proc. I.R.E.* (Ref. 6, Fig. 7).

and to pursue a program of field tests of such scope as to show clearly beyond any doubt whether or not the signal resulting from these choices was in fact possessed of the advantages claimed for it. The National Television System Committee approved the report of its Ad Hoc Committee and it proceeded in accordance with that report to establish additional panels organized specifically for the several tasks involved, as presented in Fig. 2. Panels 13 and 14 are responsible for establishing the signal specifications, Panels 15, 16 and 17, for the independent testing of the recommendations of the first-named two panels, and the remaining panels provide for important functions auxiliary to those already described. In the ensuing months the signal specification has been established, been subjected to extensive studies in both laboratory and field, and has been modified to make certain minor improvements. The committee's work is now at the point where the final field tests are expected to start in the immediate future.

II. THE BASIC PRINCIPLES

Out of the work in this field certain principles have emerged which appear to be basic to a system of color-television broadcasting if that system is to show full utilization of the portion of the frequency spectrum allocated to it. Among these principles are the following:

1. The electrical quantities in the signal shall represent the transmitted color in terms of its luminance, dominant wavelength and purity; alternatively, these may be thought of as brightness, hue and saturation.
2. The spectrum space occupied by the luminance information must be shared by the color information without adversely affecting the transmission of either.
3. The color-television signal must provide satisfactory black-and-white pictures on the present monochrome sets if color broadcasting is to grow rapidly into an important public service.

These principles are worth examination in some detail.

The Electrical Description of Color

There are many ways of including in an electrical signal three quantities which when taken together can be used to represent a color. Only two of these need concern us here. In the first of these, separate elements of the signal are used to represent the respective intensities of three primary colors — for example, red, green and blue — which taken together will produce a resultant color which to the eye is a match for the original color. This method of electrically describing a color appears to be simple and straightforward, and it can be shown to have the further advantage that the three indications may be presented successively rather than simultaneously without altering too greatly the visual result, at least over a limited range of conditions. It is therefore possible by fairly easy modifications of a black-and-white television system to arrange for the display of one field of the picture in each of the primary colors successively. Theoretical and experimental studies of such a system appear to have established the following system properties:

1. If the color-television system is to exhibit essentially the same resolution as that of a typical monochrome system, it must present as much information for each of the three primary colors as the monochrome system presents; it must therefore transmit three times as much total information and use three times as much bandwidth.
2. If the color system confines itself to the same bandwidth as the monochrome system, it must as a practical matter exhibit decreased resolution and must also operate with different scanning standards than the monochrome system.

Considering now the electrical description of color in terms of brightness, hue and saturation, we note first that these quantities must be presented simultaneously; there is no mechanism in the eye which permits these quantities to be accepted successively in the fashion that persistence of vision permits red, green and blue intensities to be accepted successively. Next we find that the visual acuity for the brightness component of color, that is, the ability to perceive fine detail, is exactly the same as that for the brightness component of a monochrome image, but visual acuity for changes of color unaccompanied by changes of brightness is very much poorer than the eye's acuity for brightness detail; this indicates that the amount of information which must be transmitted to add color to a black-and-white picture is very much smaller than the amount of information required to produce a satisfactory black-and-white picture in the first place, if the color is added by information which describes hue and saturation.[4,5]

Panel 11 of the NTSC conducted a careful set of experiments,[6] the results of which are summarized in Fig. 3. In making these tests all pictures were presented with a bandwidth for the luminance component extending out to 4 mc. The additional information required to insert color into the picture may be thought of as "color-difference" signals; two color-difference signals taken together can be used to tell how far from gray and in what direction from gray a particular color is, relative to a gray of exactly the same luminance. If the color-difference signals have a narrower bandwidth than the luminance signal, then color gradations are not as sharp on the picture although the full sharpness of luminance gradations is preserved. The horizontal coordinate (on the chart, called "crossover frequency," in reference to the specific apparatus of the test) is the amount of bandwidth devoted to each of the two color-difference signals in a particular observation. The vertical coordinate refers to the percentage of the number of observations in which the various classes of observers rated the picture quality as "satisfactory.". The curves indicate that even with a luminance bandwidth of 4 mc, and the observers permitted to sit where they wished, there was no significant improvement in pictorial quality obtained by increasing the bandwidth devoted to color-difference signals above 1 mc. The curves also show that this statement is true both for skilled and for lay observers.

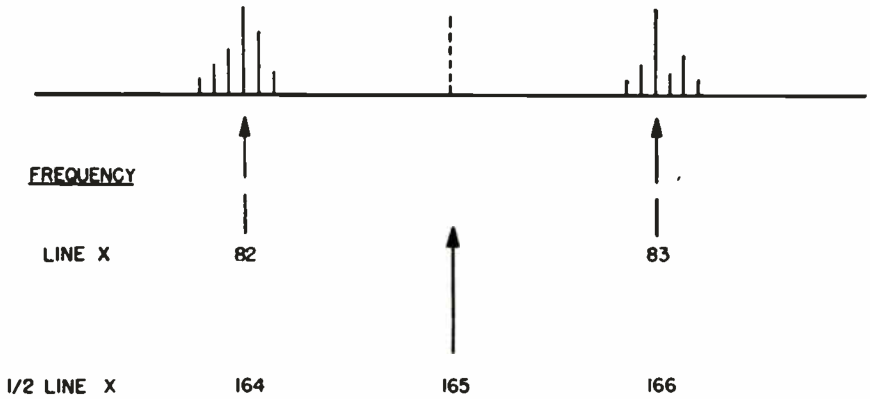


Fig. 4. Small section of the spectrum, region in the vicinity of the 82nd and 83rd harmonics of the line scanning frequency.
Courtesy, *Electronics* (Ref. 9, Fig. 1).

In the tests made by Panel 11 both color-difference signals had the same magnitude in any one observation. Subsequent tests, the results of which have not yet been published, have indicated that along a particular direction of color difference the bandwidth may be decreased to approximately $\frac{1}{2}$ mc without noticeable impairment of the picture, especially if the bandwidth in another direction is retained at the value of 1 mc or perhaps slightly greater.

We also note that the eye responds only slowly to changes in color; thus small rapid fluctuations about a correct color value go unperceived, whereas corresponding fluctuations about the correct brightness value would be perceived immediately as flicker. This latter point indicates that greater exposure to electrical disturbance may be permitted the color component of the signal without impairment of performance than may safely be permitted to the monochrome component of the signal.

Sharing of the Channel

The luminance component of a color-television signal has the task of controlling, element by element, the brightness of the received image. It is most important for successful color-television transmission that this task be well discharged. The standards of the Federal Communications Commission for monochrome television provide the means for discharging this task well, and the use of these standards should certainly be examined as a basis for a successful color-television system.

It has been known for a long time that a normal monochrome television signal by no means completely fills its channel;[7,8] the spectrum consists in general of a component at each harmonic of the line-scanning frequency, with each such component being accompanied by a cluster of smaller components spaced from the main component by the field-scanning frequency. Figure 4 illustrates a small section of the spectrum, showing the region in the vicinity of the eighty-second and eighty-third harmonics of the line-scanning frequency. The dotted line half-way between the groups illustrates the absence of any signal information at this region. The signal spectrum consists therefore of groups of components at the successive harmonics of the scanning-line frequency, or better, at the even harmonics of one-half the scanning-line frequency, and gaps corresponding to the odd harmonics of one-half the scanning-line frequency. We see, therefore, that a second television picture could be transmitted within the same spectrum occupied by our luminance picture if its signal components could be so transformed as to lie at odd harmonics of the scanning-line frequency.

It is also found that even if components are artificially injected into the signal spectrum in positions corresponding to the dotted line of Fig. 4, a normal television receiver will not reproduce these components. The diagram of Fig. 5 illustrates the reasons for this. In the upper line of the figure a signal is shown at the third harmonic of the line-scanning frequency and therefore at the sixth, an even harmonic of half the line frequency. Three full cycles of this signal appear in traversing a single scanning line, and the next scanning line shows three full cycles again. The section at the right of the figure is labeled "Line 3" or "526," and of course line 526 is the first line of the next picture, and therefore lies exactly on top of line 1 one-thirtieth of a second later. The second horizontal line in the diagram shows how line 1 and line 526 add directly to produce an augmented result. In the lower half of the diagram a signal is shown at the third harmonic of one-half the line frequency. This odd harmonic signal repeats in line 3 and also in line 526 exactly opposite in polarity to the position which it took in line 1. The lowest section of the diagram at the right shows that when line 1 and line 526 are superposed, the brighter than average regions in line 1 land on darker than average regions in line 526, and vice versa, and therefore the total contribution to brightness tends to be the same all along the line; the component is therefore not effectively reproduced. If the reproducing device is linear, and if the eye remembers fully for two picture intervals, then this cancellation is exact and complete; in the practical case neither of these requirements is fully met, and so the cancellation is theoretically incomplete but of great practical value.[9]

It is worth emphasizing that we have thus established the fact that a good monochrome television signal, suitable for use additionally as the luminance component of a color signal, has gaps in it in which additional information may be transmitted without affecting the use of that signal as a luminance sig-

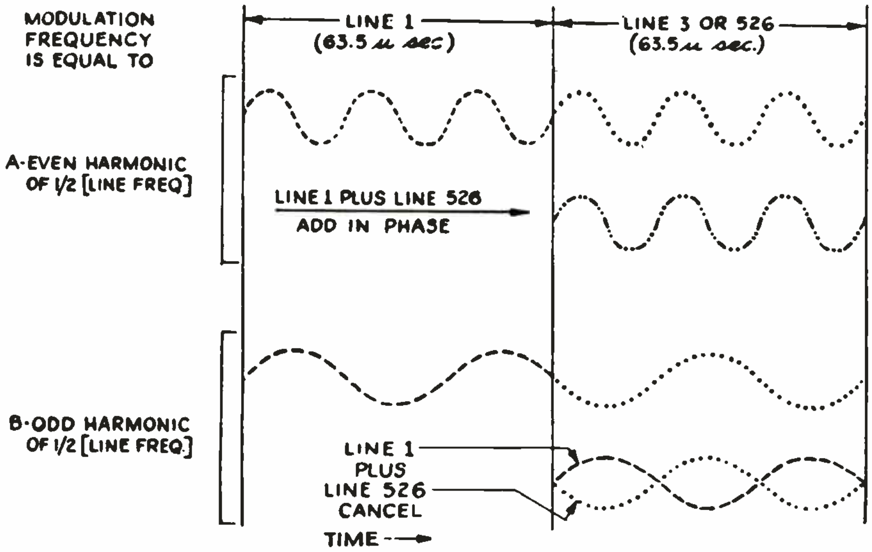


Fig. 5. Principle of interference cancellation by frequency interleaving.
Courtesy, *Electronics* (Ref. 9, Fig. 2).

nal either for color or for monochrome receivers.

Compatibility Considerations

We have seen that the signal for monochrome television and the luminance component of a color-television signal must satisfy the same set of requirements; we have also seen that idle intervals exist in the transmitted band of this signal in which another signal may be placed, and we shall presently find that the color components of the color-television signal may be placed there; we have also seen that a signal placed in these idle intervals is essentially invisible on a black-and-white receiver. There is no disadvantage then in adopting for the luminance component of a color-television transmission identically the same standards which have been found suitable for a high-grade monochrome transmission. And we should bear in mind that the performance *capabilities* of the black-and-white television signal represented by the FCC's standards, are likely to equal or exceed any demand for performance to be encountered in the foreseeable future.

But there is more to this than the mere absence of a disadvantage. If our color-television signal consists of a luminance component conforming exactly to the present monochrome standards and an interleaved color component which is essentially invisible on monochrome receivers, then our color-television broadcast is also an acceptable black-and-white broadcast, and the potential audience for any such broadcast includes not merely those who have at the time of the broadcast equipped themselves with color-television receivers, but also all viewers equipped with black-and-white receivers. A signal for color television which bears this relation to an existing signal for monochrome television, is said to be compatible with the monochrome signal; the importance of compatibility in bringing about early and widespread adoption of color television, once the color standards have been accepted and established by the Federal Communications Commission, is thus seen to be extremely great. With compatibility, color television can be given a flying start by its parent, monochrome television; without compatibility, color television must start from a complete standstill; it must face the terrible economic difficulty represented by the situation "too few viewers, therefore very little sponsor money, therefore poor programs, therefore too few viewers."

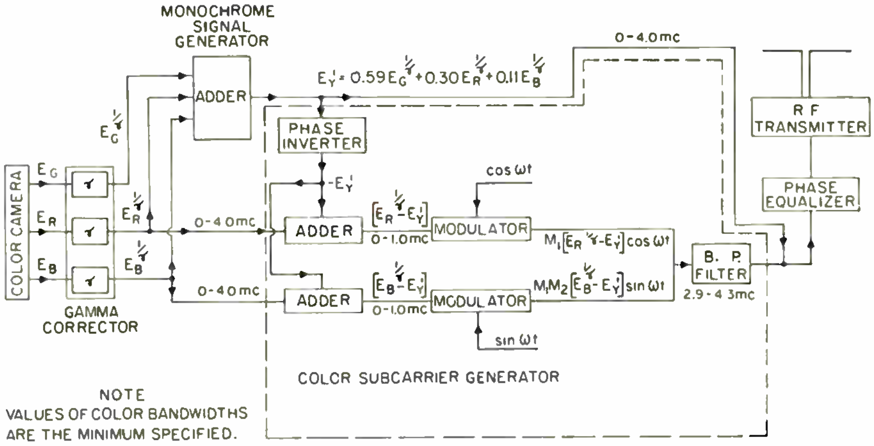


Fig. 6. Block diagram of the essential elements of the transmitting apparatus. Courtesy, *Electronics* (Ref. 9, Fig. 5).

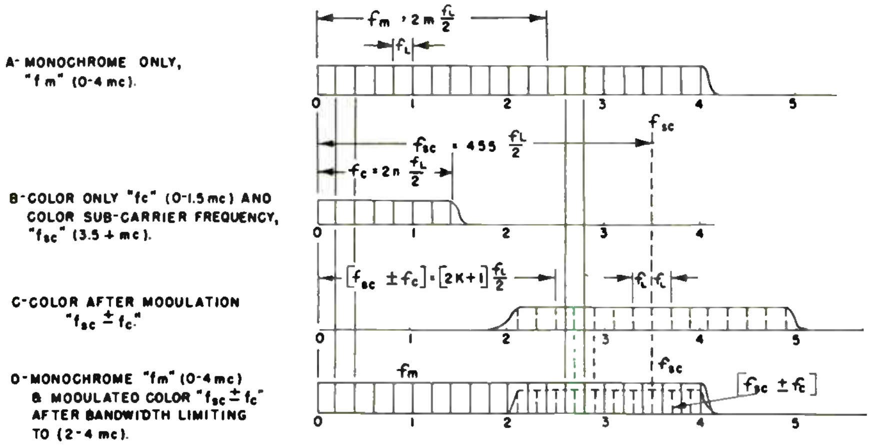
Important though compatibility is to the rapid introduction of color television, it is perhaps not important enough to justify of itself the adoption of a color-television system markedly inferior to a system which could be developed disregarding compatibility. We should note however that we are not faced with this question; instead, we have the situation in which the basic technical considerations important in the design of a color-television signal coincide with those controlling the design of a monochrome signal, and in satisfying these considerations we find compatibility as an automatic by-product.

III. GENERATION OF THE SIGNAL

A block diagram of the essential elements of the transmitting apparatus is shown in Fig. 6. A camera at the left generates three signals which collectively represent the luminance, hue and saturation of the scene, element by element; in the example shown the actual camera outputs correspond to the red, green and blue components. Gamma correction — to improve the signal-to-noise ratio and incidentally to match approximately the receiver picture-tube curvature — may be introduced at this point.

The resulting signals are electrically added, in the proportions of their respective luminances, to form the monochrome or luminance signal. Normal adjustment for the system is such as to make the three signals from the camera equal if the color represented is that corresponding to standard Illuminant C; under this condition the luminance signal E_Y' is also equal to the gamma corrected voltages E_G', E_R' and E_B'.*

The negative of the luminance signal is developed by the phase inverter; in the two adders shown below it, this signal is added to the red and the blue color signals, respectively, thus forming in the adder the two color-difference signals corresponding to these two primaries. Examining the red color-difference signal in some detail, it is noted that this signal was generated by addition and subtraction of the signals originally produced by the camera. These signals, of course, have their components at even harmonics of one-half the line frequency like the components shown solid in Fig. 4; of



f_L = LINE FREQUENCY = 15,750 ∿

f_m AND f_c ARE EVEN HARMONICS OF ONE-HALF LINE-FREQUENCY $[\text{ie } 2n\frac{f_L}{2}]$

f_{sc} IS ODD HARMONIC OF ONE-HALF LINE-FREQUENCY $[\text{ie } 455\frac{f_L}{2} = 3.583125 \text{ mc's}]$

$[f_{sc} \pm f_c]$ IS ODD HARMONIC OF ONE-HALF LINE-FREQUENCY $[\text{ie } [2n+1]\frac{f_L}{2}]$

n;m;k = ORDER OF HARMONIC = 1,2,3,4,5 ETC.

Fig. 7. Band-sharing by monochrome and color signals.

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* See the Appendix for definitions of symbols and formulas not explained in the text and illustrations.

course, addition and subtraction of such components does not change their frequency into the positions of the low-visibility, odd-harmonic components, and yet we want these components to be translated into odd-harmonic components so that they may be interleaved between the components of the luminance signal for transmission. If we generate a subcarrier frequency at such a frequency value as, for example, the 455th harmonic of one-half the line frequency, it will be a low-visibility signal, like the dotted line in Fig. 4. If we then use our red color-difference signal to modulate this subcarrier, the sidebands which appear with the subcarrier as a consequence of the modulation process, will be separated from the subcarrier frequency by the same interval that separates the original sidebands from zero frequency; in other words, all of the components of the red color-difference signal which were generated as even harmonics of one-half the line frequency, will appear as sidebands of the subcarrier at odd harmonics of one-half the line frequency, and will therefore exhibit low visibility if they are applied to any normal television reproducing system. This frequency transformation is illustrated in Fig. 7. Row A shows the luminance signal and its components in solid lines to represent their being even harmonics of one-half the line frequency. Row B shows a color-difference signal as generated, again with solidly drawn components representing even harmonics of one-half the line frequency. Row C shows this same signal appearing as modulation on a subcarrier f_{sc}. The spacings of the components are still the same but the subcarrier itself being an odd harmonic, all of the other components must themselves be odd harmonics also. Finally, Row D of the drawings shows the solid lines of the first section and the dotted lines of the third section interleaved as they are in a normal transmission.

Some other characteristics of the signal may be noted by further reference to Figure 6. For example, since the red signal and the signal E_Y' are equal on white, the output of the adder in the red channel, the red color-difference signal, must equal zero on white. It will have an amplitude which we may call positive when the scene is red and an amplitude which we may call negative when the scene is the complement of red, or cyan. Now, if the modulator of Fig. 6 is a balanced modulator, it can be arranged so that its output will also vanish on white; it is advantageous to design the system in this fashion, since this reduces still further the residual perceptibility of the low-visibility components represented by the dotted lines of Figs. 4 and 7, especially in picture highlights which are generally white or relatively unsaturated color. We find, however, that a transmission whose output vanishes when the modulating signal vanishes, is a transmission in which the carrier frequency has been suppressed, leaving only the modulation sidebands. For correct detection of such a transmission the carrier must be resupplied at the detector of the receiver, and we shall provide a synchronizing pulse in the transmission to enable receivers to generate a suitable carrier. The resupplying of a properly synchronized carrier in the receiver offers us another advantage: it permits us to distinguish successfully between phase modulation and amplitude modulation of a single subcarrier; alternatively, we may say that it permits us to modulate two subcarriers at the same frequency 90° apart in phase and transmit their sidebands over the same circuit and yet distinguish each set of sidebands from the other in the receiver. It will be seen that we make use of exactly this property to permit the transmission of the blue color-difference signal as modulation sidebands on the very same subcarrier frequency as the red color-difference signal, with the two subcarriers differing merely by 90° in phase at the subcarrier frequency.

Finally, the two sets of subcarrier sidebands representing respectively red color-difference information and blue color-difference information, are combined and are then added to the luminance signal as illustrated frequency-wise in Fig. 7. The resulting signal is then applied to the transmitter. Let us note again that this signal is in all respects a perfectly normal monochrome television signal to which there has been added, in a fashion which makes it essentially invisible on normal monochrome receivers, the color-difference information which can be used in a color television receiver to reconstruct the original image in full color.

The transmission of two independent sets of modulation sidebands based on the same subcarrier frequency over the same circuit requires that the transmission be on a double sideband basis if the two sets of modulation components are to be separated at the receiver. Consequently, the maximum frequency which we may choose for the subcarrier is a frequency enough lower than the top frequency of the expected passband of the system to satisfy this requirement for double sideband transmission. Now, if one of the modulation components has a bandwidth of a half megacycle, while the other had a bandwidth of a megacycle or greater, the necessity for double sideband transmission extends out only a half megacycle away from the nominal frequency of the subcarrier; this fact, together with the practical requirements of receiver construction, dictates a subcarrier frequency in the vicinity of 3.5 mc. The exact value of the subcarrier frequency must be, of course, an odd harmonic of one-half the line-scanning frequency; there is an additional minor advantage to be gained by making the difference between the subcarrier frequency and the frequency at which sound is transmitted be also an odd multiple of one-half the line-scanning frequency. The choice of a subcarrier frequency of 3.579545 mc satisfies these requirements without involving any change in the separation between picture and sound carriers as currently specified; a decrease in line-scanning frequency of 0.1% from the presently specified value results from this choice but this decrease is negligible compared to the tolerance presently permitted to the line-scanning frequency itself.

IV. THE COLOR RECEIVER

Color-television receivers are not the direct concern of the NTSC; the Committee's primary objective is the specifying of a signal for color-television broadcasting which is believed to be a sound basis for the founding of a nationwide color-television service, and the recommending of that signal to the Federal Communications Commission after adequate testing. (Receivers are of interest to the Committee indirectly, however, for two important reasons: first, it is essential that the color-television signal which the Committee recommends be suitable for use with receivers which can be built practically and sold commercially at prices which will interest the public; second, the verifying of the suitability of the Committee's proposed signal is an experimental process and must use both physical transmitters and physical receivers for that verification. A detailed discussion of receivers would therefore be inappropriate in this report of the work of the NTSC. A few words about the general scheme of receivers for use with the NTSC signal may, however, be appropriate.

Figure 8 shows the elements of one form of receiver for the proposed NTSC signal. In this receiver a three-gun picture tube has been used; other forms of display device are entirely possible.[10] The receiver includes all of the usual elements of a monochrome television receiver such as radio and intermediate frequency circuits, detector, video frequency circuits to feed the picture tube grid, and the usual scanning and high voltage supply circuits for the picture tube. The color circuits are energized from a tap off the main video circuit of the receiver through a filter which passes only the portion of the video spectrum containing the color components. This selected signal includes the modulation sidebands which were generated in the transmitter by application of the original color difference signals as modulation to the color subcarrier; it also includes the components of the luminance signal which appear in the selected frequency band. The luminance components are, of course, even harmonics of half the line frequency while the color sidebands are odd harmonics. A local oscillator in the receiver reproduces the subcarrier frequency which was suppressed at the transmitter; it is kept accurately in phase by reference to the periodic "burst" of the color subcarrier frequency which is transmitted during the synchronizing interval. The local oscillator signal and the color signal selected from the receiver output are both applied to the red color-difference demodulator; its output contains the beat between these, and it is found that one component of that complex beat is the original video-frequency, color-difference signal. The frequency conversion occurring in the production of this beat signal has transformed all of the color modulation sidebands which were odd harmonics of one-half the line frequency as transmitted into even harmonics as the signal appears in the output of the demodulator. These even harmonics are, of course, suitable for producing a visible image on the cathode-ray tube and we therefore apply them to the red gun of that tube. Similar procedure is followed with respect to the blue color-difference signal and the blue gun, the only difference being that the phase of the locally generated subcarrier as applied to the blue demodulator is 90° away from the phase in which that signal is applied to the red demodulator. The green color-difference signal is obtained by a proper addition of the red and blue signals, giving due regard to the algebraic signs of the signals and the required output; alternatively, it may be obtained by the use of a third demodulator if the phase of the local subcarrier applied to that demodulator is properly chosen.

V. CONCLUSION

In its work on color television the National Television System Committee has now formulated a proposal for a color-television broadcasting signal.* The design of the signal is based upon careful study of the information need of the human viewer, and it is believed that the signal is capable of adequately satisfying that need. The signal is transmitted in the same 6-mc channel as our present signals and has the incidental but important feature of being compatible with present monochrome television signals. Transmitting, networking, and receiving apparatus suitable for use with the signal is now becoming available in sufficient quantity to permit thorough field testing of the proposal. It is my expectation that the field test will show conclusively the suitability of the signal for color-television broadcasting.

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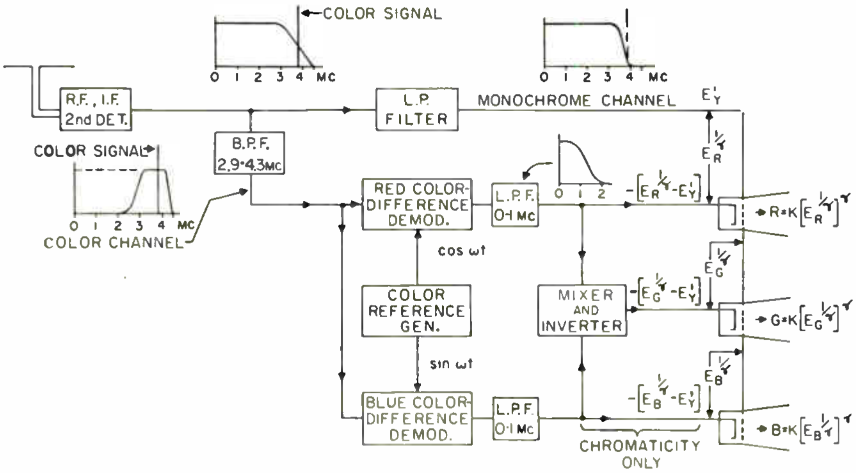

Fig. 8. Elements of one form of receiver for the proposed NTSC signal.

Courtesy, *Electronics* (Ref. 9, Fig. 7).

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APPENDIX: Revised Specifications for Field Test of NTSC Compatible Color Television

Test Specifications—Group I

1. The image is scanned at uniform velocities from left to right and from top to bottom with 525 lines/frame and nominally 60 fields/sec, interlaced 2-to-1.

2. The aspect ratio of the image is 4 units horizontally and 3 units vertically.

3. The blanking level is fixed at 75% (±2.5%) of the peak amplitude of the carrier envelope. The maximum white (luminance) level is not more than 15% nor less than 10% of the peak carrier amplitude.

4. The horizontal and vertical synchronizing pulses are those specified in Sec. 3.682 of Subpart E of Part 3 of the FCC Rules Governing Radio Broadcast Services (as amended April 11, 1952; effective June 2, 1952), modified to provide the color synchronizing signal described in Specif. 21 (Group II of these specifications).

5. An increase in initial light intensity corresponds to a decrease in the amplitude of the carrier envelope (negative modulation).

NOTE: These revised specifications were formally released on Feb. 4, 1953, by W. R. G. Baker, Chairman of NTSC, c/o General Electric Co., Electronics Park, Syracuse, N.Y., with the advice that a comprehensive field test would soon be inaugurated. Dr. Baker will welcome comments.

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* See the Appendix.

6. The television channel occupies a total width of 6 mc. Vestigial-sideband amplitude-modulation transmission is used for the picture signal in accordance with the FCC Rules cited in Specif. 4, above.

7. The sound transmission is by frequency modulation, with maximum deviation ±25 kc, and with pre-emphasis in accordance with a 75-μsec time constant. The frequency of the unmodulated sound carrier is 4.5 mc ±1000 cycles above the frequency of the main picture carrier actually in use at the transmitter.

8. The radiated signals are horizontally polarized.

9. The power of the aural-signal transmitter is not less than 50% nor more than 70% of the peak power of the visual-signal transmitter.

Test Specifications — Group II

10. The color picture signal has the following composition:

$$E_m = E_Y' + \{E_Q' \sin(\omega t + 33°) + E_I' \cos(\omega t + 33°)\}$$

where

$$E_Q' = 0.41\,(E_B' - E_Y') + 0.48\,(E_R' - E_Y')$$

$$E_I' = -0.27\,(E_B' - E_Y') + 0.74\,(E_R' - E_Y')$$

$$E_Y' = 0.30\,E_R' + 0.59\,E_G' + 0.11\,E_B'$$

The phase of the color burst is sin (ωt + 180°)

Notes: For color-difference frequencies below 500 kc, the signal can be represented by

$$E_m = E_Y' + \left\{\frac{1}{1.14}\left[\frac{1}{1.78}(E_B' - E_Y') \sin\omega t + (E_R' - E_Y')\cos\omega t\right]\right\}$$

In these expressions the symbols have the following significance:

E_m is the total video voltage, corresponding to the scanning of a particular picture element, applied to the modulator of the picture transmitter.

E_Y' is the gamma-corrected voltage of the monochrome (black-and-white) portion of the color picture signal, corresponding to the given picture element.

E_R', E_G', and E_B' are the gamma-corrected voltages corresponding to the red, green and blue signals intended for the color picture tube, during the scanning of the given picture element.

E_Q' and E_I' are the two gamma-corrected orthogonal components of the chrominance signal corresponding, respectively, to the narrow-band and wide-band axes.

ω is 2π times the frequency of the chrominance subcarrier. The phase reference of this frequency is the color synchronizing signal (see Specif. 21 below) which corresponds to amplitude modulation of a continuous sine wave of the form sin (ωt + 180°) where t is the time.

The portion of each expression between brackets represents the chrominance subcarrier signal which carries the chrominance information.

It is recommended that field-test receivers incorporate a reserve of 10-db gain in the chrominance channel over the gain required by the above expressions.

11. The primary colors referred to by E_R', E_G', and E_B' have the following chromaticities in the CIE system of specification:

	x	y
Red (R)	0.67	0.33
Green (G)	0.21	0.71
Blue (B)	0.14	0.08

12. The color signal is so proportioned that when the chrominance subcarrier vanishes, the chromaticity reproduced corresponds to Illuminant C ($x = 0.310$, $y = 0.316$).

13. Gamma correction is such that the desired pictorial result shall be obtained on a display device having a transfer gradient (gamma exponent) of 2.75. The equipment used shall be capable of an overall transfer gradient of unity with a display device having a transfer gradient of 2.75. The voltages E_Y', E_R', E_G', E_B', E_Q' and E_I' in the expression of Specif. 10, above, refer to the gamma-corrected signals.

14. The color subcarrier frequency is 3.579545 mc ±0.0003% with a maximum rate of change not to exceed $\frac{1}{10}$ cycle/sec/sec.

15. The horizontal scanning frequency is $\frac{2}{455}$ times the color subcarrier frequency. This corresponds nominally to 15,750 cycles/sec (the actual value is 15,734.264 ± 0.047 cycles/sec).

16. The bandwidth assigned to the monochrome signal E_Y' is in accordance with the FCC standard for black-and-white transmissions, as noted in Specif. 6 above.

17. The bandwidth assigned prior to modulation to the color-difference signals E_Q' and E_I' is given by Table I.

18. E_Y', E_R', E_G', E_B', E_Q', and E_I' are all matched to each other in time to

Table I

Q-Channel bandwidth
at 400 kc less than 2 db down
at 500 kc less than 6 db down
at 600 kc at least 6 db down
I-Channel bandwidth
at 1.3 mc less than 2 db down
at 3.6 mc at least 20 db down

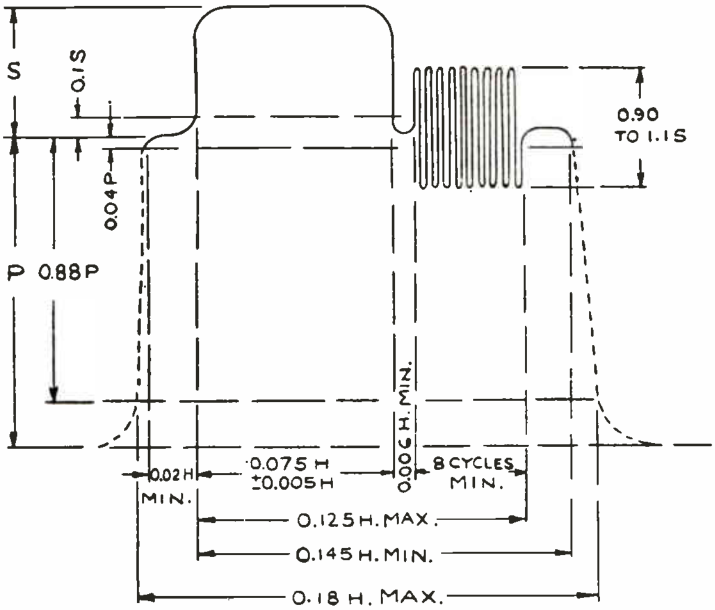

Fig. 9. Revised specifications for field test of NTSC compatible color television.

NOTES

1. The radiated signal envelope shall correspond to the modulating signal of the above figure, as modified by the transmission characteristics of Specif. 6.
2. The burst frequency shall be the frequency specified for the chrominance subcarrier. The tolerance on the frequency shall be ±0.0003% with a maximum rate of change of frequency not to exceed $\frac{1}{10}$ cycle/sec/sec.
3. The horizontal scanning frequency shall be 2/455 times the burst frequency.
4. Burst follows each horizontal pulse, but is omitted following the equalizing pulses and during the broad vertical pulses.
5. Vertical blanking 0.07 to 0.08 v.
6. The dimensions specified for the burst determine the times of starting and stopping the burst, but not its phase.
7. Dimension P represents the peak-to-peak excursion of the luminance signal, but does not include the chrominance signal.

within ±0.05 μsec. This is a tentative tolerance to be established definitely later.

19. The overall transmission bandwidth assigned to the modulated chrominance subcarrier shall extend to at least 1.5 mc below the chrominance subcarrier frequency and to at least 0.6 mc above the chrominance subcarrier frequency, at an attenuation of 2 db.

20. A sine wave, introduced at those terminals of the transmitter which are normally fed the color picture signal, shall produce a radiated signal having an envelope time delay, relative to 0.1 mc, of zero microseconds up to a frequency of 2.5 mc; and then linearly decreasing to 4.3 mc so as to be equal to −0.26 μsec at 3.579545 mc. The tolerance on all these delays shall be ±0.05 μsec relative to the delay at 0.1 mc.

21. The color synchronizing signal is that specified in Fig. 9.

22. The field strength measured at any frequency beyond the limits of the assigned channel shall be at least 60 db below the peak carrier level.

The Work of the E.B.U. Ad-hoc Group on Colour Television

By RICHARD THEILE

The E.B.U. Ad-hoc Group on Colour Television was formed towards the end of 1962, with terms of reference requiring it to undertake an objective comparison of the several systems of color television and to make proposals for the discussions of a unique standard for color television in Europe.

After a preliminary examination, the Ad-hoc Group took three systems into consideration, namely the NTSC, SECAM and PAL systems. The functional principles that these three systems have in common, and also the different manners in which the color signals are processed at the transmitting and receiving ends, are described in this article. All three systems give satisfactory results under correct conditions, differences mostly became apparent only with critical pictures and abnormal transmission conditions, therefore very detailed comparison trials are at present being undertaken. As the task of the Ad-hoc Group has not yet been finished, it is still too early to publish any conclusions.

With the development of novel principles of transmission about ten years ago, a new technique, ready for application, was created for color television. We owe this development to the remarkable research work undertaken in the United States of America. In 1953, after the official introduction in the United States of the so-called NTSC system, interest in color television increased in other countries, and in Europe, particularly, more and more attention has been given to this attractive extension of television broadcasting, which will inevitably be introduced sooner or later throughout Europe.

However, in the European countries, the introduction of color television was not at first considered urgent. The discussions at technical and scientific meetings and at international conferences on electrical communications were restricted to recommendations that the available time be used, first of all, for further experiments and investigations. New systems and variants of the technical application of the principles underlying the NTSC method were proposed, tested and put to discussion, such as, for example, the double-carrier system (TSC), the "double message system" (LEP), the Valensi system, the Henri de France/SECAM system, the FAM system and, most recently, the PAL system.

Work done in developing these systems has enriched and deepened our knowledge and experience in the field of color television, and the discussions have been kept alive. In the meantime, the general situation in Europe had been changing. The normal monochrome television service was well established, new frequency bands were added for further programs and, after the welcome agreement on a uniform number of 625 lines for UHF television broadcasting in Europe, the desire for a uniform color-television standard became particularly pressing. The time seemed to be ripe to exploit jointly the experience gained with tests made with the NTSC system and its variants and to undertake an exact, objective comparison of the different systems, for the purpose of drafting, as soon as possible for discussion within the C.C.I.R. In this way, the E.B.U. Ad-hoc Group on Colour Television was formed towards the end of 1962, after preliminary discussions between the E.B.U. Technical Centre — special mention should be made of the initiative shown by G. Hansen, its Director — and the specialists from the countries where work on color television had for some time been going on intensively. Details of participation, organization, sub-groups and of the meetings held so far are known to the readers of the *E.B.U. Review** and will not be repeated here. It is particularly satisfactory that the circle of collaborators did not remain restricted to Members of the E.B.U., but that representatives of the Telecommunication Administrations and the radio manufacturers take part and, in this way, many leading experts are participating in this important task.

The work was everywhere taken up with great enthusiasm and is now in full swing. It would be rather difficult and also not appropriate to give a general report on the results of the comparisons, as the work has not yet been completed. Since, however, inquiries are often made concerning the functioning of the color-television systems under discussion, it would appear to be reasonable to give a summary, explaining and comparing the principles of the systems under study. Evidently, such a representation, as it is made in the following text by means of schematics, must necessarily be restricted to fundamentals and assumes a certain basic knowledge of the NTSC system.

As a result of the initial discussions and demonstrations, three systems were chosen for study; the original NTSC system (modified for 625 lines) and two variants, SECAM and PAL. The three systems have much in common, as they are all based on the new fundamentals of compatible color-television transmission, which were introduced in the development of the NTSC system. However, they differ in the manner of transmitting the two chrominance components with a subcarrier within the video band. Figure 1 shows the common principles, Figs. 2 to 4 explain the differences.

Among the transmission characteristics that are common are: (1) the separation of the luminance and chromaticity information; (2) the transmission of the chromaticity information in the form of two chrominance signals (color-difference signals) which modulate a color subcarrier; (3) the choice of the color-carrier frequency in the upper range of the luminance signal, that is to say, the insertion of the frequency bands carrying the chrominance information into the available video band of the luminance signal (band-sharing technique).

Figure 1 shows in schematic form the practical accomplishment of this kind of color-television transmission. On the left, the three primary-color signals (after gamma-correction) R', G' and B' arrive from the picture generator. In a matrix circuit there are produced, by weighted summation, the luminance signal Y', as well as the two color-difference signals $R' - Y'$ and $B' - Y'$, or the two linear combination signals I' and Q' derived therefrom. These signals modulate the color carrier f_c via M. The modulated color carrier is added in A to the Y' signal. The frequency spectrum of the combined color-television signals is indicated at the bottom of Fig. 1.

After transmission by radio, the color-television signal is reconstituted in the video band *via* transmitter T and the radio-frequency section of receiver R. A bandpass filter BP filters out the band of the modulated color carrier and feeds this information to the demodulator D. From the color-difference signals obtained by demodulation, the primary-color signals R', G' and B' are finally reproduced *via* the reciprocal matrix with the total video signal Y' (from which the color carrier was removed). In addition, in the transmission are inserted auxiliary signals which are needed for synchronizing the modulation with the demodulation in suitable form. So far, everything is common to the three systems. We now come to the differences, which relate to the method of transmit-

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Reprinted with the permission of G. Hansen, Director, European Broadcasting Union, 32 Ave. Albert Lancaster, Brussels 18, from the *E.B.U. Review, Part A, No. 80:* pp. 138–141, Aug. 1963. Prof. R. Theile, the Director of the Institut für Rundfunktechnik, Munich, is the Chairman of the E.B.U. Ad-hoc Group on Colour Television.

* See *E.B.U. Review* No. 76-A, p. 298, No. 77-A, p. 44 and No. 78-A, p. 92.

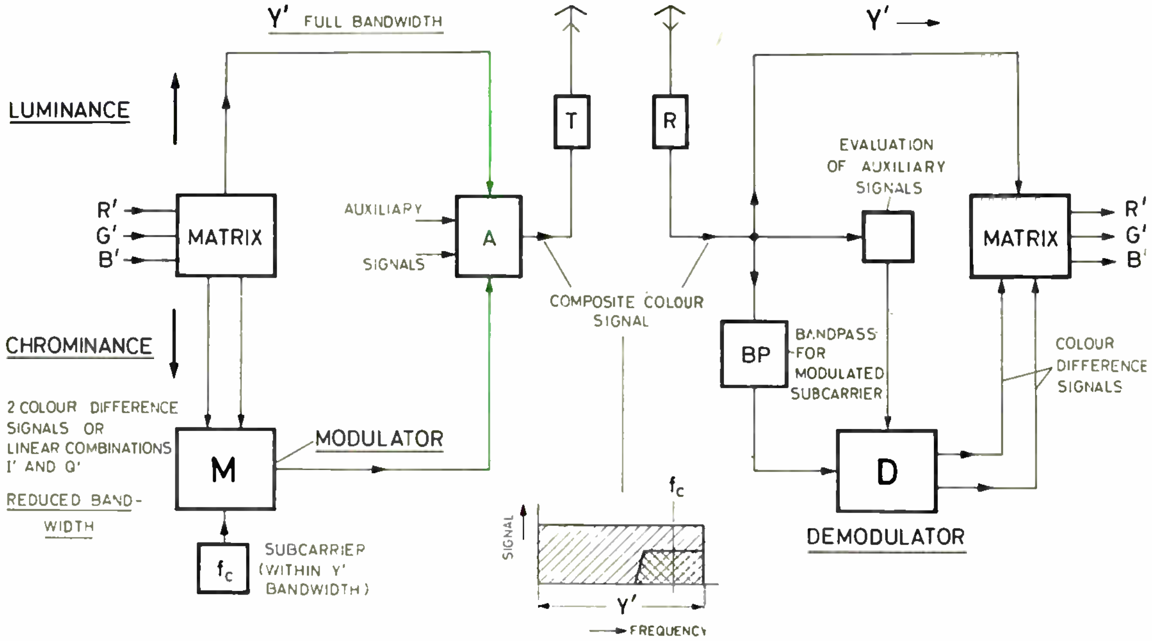

Fig. 1. Schematic of the common transmission principles of the three color-television systems under consideration.

ting the two color-difference signals over a single subcarrier, that is to say, to the technique of modulation M and demodulation D.

Figure 2 compares the different forms of modulation. In the NTSC system, we find a simultaneous double-amplitude modulation with suppressed carrier. The carrier frequency is fed to the modulators for the two color signals in two phase conditions that are displaced by $\pi/2$, the modulated color-carrier components being added. In this way, a carrier is obtained with amplitude and phase modulation. The amplitude is a measure of the color saturation, the phase of the hue. In order to obtain an offset position of the color carrier, the frequency f_c has a value chosen correspondingly (odd multiple of half the line frequency, $f_c = 4.4296875$ mc/sec.) An oscillation of frequency f_c (the "color burst") is inserted during the period of the back porch of the horizontal scanning, as auxiliary signal for the necessary synchronous demodulation.

The modulation process in the PAL system is rather similar. An additional measure is the periodical alternation of the phase of one of the modulation components by the amount of $\pm\ \pi/2$ from line to line. The carrier frequency f_c has here, too, an offset (which, however, differs slightly from that of the NTSC system). In order to identify the alternation, it is necessary to insert, as auxiliary signal, a switching pulse in addition to the color burst; this occurs at the end of the vertical scanning period.

In the SECAM system only a simple frequency modulation of the carrier is used. Since the information of the two color-difference signals can no longer be transmitted simultaneously, an electronic change-over switch alternately feeds one signal or the other to the modulator. The

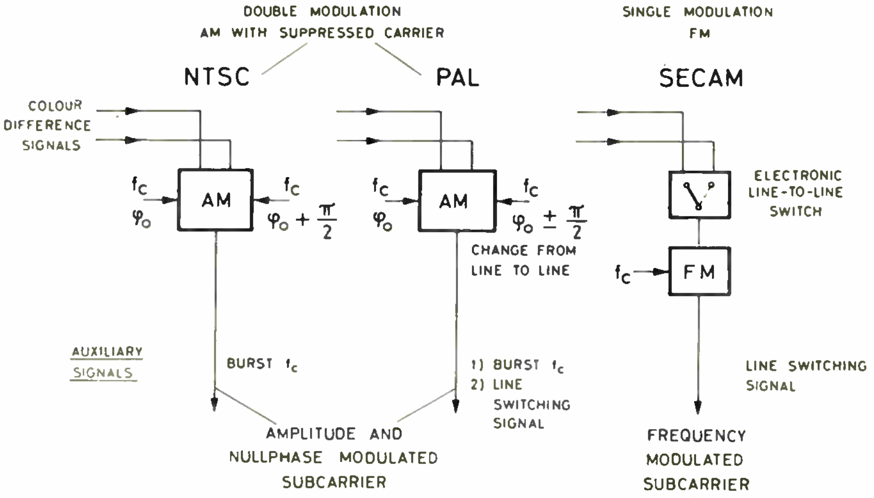

Fig. 2. Comparison of the different ways of modulating the color carrier with the two color-difference signals in the three systems.

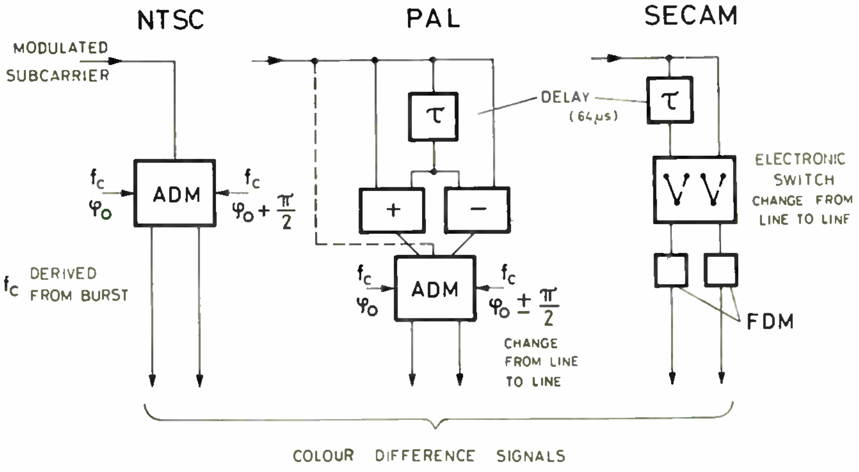

Fig. 3. Comparison of the various ways of demodulating the color carrier and reconstituting the color-difference signals in the three systems.

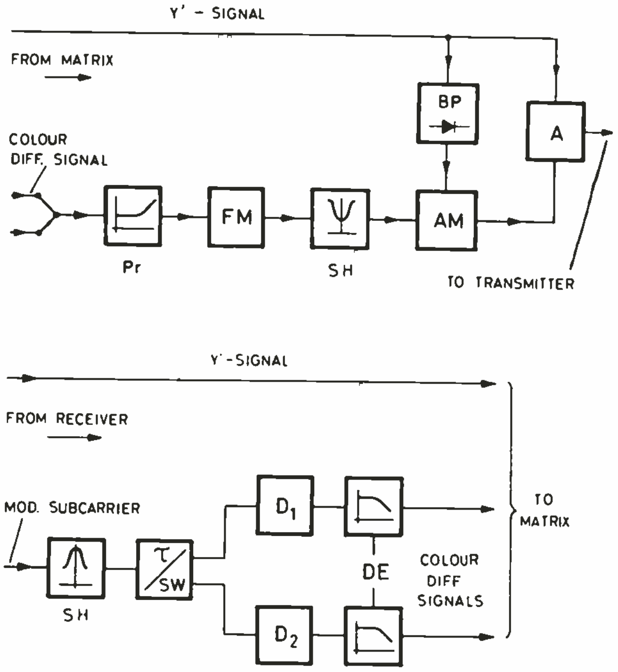

Fig. 4. Details of the formation of signals in the SECAM system.

alternation occurs from line to line. An identification pulse for the switching sense is inserted as an auxiliary signal during the period of the vertical scanning interval. It should be mentioned, furthermore, that the phase of the color carrier is changed by the value π with every third line and also from field to field.

So much for the different forms of modulation. The methods compared in Fig. 3, for demodulating and reconstituting the two color-difference signals at the receiving end are also correspondingly different. With the NTSC system, a synchronized amplitude demodulation *ADM* produces the two partial signals by adding the regenerated carrier f_c, synchronized by the burst, in two phase positions displaced by $\pi/2$.

With the PAL system, demodulation may be done in the same way (see the interrupted line direct to *ADM*) with the change of the phase of one of the additional carriers by the value of $\pm \pi/2$ from line to line, where the correct sense of the alternations is maintained by means of the switching pulses sent at the same time. A better method of obtaining the signals uses, before the demodulator, a sum and difference operation of the direct signal with the same signal after it has been delayed by about 64 μsec (almost exactly the period of a line). As may be seen in Fig. 3, a delayed signal is derived from the modulated carrier signal *via* a highly stable delay line accurately adjusted to produce the delay τ. The delay-line is adjusted in such a way that, by subtracting (−) from and adding (+) to the direct signal, there is obtained in one branch the components of the color carrier modulated with periodical phase change, and in the other branch only the components modulated without phase change. The signal components separated in this way are then demodulated in *ADM* with the addition of a synchronous carrier. Reciprocally to the switching process in the modulator, the phase of the additional carrier is alternated in one of the branches.

The reconstitution of the signals of the SECAM system occurs through a delay line (delay-time one horizontal period) and a synchronized switching circuit. In this way, the two color-difference signals sent line-sequentially are simultaneously available, in the right order, in the receiver, one of them being direct and the other from the previous line *via* the delay line τ. The two partial signals then reach the frequency demodulator *FDM* after limitation. In addition, we find in the SECAM transmission system certain special methods of forming the signals, as shown in Fig. 4. These are the pre-emphasis (*Pr*) and the de-emphasis (*De*) of the color-difference signal and an amplitude correction *SH* (shaping) dependent on frequency after the frequency modulation FM and a corresponding correction *SH* before demodulation *D* in the feed to delay-line τ and to the electronic switch *SW*. In addition, provision has been made for an amplitude modulation *AM* which is controlled by those parts of the luminance signal Y' that lie within the band of the color carrier modulation (derived *via* a bandpass filter *BP* and rectification).

As has already been mentioned, only the basic principles of operation are given in the schematics. All further details and more accurate quantitative information for the three transmission systems are set out in various documents and specifications; they are very voluminous, one of the reasons being that three different 625-line standards (having different spacings of the vision and sound carriers) had to be taken into account. Further details may be found also in the original publications concerning the systems.

The above explanation of the various functions was purposely given without stating the reasons and without mentioning the advantages and disadvantages that result. The reason for this is that a detailed discussion of the problems was not possible within the framework of this brief article, and also it was particularly desired to avoid any premature appraisals that might be deduced from the simple mention of the advantages and disadvantages.

All three systems work well in practice and give excellent picture quality under correct transmission conditions. Differences are found only as concerns certain parameters of the transmission process; they are very slight in general and mostly become apparent only with critical pictures and abnormal transmission conditions. The task of comparing the systems is therefore not an easy one. The necessary bases for the final evaluations and recommendations will be founded mainly on analyses, experiments and discussions in the sub-groups. In addition, general comparative tests and demonstrations have enabled the members of the Ad-hoc Group to expand even further their experience. Thus, impressive and instructive demonstrations were given in January, 1963, at Hannover, in March, 1963, in Paris and in May, 1963, at Eindhoven, as well as, upon a large scale (not restricted to members of the Ad-hoc Group) in July, 1963, in Britain. With all these contributions and when the conclusive reports of the six sub-groups are available, the Ad-hoc Group will be well equipped to take up in the autumn the evaluation of the material available.

Apart from the utility of the work done, it may be stated that this kind of cooperation between experts in Europe sets an excellent example; the good relations thus developed between the experts will prove to be very favorable for cooperation on other television problems.

3

Color Films

Considerations in Color Film Production for Color Television

A Committee Report, John M. Waner,
Subcommittee Chairman

A joint subcommittee of the Television and Color Committees has been working to establish recommended practices for density and contrast range for color films for color television. During the subcommittee's work it became evident that optimum control of release print density range could be achieved only if the original photography were carefully controlled; therefore, it was felt essential to provide an appendix to the recommended practice which would discuss in some detail the "considerations in color film production for color television."

Certain factors in color TV film transmission and reception make it desirable to control the characteristics of the color print. The degree and type of controls that can be applied are affected by properties of the color film. The density range of the color print is most effectively and economically controlled in the staging and photography, rather than in the final printing. Reflectance of fully illuminated scene elements that are to be reproduced with good detail should be held between recommended maximum and minimum limits to control the "reference white" and "reference black" of each scene, and face tones should be properly related to these limits. For a fully lighted day interior scene, a lighting ratio of 2:1 is recommended. Higher ratios may be used for special effects and night scenes.

This presentation is intended to furnish practical suggestions for the production of color motion pictures for color television and is given to better enable production personnel — such as directors of photography, set and costume designers, etc. — to ensure a more effective translation of their skills and artistry into the final picture as received on the home television set, irrespective of whether the reception is in color or black-and-white. It is only by proper understanding and control at all stages in the production of color film for television that the optimum relation of the photographic art with the technical requirements of television can be achieved.

Much of this material as presented will be equally applicable to photography with black-and-white films for presentation on black-and-white television systems.

These suggestions are made to take into account the limitations of the systems involved in the process of reproducing an original scene onto the home receiver while still permitting the use of economical procedures throughout.

Considered use of these suggestions should contribute to the accomplishment of the following:

(1) better and more consistent gray-scale reproduction on home receivers,

(2) enhanced sharpness and detail rendering on the home receiver,

(3) minimized need for corrective video adjustment in transmission,

(4) minimized variations in the negative in order to simplify production of quality prints,

(5) better matching of color balance and contrast among various types and sources of prints, and

(6) the presentation of pleasing pictures with as wide a brightness and color gamut as possible.

The procedures to be used in making color motion pictures for color television are similar to those used for theatrical production, but with certain variations from those techniques. As in theatrical film production, the best professsional guidance, equipment and methods are to be recommended if successful results are to be obtained.

Television System Characteristics

From a technical standpoint, it is important to recognize certain properties of the television system that necessitate control in the making of a film print suitable for color television transmission. Among these are the following:

(A) Control of transmission (video control) is directly related to the extremes of highlight and shadow densities of each scene of the print. The control of these densities must be exercised at various stages of production, starting with the design of sets and costumes, followed by lighting of the scene and exposure of the camera film, to the making of the print.

(B) Lowlight (shadow) reproduction suffers in television transmission and reception through a combination of effects: flare in the projector optics; incorrect "black-level voltage" adjustment; flare in the receiver picture tube; but primarily, incorrect receiver brightness setting by the home viewer, and ambient light falling on the home picture tube tend to degrade the delineation of detail in the darker areas of the images. Careful control of the print shadow densities by use of proper techniques in stage practices and photography will improve detail of these darker areas.

(C) Home color television viewing utilizes characteristically small viewing angles in which the eye can make extremely critical color judgments; furthermore, the high degree of color saturation available in the television system often tends to exaggerate any color mismatches. Additionally, because of constant reference room illumination, usually not a factor in theaters, the home viewer cannot readily accept changes in program color balance, thus necessitating increased accuracy in color balance from show to show, or even from station to station. Therefore, color prints for television demand scene to scene color timing at least as accurate as the high standards applied to theatrical release prints.

Color Film Characteristics

Conversely, certain properties of color films and the manner of their use in television affect the degree and type of controls that can be applied.

(A) In a black-and-white print, printer

A report of the Society's Color & TV Subcommittee, presented April 13, 1964, at the Society's Technical Conference in Los Angeles, by Edward P. Ancona, Jr., for John M. Waner, Chairman of the SMPTE Color Committee, c/o Eastman Kodak Co., Motion Picture Film Dept., 6706 Santa Monica Blvd., Hollywood 38, Calif.
(This report was received in final form on April 6, 1964.)

exposure (print density) and the extent of development (contrast) may be altered to assist in obtaining a density and contrast range optimum for television. In color printing and processing, such modifications are not easily available, or controlled, and may produce undesirable side effects, such as changes in color balance or saturation and failure to produce a uniform gray reproduction from white to black.

(B) The problem of consistent color balance throughout an entire show becomes particularly acute in some instances; for example, in reel-to-reel balance, and particularly in those cases where commercials, trailers, etc., which are printed at one laboratory are intercut into the main body of a show printed at another laboratory or printed on a different type of release print material.

Observations of trained technicians indicate that intercut print material, including reel-to-reel differences, should be within approximately ±0.04 log *E* (approximately a ±0.05 color correction filter) in color balance differences and ±0.04 log *E* (approximately ±1 printer point) in density variations.

Recommendations for color balance for the various intercut components of the show (or from show to show) cannot be made in terms of densitometric readings of a neutral test chart, since various dye systems represented by different film products will rarely result in the same visual appearance of a neutral object when faces have been timed to match, and, conversely.

An approach to the solution of this problem of balancing intercut print material includes correlation among laboratories by means of exchange of representative material or careful coordination by the consumer among his several sources of supply.

(C) It is important to recognize that the reproduction of the original scene by the film in regard to hue, saturation and brightness range is not necessarily required to be exact; it is usually required only that it be "pleasing." Where more exact color reproduction is required, as, for example, in commercial product packages, it is suggested that a photographic test be made. The test should include the product package, a normal face and a gray scale, if possible. Ideally, the evaluation of such a test would include closed-circuit viewing of a timed color print, either from the original negative or from a duplicate negative if a duplicate is required to produce the commercial.

Since there are certain colors and combinations of colors which cannot be accurately or even approximately matched by a film-and-television process, it may be found necessary, if a close match is required, to photograph a "dummy" object (with changed or enhanced color) to obtain a reproduction which matches the color of the original.

(D) In the day-to-day production of television films, a great number of variables enter into the images appearing on the negative from which the final prints are to be made: shooting may be done in bright sunshine, or on overcast days; different types of lighting units may be utilized from time to time on different sets; an almost infinite variety of sets, set decoration and wardrobe will be encountered; and a wide assortment of different flesh colors will be seen in the various actors, guest stars and extras appearing in the scenes. Superimposed on all this are the different artistic expressions in lighting and staging which are employed by the photographers and directors; and the economic and time limitations which may, in the last instance, influence and sometimes limit the scope and quality of the final result.

Additionally, there are usually variations in camera exposure, small variations in color balance or contrast between different emulsions or between different film manufacturers' products and variations in processing from day to day.

Obviously, the particular densities of various areas shown in a color print, which is a record of the brightness and color of corresponding subject areas, are not a property of the print alone; they are the end-product of a sequence beginning with the materials (that is, wardrobe and set selection, make-up, etc.) on the stage, and including the intensity, type and distribution of lighting, negative exposure, negative processing, printing and print processing.

Color prints are timed and balanced in a laboratory on the basis of subjective viewing by direct projection. However, in view of the few controls which are feasible to employ in color printing (primarily density and color balance for scene-to-scene correction), it is the intent of this paper to emphasize that *the most effective way to control the quality of a television print is to exercise control in the stage practices.* Therefore, this paper includes a description of some practical stage techniques and procedures that will make possible production of prints that will meet the limitations of the complete system.

Stage Practice Recommendations

The images on a color film may be considered to consist of two independent *visual* components: first, the gray scale or brightness (luminance) values, and, second, the color (chromaticity) values. Of the two, the brightness component is the more important factor to be controlled in the photography for optimum television reproduction. This brightness component becomes the signal displayed by black-and-white receivers tuned to a color broadcast, and it is the chief parameter monitored during the picture transmission by the video operator. Therefore, if high quality picture transmission (video operation) and optimum gray scale rendering (good highlight and shadow detail and effective placement of face tones) are to be easily obtained, then the integral density range of the print must be controlled within a certain range as dictated by the limitations of the color film and color television systems.

The film densities are a direct function of the reflectances of the elements that are photographed, of the intensity and distribution of light and of the camera exposure. Control of these factors results in a negative from which satisfactory prints can be made.

Reflectance of wardrobe, set decoration and title artwork materials should be controlled to eliminate or "gray down" the lighter whites and to avoid the darker tones where any texture or detail is to be seen. For color television photography using professional color motion-picture films, it is recommended that the reflectance of important fully-illuminated objects be held between 60% maximum and 3% minimum.

Neutral reference material of these reflectance values* are useful for evaluation of wardrobe, set, or artwork reflectance values.

The brightest element in any scene (excluding a few glints or areas smaller than about 1% of the area of photographed image) becomes the "reference white" of that scene, and is adjusted by the video operator or automatic video control to 100% signal voltage.

The recommended maximum reflectance of 60% is intended to apply to any fully illuminated white object which will be the "reference white" of the scene. (This might be, for instance, a white collar in a medium close-up, a white tablecloth in a long shot, etc.)

If the reflectance of this element has been properly controlled *during photography*, then face tones and other scene elements will have good placement on the gray scale and will have optimum color saturation.

If any object in the scene becomes brighter than the recommended "reference white" it will either lose texture and detail in its reproduction or will, by action of the video control, become an improperly high "reference white," causing the remainder of the scene to be reproduced unnaturally dark and with low contrast. On the contrary, if the scene does not contain a "reference white,"

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* Such reference material can be obtained from the Munsell Corp., 2441 N. Calvert St., Baltimore 18, Md.; and Container Corporation of America (Ostwald), 11 Dearborn St., Chicago 3, Ill. Approximately 60% reflectance is equivalent to a Munsell N8.0/ or an Ostwald C. Approximately 19% reflectance is equivalent to a Munsell N5.0/ or an Ostwald G. Approximately 3% reflectance is equivalent to a Munsell N2.0/ or an Ostwald P.

action of the video control may choose an improper reference point, causing the scene to be reproduced unnaturally bright and with too much contrast. (*Note:* This factor is more important in systems using automatic gain control.)

Almost any scene will have shadowed or unilluminated black areas and these black areas (excluding areas of less than about 1% of the photographed area) become the "reference black" of the scene and are normally adjusted by the video operator or automatic video control to 0% picture signal voltage.

The recommended minimum reflectance value of 3% is intended to apply to any fully illuminated dark areas or objects in which detail is to be seen and which are to be identified as *lighter* than "reference black."

If the brightness of the dark areas in which detail is to be seen are properly controlled *during photography* with respect to the darkest (unilluminated) blacks, then the shadow detail of the image will have good visibility on the receiver. In a scene containing a proper "reference white," any objects or areas darker than a fully illuminated 3% reflectance object will be reproduced with little or no contour or detail and will not be distinguished or separated from the unilluminated blacks.

Furthermore, with "whites" and "dark areas" controlled as outlined in the preceding paragraphs, the resulting color print will transmit with a minimum of picture transmission (video operation) problems.

One of the most important considerations that arise in shooting color films for television is that, currently, a majority of the receivers tuned to a color broadcast will be black-and-white receivers. It should be noted that materials which have contrasting colors might have similar brightness values in their reproduction on a black-and-white receiver, and, therefore, have very little effective separation or contrast. In addition to providing good color separation or "color contrast" on the stage, therefore, care should be taken to provide good brightness separation in lighting and in choice of set decoration and wardrobe.

Effective brightness values of colored materials may be estimated after some experience by viewing the materials through an approximately 2.0 neutral density filter. The effective brightness values that will actually appear in a black-and-white receiver can of course be seen by a closed-circuit evaluation from a timed color print.

If dailies (rushes) are made on black-and-white release print stock from a color negative, it should be noted that this stock produces what is, in effect, a "blue separation" equivalent and, therefore, does not give any indication of the tone or gray-scale reproduction to be seen later on black-and-white receivers as transmitted from the final color print. Additionally, such dailies are an inadequate medium from which to judge make-up, wardrobe and other color values. For day-to-day evaluation of exposure, set color values, lighting, etc., it is suggested that color Cinex (or timed pilot) tests be obtained if color daily rush prints are not made. To answer questions with respect to overall photographic quality of the production, that is, with relation to costuming, make-up, etc., it is often desirable to make timed color dailies on selected scenes.

For television generally, and color television in particular, faces are the dominant point of interest, and the small viewing angles require that the natural highlighting and contours of the faces be preserved. Make-up should enhance these natural features of the face, and excessive flatness of make-up is neither necessary nor desirable. Even though, in real life, people have flesh tones of greatly different color and density, there is less viewer tolerance for such differences under the restricted conditions of home color television viewing. Therefore, make-up should also be used to reduce such differences except, of course, where racial or other particular characteristics are involved.

It is not within the province of this technical article to state rigid specifications for such a highly subjective factor as flesh tones; however, as a guide line it can be stated that, for effective color television reproduction, the average reflectance of properly made-up flesh tones will be approximately less than one-half of the recommended value of 60% reflectance given for the "reference white." Thus, the film densities (or range of video voltages) produced by face images would be near those produced by images of 18 to 25% reflectance reference materials which were photographed in the same illumination.†

Lighting Recommendations

A "fully lighted" day interior scene should employ a lighting ratio of about 2 to 1 (key light plus fill light to fill light alone) in the key position. This ratio is somewhat lower than that typically used for theatrical photography (although still commercially acceptable for theatrical release) and is advisable to control contrast range in order to avoid a loss of background shadow detail in television transmission and reception.

To assist reproduction of facial detail, backgrounds should generally be held down in brightness, i.e., to be less bright than the face tone. This means that background illumination in a set of average reflectance should be about one-half of the foreground illumination.

The low lighting ratios and restricted subject reflectance that have been recommended are not meant to imply that the picture should be "flatly lighted." Higher lighting ratios can be employed for effect: night scenes may use very high ratios; and backlight and modeling give a sense of sharpness and saturation to the picture. The use of specular, rather than diffuse key light, will provide better highlight detail and enhance image sharpness. Therefore, it is suggested that the two types of key lights should not be interchanged between scenes, particularly on cut-back scenes. Although the range of recommended *subject brightnesses* is somewhat limited, the photographic artist can have a wide freedom to employ many different lighting effects. Whenever the actors are walking around on the set, it is advisable to keep the faces in as constant illumination level as possible; when a departure from this condition exists, it is preferable to have the faces pass through an area of lesser rather than greater illumination.

Exterior day scenes will contain many elements of uncontrolled brightness, such as white clouds and unilluminated shadow areas. Here it is essential that supplementary lighting be used to bring face tones or other points of interest up to correct relationship with the brightest parts of the scene (the "reference white"); this will then represent the best compromise for control of this type of situation. The color temperature of this supplementary lighting should approximate that of the surrounding daylight illumination.

Night effects are best obtained by adjustment of the lighting contrast rather than by shooting "day for night" and "printing down" (overprinting). The ideal night-effect photography for television would result in prints that have the same density range as a print for a day scene. The use of little or no fill light on the key position, sketchy background illumination, lighted windows, etc., — all create the *effect* of a night scene without the necessity of "printing down" the particular scene. This technique will eliminate the need for special cuing and minimize the need for making video adjustments.

Although "day for night" scenes are generally not recommended for an optimum night effect on television, economic and physical limitations in production will often prohibit the shooting of the more effective but more expensive "night for night" scenes. Therefore, the following paragraphs outline procedures which can achieve effective results from "day for night" scenes.

(A) To create the illusion of night, two of the essential requirements for any exterior night scene are that the sky

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† For a more detailed description of make-up techniques, a suggested reference is *Elements of Color in Professional Motion Pictures*, published by the Society of Motion Picture and Television Engineers.

should appear dark and that shadow areas appear generally without detail. In black-and-white photography this is partially accomplished by the use of a filter that darkens the blue sky. In color photography, the sky can be darkened in some instances with a polarizing filter. Other techniques would include the use of a graduated (or "wedged") neutral filter, or selection of a camera position that avoids having the sky in the frame. (These techniques might limit the staging, but should be strongly recommended by the cinematographer if the illusion of the night scene is to be maintained.)

(B) The color negative should be underexposed from 1 to 2 stops and the natural or supplementary lighting should create an effect of high-contrast lighting. The inclusion of a lighted window or lamp (of warmer color) in the scene will assist in creating the illusion of night. It is desirable to "break up" the direct sunlight and artificial illumination with random patterns to emphasize the lighting contrast subjectively associated with night.

(C) It is often traditional to print night scenes colder (blue) to enhance the night effect. If this is desired, it is best done by print timing in the laboratory and not by omitting the recommended daylight conversion filter during the photography with tungsten balanced films. In some combinations of 16mm photography and printing, scene-to-scene color timed prints may not be readily available and the cinematographer should consider this in his original photography.

It is important that the different sources of illumination which are used to light and fill the faces are essentially equal in color temperature. The exceptions would constitute the cases of special effect lighting, such as "warm" firelight or "cold" backlight in night scenes.

The use of a professional color temperature meter is helpful and advisable; however, care should be exercised in reading light sources which have emission characteristics different from tungsten lamps, which have a continuous or "black-body" type of radiation. In particular situations where unusual types of light sources (such as fluorescent lamps) are employed, it would be desirable to make a photographic test.

In the event that special color lighting effects are desired, unless a "normal" reference of proper illumination is included in the scene, the final print will generally be color timed to eliminate the desired effect, or the effect could be inadvertently eliminated by the video control operator or home viewer.

Title artwork and animation exists in one plane and is lighted with completely flat illumination. Here, subject reflectance alone determines the subject contrast and the artist should use nothing lighter than a 60% neutral reflectance material and, where "shadow" detail is to be seen, nothing darker than a 3% reflectance material. Areas darker than 3% reflectance (equivalent to unilluminated areas in a stage setting) may be used for effect and should be used in at least a small portion of every scene to establish a "reference black" for the video operator.

Titles often use "burn in" letters over artwork or an action scene. These "burn in" titles are considerably lighter than a *photographed* 60% neutral reflectance material and, therefore, constitute an improperly high "white reference" that can result in a desaturated or flat reproduction of the underlying artwork or action scene. If effective reproduction of the underlying scene is considered to be important, the title letters should be printed as a *color* or as a white no brighter than the recommended "reference white."

Although this article has described procedures which are most adaptable to day-to-day television film production, it is not intended to imply that more extensive controls could not be applied either in photography, printing or television transmission. Photographic exposure and lighting contrast could be controlled to a high degree of accuracy by use of a spot photometer; the laboratories could apply densitometric control of scene-to-scene highlight densities; contrast control of color films may be made practical some day; or specialized systems of video control could be developed.

Conversely, it is realized that in day-to-day production, owing to physical or script limitations, it is not always possible to adhere completely to these recommendations. Under such conditions, the photography in general should follow these recommendations as closely as possible.

There is no sharp dividing line between color prints which would be generally regarded as acceptable for television transmission and those which would be considered unacceptable. The particular recommendations for color television films which are described herein represent observations taken from films with scenes which did reproduce well on a typical color television system. Deviation from these recommendations should be accompanied with caution and should be undertaken only if a particular effect is desired or if tests show that good color television reproduction can be obtained from such films and that they can be printed and intercut properly with films which are known to transmit successfully.

Summary

Certain factors in color television film transmission and reception have a direct bearing on the effectiveness of the reproduction of a color motion-picture film.

Considering these factors, it is desirable (1) to limit the density range of the color print and (2) to include a "reference white" and "reference black" in the scene.

The recommended maximum and minimum reflectances of fully illuminated materials which are to be reproduced with good detail are 60% for whites and 3% for blacks with existing film products and techniques.

For a fully lighted day interior scene, a lighting ratio of 2:1 is recommended. Higher ratios may be used for special effects and night scenes.

It is emphasized that the most important, practical and effective way to control the density range of the color print is in the staging and photography, rather than in the final printing.

Discussion

Lawrence L. Werner (Screen Gems, Inc.): We have had some problems in color transmission of our films in recent years; I know you are well aware of them. It seems to me that what was just stated in this report is at some variance with a previous paper which you read. You are going toward the automatic chain. I understand that you will be going toward it in color. Now I know from the way you time our shows that you print color film for good flesh tone; yet the automatic chain will take the lightest and brightest point in the scene — irrespective of flesh tone — and make of it reference white. Now, how can you correlate these two things? If the control changes the pedestal or the gain, it is going to change the color value of the flesh tones. And it is going to be a very disturbing jump from cut to cut.

Edward P. Ancona, Jr. (Session Chairman): In a color television system, an automatic gain control or a video operator, in adjusting the lightest element of the scene to 100% signal voltage, would not change the hue of the face tone but would only change the apparent saturation, as transmitted.

Mr. Werner: Wouldn't that be equally disturbing, to change the saturation? If the face has a good pleasing rosy quality in one cut, and in the next cut is a very pale, washed-out, almost deathlike mask, wouldn't that be very disturbing to the continuity of the scene?

Mr. Ancona: Anything which makes the picture unpleasing is certainly not to be recommended — and I don't think this Committee paper, or my earlier paper, advocates any system of video operation which would make the transmitted picture less pleasing. That certain field conditions do make the picture less pleasing may be the case; but this Committee paper is not advocating any particular system of video control. I think that both of these papers attempt to describe conditions as they exist and which the photographer might encounter.

Mr. Werner: The reason I'm bringing this up, actually, is that we have had a relatively good, transmission of our color shows recently. But we've had some bad experience in black-and-white on the automatic chain, and I am wondering if the automatic chain is not going to create more problems than it solves?

Mr. Ancona: I think both of the papers emphasized that the problems that were given to the photographer will be more serious and more difficult to handle, if he is to successfully anticipate the action of the automatic video control. In terms of picture quality the automatic video control is certainly no substitute for a competent, human video operator. And what you say is true; the automatic video control may very well give you at times an incorrect adjustment and an unpleasing transmission. What both of these papers attempted to point out is that the photographer should realize this and that any time he knows his picture is to be played on a system using automatic video control, he is best advised to use certain techniques given here.

In the production of pleasing pictures, there is no substitute for what the photographer can do. The Committee paper attempted to emphasize that the control of the print and successful transmission depend very greatly upon the stage practices. What the laboratory can do and what takes place later in the video chain are secondary, and the photographer, by following these recommendations, can go far toward insuring the best possible reproduction of his films.

Frank Baird-Smith, Jr. (*National Broadcasting Co.*): The design of the automatic control systems is by no means frozen. It is apparently quite wide open at this point.

One of the techniques, among those which are possible in color television and which are not possible in a film system, is color correction which does not affect neutral areas; or, to put it another way, the automatic device can be caused to set pedestal and gain to be the same in all three channels, red, blue and green. And then, from there, you can achieve color shifts, in the colorplexor, by operating on the I and Q signals, without operating on the Y signal. By doing this, if you have included a neutral object in the original scene and even if there is an error in the printing or the negative system, the error will be cancelled out by the automatic gain control, so that the original neutral will appear neutral in the television system. At this point corrections could be made. However, since the correction would have to be subjectively judged, there would have to be a system set up whereby such correction could be put in, scene by scene, and switched in some way to follow the scene changes. That is quite a bit ahead of the state of the art right now; we are nowhere near that; but eventually it could be done. I think the earlier discusser was wondering whether you could have automatic gain control in the three channels — and not destroy deliberately colored scenes, such as, an all-red scene. That can be done too — automatically — and it probably will be, in eventual automatic systems.

SMPTE Color Television Subjective Reference Test Films and Slides — Issue No. 3

By JOHN M. WANER and
EDWARD P. ANCONA, JR.

This paper describes the content of the SMPTE Color Television Subjective Reference Test Film and Slides, Issue No. 3. Much of the technical material, history and general discussion relating to Issue No. 2,[5] and which applies to Issue No. 3, has been included in this paper.

Both theater projection of color films and color television transmission of color films place certain limits on the variation of color and density balance between reels of a feature presentation or between the different intercut materials which make up a complete television show. While these limits may be the same in both cases, the problem of achieving such control is much more apparent in color television because of the nature of television programing.

In a theater, a single feature can be the only color material projected, and it may be run for several weeks. Competent film laboratories can, of course, make this one feature consistent in color balance throughout, and the opportunity for comparison with other color films from other sources would not ordinarily arise.

In color television, however, a single presentation usually has commercials spliced in. Throughout a day's or evening's programing there may be several different color films run consecutively, each with spliced-in commercials. The various shows and commercials may have come from different laboratories, may have been made at different times, and may have been printed on different types of release print material. The problem of consistent color balance is, therefore, particularly acute.

Recommendations for color balance of the various intercut components of the show (or from show to show) cannot be made in terms of densitometric readings of a neutral chart, since the various dye systems used in different film products will rarely result in the same appearance of a neutral object when faces have been timed to match, and conversely. *The subjective color balance of prints (visual appearance) is the necessary criterion for satisfactory television use.*

In view of the difficulty of expressing print color balance in terms of densitometric readings, it has been customary to express the accuracy of a subjective match between a given color print and a reference standard print in terms of the printing filter or printer exposure corrections estimated to be necessary to achieve the closest possible match. Printers of different design may, of course, use different increments of exposure control. Typical subtractive printers may use color correction filters graduated in steps of 0.04 density difference, which produce approximately a 0.04 log exposure difference (equivalent to about 1/7 *f*-stop). Typical additive printers may use somewhat smaller control increments which produce approximately a 0.025 log exposure difference. Due to the rather high gamma or contrast of color print materials, a 0.04 log exposure difference can result in a print density difference of 0.10 (at a total density level of about 1.0). It should be understood, therefore, that while two color prints can be compared on the basis of density readings, the accuracy of the "match" between the two prints should be expressed in terms of the estimated printing corrections necessary to achieve the closest possible match, the estimation being made by trained and experienced personnel on a subjective comparison of the two prints under standard review room conditions.

Observations of experienced technicians indicate that the subjective balance of intercut print material should be within ±0.04 log exposure (approximately ±0.05 color correction filter) in printing color balance differences, and ±0.04 log exposure (approximately ± one printer point) in printing density differences. These tolerances apply to the subjective match of scene-to-scene, reel-to-reel, and show-to-show, and to the subjective match of any show to the SMPTE Subjective Reference Test Films.

Committee Work

In July 1962, a joint subcommittee of the SMPTE Color and Television Engineering Committees was formed. Its first assignment was to determine recommendations for the density and contrast range for color film in its use in color television broadcasting. Additional roles of the Committee were to prepare recommendations and to assist in obtaining a reference set of SMPTE color test slides for use by the industry. A subsequent assignment was the preparation of color motion pictures in both 35mm and 16mm.

Because the solution of the problem of balancing intercut print material includes close correlation among laboratories, representatives from these organizations were requested to work with the subcommittee.

During the subcommittee's work, it became evident that optimum control of release print contrast and density range could be achieved best if the original photography were carefully controlled; therefore, it was felt essential to provide an appendix to any future recommended practice which would discuss in some detail the problems of color film photography for color television. A paper en-

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A report of the joint subcommittee of the SMPTE Color and Television Engineering Committees, submitted on May 17, 1967, by John M. Waner, Motion Picture and Education Markets Division, Eastman Kodak Co., 6706 Santa Monica Blvd., Hollywood, Calif. 90038; and Edward P. Ancona, Jr., National Broadcasting Co., Burbank, Calif.

titled "Considerations in Color Film Production for Color Television," was presented as a joint subcommittee report.[1]

Another result of subcommittee work was the article by H. N. Kozanowski entitled "Infrared Transmission Characteristics of Various Color Release Prints and Their Effects on Color Television Reproduction."[2]

Color Television Test Reels and Slides

The initial 35mm color negative photography was accomplished in August 1964 and resulted in the release in 1966 of Issue No. 2, an updating of Issue No. 1, which had been photographed in 1954. Many of the comments received concerning Issue No. 2 were used to photograph new material in June 1966 using earlier recommendations.[1] This new material combined with the scenes from Issue No. 2 resulted in Issue No. 3.

The aim for color balance and density timing of prints of Issue No. 3 will be the same as Issue No. 2, originally agreed upon at the 98th Technical Conference in Montreal in 1965 and confirmed at the 100th in Los Angeles in 1966 by the Color and Television Engineering Committees. The color balance and density of these materials have been established so that optimum reproduction on color television will be obtained in addition to a good quality on direct projection.[3,4]

These films and slides are intended to fulfill two separate functions. First, they should serve as the "subjective reference prints" mentioned above. The use of these films in the laboratory can be as a reference for the subjective evaluation of color balance and density of prints being prepared for color television transmission. A reference print can be screened simultaneously with the print being reviewed, using identical projection systems, or it may be screened immediately prior to the print being reviewed. By this reference method the color timer can correct the overall balance of the print in a direction which will produce a good subjective match with the reference print (using, of course, the 35mm motion-picture reference print for 35mm motion-picture timing; the 16mm reference print for 16mm motion-picture timing, etc.). Wide use of these reference prints in this manner can result in a more consistent balance of the color print material delivered for color television transmission.

Second, these films and slides should be used by broadcasters for subjective evaluation of the performance of a color television film transmission system, after the system has been properly set up. Satisfactory reproduction of these films and slides should assure satisfactory reproduction of other films and slides of similar color balance and contrast range.

Contents

The contents of the 35mm and 16mm test reels, which have a running time of slightly over 4 minutes, are identical and consist of the SMPTE Universal Leader, titles (beginning and end), and 18 scenes, including exterior, interior day and night, and special purpose scenes. The 16mm reel is a contact print from a 16mm color duplicate negative which was made from 35mm separation master positives. The 35mm reel is a contact print from the original 35mm color negative. No soundtrack has been provided for Issue No. 3. The 2 × 2 inch slides are printed from an original color negative with a scene content essentially the same as that of the Subjective Reference Motion-Picture Films.

These color prints and slides, as supplied by the SMPTE, are inspected visually — primarily for the more important areas of flesh tones. Tolerances for acceptance are identical to or less than those published earlier.[1] It should be emphasized that these films and slides are designed for subjective reference and not as alignment tools to set up a color television film reproduction system. Suitable test films are either in existence or in preparation by the SMPTE for this latter procedure.

Each of the scenes was chosen and photographed using stage practices recommended earlier[1] and demonstrating typical conditions which the television system may be required to reproduce. Certain effect-type scenes demonstrate that artistry and mood-type photography can be accomplished satisfactorily for color television transmission.

Scene 1 and 2 are exterior sunlight scenes of a group of bathers. The contrast in these scenes is typical of exterior sunlight conditions.

Scenes 3 through 6 are a day interior sequence of a couple in a large living room, the sequence including a long shot, medium 2-shot, and two close-ups. Spot luminance readings in this scene showed a luminance range of approximately 25:1, with the reference white at 100% relative luminance, female face at 30–35%, male face at 20–30%, and lowest measurable dark area at 4% relative luminance.

Scenes 7 through 10 are a night interior sequence of another couple in the same living room, the sequence including a light change to low-key night and two close-ups with low-key night lighting. Spot luminance readings in this sequence again showed an approximately 25:1 luminance range, with the reference white at 100% relative luminance, female face at 8–45%, male face at 10–40%, and lowest measurable dark area at approximately 4% relative luminance.

Scene 11 is a stage "exterior" night scene which is a long-shot of a couple on a balcony. Scene luminance range is similar to the night scenes above, with reference white at 100%, faces at approximately 40%, and lowest measurable dark areas at 4% relative luminance. Torches used in a portion of this scene, however, showed a relative luminance of 500%. Optimum video gain setting for this scene would place the reference white at 100% video level and allow the signal from the image of the torches to go into the clipper. Automatic video gain control systems may, of course, produce a considerably different gain setting.

Scenes 12, 13, and 14 are of a young lady in a smaller living room, the sequence including a long shot with normal — as opposed to low-key — night interior lighting, a direct cut to day interior lighting, and a close-up with day interior lighting. Transmission of all the above scenes should require little or no manual gain or pedestal adjustment. Black-and-white receivers without dc restoration can give an acceptable reproduction of the night scenes because of the subjective effect of the lighting contrast. The transmission system should not evidence any bounce or drift of black level in the cuts between the day and night scenes.

Scenes 15 through 19 are a group, each of which is designed to provide particular demonstration or test material.

Scene 15 is similar to scene 14, except that a three-step gray scale of Munsell neutrals of values 8.0 (60%), 5.0, and 2.0 (3%) has been added for a check on the general appearance of neutral color and a demonstration of the reproduction contrast obtained from a 20:1 subject contrast. Insofar as the various dye systems represented by different film products will rarely result in the same visual appearance of a neutral object when faces have been timed to match, it should be noted that the gray scale in this subjective reference test film is not intended as an alignment tool for balancing the color television camera. The aim for this scene should be for an acceptable subjective color balance of the model's face and surrounding areas of the set and not necessarily for perfect tracking of the three-step gray scale.

Scene 16 is a medium shot of a girl in a green dress against a neutral background. In this scene, the large area of background should appear uniform in color. Field impurity, either in the color camera or in the color monitor, will show up as a lack of uniformity of color in the background.

Scene 17 is of a young lady working in a kitchen. Wardrobe and set colors used in this scene have provided good color contrast but relatively low brightness contrast. Reproduction on black-and-white monitors may appear somewhat flat.

Scene 18 is a long traveling shot in which the camera moves past a group of 10 bolts of cloth of different colors. A girl's hand remains in the frame to provide a constant flesh tone reference. Spot luminance values of the various colors ranged from 100% to 10% relative luminance, with the girl's hand at approximately 25% relative luminance.

CAUTION[6]

Users of these Color Television Test Films are cautioned that the dyes in these films, like other dyes, may in time change

Motion-picture prints are normally subjected to the heat and intensity of the projector beam for only a fraction of a second during projection. If these prints are used in slide projectors, they receive prolonged exposure to the heat and intensity of the projector beam. Under these latter circumstances changes in the dyes will take place more rapidly. The life of these reference test films when projected as slides can be prolonged by insuring that a filter absorbing the infrared beyond 700 nanometers is inserted in the projector optical system.

The motion-picture and television industries owe a debt of gratitude to many organizations and individuals for accomplishing a nearly impossible but highly necessary task. The Society, speaking for all concerned, wishes to acknowledge with appreciation the hundreds of difficult hours contributed by the subcommittee members as well as the valuable services of their and other organizations.[5]

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Credits for the preparation for Issue No. 2 are listed in Ref. 5.

Issue No. 3 Subcommittee

H. W. Pangborn, Chairman
Columbia Broadcasting System
E. P. Ancona, Jr.
National Broadcasting Co.
N. K. Morong
American Broadcasting Co.
R. G. Neuhauser
Radio Corp. of America
A. S. Quiroga
National Broadcasting Co.
E. H. Reichard
Consolidated Film Industries
J. M. Waner
Eastman Kodak Co.

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CBS-CBS Studio Center, Hollywood, Calif.
Consolidated Film Industries, Hollywood, Calif.
Eastman Kodak Co., Rochester, N.Y.
Paramount Studios, Hollywood, Calif.
Joseph Flaherty, CBS, New York
Richard Putman, General Electric Co., Syracuse, N.Y.

Infrared Transmission Characteristics of Various Color Release Prints and Their Effects on Color Television Reproduction

A Report to the SMPTE Color Committee by H. N. KOZANOWSKI

In September, 1963, K. D. Erhardt of National Broadcasting Co., Burbank, made preliminary tests on vidicon color television film chains which indicated that the annoying changes in color rendition between Eastman Color Print Film, Type 5385, and Technicolor 35mm (Imbibition Print) film can be minimized by including an infrared cutoff filter in the red vidicon channel.

To obtain a better understanding of the mechanism of these changes we, at Radio Corp. of America, Camden, measured the visible and infrared transmission characteristics of identical selected frames of Eastman and Technicolor 35mm prints supplied by John M. Waner. These were mounted in slideholders and could be observed both on direct projection and on a Color Television Monitor after transmission through a three-vidicon color television system. Typical measurements (Figs. 1 and 2) of dark areas in the film show that in the region of 700 to 750 millimicrons, Technicolor Film is 5 to 6 times more transparent than Eastman film.

On direct projection the scenes appear identical. Yet, through a color television system this increased infrared transparency for Technicolor Imbibition Print Film produces an undesired red-signal which can be described as red "flare" throughout the raster. This can be subtracted from the television signal by suitable red pedestal control. However, the procedure leads to difficulties because Eastman Color Print Films now shown without system readjustment will be deficient in reds. Thus the color chain must be readjusted to eliminate the *unwanted* signals produced by the product of the vidicon sensitivity and the infrared film transmission characteristics.

By choice of a suitable infrared cutoff filter, for example as shown in Fig. 3, the response of the vidicon tube at 680 millimicrons and beyond can be reduced to practically zero, the effects due to the differences in infrared transmission vanish completely, and the problem disappears.

The tests were repeated at NBC, New York and verified the conclusions just stated. However, detailed checks showed that an early 1954 model RCA infrared filter shown in Fig. 3 built into the equipment has inadequate infrared rejection. The experimental Technicolor T-1247 and F-S (Fish-Schurman) infrared cutoff filters are both well behaved.

At the suggestion of Mr. Erhardt we made available a combined red-trim and infrared cutoff filter disc having the overall characteristics shown in Fig. 4. This eliminates one element in the optical path which tended to produce "ghost" reflections.

This filter disc has been tested and has minimized the prob-

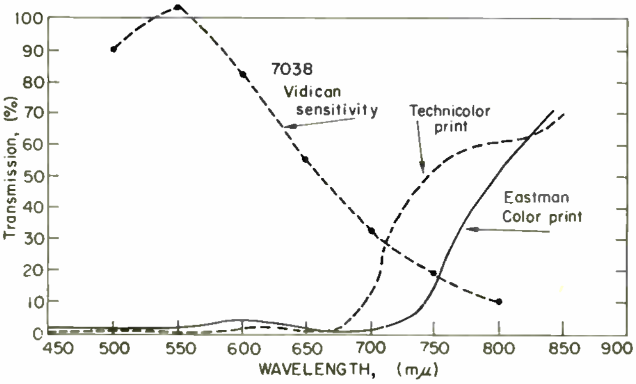

Fig. 1. Comparison of Eastman Color Print Film (solid line) and Technicolor Imbibition Print Film (dashed line) using identical selected frames, indoor scene. Data on dark area 3.5 mm × 9.0 mm.

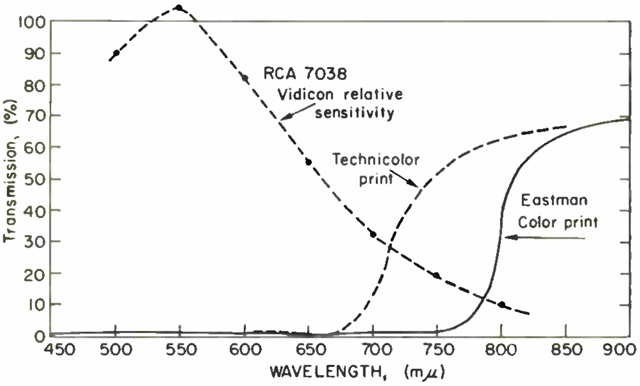

Fig. 2. Comparison of Eastman Color Print Film (solid line) and Technicolor Imhibition Print Film (dashed line) using identical selected frames, outdoor scene. Data on dark area 3.5 mm × 9.0 mm.

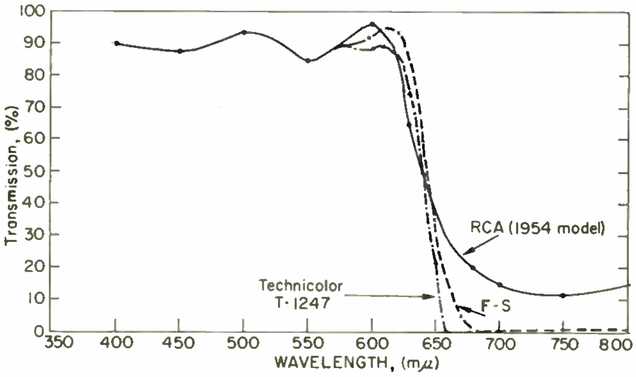

Fig. 3. Cutoff characteristics of red filters for 3-V color film. (● = RCA; × = Fish-Schurman; ▲ = Technicolor T-1247).

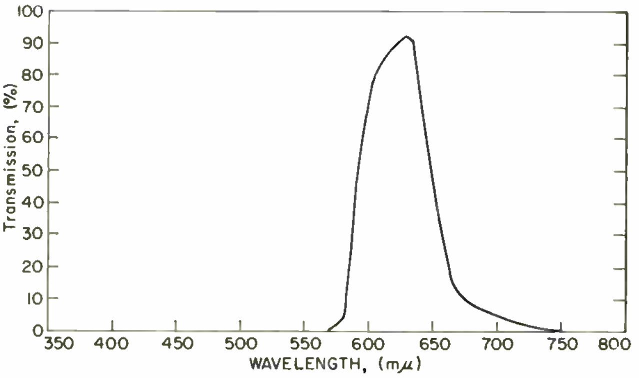

Fig. 4. Nominal transmission characteristics red trim filter OG3-650 for 3-V color film chain.

Submitted on October 6, 1964, for publication; prepared for the SMPTE Color Committee by H. N. Kozanowski, TV Camera Advanced Development, Radio Corp. of America, Bldg. 10-3, Camden 2, N.J.

lem of infrared flare. Edward P. Bertero has informed that NBC has installed it in all their film chains. RCA has made this filter available to all Broadcasters who wish to use it.

We wish to thank the members of the SMPTE Color and Television Committees who have generously provided the test films and who have assisted in the solution of the problem and the evaluation of the color television performance.

Edit. Note: Tests were made at Radio Corp. of America, Camden, N.J., to provide the data for Figs. 1–3 on Oct. 10, 1963, and on Jan. 23, 1964, for Fig. 4.

Colour Films for Colour Television

By C. B. B. WOOD

Although a high proportion of colour television programmes includes films made specially for television presentation, the technical characteristics of the prints shown still tend to be suited more to optical projection than they are to the newer medium. The long experience of the motion-picture industry enables it to produce prints which are wholly acceptable to cinema audiences from the viewpoints of contrast, detail and colour fidelity but broadcasting organisations are finding that their requirements are not identical with those of the cinema theatre. Technical characteristics which are desirable for the cinema do not necessarily suffice for colour television. There are many problems to be dealt with before colour film and colour television can successfully be married, and this paper describes some of the difficulties encountered.

Contrast

It is, at the moment, unfortunately true that few of the many colour films which look quite good by optical projection reproduce well on colour television. There seem to be two main reasons for this. The first lies in the poor ability of the television display to handle high-contrast pictures. (It should be noted that the word contrast is used in the television sense, meaning the ratio of the highlight brightness to that of the darkest discernible detail in the picture.) The contrast-handling ability of a colour television system is limited primarily by the display cathode-ray tube. If the television picture is viewed in complete darkness, the blacks in an average scene will probably be raised to about 1/60th of peak brightness by flare in the face-plate of the colour cathode-ray tube. As this flare is caused by internal reflections of light from other parts of the picture, the exact figure will depend on picture content as well as on the characteristics of the face-plate glass. If we now consider domestic viewing conditions and allow a typical amount of ambient light to fall on the tube face, the contrast will drop still further, possibly to about 20:1. The contrast-handling ability of a colour television system under ordinary home-viewing conditions is therefore likely to be somewhere between 20:1 and 30:1. In a cinema, the viewing conditions are, of course, carefully controlled and hardly any ambient light is allowed to fall upon the screen. The figure for contrast in typical optical projection is about 160:1.

If the contrast of any television display or optical projection of film is reduced by the addition of a constant due to ambient light falling on the screen, the brightness range of the original scene is no longer reproduced correctly and the detail in the dark shadows of the scene is compressed in its brightness scale to give a noticeable distortion in the picture. One might expect that films intended for the high available contrasts of optical projection would be given a contrast characteristic which neglects any limitations due to flare in the projection because this will affect only the very darkest shadow detail, if it has any effect at all. Nevertheless, it is found advantageous to reduce the slope in the highlights and lighter greys by working around the toe of the characteristic of the print film; the darker parts of the picture are then of steeper relative slope, and this compensates for the small amount of flare in optical projection. In colour television, where the contrast of the display is so much reduced by the flare and the unfavourable viewing conditions, the "flattening" of the brightness characteristic in the darker tones is very pronounced and for good subjective presentation of the picture information it is necessary to transmit signals with a considerably higher slope in the dark shadow detail.

It may also be noted that films of much greater contrast than can be handled by the television system often appear also to have incorrect colouring in the shadows and highlights. The most pleasing way in which a high original scene contrast may be compressed into the restricted contrast of colour television is to re-distribute the compression of the brightness scale so that shadow detail does not suffer too severely. Obviously, it is impossible to reproduce, say, 160:1 of scene contrast upon a display of 30:1 contrast without some distortion, but it seems better to compress the lighter tones than the dark ones.

Print Characteristics

The problem of picture reproduction within a restricted contrast range is not new; it has always existed in photography where it is desired to make prints on paper. A typical paper print is capable of a contrast of about 28:1 and it is therefore very similar to a typical colour cathode-ray tube. In an attempt to find colour films to suit the special requirements of colour television, it would seem that one may be able to profit from the efforts of the photographic industry to find the ideal characteristic for paper prints. Television displays and paper prints both require the principle of steep-slope in the shadow detail operating at a much lower contrast than that required for optical projection. The light-transmission characteristic of the film should be so shaped that shadow detail is not lost by being unduly compressed in contrast by the television display, while at the same time preserving good colour reproduction over the whole contrast range. The realization of such a characteristic may be difficult because the characteristics of colour films cannot be amended in the same way that one raises or lowers the gamma of a black-and-white film by different developing techniques. Whether a fully satisfactory result can be achieved with existing conventional film stocks seems rather doubtful; for first-class results we need a special television film material.

For most documentary films and features, a negative/positive process is used, and therefore we must have available a film print stock capable of giving the special characteristic required for television presentation. The ideal arrangement would be a single colour negative which may be printed on conventional colour print film for optical projection, and on special colour print film for television presentation. Already the requirement is being met by film manufacturers and special low-contrast film print materials have been produced for television presentation in Europe. These produce a print from a normal negative which goes a long way towards giving the overall characteristic of scene brightness to film transmission best suited to the needs of colour television presentation. It is hoped to improve still further on this situation and a draft specification for colour film has been drawn up in which the overall characteristic of scene brightness to film transmission is based upon the concept of

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This paper, slightly abridged, by C. B. B. Wood, Research Dept., British Broadcasting Corp., Kingswood Warren, Tadworth, Surrey, England, is reprinted from the June 1967 issue of *The Photographic Journal*, by permission of the publishers, The Royal Photographic Society of Great Britain, L. E. Hallett, Secretary.

scene of contrast 160:1 to be compressed as pleasantly as possible into a television display of only 30:1. The required characteristic is very similar to that for paper prints.

It is expected that 16mm reversal film originals will be used for news actualities, but a duplicate of the camera original will be used wherever possible. In any case, reversal duplicates will be made for repeat broadcasts, archives and distribution. The technique of making reversal prints from a reversal original can give very good results. Certain reversal materials of low contrast, duplicated on to a low-contrast reversal print material can sometimes give most acceptable prints for television presentation. There are, however, objections to the use of the reversal film. In the first place it has less exposure latitude than colour negative, and for news operations in particular this is an important disadvantage. Secondly, it is difficult to maintain consistently a high standard of colour accuracy, with low contrast, in a reversal duplicate. The negative/positive process is a much better-tempered system.

Colour Accuracy

Assuming that a print of suitable quality became available, the broadcaster would usually attempt to deal with the film objectively; that is to say, he would endeavour to make the combined performance of his television film scanner and the receiver as nearly like that of an optical projector as possible. In the BBC the thought has been along somewhat different lines. The information carried by the film is turned into three electrical signals and this opens up possibilities for corrections which are not possible in optical projection. The three signals relate to the red, green and blue components of the scene and are referred to as colour-separation signals.

In a practical colour television system the colour accuracy is limited at both the analysis and reproduction stages. The colours of the three fluorescent screens in a colour cathode-ray tube must place an absolute limit on the range of colours that can be reproduced by the receiver. From a knowledge of the primary colours which may be reproduced by the cathode-ray tube in the receiver, it is possible to calculate the optimum characteristics for the red, green and blue colour-analysing filters to be used in the television camera or the film scanner to separate the red, green and blue components of the scene. Similarly, the three optimum colour-sensitivity curves for a colour film material can be deduced from a study of reproducing dyes in the positive print and all the associated processes. In practice, the analysis characteristics of a colour film material are a little different from those in a colour television camera, but in either case the scene is analysed into three images related to the three chosen primary colour components.

It will be noted that when a colour film is reproduced by colour television there is a grave danger of trying to perform the analysis operation twice. The colour negative film used in the cine camera has already analysed the scene into the three primary colour contributions and therefore it is undesirable that the positive print film should reassemble the three sets of information into a rather imperfect reproduction of the original scene, followed by a repetition of the analysis operation in the colour television film scanner. This double-analysis is the second main reason why there is often disappointment when colour film is replayed by television. It would be desirable to use the colour print as though it were three entirely separate records of the three sets of colour information acquired by the negative. There have been proposals in the past to make special films for television by using three separate films or triple colour-separation frames of about 16mm film frame size fitted into a 35mm frame on black-and-white material.

Such proposals, reminiscent of the early days of colour photography, seek to use the ability of television to reassemble a colour picture from three sets of monochrome information. There is, however, no reason against the use of a conventional integral tripack colour film, provided the three layers can be read quite independently of each other. The advantage of a standard film, suitable also for optical projection, is thus retained. Difficulty arises, however, because the dyes used to produce the primary colour images in colour film are fundamentally unable to act over one part of the visible spectrum without having some unwanted effect upon the remainder of the spectrum. Figure 1 shows a graph of the density of three typical dyes used in colour print material. It will be seen that each dye absorbs some light of wave-lengths other than those over which it is required to exercise control and hence each dye-image influences colours that it should not affect at all. The more saturated a reproduced colour should be, the more it is affected by the other dyes because they are required in greater density.

Electrical Correction

The physical characteristic of available dyes makes it impossible to manufacture a colour film in which the three sets of colour information, the yellow, magenta and cyan images, do not interfere with each other. The television engineer would call this cross-modulation. The result of this cross-modulation is that colours become distorted; that is to say, colour of the original scene are reproduced with a loss of saturation, and high-luminance colours are usually reproduced with reduced brightness because of unwanted absorptions by the dyes. The straightforward process of colour photography thus distorts the brightness of objects and reduces the saturation of the reproduced colours. Experience shows, of course, that for optical projection this distortion is acceptably small if it is carefully controlled by the film manufacturer. If the distortions of the television process are added, however, then the overall result may well be unacceptable.

It can also be seen that the film must be a perfect reproduction of the original scene, and not merely a pleasing representation, if the television picture is to have the same appearance as it does when a live colour television camera is used. If the colour-analysis process is allowed to occur twice, the facts that the film reproduces the scene with the aid of imperfect dyes and that the result is then analysed in the television system with imperfect analysis characteristics will render a perfect reproduction impossible. The film and the television processes

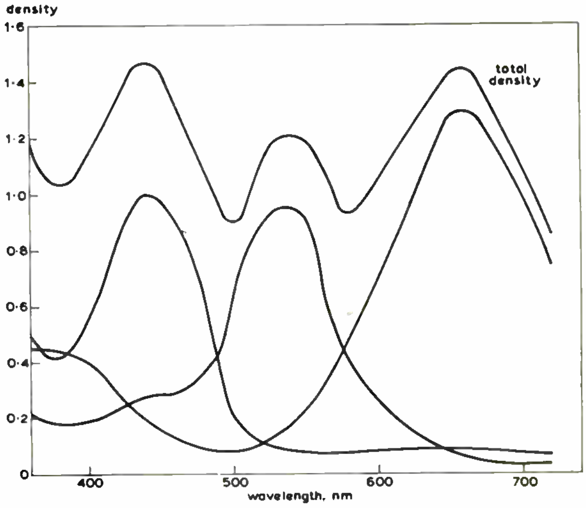

Fig. 1. Density of dyes used in typical colour positive print film.

must be treated as an integral whole. The film must be allowed to perform a colour analysis of the original scene, and the television system must be allowed to make a reproduction of that scene from information that it obtains from the film, but the intermediate processes should be completely free from cross-modulation and errors, as though there were three completely separate, insulated conductors conveying information from the colour negative film direct to the cathode-ray tube. Although this cannot be achieved in that manner, the same effect may be obtained by making corrections to the electrical signals derived from scanning the film. If the cross-modulation in the film due to the dye characteristics is known and an equal amount of cross-modulation, but of opposite polarity, is deliberately introduced into the electrical signals, the errors will be cancelled.

Measurements are made of all colour film materials to determine the distortions occurring in the reproduction of the original scene. A calculation of the effects of the cross-modulation between the three dyes in the colour print and also of the errors due to imperfect colour analysis of the scene indicate the errors fundamental to each type of film. Each type of film requires a different compensation, depending on the characteristics of the dyes used; and in the film scanner switched circuits labelled with the names of the different film stocks will introduce the appropriate electrical correction for the colour distortion which has been measured, calculated and found to occur in that particular material. The correction remains a calculated value applied to every print made on that film material and it is independent of the exposure of the film, the picture content or even the processing of the film, provided the dye characteristics remain unchanged.

The process of electrically correcting for errors due to cross-modulation is called electronic masking, deriving its name from the process which is used when colour film duplicates are made by photographic means. The cross-modulation due to the unwanted absorptions of the dyes is a function of the density of each dye and is a logarithmic quantity; it is therefore necessary to pass the signal through a logarithmic amplifier before applying the corrections. After adding or subtracting the corrections, it is necessary to take the antilogarithm of the corrected signal with the aid of a suitable non-linear amplifier. The instrumentation of this technique is difficult and calls for sophisticated apparatus: in particular very high stability of black-level and precision clamping to peak-white signal are essential features.

With a television film scanner equipped with electrical correction for the errors known to be introduced by the film, we are now in a specially privileged position. We no longer set out to reproduce the film as the eye sees it on optical projection, but we can now aim to reproduce the colours of the original scene more accurately than they appear in the film.

A very important benefit of electronic masking in television is that it makes possible the use of filmed sequences intercut with live television drama. This technique is used a great deal in Britain — in all outdoor scenes and in many other sequences where it increases the operational flexibility in the studio, the action is shot on film in advance of the studio production and is intercut at the appropriate times. In colour, the high colour saturations and accuracy of the live television cameras would make it impossible to cut to a filmed sequence with much lower colour saturation and an additional set of errors. It is found that with accurate electrical correction we can make the film-plus-television process a good match for the television-only process.

Acknowledgement: The author wishes to thank the Director of Engineering of the BBC for permission to publish this paper.

Some Considerations in the Television Broadcasting of Color Film

By C. B. B. WOOD

It is desirable that television films have characteristics specially suited to the viewing conditions and contrast-handling ability of the TV system. With modern telecine techniques, a wide range of contrast in films can be handled successfully. Electronic enhancement of the color saturation in the reproduced picture is now in operational use. Despite these improvements, it is desirable that television films should have characteristics specially suited to the viewing conditions and contrast-handling ability of the television system.

THE PROPERTIES of the conventional color television system are such that when it is used to display color motion-picture film, it places constraints upon the technical characteristics of films that may be handled successfully.

It would seem unrealistic to modify the characteristics of motion-picture color film to suit the deficiencies of color television without at least giving very careful consideration to the properties of the system and making sure that the broadcaster is doing all that is possible to avoid distorting the pictures. Some of the constraints imposed on film by television presentation are inevitable: they stem from the basic differences between viewing conditions in the home and those in the cinema theater, but in other cases further improvements in technology could better equip the television film scanner to deal successfully with color films.

Some of the deficiencies of the color television system may readily be observed by a simple comparison between the optical and the television presentations of the same roll of film: after being disappointed by the television display of what had seemed optically to be a film of reasonably good picture quality it is interesting to return immediately to the optical review theater and see the film again. This time the magenta shadows, unnatural skin tones and other defects so obvious on television will be noticeable, although to a lesser extent. One important result of presenting a film by color television is to exaggerate defects which pass unnoticed on most occasions of optical projection, but this is not all: the telecine (in conjunction with the kinescope display) does not have the spectral response associated with the human eye and therefore does not view the film in the same way that it is seen in optical projection. Television presentation of films by means of unsophisticated film scanning apparatus may thus create errors for which the film cannot be blamed. It is, however, possible to overcome some of the present difficulties and possible courses of action will be suggested.

The principal picture defects observed during television reproduction of color motion-picture film may be classified as follows:

(a) Increase of Contrast: This almost invariably results in distortions of the luminance scale since the contrast-handling ability of the television system is limited.

(b) Color-Balance Errors: The subjective impression gained from optical review is not repeated upon television presentation.

(c) Color-Saturation Errors: The imperfect color saturation performance of color motion-picture film is further degraded upon television presentation.

Contrast Distortions

Film Contrast Characteristics

Many of the defects observed in television reproduction of color motion pictures arise from the fact that the brightness contrasts of the original scene, already distorted in the film, are further distorted when the film is reproduced by television. Sensitivity to errors in the reproduced brightness of colors is linked with the accuracy of reproduced color saturation. The inevitable loss of color saturation is substantially offset subjectively by an increase in the contrast of the film; therefore, in an average color film, the overall characteristic relating density with log brightness of the original scene is found to have a slope of between 1.5 and 2.0 in the straight portion of the characteristic. Experience has shown that this exaggerated contrast, combined with the practical color saturation of typical color films, achieves an acceptable result even if it is not objectively accurate. However this approach has so far been based upon the assumption that the film will be presented to the viewer by optical projection.

Television Camera Contrast Characteristics

The light output of a shadow-mask color kinescope tube is related to the input signal by a close approximation to a pure power-law. The index of this power-law varies a little from one tube manufacturer to another and is dependent upon the way in which the signals are applied to the tube electrodes; but a typical value of gamma for the color tube is 3.0, considerably in excess of the nominal value of 2.2 stated in the NTSC specification. An electrical correction for the light transfer characteristic of the receiver kinescope tube is, of course, always included in the parameters of the transmitted television signal, but it is very rarely of such a form that it represents the reciprocal of the law of that tube.

In the case of monochrome television cameras employing the image orthicon pickup tube, accurate gamma correction is rarely practiced since the output signal of the camera tube neither is linear nor does it conform with any pure power-law. Nonlinear ("black-stretch") corrections are applied to the signals before transmission but they result only in crude approximation to any characteristic which might have been prescribed mathematically.

Some color television cameras employing the Plumbicon pickup tube (a linear device) introduce gamma correction which gives a close approximation to a pure power-law over contrast ranges of 30 : 1 or 40 : 1. It is, however, unusual for television cameras to be corrected more completely than to conform to a power-law of 1/2.2. The choice of this value is in part traditional since it represents the complete correction of the nominal (and effectively nonexistent) color kinescope of the NTSC specification.

A more practical limitation is imposed by the visibility of random fluctuation noise in the darker parts of the picture if gamma correction is carried to the correct mathematical conclusion. Complete gamma correction necessitates very high relative amplification in those parts of the signals representing the darker parts of the picture: the inevitable noise accompanying the signal is also greatly increased. Furthermore, it is a property of the Plumbicon tube (and also the vidicon) that an object moving in the scene is, at low light levels, portrayed

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as being followed by a trail of incompletely-erased picture information relating to its position in earlier fields. Complete gamma correction increases the visibility of this lag signal.

Hence, a color television system using a modern high-grade color television camera and a typical shadow-mask color kinescope display will have a contrast characteristic such that the slope is approximately 3.0 × 1/2.2, i.e. about 1.36. It is unlikely to be less than this value and in many cases will be more, but over 30 : 1 or 40 : 1 it should conform reasonably well with a simple power-law. The increased contrast in the reproduction of the original scene is usually acceptable to the viewer and does not often give rise to serious degradation of the picture.

Telecine Contrast Characteristics

In Europe where the television field rate is 50 fields/s, the flying-spot telecine is generally preferred; this uses photomultipliers which give primary signals linearly related to the light transmitted by the film. The primary signals are then gamma corrected by means of nonlinear amplifiers, and as a rule conform fairly closely to a power-law of index 1/2.2. Again a reason for this choice is the amplification of noise in the darker tones of the picture. In the case of a photomultiplier output, however, the noise is not a constant added to the signal as in the Plumbicon or vidicon camera, but varies as the square-root of the signal; the effect of extreme amplification of signals relating to very dark areas of the picture is less objectionable.

In countries where the television field rate is 60 fields/s and the flying-spot principle is inconvenient, vidicon pickup tubes are generally used in telecine machines. The correction of the signals to compensate for the high gamma of the kinescope tube is carried out in a manner similar to that of the live television camera. The objections to complete correction for the gamma of the kinescope tube arise, as before, partly from noise in the dark tones of the picture and partly from increased visibility of lag signals.

Contrast Limitations Imposed by Television

The important outcome of a consideration of present gamma-correction techniques is that the contrast characteristic of a color television system has a slope of not less than 1.36 and that this slope is much the same whether a television camera is used to view a natural scene or whether a telecine chain reproduces a color film. The natural scene viewed by the camera has a contrast characteristic slope of 1.0, but the telecine is viewing a scene as reproduced on the film which already has a slope of between 1.5 and 2.0. It is the subsequent increase in contrast of an already high-contrast reproduction which causes the overall film-plus-television system to run into severe distortion.

The shadow-mask color kinescope tube has a restricted ability to handle high-contrast scenes, partly because flare in the faceplate of the tube reduces the ultimate contrast which may be displayed and partly because it is almost invariably viewed under higher ambient light conditions than those obtained in the optical projection theater. Furthermore, the electrical circuits of typical color television receivers do not maintain a true black level with the accuracy required to reproduce high-contrast and low-contrast scenes with equal fidelity.

Estimates of the contrast-handling ability of a color television system vary considerably and, of course, much depends on the precise viewing conditions, but it is substantially less than that achieved by good optical projection. Thus, even if the television system did not increase the contrast of the film at all, there would still be a danger that films successful in optical projection would be shown with black crushing or other distortion on color television. The enhancement of contrast by the television system places a serious constraint upon the contrast which may exist in films intended for color television.

Color Balance

Television White-Point

For 35mm films the projector light sources have correlated color temperatures lying in the region between 5000°K and 6000°K; it is therefore logical that color film characteristics should have been designed to give the best subjective results when used in conjunction with these light sources. The specified white point of the NTSC color television system is Illuminant C (6770°K) but more recently opinion has been in favour of Illuminant D (6500°K) as the white point for color television. It is unfortunate that very many television receivers are not balanced to either of these standards but have a white point between 9000°K and 10,000°K. The color signal specification assumes that white or gray is displayed when the color separation signals are of equal magnitude (i.e., R = G = B). If the broadcaster adjusts the telecine so that the three signals are in fact equal for a neutral gray in the film, then the effective projection color temperature is determined by the balance of the television receiver.

Color temperatures much in excess of 6500°K have a particularly bad effect upon the reproduction of skin tones; it is most desirable that the receiver white point should not be significantly different from that intended in the production of the film. Some subjective tests carried out in the BBC Research Department (see Fig. 1) indicated that observers preferred the white point of a television display to lie between 5000°K and 6000°K, even when viewing was carried out under quasi-domestic conditions with a typical level of ambient illumination derived from tungsten light sources. The presence of tungsten ambient illumination lowered the preferred color temperature by about 500°K but it nevertheless remained within the bracket already stated. It would therefore seem that there is no great incompatibility in respect to color balance between films intended for optical projection and those intended for television presentation, provided the television receiver is balanced in accordance with the NTSC specification. There is, however, likely to be some difference between the acceptable tolerances for color balance, depending on whether the film is to be viewed under television or review-theater conditions.

Film White-Point

If a film is viewed by optical projection in an otherwise completely dark theater the eye will adapt to a white point which may be substantially different from the preferred value in the region of 5500°K and the viewer will be reasonably satisfied with the result. Domestic viewing of color television is generally carried out in the presence

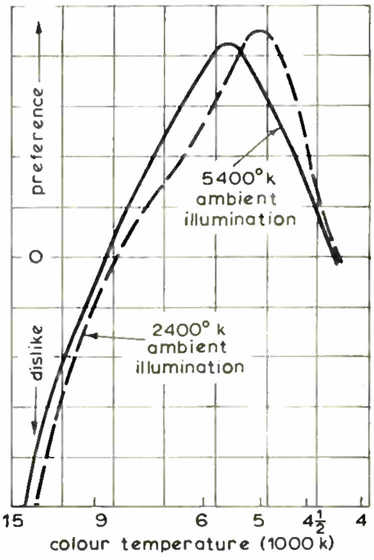

Fig. 1. Subjective test results: viewers' preferences for color television receiver white point; 30 observers, indoor and outdoor scenes, total 10,850 observations.

of substantial level of ambient illumination. The presence of familiar objects within the field of view seems to act as a stabilizing reference for the eye which becomes much more critical of changes of color balance in the television picture and does not adapt so readily as it does in a darkened projection theater.

It follows that neutrals in the color film print intended for television must be balanced to a closer tolerance than is perhaps strictly necessary for optical projection.

Telecine Color-Analysis Characteristics

Aside from the necessity of achieving subjectively accurate neutral balances in films intended for television presentation, there is another problem associated with television reproduction of these films. Color film is made up of three light-absorbing dyes which operate on various parts of the visible spectrum of light emitted by the projection source. The sum total of the three absorption curves does not, however, create equal attenuation of all wavelengths of light. Some wavelengths are attenuated more than others and when a subjectively neutral balance is achieved with the conventional tripack color film it can only be a metameric match with a true neutral. This is the case where the eye integrates the energy at all wavelengths of light and judges the effect to be identical with that produced by a true neutral-density filter which attenuates uniformly throughout the spectrum. The analysis characteristic of the telecine (taken in conjunction with the kinescope display) must therefore be a strict analog of the human eye if it is to reproduce the film exactly as in optical projection: in particular, it must produce equal color separation signals to represent parts of the film which are metameric matches for a true neutral density.

If the telecine is to have analysis characteristics which precisely match those of the human eye for all colors contained within the triangle bounded by the synthesis primaries, then negative responses must necessarily be included in the analysis and the required characteristic is shown in Fig. 2. It is, of course, theoretically possible to design a telecine to have this characteristic; the negative lobes would be achieved by analyzing positively in separate sensors and, afterwards, changing the sign of the minor signals before adding them into the appropriate primary color separation signals. Given that this characteristic were achieved, the telecine would reproduce films as they are seen upon optical projection, excepting any limitations imposed by the shadow mask display.

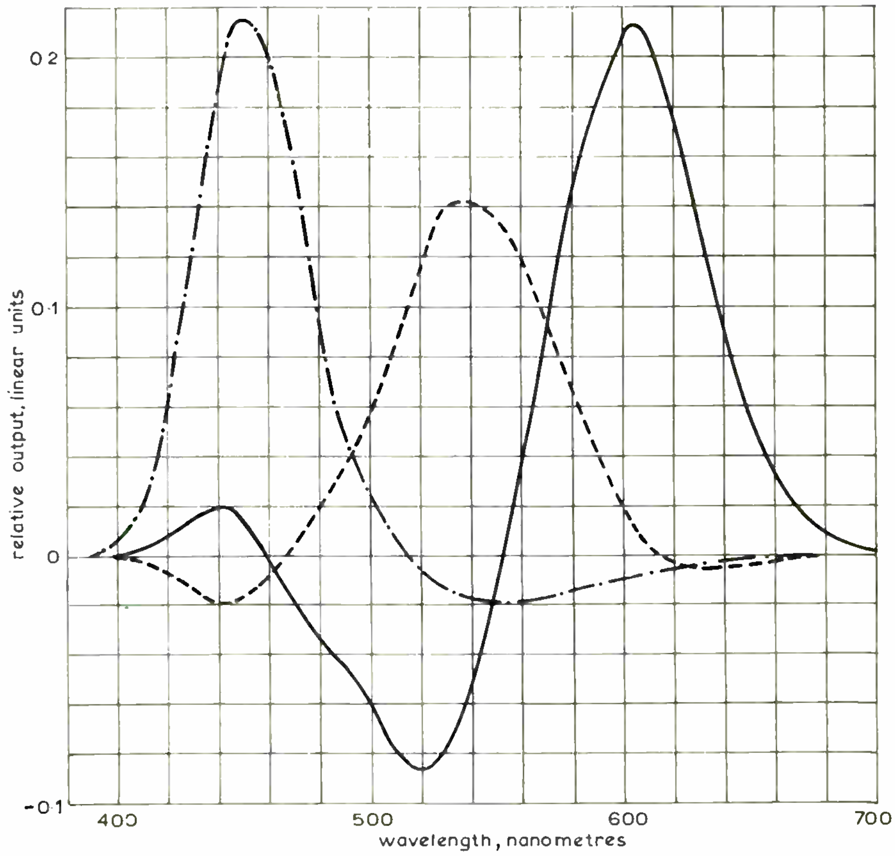

Fig. 2. Ideal analysis characteristic for typical modern color television receiver phosphors and white point set to Illuminant D 6500.

In any practical color analysis arrangement for a telecine, the light is divided into three contributions relating approximately to the red, green and blue components of the input. (This refers only to the color sections of the analysis system. Light to create a separate luminance signal in four-tube telecines will have been collected before color analysis.) The simple analysis characteristic therefore consists of three "positive-only" lobes of suitable spectral sensitivity: it would be largely fortuitous if the light transmitted by a color film which has only a metameric match with a true neutral density were to cause the three sensors to produce three precisely equal signals. It is possible to adjust the gains of a simple "positive lobes only" telecine so that any particular color or neutral at any particular luminance level is correctly reproduced but it does not follow that other luminance levels and other colors will also be correct. The technique of adjusting for optimum facial skin tones after a general line-up of the telecine has grown out of the inability of the simple analysis characteristic to reproduce the film as it is seen by the human eye.

More sophisticated methods of color analysis of the light transmitted by the film are available and in use. These will be discussed later.

Color Saturation

It is well known that the dyes available for the manufacture of color film materials are far from ideal. Each dye would desirably influence only one part of the visible spectrum of light transmitted by the film and remain completely transparent to other wavelengths of light. This is not possible because each of the three dyes in practice has unwanted absorption of light of wavelengths to which it should be transparent so that the luminance of a wanted color of high saturation is always diminished by unwanted attenuations imposed by the dyes which are necessarily present. Conversely, the desired absorption of light by any one dye is incomplete over the total band of wavelengths which should be removed from the light transmitted by the film. Attempts to reproduce a saturated color are therefore not completely successful: saturated colors suffer some dilution by wavelengths which should not be present; they are also subject to reduction of luminance by unwanted absorptions. When this somewhat imperfect reproduction of the original color is reanalyzed in the telecine there is usually a further desaturation. The television display is thus a reproduction of a reproduction and unless suitable action is taken in the design of the telecine to compensate electrically for the loss of saturation due to reanalysis of the reproduced scene, the total desaturation may well be unacceptable.

In the most up-to-date technical approach to telecine design, the losses of saturation due to unwanted absorptions of the dyes used in the manufacture of the film are also compensated, so that the reproduction of the original scene by the overall film-plus-television system can now be made superior in color fidelity to that which is achievable by film alone.

Action Possible by the Broadcasters

Having outlined some of the technical problems concerned with reproduction of color motion-picture film by color television, it may be useful to consider what can be done to bring about improvements. It is always difficult to embark upon any large-scale modification of existing broadcast equipment since the design of any one part of the apparatus is usually influenced by the remainder. Major improvements to telecine performance must usually await the introduction of new machines of integrated design incorporating all possible technical improvements. It might, however, be possible to improve some existing machines by piecemeal modification.

Telecine Gamma Correction

It would seem that a substantial improvement could result from the reduction of gamma in telecines. Experience indicates that if the contrast law correction of a telecine can be reduced from the present value of 1/2.2 to 1/3, there is a surprising improvement in freedom from distortions due to excessive contrast. It is, of course, a relatively simple matter to construct new gamma-correctors for the telecine which conform to a power law of 1/3. Unfortunately, the introduction of this modification in isolation is very likely to show an objectionable increase of random fluctuation noise in the darker tones of the picture and, in the case of vidicon scanners, there may also be an increase in the visibility of lag signals. To reduce noise, and thereby permit the use of revised gamma correctors, an ambitious program of modification might very well include new preamplifiers for a vidicon telecine. With modern field-effect transistors it is possible to achieve signal-to-noise ratios considerably better than those which were the best available a few years ago.

A useful method of reducing visibility of noise in the darker tones of the picture is to use level-dependent aperture correction. This technique is used in Plumbicon color television cameras where the comparatively low resolution of the Plumbicon tube is electrically corrected only when the signals are of greater magnitudes than, say, half the maximum value. The subjective sharpness of the picture is not noticeably diminished by the absence of aperture correction in the dark tones but a very useful reduction in the visibility of noise is achieved. This technique alone can make the application of complete gamma correction practicable where otherwise the noise would have been intolerable.

Color Balance and Saturation

Modification of the color analysis characteristic of a telecine is not, as a rule, a simple matter. An expert knowledge of colorimetry is required and most colorimetric calculations in this field are best carried out by optimization programs in a computer. It is sometimes possible to calculate the coefficients of a simple 3 × 3 matrix of the color signals[1] to bring about a substantial improvement in the color analysis of a telecine without replacement of the dichroic light splitters and shaping filters. In the 3 × 3 matrix of the color signals, each separate signal has certain fractions of the remaining two signals added or subtracted in such a way that the total effect is to give the analysis a characteristic nearer to being the analog of that representing the human eye. The linear matrix technique is successfully used in Plumbicon color television cameras and although it does not give precise corrections in a telecine, it can nevertheless substantially improve the ability of the apparatus to reproduce film in a manner closer to that associated with optical projection.

The suggestion has been made that there should be a "standard telecine characteristic" which would always be used when appraising films for television. This suggestion underlines the findings of broadcasters that different telecines can give quite different reproductions of the same film. The variations arise from differing color analysis and differing gamma correction characteristics. To some extent it seems to be a matter of chance that a given film will be satisfactorily reproduced. Much would depend on the scene, the film contrast, the film dye characteristics and the presence of any slight color casts which might compensate or reinforce the errors due to telecine analysis of the film. A standard telecine would be very desirable if it could be agreed to represent the best possible technical approach to broadcasting color film but it would not be progressive to aim the technical quality of films to suit the constraints of the present telecine performance.

A recent approach to the design of telecines employs comprehensive electrical correction of the signals derived from scanning the film.[2] The objective is to derive signals proportional to the quantities of dye present in each of the three layers of the film and then to modify these signals to compensate for the known deficiencies of analysis and film-dye characteristics. Initially, signals proportional to the light transmitted by the film are derived in the conventional manner; these are then passed through logarithmic amplifiers. Once the three signals, log R, log G and log B, have been obtained, it is possible to compensate for the unwanted absorptions of the dyes in the film. The technique, known as electronic masking, not only gives the scanner an effective analysis characteristic very close to the optimum but is, in brief, a method of deliberately introducing equal but opposite errors into the electrical signals as compensation for the measured errors due to the physical properties of the film. The theory was described as long ago as 1954,[3] but it is only comparatively recently that the technology of film scanning has advanced to the point where it can be employed operationally on a wide scale.

The modern telecine incorporating electronic masking is usually equipped with fairly wideband optical color analysis characteristic and yet can produce color fidelity in the reproduction superior to that obtained by other means. The creation of signals proportional to the logarithm of the light transmitted by the film is a moderately difficult task requiring very high relative amplification of signals relating to darker parts of the scene. An extremely stable black-level reference is necessary from which to originate the signals. The technique has successfully been worked out in connection with flying-spot telecines and comprehensive electronic masking with low gamma transmission of the signals derived from color motion-picture film and is now in operational service with the BBC. It is not known whether the black level of signals derived from a vidicon film-chain camera, taking account of flare, etc., would be sufficiently stable to be used sucessfully in connection with classical electronic masking techniques. It might be that some improvements to the balance and color saturation of color films could be made by matrix treatment of the gamma-corrected signals rather than by the creation of the theoretically necessary logarithmic signals, but the following observations seem to be undeniable:

(1) that a simple "positive lobes only" telecine is not technically capable of giving an accurate reproduction of color film,

(2) that a simple 3 × 3 matrix of signals which are proportional to the light transmission of the film may improve color accuracy in the reproduced picture, and

(3) that comprehensive correction of the color analysis of the film by the telecine and the restoration of brightness levels and saturation losses due to the physical qualities of the dyes used in the film can only be made by means of a sophisticated telecine. This requires that linear signals are passed through logarithmic amplifiers before the calculated matrix operations are carried out upon the signals. This type of scanner is a practical possibility and is in operational service.

Action Possible in Color Film Production

It seems that more thought has been given to the production of color films to suit the constraints imposed by color television than has been given to the relaxation of those constraints. An excellent SMPTE committee report[4] outlines the problems, gives sound advice on color film characteristics and makes useful recommendations for lighting and stage practice. There is need for further investigations into characteristics of color film materials suited to color television presentation: it is hoped that film manufacturers will undertake this work as quickly as possible.

The greater-than-unity gamma of color television further increases the already high contrast of the conventional color motion-picture process to the point where it is almost inevitable that there will be black-crushing and color distortion due to the inability of the television system to handle these contrasts. Even where the broadcaster is able to reduce the overall gamma of the television system to a value of unity, or thereabouts, with new telecine apparatus of sophisticated design or by the modification of existing equipment, it is still desirable, from the television point of view, to have a low-contrast print because the contrast-handling ability of the television kinescope is less than that of optical projection. Hence, the need is for a low-contrast color print material having a characteristic curve shape specially designed to reduce the unwanted effects of flare and other distortions in the television system, and to give the best subjective impression of the scene when it is televised. These requirements are not compatible with the optimum print for optical projection and it seems that two print materials, one for optical projection and one for television presentation should be available. It is, however, desirable that a common color negative material be used for either process. It is anticipated that the emphasis in designing a new color film material for television would be on characteristic curve shape, while the film would also be designed to yield a satisfactory print under conditions of both high-contrast and low-contrast original scenes. It is only an expedient to suggest that lighting and stage techniques be restricted to permit the production of suitable films by means of existing high-contrast print materials; in many cases, particularly in Europe, shooting for television takes place on locations where there is very little control over the lighting.

The precise shape of the chosen characteristic curve of the photographic process can probably only be determined by subjective appraisal in a modern telecine since the undoubted requirement for lower contrast must not be allowed to cause losses of other desirable picture characteristics. It is, for example, well known that low contrast in high-luminance detail spoils the subjective impression of sharpness. The optimum curve shape is by no means an obvious choice.

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Subject-Lighting Contrast for Color Photographic Films in Color Television

By F. T. PERCY
and T. GENTRY VEAL

Set-lighting in making motion pictures for color television is described. It was found that optimum television picture quality was obtained when the subject-lighting contrast was reduced to correspond more nearly with the range of brightness which can be reproduced over a color-television system.

Ever since the first photograph was made over a century ago, photographers have been concerned by the fact that many of the scenes they tried to reproduce had a brightness range (or, in modern terminology, a luminance range) much greater than the photographic process was capable of handling. Luminance ranges in nature may exceed 300 to 1, while most photographic transparency processes will only reproduce satisfactorily a range of approximately 100 to 1. The common "soot and whitewash" effect of most amateur snapshot prints shows what happens when the luminance range of the process is greatly exceeded by the range in the scene; the highlights are washed out and the shadows are barren of detail; even the reproduction of the middletones is unsatisfactory. A similar situation exists when photographic films having a luminance range of 100 to 1 are used as a source of material for monochrome television, which will not reproduce a luminance range greater than about 30 to 1. When motion-picture films are projected onto a television film camera for subsequent transmission, and these films have a greater luminance range than the television system will accept, it results in (a) excessive compression effects that render shadow detail invisible and (b) a general degradation of picture quality. The compression effects become acute when the problem of shading, signal storage and signal-to-noise ratios are taken into consideration in the operation of a television film camera.

In the artificially lighted scenes that are commonly used for television, the photographer controls the luminance range of the scene by the intensity and posiiton of his lamps. Here he must depart from standard motion-picture technique and limit the luminance range recorded on the motion-picture film by proper subject-lighting contrast. Subject contrast might be considered as a property of the scene before the camera lens. However, it should be remembered that the term subject-lighting contrast should not be confused with subject contrast or subject-brightness range. The subject contrast or subject-brightness range is usually much higher than the subject-lighting contrast, since it takes into account the difference in reflectance of the various elements of the scene.

Fig. 1. Subject-lighting contrast 4 to 1.

Fig. 2. Subject-lighting contrast 2 to 1.

Figure 1* shows a subject illuminated with two lamps. The first lamp, known as the key-light, sets the general level of illuminance and the distribution of shad-

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* Figures 1 through 14 were rephotographed particularly for this printing. The original figures for this paper were made in 1953 and could not be located for this reprint. The authors wish to thank Earl Kage for his efforts and suggestions in remaking the photographs for this publication.

ing over the subject. The second lamp, known as the fill-light, is placed to fill in the shadows suitably and to soften the effect. In this figure, total illuminance on the subject from the key- and fill-light is four times luminance from fill-light alone, or, in photographic parlance, subject-lighting contrast is 4 to 1. This is common practice in making ordinary motion pictures for theaters. In Fig. 2 is the same subject when the subject-lighting contrast has been reduced to 2 to 1. This picture could be reproduced by monochrome television satisfactorily, and it is good practice to run the contrast to 2 to 1 for this purpose. In both pictures, supplementary illumination has been added to the background.

At first thought, there seems to be a wide discrepancy between a subject-lighting contrast of 2 to 1 and the luminance range of 30 to 1 that a television system will transmit. However, this discrepancy is only apparent, as can be seen in Fig. 3. In the figure, the man's shirt reflects 110 times as much light as his suit, when both are illuminated by the same amount of light. In the present instance, the subject-lighting contrast is 4 to 1; the shirt is in the most brightly illuminated region and part of his suit is in the deepest shadow. The luminance range of the entire scene is not 4 to 1 or even 10 to 1, but 110 to 1, a range too great for any commercial television system to reproduce. To correct this scene for television transmission would require either limitation of minimum reflectances by the choice of wearing apparel or supplementary lighting of regions of low reflectance.

Fig. 3. Subject-lighting contrast 4 to 1.

Fig. 4. Subject lighting with key light only.

The effect of varying the subject-lighting contrast can be clearly seen from from the next three figures. A key-light alone was used for Fig. 4, so the only light in the shadows was the light reflected from the walls of the room. A fill-light has been added for Fig. 5 to lower the subject-lighting contrast to 4 to 1, as in black-and-white motion-picture photography for theaters. Nevertheless, the luminance range is still too great to be reproduced satisfactorily even in monochrome television. Figure 6 shows the effect when the subject-lighting contrast has been lowered to 2 to 1. The key-light was at an angle of about 45° from the camera; the fill-light was near the camera. For Fig. 6, no supplementary illumination was used on the background, as was done for Figs. 4 and 5, which explains why the impression of depth is less marked in Fig. 6.

The advent of color television has restricted the permissible luminance range still further because the maintenance of proper color balance requires a fixed relationship as well as a degree of similarity between the transfer characteristics of the three color channels. The only control common to all three channels is the iris diaphragm in the light path of the three light-sensitive receptors. By holding the luminance range on the motion-picture film to a range the color-television system will accept, the control operator is able to operate the system at an optimum level to provide the best picture quality obtainable. The transfer characteristics of the three color channels in a television system must be adjusted to give proper color balance or gray scale throughout the luminance range. It is not practical to correct for neutral balance with luminance changes.

It is normal monochrome practice to allow the image orthicon and iconoscope to operate in such a manner that the scene highlights are allowed to extend beyond the knee of the transfer characteristic curve. Color cameras, whether used for live pickup or film pickup, should be operated with the highlights certainly not beyond the knee of the transfer characteristic curve. If they are operated beyond the knee, a loss of color balance will result. This is also true if the range of photomultipliers is exceeded when used in flying-spot scanners, although the range is considerably greater than with storage tubes. This factor alone indicates the desirability of holding highlight brightness and overall brightness range well within the brightness limitations of the color-television system. The effect of varying the subject-lighting contrast in color television can be seen from Figs. 7–9. In Fig. 7, the lighting contrast is 3 to 1.

This reproduction is fair, but still the contrast is somewhat high. Figure 8 shows the same subject when the lighting contrast is 2 to 1. We have made many tests, and our conclusions are that, in general, this contrast is the most suitable for reproduction by color television. In Fig. 9, an attempt has been made to reduce the lighting contrast to 1 to 1. It is difficult to obtain such a low contrast when several lamps are used without resorting to diffusing materials on the lamps, and despite the care taken in lighting this scene, the lighting contrast probably was not exactly 1 to 1. Even so, the scene is not unpleasant or abnormally flat.

But there is another feature of the scene that is important in securing a pleasing and lifelike representation. That is the tone of the background, as has been pointed out in passing. In Fig. 10, the background is illuminated only by lights used to illuminate the subject herself. The scene appears to have little depth, and the subject looks like a paper cutout pasted against the background. Figure 11 is the same scene but with adequate background lighting, and one now realizes that the subject is standing about six feet in front of the background. Figures 12, 13 and 14 show a typical commercial subject under the same conditions. No extra lighting was used on the background in Fig. 12. Additional back-lighting was used on Fig. 13 to create depth. Figure 14 certainly gives a stronger sense of nearness to the observer. In all of these scenes, the subject-lighting contrast was 2 to 1, in accordance with our recommendations.

In conclusion, we recommend that, when color films are used as a source of material to be transmitted in color by a television system, the subject-lighting contrast be of the order of 2 to 1, unless the conditions are unusual. Furthermore, we recommend that the background be lighted adequately to give a sense of depth to the scene. These recommendations are not dependent on the type of photographic material or on the type of television film camera used. This also includes flying-spot scanners. Masking techniques have been described recently for improving the purity of the colors on the television screen, but there is no reason to believe that the adoption of such techniques will require the alteration of our recommendations.


Fig. 5. Subject-lighting contrast 4 to 1.


Fig. 6. Subject-lighting contrast 2 to 1.

Fig. 7. Subject-lighting contrast 3 to 1.

Fig. 8. Subject-lighting contrast 2 to 1.

Fig. 9. Subject-lighting contrast 1 to 1.

Fig. 10. Subject-lighting contrast 2 to 1, no background illumination.

Fig. 11. Subject-lighting contrast 2 to 1, with background illumination.

Fig. 12. Subject-lighting contrast 2 to 1.

Fig. 13. Subject-lighting contrast 2 to 1, with back light.

Fig. 14. Subject-lighting contrast 2 to 1, with back light and additional background illumination.

4

Color Television Cameras and Studio Practices

A Survey of Camera Tubes for Television Broadcasting

By WALTER E. TURK

The evolution of television camera tubes is traced with major changes and improvements described. The survey covers dynode structure change, image section change, and target changes brought about through use of the electronically conducting glass target.

This paper deals briefly with the vidicon and image-orthicon types of television camera tubes.

Since its introduction some twenty years ago the image orthicon has undergone little basic design change. The 5820 design of 1949[1] is still very popular after a very long operational life and is now being used in color cameras.

Vidicon

The vidicon, in spite of considerable processing advances in recent years, does not seem to have become established as a general purpose broadcast tube. It has not fulfilled its early promises of extreme simplicity and economy. Even in the industrial field its acceptance has been a very slow process largely because of its chief defects — picture lag and insensitivity. Of late, however, it is being applied increasingly to the field of educational television, where its broadcast limitations are less important. The newest member of the photoconductive group, the Plumbicon[2] introduces the concept of a reverse biased photodiode as applied to a large area. Its sensitivity is higher and it has lower lag properties but introduces new features such as the absence of an inbuilt signal attenuator at the higher levels.

There have been only two important design changes in the vidicon. First, the uniformity of the photoconductor was improved with the introduction of the cold seal technique for the faceplate.[3] Second, the early 6326 tube with provision for improving corner resolution by focus modulation has developed into the 8625 in which improved uniformity of picture response is achieved by applying a separate potential only to the field mesh of the tube (Fig. 1). The demands of the 4-tube color camera will undoubtedly produce future photoconductive layers with different spectral sensitivities until the industry settles down to an acceptable system of color pick-up. Figure 2 shows typical examples of currently available spectral sensitivities.

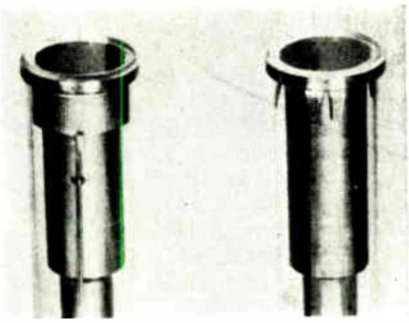

Figure 1

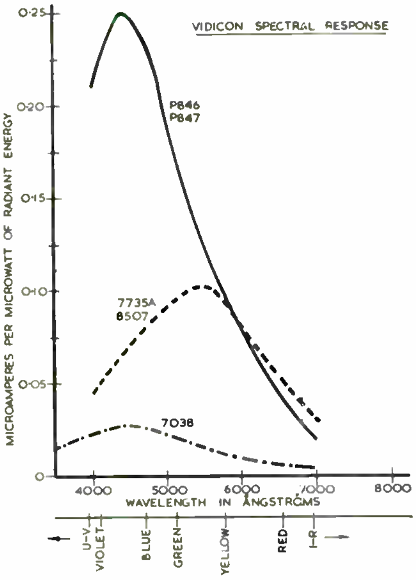

Fig. 2. Typical examples of spectral sensitivities available with present-day vidicons.

Image Orthicon

With the image orthicon the picture is different — it can be said that the image orthicon still has the edge on the vidicon! Edge enhancement of picture detail at the image-orthicon target, due to the unavoidable redistributed electrons, produces a sharpness which cannot be obtained in a vidicon. It is this edge effect which has received so much attention in the last decade[4] and which was one of the reasons for the emergence and success of the $4\frac{1}{2}$-in. image orthicon[5] since in 3-in. tubes it assumes undesirable magnitudes. It is well known that the $4\frac{1}{2}$-in. tube optimizes edge effect by combining a close spaced target with a field mesh and the tube has changed very little since its successful launching ten years ago. This indicates the efficiency of its basic design. However, changes have been made to the gun structure to prevent its limiting aperture appearing on picture. Also, new materials, such as magnesium oxide, are being used to coat the first dynode electrode to increase its gain factor. A decrease in its visibility on picture has also been achieved by reducing its grain structure.

Fig. 3. Picture of model taken with panchromatic celluloid film.

The 3-in. image orthicon is being made by at least a dozen manufacturers and it is therefore not surprising that it has appeared in a number of variants. The most important are the introduction of the higher sensitivity tri-alkali photocathode and nonstick targets such as magnesia and elcon. The new photocathode, developed by Sommer,[6] can have sensitivities up to about 300 μA/lm compared with a reasonable maximum of 100 μA/lm for the bismuth-silver-caesium-oxygen photocathode. The relative quantum efficiencies are about 20% and 7% respectively. While this higher sensitivity gives an apparent increase of more than one operational lens stop, it is regrettable that most of this lies in the red spectral region so that, with tungsten lighting, an unnatural tone rendition results. For example, Fig. 3 is a photograph of a model taken with panchromatic celluloid film. Figure 4 shows the same model holding a photographic color chart and taken with a television camera using an image orthicon with a BiAg

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Presented on April 1, 1965, at the Society's Technical Conference in Los Angeles by Walter E. Turk, English Electric Valve Co., Ltd., Chelmsford, Essex, England.
(This paper was first received on August 3, 1965, and in final form on February 28, 1966.)

Fig. 4. Picture of model taken with a television camera using an image orthicon with a BiAg photocathode.

Fig. 5. Picture of model taken with tri-alkali image orthicon used in the camera.

photocathode. Figure 5, is again the same object when a tri-alkali image orthicon is used in the camera. It can be seen that in the latter case, the lips have an unnatural appearance. The higher red sensitivity is also indicated on the color chart which has on its left side a series of colored chips, red at the top through yellow to blue at the bottom and on its right their monochrome equivalents when panchromatic film is used in a camera in daylight. Corrective optical filtering is of no avail since all the increase in sensitivity is lost by the natural absorbtion in the filter. One manufacturing problem with the potassium, sodium, caesium, antimony mixture which constitutes the tri-alkali photocathode is the inability of the normal soda glass target of the image orthicon to withstand exposure to the vapors of these materials at the high temperatures necessary for photocathode formation. The 7037 failed for this reason, some years ago.

If the spectral response curve of the tri-alkali photocathode is examined together with that of the above mentioned BiAg and the older SbCs, it is seen in Fig. 6 that, in the blue region, an output much higher than that of the best alternative can be obtained. In a color camera, therefore, an increase of at least one stop of operational sensitivity can be realized if such a photocathode is used for the tube in the blue channel. This increase has, in fact, been achieved and serious consideration is being given to such a possibility. It is also becoming customary to utilize the SbCs photocathode for the blue channel. The final choice — without taking into consideration the advent of the Plumbicon — will depend entirely on the desired blue passband of the optical-splitter system in the camera. If the preference is for the tri-alkali layer, then as mentioned earlier, normal soda glass cannot be used as a target material and a new material, such as the new nonstick glass recently announced by the English Electric Valve Co., must be incorporated.[7]

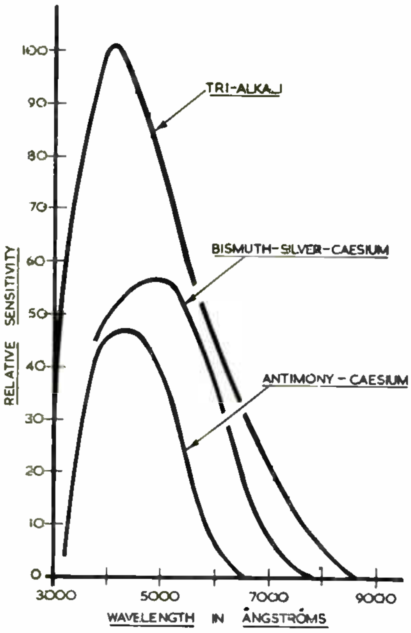

Fig. 6. Comparison of spectral response curves of the tri-alkali, Bi-Ag and Sb-Cs photocathodes.

At this point it is perhaps interesting to consider a few historical facts. Before the last war it was obvious that no form of the high-velocity-scanned iconoscope could survive as a television pick-up tube. Low velocity scan was considered essential as a first step towards better picture uniformity,[8] and then, as a second step, a double-sided storage mosaic was necessary. This mosaic would be charged from one side and discharged from the other. Its structure would allow infinite conductivity from back to front and infinite resistance across either surface. It was to be a lamina of stacked, or bundled, mutually insulated conductors. However, such an ideal target proved impossible to manufacture. Space does not permit a detailed account of experimental targets made variously from mesh based membranes, thin film oxides, etc. Eventually Rose and Iams of RCA[9] proposed an elegant solution to the problem — the use of a glass film of micro-thickness. That glass film had the disadvantage of deteriorating in performance with life. Although not perfect, it worked, was popular and was the basis for what has become the most widely used camera tube — the low-velocity-scanned 3-in. image orthicon. However, there was one obvious problem: the aging process of the target. This had to be eliminated. A suggested remedy introduced a few years ago was the thin film magnesium oxide target for the 3-in. image orthicon. A decided improvement in camera sensitivity also resulted. However, the target, due probably to its extreme thinness, was particularly susceptible to shock microphony and has seen only limited use in the entertainment field.

The new English Electric target, based on a titania glass, does not have the disadvantages associated with magnesium oxide. Its thickness is approximately one-half that of a "standard" target and conventional target spacings are possible.

Its invention may be considered to end the search for an ideal image-orthicon target started some thirty years ago.

Tests on this target, both in the field and in the laboratory have, so far, been very encouraging. Absolute statistics are difficult to obtain but many operators have reported lives up to 6000 hours compared with 1500 to 2000 hr obtained with conventional target tubes. This seems to be the general pattern – tube life is extended to up to three times that formerly experienced.

In addition to longer life, sensitivity

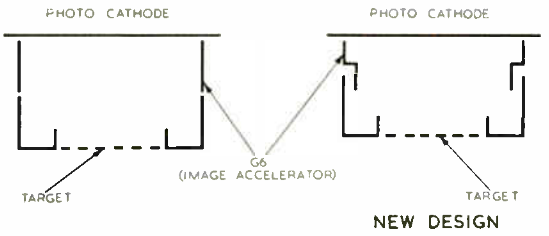

Fig. 7. Modification of shape of image-section electrodes.

Fig. 8. Image of candle with and without ghost image.

has proved to be more stable. Compared with the usual two stops formerly accepted, elcon target tubes show a fall less than half a stop after 500 hr of use.

A small proportion of these tubes has been reported to show a slight fall in resolution after some hundred hours of operation and research is currently being undertaken to investigate the claims. It is possible that the nonstick facility has led to slightly less care being exercised in operating the tube. On the subject of resolution it may be opportune to consider whether it will be necessary for future camera designs to have more reliable and accurate temperature control in order that tube developments in this and other areas may be fully exploited. Transistorization of cameras is of considerable interest in this respect.

Two other small changes have been made to the 3-in. image orthicon during the past few years. These are in the image section. The first arose from televised pictures of ice hockey which showed a second image of the puck. The unwanted one was an electronic ghost produced by photoelectrons being specularly reflected at the target and returning to it at a different point. The problem was solved by a modification to the shape of the image sections electrodes, Fig. 7 shows the change. The new design almost eliminates electronic ghosting by changing the electric field so that reflected photoelectrons return to the target at their point of reflection. Figure 8 shows the traditional candle with and without its ghost image. A second change was made in the field mesh tube to render the field mesh less visible — this was to place it between the decelerator and the target instead of using it as a termination to the beam focus electrode. The new design allows much better utilization of the decelerator and also makes the decelerating field in front of the target stronger or more uniform.

Plumbicon or Lead Oxide Vidicon

The Plumbicon has been discussed elsewhere[10] and has been used on an appraisal basis in many organizations over the past year and is being used very successfully in three tube color cameras and is also a strong contender for the luminance tube in a four tube camera.

The tube combines a sensitivity comparable with that of the 4½-in. image orthicon — adequate for the majority of purposes — with a small size which simplifies the design of the optical splitter system and enables overall a camera of reasonable size and weight to be produced. The three or four tube Plumbicon color camera is approximately the same size as a 4½-in. image orthicon monochrome camera.

The Plumbicon has no image section and the light transfer characteristic is quite constant from tube to tube. Both these features allow fairly easy line-up and tracking of the component tubes in color cameras. Geometrical matching errors are minimized to give more faithful color separation in the final kinescope picture.

The author has little personal experience of the practical performance of the Plumbicon but partly as a result of laboratory work and partly from general but limited experience in the field, several interesting facts are emerging. The tube is difficult to make and the time and temperature stability of the myriad of photodiodes which may be said to constitute the photoconductive layer has still to be learned from operating experience but results to date are by no means discouraging.

The transfer characteristic of the doped lead oxide photoconductor is substantially linear[2] and, while this is of mathematical convenience to the circuit engineers, it also presents some problems. Apart from the CPS Emitron or orthicon, camera tubes so far have had a self limiting type of transfer characteristic which meant that any highlight overload was conveniently suppressed within the tube leaving the head amplifier completely unaffected. This new material on the other hand, does not limit its output except by its beam current, and this has to be more than adequate for full white visibility to avoid certain other unpleasant features. Circuit engineers are having to evolve new techniques to control gamma, etc., under these conditions.

One other feature of the lead oxide tube which has come as a disappointment to some camera designers is the inability to use target voltage as a sensitivity control as is possible with conventional vidicons. Evidently, unless a certain minimum field is established across the *p-i-n* layer one cannot realize the full performance characteristics. Of course it could be argued that it is advantageous not to have to control target volts.

There has been much criticism of the spectral sensitivity of the lead oxide photo-surface, mainly of its low output at the red end of the spectrum as indicated in Fig. 9. This is an aesthetic problem. In a color camera any deficiency can usually be remedied by increasing the gain of the red channel; an easy solution in a studio using tungsten light provided that the rendition of deep reds is not too important. For outdoor daylight remotes the problem may be a little more difficult to overcome. The low red response is of greater importance in monochrome work. It is suggested that only in operations where very strict control over face tones is required and darker lips are considered objectionable, i.e. the locations where the 7735A type vidicon is not used because it is too red sensitive, will the lead oxide type of tube not be accepted. On the other hand there are many broadcasters who are not so worried about this detail and who will welcome the obvious advantages of a simple

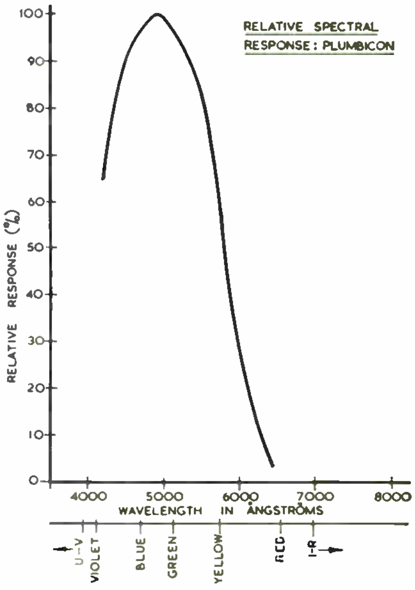

Fig. 9. Relative spectral response curve of the Plumbicon.

small size camera. There are certain additional difficulties in producing red-sensitive Plumbicons[11] but it is unlikely that the nonarrival of such tubes will prevent the fairly large scale adoption of this new tube with its promises of extreme economy and stability of operation.

Other pick-up tubes incorporating *p-i-n* type layers have been demonstrated (RCA Selenicon) and it is clear that the achievement of the extremely delicate balance between the several constituent materials of these complicated films is, and will probably remain, a severe manufacturing problem.

To conclude this paper it is perhaps appropriate to mention a tube which combines the design features of both the image orthicon and the vidicon, namely the S.E.C. Vidicon.[12] This tube has an image-orthicon type of construction where the target is a material in which conductivity is induced by secondary electron emission, and the signal, unlike that of the image orthicon, is taken from the conducting membrane attached to the support of the special target. Instead of signal multiplication in a separate multiplier system, this is accomplished within the target itself where gains of about 200 times are claimed. One may expect that the noise, halo effect, and poor resolution of the image orthicon together with the lag, lack of sensitivity, and poor resolution of the vidicon will be eliminated in this new tube but one has yet to see whether operational samples live up to these claims.

The trend of future design is difficult to forecast. One tube, the image isocon,[13] has been described many times and has many attractive features which may justify a re-examination of its present disadvantages.

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The Plumbicon: A Camera Tube With a Photoconductive Lead Oxide Layer

By E. F. DE HAAN
and A. G. VAN DOORN

The photosensitive layer of the Plumbicon is an evaporated microcrystalline layer of lead monoxide. The most significant advantages of the Plumbicon are the low dark current, the high speed of response, which is independent of light intensity, and the high sensitivity. In the Plumbicon, every picture gives a signal that is dependent solely on the light-intensity projected on that particular picture element within the proper time-limits and is unaffected by disturbing effects known from other pickup tubes. This new tube is expected to prove especially suitable for color television.

THE PLUMBICON* is a small, lightweight television camera tube which utilizes the photoconductive properties of lead-monoxide (PbO) (Figs. 1, 2) instead of Sb_2S_3 or Se as is normal for camera tubes of the vidicon type. The photoconductive layer is applied to a transparent and conductive SnO_2-layer which is deposited on the tube face and is used as a signal electrode. The photoconductor is an evaporated microcrystalline layer of the red, tetragonal modification of PbO, which has a bandgap of 2.0 ev. The thickness of this layer is 10 to 20 microns, and the crystallites are needles with dimensions of about 0.1 to 1.0 micron.

Externally a Plumbicon tube is 20 cm long (8 in.) and 3 cm ($1\frac{1}{4}$ in.) in diameter. The useful sensitive area is 2 cm (0.8 in.) in diameter. From these figures it can be concluded that neither the thickness of the layer nor the dimensions of the crystallites limit the resolution of this camera tube, since the distance between two adjacent television lines is about 20 microns.

The principles of operation of this pickup tube are as follows: Each picture element represents a capacitor, one plate of which is at the positive potential of the signal electrode and the other floating, that discharges as a result of leakage through the layer. The amount of charge which leaks through the layer depends on the illumination; hence there appears on the gun side of the entire layer surface a positive potential pattern composed of the various element potentials, corresponding to the pattern of light whose image is formed on the layer. When this positive potential pattern is scanned by the electron beam, electrons are deposited from the beam on the layer until the surface potential is reduced to that of the cathode of the electron gun. These charging currents of the capacities of individual picture elements constitute the video signal. Complete storage of the information present in the light beam will be achieved if the discharging time constant of the target capacity is greater than the frame period.

From this follows the requirement that the specific resistance of the photoconductor must be greater than 10^{10} ohm/cm. There are of course requirements for all the parameters of this type of camera tube which have necessarily to be fulfilled simultaneously in order to make it a useful pickup tube in practice. The most important parameters are:

(1) dark current or other spurious signals;

(2) resolution;

(3) sensitivity: (a) sensitivity to incandescent light determining to a large extent the signal-to-noise ratio; (b) spectral sensitivity;

(4) speed of response.

It will be obvious that the above parameters are determined to a large extent by the physical properties of the photoconductive layer. The photoconductor of a Plumbicon tube consists in principle of three layers. The layer in the middle is almost pure lead-oxide; in other words, it is an intrinsic semiconductor. In the layer on the gun side the lead-oxide is transformed by an appropriate doping process into a *p*-type semiconductor, and on the side of the signal electrode (SnO_2) into an *n*-type semiconductor. The doped areas are both thin in comparison with the total thickness of the lead-oxide layer.

This means that the photoconductive layer of a Plumbicon tube is, in principle, when the tube is in operation, a *p-i-n*-diode connected in the reverse direction (Fig. 3). The fact that the Plumbicon can satisfy the stringent demands of broadcast television is largely the result of this special *p-i-n*-diode structure of the photoconductive PbO layer.

As expected, the dark current of a Plumbicon has a diode characteristic (Fig. 4), which means that it becomes saturated as target potential increases. As a result of this very low dark current the absolute variation of the dark current will also be small, therefore the black level uniformity is extremely good. This becomes especially important when the Plumbicon tube is used in color-TV cameras.

An ideal pickup tube would be one in which every picture element gave a

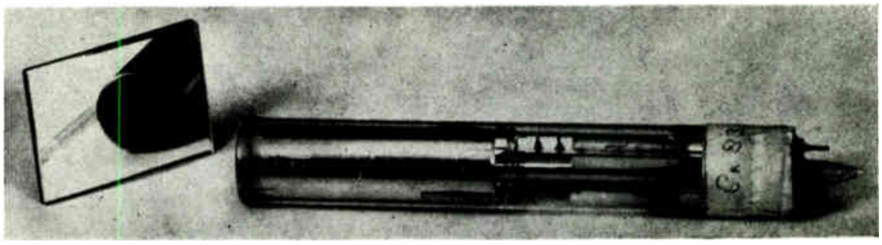

Fig. 1. The Plumbicon tube.

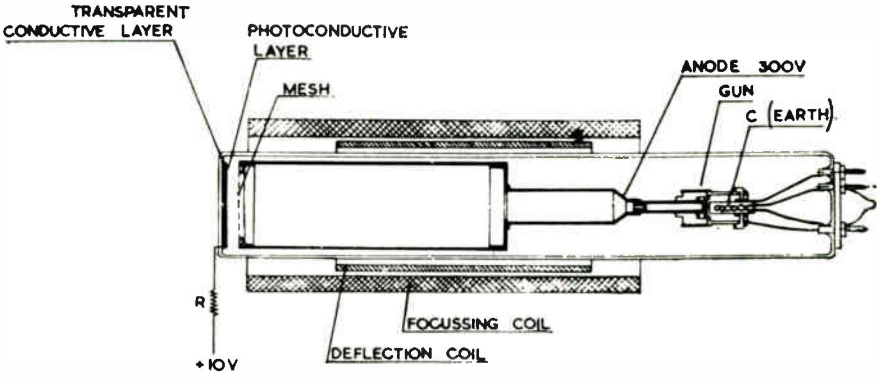

Fig. 2. Diagram of the Plumbicon.

Presented on April 13, 1964, at the Society's Conference at Los Angeles by E. F. de Haan (who read the paper) and A. G. Van Doorn, Philips Research Laboratories, N. V. Philips Gloeilampenfabrieken, Eindhoven, The Netherlands.
(This paper was received on March 6, 1964.)

* E. F. de Haan, A. v. d. Drift and P. P. M. Schampers, *Philips Technical Review, 25:* 1963/64, no. 6/7.

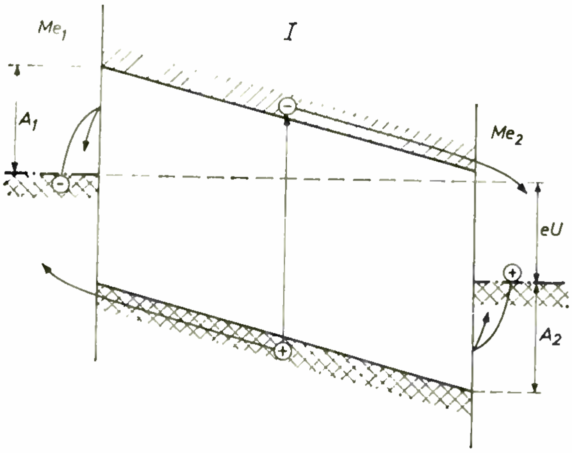

Fig. 3. The p-i-n diode structure of the Plumbicon tube.

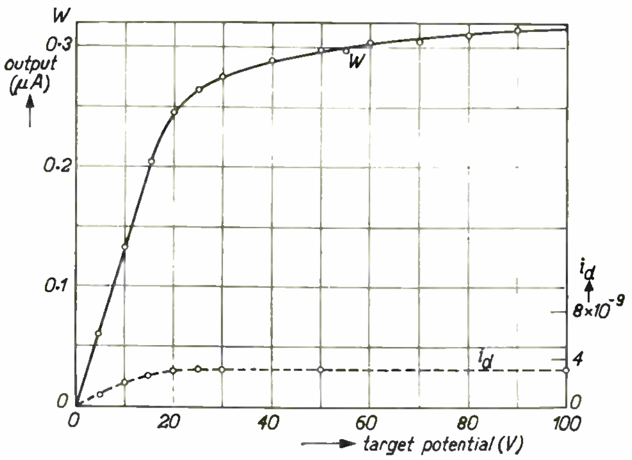

Fig. 4. Photocurrent of a Plumbicon versus target potential (ordinate on the left) exposed to incandescent light of 2870 K (W). Dark current versus target potential (ordinate on the right).

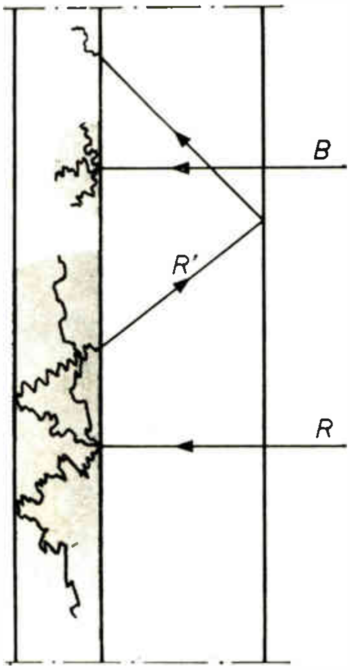

Fig. 5. Effect of light scattering in the photoconductor on resolution.

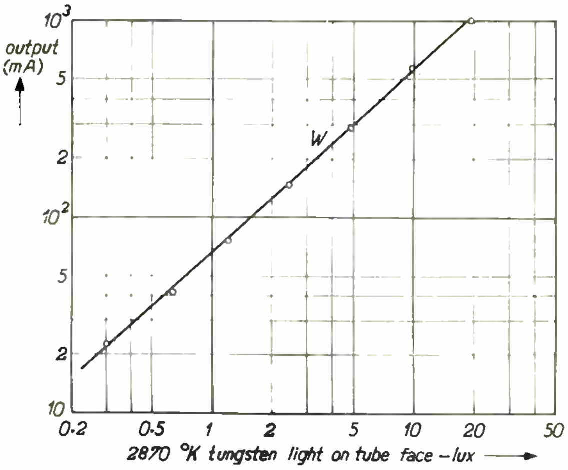

Fig. 6. Light transfer characteristic of an average Plumbicon tube.

signal which was solely dependent on the light intensity projected on that particular picture element in the proper time limits and which would be unaffected by disturbing effects such as dark current and persistence of the photoconductor (Sb_2S_3 vidicon), dark halo and shading-signals (image orthicon). In this respect a Plumbicon is superior to all pickup tubes now used in practice.

The sensitivity of a Plumbicon tube is due to the intrinsic part of the diode of the photoconductor which is situated between the *p*- and *n*-type region. In this intrinsic region the conductivity is low and the electrical field strength high, which means that all the liberated charge carriers in this area of the lead-oxide will contribute to the photocurrent if the target potential is high enough.

If a common *p-n* junction had been used the sensitivity would have been low because the effective intrinsic area would then have been very thin.

A high sensitivity can therefore be obtained by making the *i*-region as thick as possible. The optimal thickness is determined by the desired resolution, especially for red light (Fig. 5). The scattered light will cover an area with a radius comparable with the thickness of the layer.

It will be clear that, like the dark current, the photocurrent will show a diode characteristic and become saturated with increasing target potential (Fig. 4).

It can be understood that, if the tube is used at a target potential where the photocurrent saturates, beam landing errors will not introduce signal non-uniformities.

From the light transfer characteristic ($i = L^\gamma$) (Fig. 6), which is the photocurrent-output as a function of the incandescent light intensity on the faceplate in lux (10 lux ≈ 1 ft-c), it can be concluded that the gamma is constant and has a value between 0.8 and 1 up to a photocurrent of 1 μamp. For this reason it is possible to give in one figure the sensitivity of the tube in microamperes per lumen without specifying what light-intensity has been used. For the Plumbicon tube a sensitivity of 300 μamp/lm(2870 K) can easily be obtained. This means that even at light levels of 10 to 12 ft-c on the scene high-quality images can be obtained at a lens setting of *f*/2.8, which is comparable to image-orthicon cameras at *f*/5.6 for the same depth of focus. The constant gamma of the Plumbicon tube makes the tube especially suitable for color TV, because excellent color-rendition can be expected over a large range of varying lighting conditions.

The spectral response curve (Fig. 7) is to a large extent determined by the fact that the red modification of PbO (bandgap E = 2.0 ev) is used; this means that the edge wavelength of the red sensitivity is about 6400 A. The maximum sensitivity of a Plumbicon is at 5000 A. The fall-off in sensitivity in the region of shorter wavelength is due to the fact that the absorption of this type light takes place mostly in the thin *n*-type region which is an almost field-free area where the rate of recombination is accordingly high.

The resolution of a TV camera tube is usually defined by expressing the modulation depth at 5 mc/sec (in the European 625-line system corresponding to 400

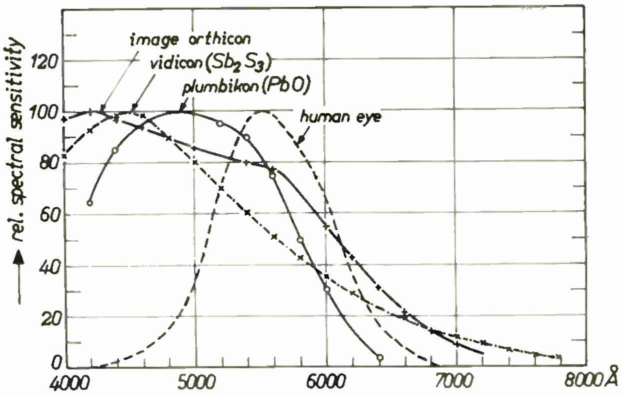

Fig. 7. An equal energy relative spectral response curve of an image orthicon, a Sb_2S_3 vidicon, a Plumbicon tube and the human eye.

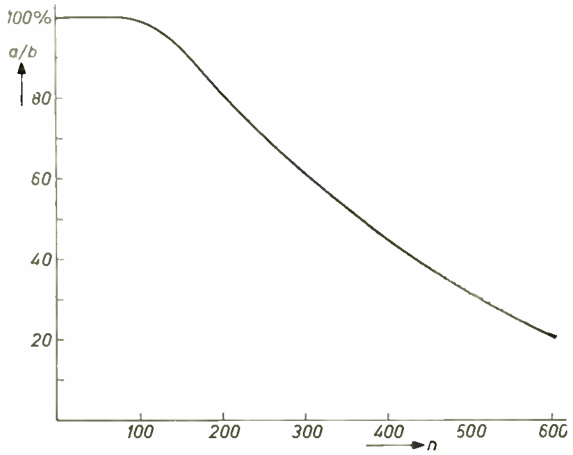

Fig. 8. Modulation depth from a square-wave test pattern as a function of the number of lines.

lines per picture height) as a percentage of the value at 0.5 mc/sec (Fig. 8). A modulation depth of 50% can be obtained with a Plumbicon. This is comparable with the resolution of a standard 3-in. image orthicon. This can only be obtained if the cathode region of the photoconductor, despite being strongly *p*-type, has a very low conductivity along the surface on the gun side.

In a Plumbicon tube the persistence of the photoconductor is hardly noticeable. This can be shown by the following experimental figures obtained at a target potential such that the photocurrent is saturated. If the light intensity changes from L_I to L_{II}, the photocurrent i will attain the value $i_{II} \pm 0.1$ $(i_I - i_{II})$ after 3 frames, and after 10 frames the value i_{II}, independent of light intensity. The absence of objectionable persistence is due, first, to the fact that the capacitance of the layer is chosen as low as possible to avoid a slow response due to the beam resistance, and second to the elimination of disturbing trap centers in the intrinsic region; with increasing target potential the persistence of the photoconductor decreases and at 50 v is fully acceptable.

The life of tubes of the Plumbicon type is quite satisfactory. Most characteristics have been found to remain unchanged after the tube has been operated for several thousand hours. It can be concluded that a Plumbicon has the advantage of simple construction and operation, with a high sensitivity and a low dark current together with freedom from objectionable persistence, thus ensuring an excellent final gradation of high-contrast pictures. These properties make this tube suitable for a large number of television applications. Especially for color TV cameras, the Plumbicon tube is almost the ideal pickup tube.

In fact, the reason why development of this tube was started, a few years ago, was the urgent demand for pickup tubes suitable for color television.

Several 3-Plumbicon color TV cameras have been built on a laboratory basis (Fig. 9). These Plumbicon cameras have the advantages of small size, easy operation, excellent stability, good color rendition and a high sensitivity.

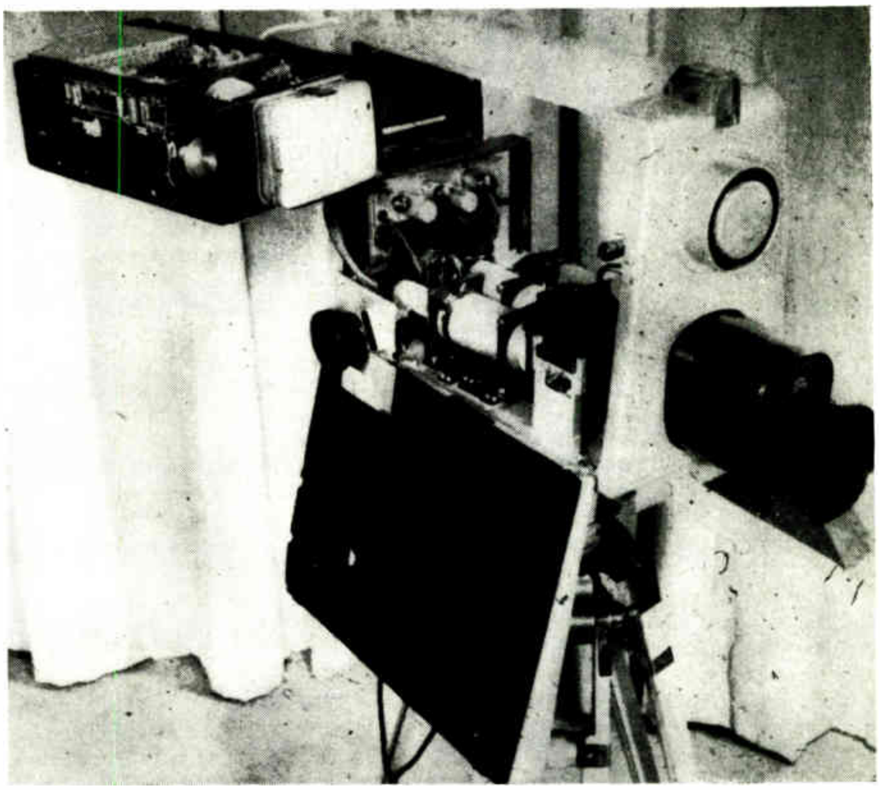

Fig. 9. Experimental 3-plumbicon color camera with zoom lens.

With a lighting level of 100–150 ft-c fully saturated color-pictures can be obtained at a lens setting of f/2.8. In that case, the signal-to-noise ratio in the Y-channel will be better than 40 db.

Discussion

Wayne T. Hogue (General Dynamics Corp.): Are these tubes on the market and how does the cost compare with others?

Dr. De Haan: The Plumbicon will be available at the end of this year. Coming from the Research Laboratories, I can only say that I think it will be cheaper than the image orthicon. The tubes are expected to be available from Amperex and the cameras also are expected to be supplied by North American Philips.

Mr. Hogue: Would there be any trouble from particles if the tube looked straight down?

Dr. De Haan: I would not advise doing it with any pickup tube. The difficulty of operating a camera tube like this is always that if there is, for example, some dust in the tube there is a possibility that this will result in a spot in your pictures. This holds for every camera tube, not only the Plumbicon.

Mr. Hogue: Some tubes have recently been made with a particle catcher.

Dr. De Haan: There is a particle catcher in the Plumbicon; but I would still emphasize that it is very dangerous to use a camera tube upside down.

Joseph Roizen (Ampex Corp.): What is the expected life of the Plumbicon?

Dr. De Haan: In the Research Laboratory we do not know exactly what the guarantee will be. It will be longer than any other pickup tube now in use. In our laboratory, we have had the tube running for several thousands of hours.

Mr. Roizen: There is apparently a very straight curve on the tube, which means the gamma is not too good for monochrome. Is this being changed for monochrome work?

Dr. De Haan: A gamma correction will be built into the camera. That has to be done with any tube in order to obtain pictures with a good gradation.

Hal Kuerschner (Academic Communications UCLA): Will the anode voltage on the Plumbicon be similar to that of the vidicon?

Dr. De Haan: Yes, you can choose the anode voltage: for example, 300 volts; if you want to increase the resolution a bit, you can increase it to 600 volts. It is the same type of tube as the vidicon as far as the handling of the tube is concerned.

John G. Downes (J. M. Schuller Import-Export): Could you tell us the limits of faceplate temperature for satisfactory operation?

Dr. De Haan: We have used the tube up to 70°C. I don't know exactly what the limitations are.

Optimum Color Analysis Characteristics and Matrices for Color Television Cameras With Three Receptors

By A. H. JONES

The color fidelity of a color television signal source may be substantially improved if a linear matrix is included in the signal chain. This improvement is greatest when the optical color analysis characteristics of the source are chosen together with the matrix coefficients. This paper describes computations made to determine the optimum matrix for use with a given set of color analysis characteristics. The method is then extended to enable the analysis characteristics and the matrix to be optimized together. The resulting characteristics are found to give an improvement not only in color fidelity but also in noise performance, when compared with the characteristic giving best color fidelity when a matrix is not permitted.

Introduction

For accurate reproduction of color within the gamut of the primaries of a system of additive synthesis, such as color television, the signals controlling the reproducing primaries must be derived using particular spectral sensitivities. The characteristics shown in Fig. 1, curves (a), for instance, define the analysis necessary for accurate color reproduction when the standard NTSC primaries are used.

These ideal characteristics are however very difficult to achieve in practice. If each of the subsidiary as well as the main lobes were to be accurately instrumented, a large number of receptors would be needed, each having an optical path whose spectral transmission characteristic is suitably adjusted. Both this requirement, and also the necessity for a relatively high sensitivity in the "red" and "green" color channels at the spectral region where the major lobes of the corresponding characteristics cross, would imply a very inefficient photoelectric conversion.

The fundamental method of signal generation employs three receptors only, one for each color channel. Such an arrangement involves errors of color reproduction because the system's analysis characteristics can have only positive lobes.

If the analysis characteristics are wholly positive, the resulting color errors can be reduced by making the curves somewhat narrower than the major positive lobes of the ideal curves, as for example, curves (b) of Fig. 1. Use of these narrower analysis curves results in a loss of sensitivity. Most manufacturers have therefore tended to use broader curves, such as curves (c) of Fig. 1. This effects a compromise between sensitivity and color fidelity. It has been calculated that the errors* resulting from analysis according to curves (c) may on average be expected to be about 30% greater than would have resulted from curve (b).

It has long been realized[1] that the analysis obtained using three receptors only could be improved if a linear matrix were included in the circuitry at some point at which the three color signals have magnitudes that are proportional to the incident light flux. Wintringham has pointed out that certain color mixture curves are wholly positive. One might therefore aim to instrument a set of response curves of this type and then operate upon the resulting signals by applying to them the linear matrix necessary to convert the positive-only color mixture curves to the ideal characteristics given in Fig. 1(a). Such color mixture curves, however, have even greater major lobe overlaps than do the NTSC curves. Therefore this approach would also lead to an inefficient photoelectric conversion.[2]

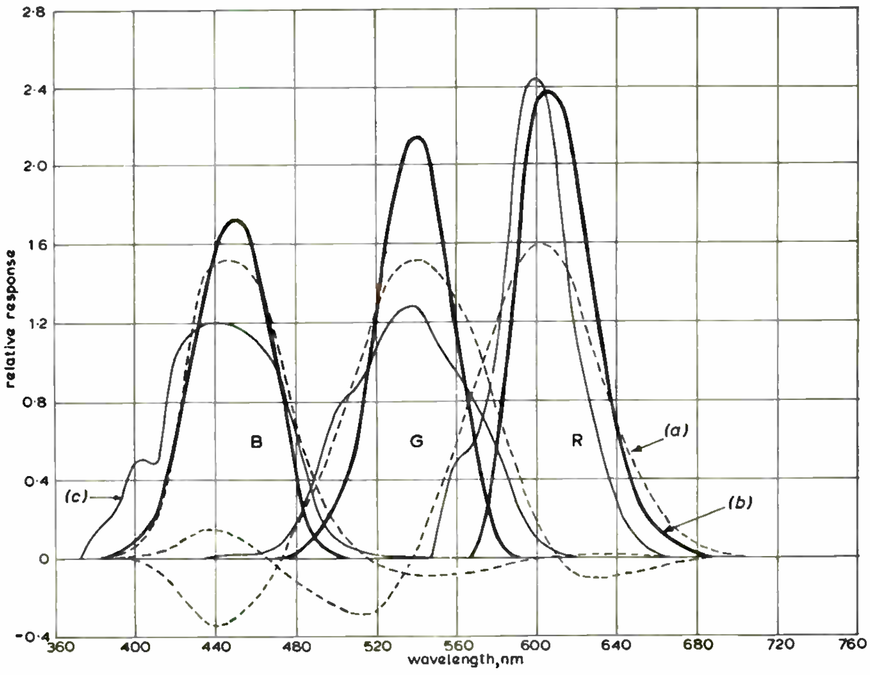

Fig. 1. Analysis characteristics considered; equi-energy, normalized to illuminant C: (a) ideal analysis for NTSC primaries; (b) optimum "positive only" analysis; (c) broader analysis curves typical of current practice.

If, however, some inaccuracy in the instrumentation of the ideal characteristics given in Fig. 1(a) may be tolerated, a somewhat simpler approach to matrix correction may be adopted. The ideal "green" analysis characteristic for example, has a negative lobe peaking at about the same wavelength (448 nm) as does the major positive lobe of the ideal "blue" characteristic. Thus a receptor designed to produce the major portion of the "blue" signal could be arranged to feed a small amount of negative signal into the "green" channel. This would be equivalent to introducing a negative lobe into the characteristic of the "green" channel. Similar considerations apply to the other subsidiary lobes shown in Fig. 1, curves (a). When a correction of this nature is made, however, there is a deterioration in signal-to-noise ratio (SNR). This is because the noise components of the two signals are uncorrelated. Their noise powers are added, while their signal amplitudes are subtracted. Hence this procedure can only be employed when the original signals have a more than adequate SNR.

Until the introduction of the Plumbicon, the principal tube used in studio color cameras had been the image orthicon. For a number of reasons, the usual practice was to operate such a camera so that the charge on the target for peak white was the same as the predetermined value for all three tubes. It follows that

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A contribution submitted on February 21, 1967, by A. H. Jones, The British Broadcasting Corp., Research Dept., Kingswood Warren, Tadworth, Surrey, England.

* A quantitive definition of the errors is given in the next section.

sensitivity and SNR are independent and cannot be exchanged. Since the SNR is in any case barely adequate for color, a further loss due to matrixing is unacceptable.

The Plumbicon tube, if provided with sufficient light, can give a SNR in excess of the minimum requirement. There is a useful range of light inputs in which SNR and sensitivity can be exchanged. It follows that the increase in noise caused by matrixing might be offset by avoiding the loss of light implicit in the use of the narrow analysis curves, shown in Fig. 1, curve (b). Moreover, the Plumbicon has a linear transfer characteristic so that the introduction of a matrix causes little difficulty. The matrix would, in fact, precede gamma correction. The introduction of this tube therefore points to a reexamination of the possiblity of matrixing.

This paper describes calculations made to determine the optimum linear matrix for use with a particular Plumbicon camera. It shows how the calculations were extended to optimize (within practical limits) the transmission characteristics of the optical system by which the three input signals to the matrix are derived. Primary analysis characteristics[†] and matrix values enabling a highly accurate reproduction of color are given.

Optimization of Matrix to Suit a Given Analysis

Method

The method used to determine the optimum linear matrix involved an optimization of the reproduction of a number of test colors. Three sets of test colors were used. It was hoped that each set would be a fair representation of the very large range of colors encountered in practice. The close agreement between the results obtained suggests that this was indeed so, considering that the sets were chosen in quite different ways.

The first set comprised the seven Courtauld fabric colors adopted by the European Broadcasting Union for use when comparing color television systems.[3] The second set comprised sixteen colors, the eight used in the BBC Color Test Light Box,[‡] and eight others of a hue similar to those in the Light Box but of about half the saturation. The third set comprised 27 entirely fictitious colors. Twenty of these were the colors produced by twenty different materials having approximately Gaussian-shaped spectral reflectance curves, each one superimposed upon a uniform reflectance of 9%. The other seven were the magentas produced by materials with trough-like spectral reflectance curves. The troughs were situated at seven different wavelength positions and had Gaussian-shaped sides with flat bottoms of 20-nm width.

Assuming the use of an illuminant C light source, the chromaticities and luminances relative to that of peak white of each of the test colors in a set were calculated, together with the unity-gamma signal voltages R, G and B necessary to reproduce them without error, using NTSC primaries. The signal voltages R_1, G_1 and B_1 resulting from the analysis corresponding to curves (c) of Fig. 1 were then calculated. The chromaticities and relative luminances of the uncorrected reproductions were derived. The mean error was obtained as:

$$n = [\bar{n}_c^2 + \bar{n}_L^2]^{\frac{1}{2}} \text{ jnd}[§]$$

where $\bar{n}_c$ is the mean chromaticity error and $\bar{n}_L$ is the mean luminance error. For each color:

$$n_c = [(u_0 - u_1)^2 + (v_0 - v_1)^2]^{\frac{1}{2}}/0.00384$$

(u_0, v_0) and (u_1, v_1) being the chromaticities of the original and reproduced colors expressed in terms of the 1960 CIE-UCS coordinates, and

$$n_L = |\log_e L_1 - \log_e L_0|/0.0198[\#]$$

L_0 and L_1 being the luminances of the original and reproduced colors relative to that of peak white.

The object of inserting the matrix was to reduce the mean error n as far as possible, that is, to convert R_1, G_1 and B_1 arising from the actual camera analysis into R, G and B, the signals required if the color in question were to be reproduced accurately.

The matrix coefficients were derived by means of a computer program that was divided into two parts. An approximate solution was first obtained by applying the method of least squares[4] to sets of equations linking R, G and B with R_1, G_1 and B_1. This was done partly to save time and partly to enable the accuracy of the result so obtained to be subsequently assessed.

The matrix required to transform R_1, G_1 and B_1 into the three new values that we would like to be equal to R, G and B may be expressed as follows:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & j \end{bmatrix} \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}_{\text{in}}$$

where a to j are constants.

In order not to alter the reproduction of white, a unity matrix was ensured by putting $a + b + c = d + e + f = g + h + j = 1$. Therefore:

$$R = aR_1 + bG_1 + (1 - a - b)B_1 \text{ etc.}$$

Upon substituting the calculated values of R, G, B, R_1, G_1 and B_1 into the above, three sets of N equations in two unknowns were obtained, N being the number of test colors used. Clearly if $N > 2$ the equations cannot in general all be satisfied simultaneously. Nevertheless, the method of least squares enables a "best fit" solution in one sense to be obtained.

The ultimate aim was not to minimize the errors existing between R_1, G_1 and B_1 and R, G, B but to minimize n. The values a, b, c, etc. thus derived were then used as starting values in a slightly modified form of the Elliott 803 Library Program for System Optimization.[¶] The computer was supplied with the sets of values, u_0, v_0, L_0, R_1, G_1 B_1 together with the approximate values of a, b, c, etc. and instructions for calculating the mean error n. The quantities a, b, c, etc. were then allowed to vary in a controlled manner, after exploratory variations of a, e and j in steps of 0.1% and of the others in steps of 0.25% until the minimum value of n was reached. This minimum value, together with the associated matrix coefficients and the chromaticities and luminances of the colors as reproduced using the matrix, was printed out.

The whole procedure was carried out three times, using the three sets of test colors defined above.

Results

It was found that a substantial improvement in the reproduction of all three sets of test colors could be obtained by the use of a matrix. Moreover the residual errors when the matrix was inserted were much less than would have resulted from an analysis using the optimum positive-only characteristics.

Very similar results were obtained from the three calculations. Those to be quoted relate to the second set of test colors.

The optimum linear matrix was as follows:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1.12 & -0.16 & 0.04 \\ -0.02 & 1.23 & -0.21 \\ -0.02 & -0.01 & 1.03 \end{bmatrix} \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}$$

The improvement achieved using this matrix is indicated by Table I which gives the values of n obtained. Also included for comparison is the value of n corresponding to an analysis using the optimum positive-only curves (Fig. 1, curves (b)).

[†] To prevent confusion, the expression "primary analysis characteristics" will be reserved for a description of the analysis made by the optical elements and receptors that generate the original color signals. The overall analysis obtained by the action of the matrix on these primary characteristics will be described in terms of "effective analysis characteristics."

[‡] A device for testing cameras and containing nine differently colored filters illuminated from the rear.

[§] Just noticeable differences. The expression used to calculate n gives only an approximate measure of the observed color difference, but the accuracy is regarded as sufficiently good to enable an optimum analysis to be determined.

[#] This is an expression of the Weber-Fechner Law, the Fechner fraction $\Delta L/L$ being assumed to be constant over the range of luminances considered, i.e. $L_1/L_0 = (1.02)^{n_L}$.

[¶] The method employed is a refined gradient technique similar to that described by J. R. Dickinson in *Transactions of the Engineering Institute of Canada*, 2: No. 4, Dec. 1958.

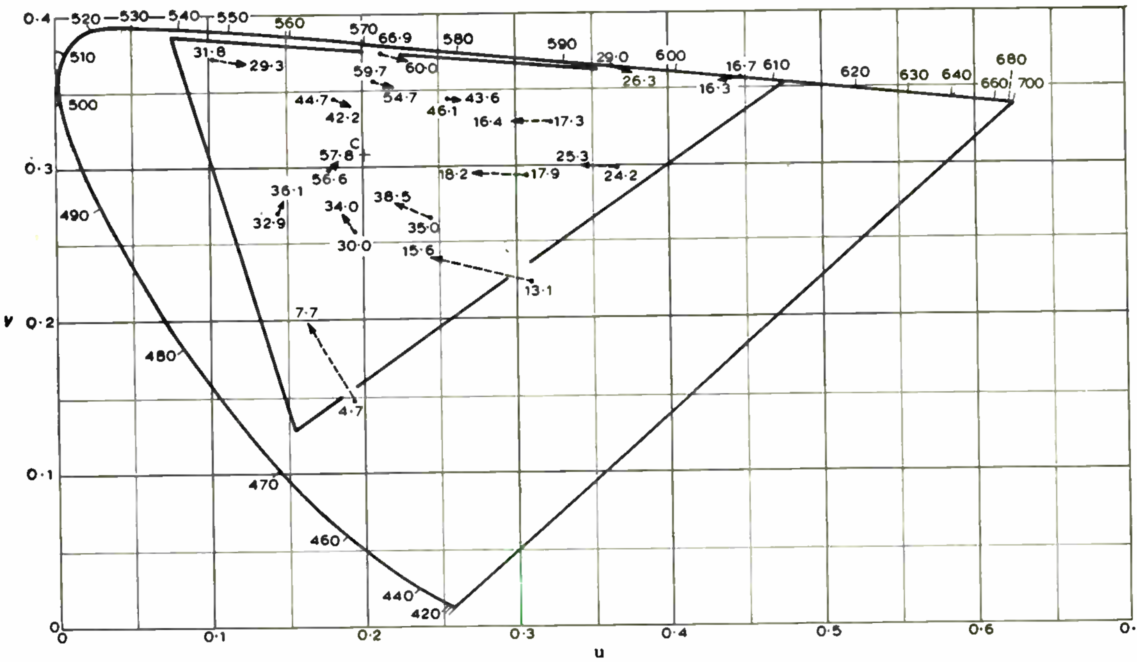

Fig. 2. Reproduction of second set of test colors using the given analysis characteristics [curve (c) of Fig. 1]; synthesis by NTSC primaries. Reproduced colors at arrow heads: figures are relative luminances expressed as percentages; error figure n = 7.88 jnd.

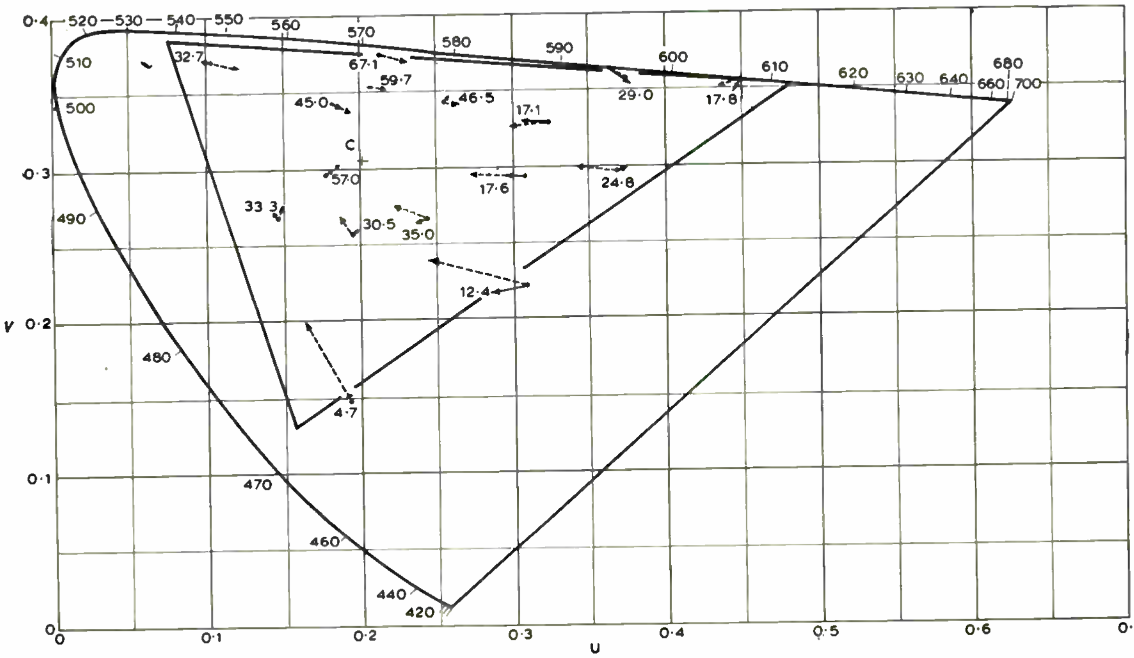

Fig. 3. Comparison of reproduction of second set of test colors using the given analysis characteristics [curve (c) of Fig. 1] and optimum linear matrix with that obtained without the matrix; synthesis by NTSC primaries. Reproduced colors at arrow heads: ——— reproduction using matrix; error figure n = 2.01 jnd; - - - - reproduction without matrix.

Figures 2 and 3 show on a chromaticity diagram the reproduction of the second set of colors obtained before and after the matrix is included.

The optimum matrix effectively modifies the analysis characteristics of the camera in the manner shown in Fig. 4. With the matrix connected, curves (b), the analysis approximates much more closely to the ideal, curves (c), and negative lobes are produced in the region of the larger negative lobes featured in the ideal analysis.

When NTSC phosphors are used, the luminance of the displayed color is given by:

$$Y = 0.299R + 0.587G + 0.114B$$

In the absence of a matrix, therefore, the relative contributions of equi-energy spectral components in the displayed luminance are given by:

$$Y(\lambda) = 0.299R(\lambda) + 0.587G(\lambda) + 0.114B(\lambda)$$

where $R(\lambda)$, $G(\lambda)$ and $B(\lambda)$ are the analysis characteristics of the camera.

The luminance characteristic of an uncorrected camera using the analysis curves (c) of Fig. 1 is plotted as curve (a) of Fig. 5. It should be compared with curve (c) which shows $\bar{y}(\lambda)$, the photopic response of the eye, this being the ideal luminance characteristic of a color reproducing system.

When the matrix is used, $Y(\lambda)$ becomes equal to:

$$0.321R(\lambda) + 0.673G(\lambda) + 0.006B(\lambda)$$

which is plotted as curve (b) of Fig. 5. It will be seen that the formerly excessive

Table I. Improvement Using Matrix.

Mode of analysis	Color error, *n, jnd*
Uncorrected analysis. . . .	7.88
Optimum positive-only analysis	6.35
Corrected analysis using optimized matrix	2.01

blue response has been reduced. The characteristic now approximates more closely to the ideal.

Optimization of Analysis and Matrix

Method

These calculations were similar to those described above, except that the number of unknown parameters was increased from six to fifteen so as to include a description of the optical transmission characteristics that determine the primary analysis of the system.

The specification of a proposed primary analysis characteristic could involve the use of many independent parameters. For instance, if it is to be expressed by a series of quantities representing its magnitudes at particular wavelengths, these quantities may in theory be chosen independently of one another. Moreover, the total number of possible values that could be ascribed to each one is inversely related to the accuracy with which the quantities need to be specified.

In practice, however, only certain analysis curve shapes can easily and efficiently be instrumented. This effectively limits the number of parameters necessary to define a possible curve. Four separate curve shapes were used to form the optical transmission characteristics investigated. The optimum solution, however, was shown to be relatively insensitive to the shape of curve used. Therefore only results relating to one curve, the best of the four, will be given. This curve shape is shown in Fig. 6. It is typical of what can be produced using available types of dichroic and shaping filters.

The curve shown in Fig. 6 was stretched or compressed in the wavelength direction and positioned against a wavelength scale in such a way as to build up independently the abutting "low-wavelength" and "high-wavelength" sides of each of the three peak-normalized optical transmission characteristics. Thus a total of six different scale factors, three positive and three negative, were applied to the one curve shape. The parameters used to control this process are defined in Fig. 7. They comprise the wavelengths λ_b, λ_g, λ_r, λ_{bg} and λ_{gr} at which the peaks and crossovers of the peak-normalized characteristic were to occur, the heights h_{bg} and h_{gr} of the crossovers, and the wavelengths λ_p and λ_q at which the low wavelength side of the "blue" curve and the high wavelength side of the "red" curve were to have 50% peak transmission. The choice of these particular nine parameters was made because previous calculations had indicated that they had a particularly sensitive influence on color fidelity.

Three separate sets of initial values were then proposed for the above parameters. It was felt that if the final values obtained by the optimization were independent of the initial values used, a genuine optimum reproduction of the test colors would have been reached. The initial values proposed were those best approximating to the ideal analysis (Fig. 1, curves (a)), to the optimum positive-only analysis (Fig. 1, curves (b)), and to the analysis (Fig. 1, curves (c)), for which a matrix had already been calculated. (The results were in fact found to depend to a small extent on the starting values used. Since *n* is a complicated function of fifteen parameters, the search

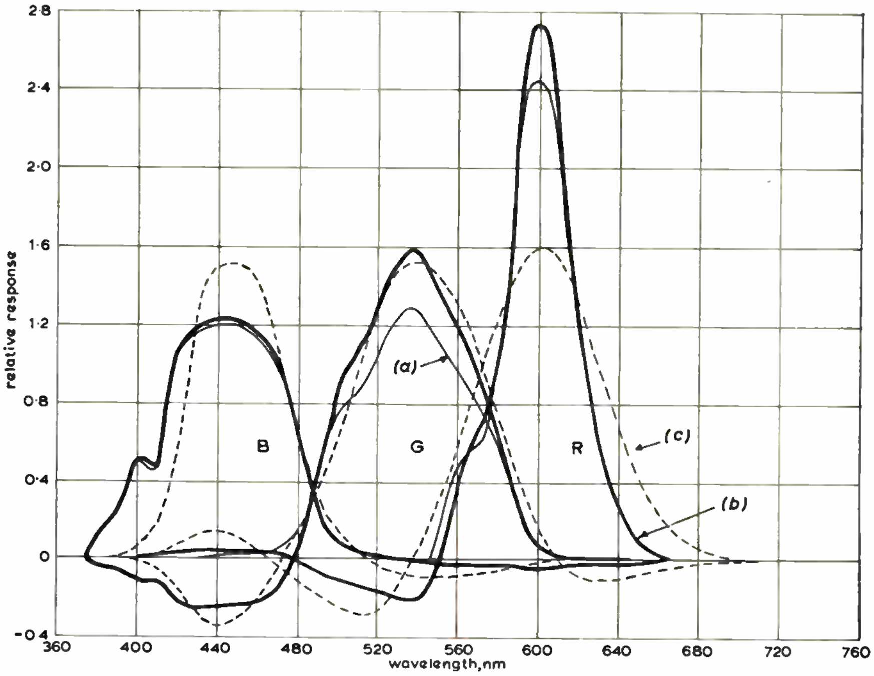

Fig. 4. Effect of optimum matrix on analysis of camera: (a) uncorrected camera analysis; (b) analysis with matrix inserted; (c) ideal analysis for NTSC primaries.

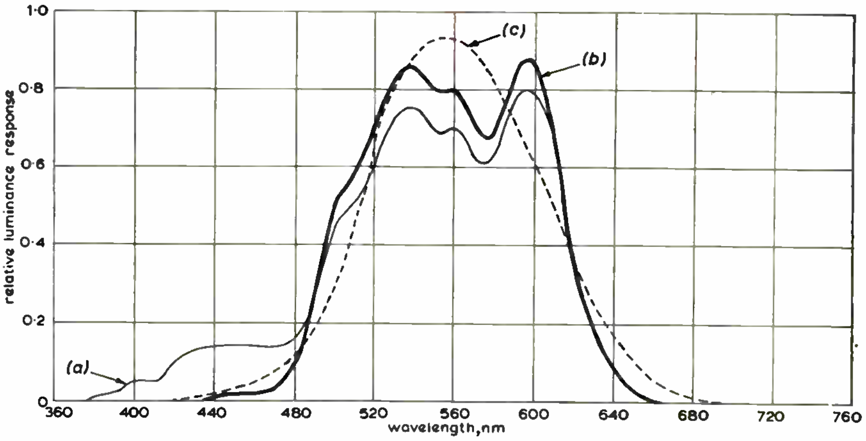

Fig. 5. Effect of optimum matrix on equivalent luminance characteristic of camera: (a) uncorrected characteristic; (b) characteristic modified by matrix; (c) photopic response.

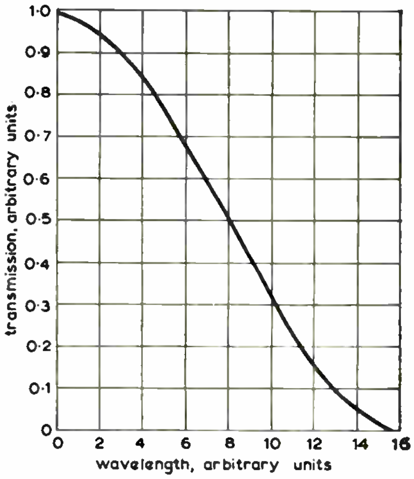

Fig. 6. Curve shape used to define transmission characteristics.

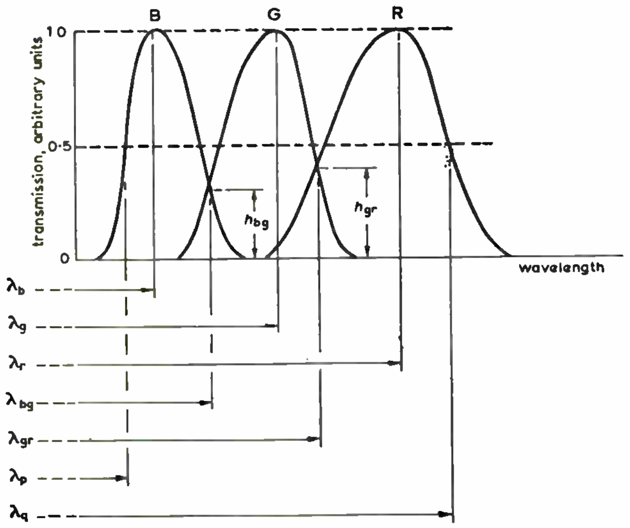

Fig. 7. Diagram indicating parameters used to define transmission characteristics.

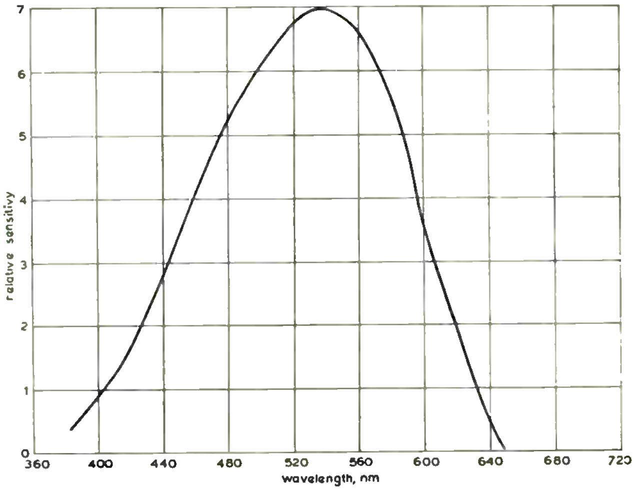

Fig. 8. Product of response characteristic of typical Plumbicon camera tube and spectral emission characteristic of 3000 K source.

for a minimum value of n amounts to an exploration to find the lowest point of a fifteen dimensional hypersurface. The results obtained suggest that this surface in fact has a cluster of local minima situated within the region immediately surrounding its lowest point, so that the minimum actually reached depends on the direction from which the region is approached, and hence on the starting point. However, the resulting differences in the final values of the parameters were well within instrumental tolerances, and were therefore negligible from a practical point of view.)

Having been formed up in the manner described above, the initial transmission characteristics were first multiplied by the spectral sensitivity of the camera tube and the spectral energy distribution of the illuminant. The resulting primary analysis characteristics were then normalized to ensure that equal output signals would result from exposure to a white in the scene. It was considered of interest to find the optimum effective analysis characteristics for two types of signal source. The first was supposed to incorporate an ideal camera tube whose response is constant throughout the visible spectrum. These results could also be used for a system in which the photoelectric devices had a nonuniform response that does not restrict the choice of low wavelength "blue" or high wavelength "red" characteristics. Thus the primary analysis characteristics themselves, as well as the transmission characteristics that helped to form them, were assumed to be subject to the curve shape shown in Fig. 6.

For this calculation it was assumed not only that the display device was adjusted in accordance with normal practice to give a white that matched illuminant C, but also that this illuminant was used in lighting the original scene.

The second calculation related to signal sources that employ Plumbicon camera tubes and are used with interior lighting.

A typical Plumbicon camera tube (Philips type 55875 B) has a spectral sensitivity which when multiplied by the spectral emission of a tungsten source operated at 3000 K produces the characteristic shown in Fig. 8. When a camera employing such tubes is used together with a 3000 K illuminant, its primary analysis is given by the product of the above characteristic and the spectral transmission characteristics of its optical system. Thus these conditions of operation were taken into account by replacing the illuminant C spectral energy characteristic that had been used to multiply the optical transmission characteristics by the characteristic shown in Fig. 8.

(Note that although a tungsten source at 3000 K was now supposed to illuminate the scene, the display was still assumed to be set up so that its white matched illuminant C. The system was therefore required to reproduce the original scene as it would have appeared if illuminated by illuminant C. This cannot, even in theory, be done with complete accuracy except with the aid of a color temperature raising filter. The unavoidable errors introduced, however, are generally quite small.)

An initial linear matrix to work with the initial primary analysis characteristics described above was calculated using the method of least squares.[4] The error figure n relating to reproduction of the test colors using the initial set of effective analysis characteristics thus defined was then determined. This error was then reduced as far as possible by means of the optimization program. In these calculations the values not only of quantities a, b, e, f, etc. but also of λ_b, λ_g, λ_{bg}, etc., 15 parameters in all, were allowed to vary. The test colors used were those that comprised sets 1 and 2 in the previous calculations.

In the choice of initial values, and in all but one of the optimizations, a further practical limitation was imposed. An ideal optical system having no loss of light at wavelengths corresponding to the peaks of the transmission characteristics can only comply with the principle of the conservation of energy if the sum of the three characteristics is never greater than the height (100%) of their peaks. In a practical system, however, the dichroic filters used have regions of unwanted reflection and transmission, while the shaping filters have regions of unwanted absorption. Consequently, the peaks of the transmission characteristics must always be less than 100%. Under certain circumstances, therefore, and in crossover regions, the sum of the three characteristics could exceed individual peaks. An excess of this nature would be indicative of an inefficient analysis, however, while any attempt to promote or increase it could be made only at a substantial cost in terms of sensitivity or noise performance. It was therefore considered that, subject to colorimetric requirements, a high optical efficiency would be ensured by preventing the crossover heights h_{bg} and h_{gr} from rising above 50% of the peak height to which the transmission characteristics were normalized.

An additional calculation made with the 50% limit removed indicated, however, that although it did operate as a restriction, its small adverse effect on color fidelity was outweighed by its benefit to noise performance.

Note that the calculations assumed that the display device would use NTSC primaries. When other primaries are envisaged, a close approximation to an optimum analysis may be obtained by using the recommended optical transmission characteristics and pre-multiplying the recommended linear matrices by the matrix necessary to convert signals suitable for NTSC primaries to signals suitable for the primaries to be used. If,

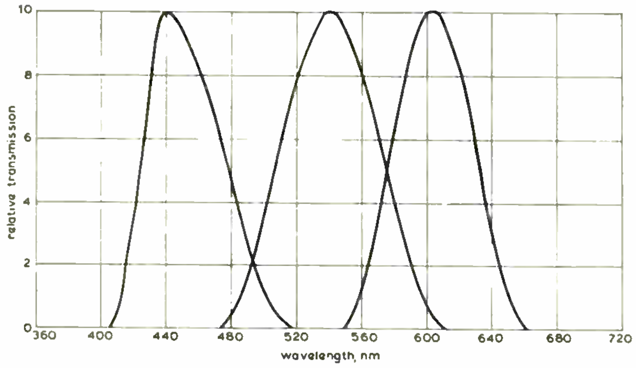

Fig. 9. Optimum transmission characteristics calculated assuming photoelectric devices having uniform spectral responses.

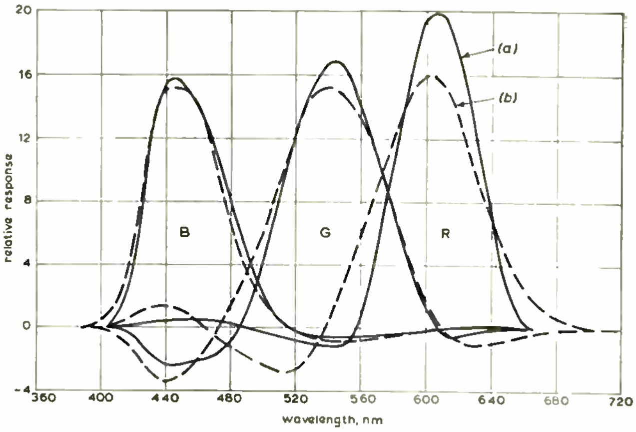

Fig. 10. Comparison of effective analysis characteristics obtained using primary characteristics shown in Fig. 9 together with the optimum matrix and ideal characteristics for NTSC primaries: (a) effective analysis; (b) ideal analysis; error figure n = 1.50 jnd.

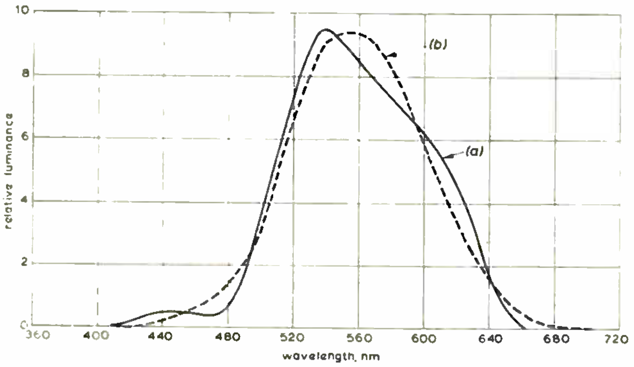

Fig. 11. Comparison of (a) equivalent luminance characteristic obtained using effective analysis characteristics shown in Fig. 10 with (b) ideal (photopic) curve.

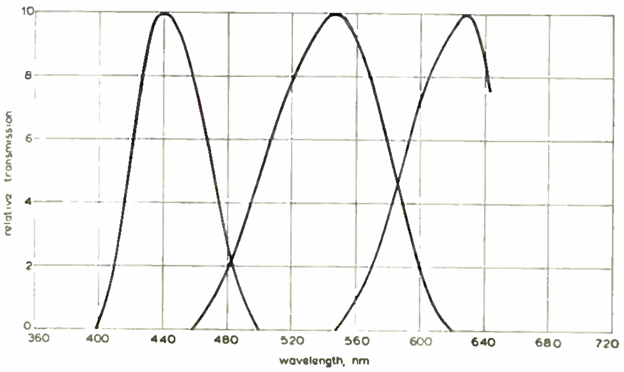

Fig. 12. Optimum transmission characteristics calculated using characteristic shown in Fig. 8.

for instance, sulfide phosphors are envisaged, the necessary conversion matrix is:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1.292 & -0.207 & -0.085 \\ -0.052 & 0.977 & 0.075 \\ -0.009 & -0.097 & 1.106 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{in}}$$

Results

Optimum Characteristics for Use Where the Spectral Response of the Camera Tube Does Not Limit the Analysis

The optimum transmission characteristics derived assuming these conditions are shown in Fig. 9. They are intended to be used in conjunction with the following linear matrix:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1.06 & -0.09 & 0.03 \\ -0.03 & 1.20 & -0.17 \\ -0.01 & -0.04 & 1.05 \end{bmatrix} \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}_{\text{in}}$$

This combination gave a minimum error figure n of 1.50 *jnd*. This error figure should be compared with the figure of 6.92 *jnd* that results from use of the optimum positive-only characteristics shown in Fig. 1 curves (b) with these test colors.

The resulting effective analysis characteristics are shown in Fig. 10, curves (a). It will be seen that a quite close approximation to the ideal curves (b) has been achieved. There is some discrepancy between the curves in the region of the negative lobe of the "red" characteristic, but this is to be expected since the primary analysis which, with the matrix is used to produced the negative "red" lobe, is also required in forming the major positive lobe of the "green" characteristic.

It is of some interest that the "red" analysis characteristic is not required to extend beyond about 660 nm, whereas the ideal "red" analysis extends to beyond 700 nm. A series of calculations was therefore made to ascertain the reason for this. The results of these calculations suggested two possible explanations.

The first was that the negative lobe in the optimum red characteristic could be produced only in the region of the main green lobe and was therefore at a higher wavelength than the ideal. The positive red lobe was therefore forced to commence at a higher wavelength than ideal. To compensate for this, the curve rose steeply to a high peak. This in turn could have necessitated a sacrifice of response in the deep red region.

The second explanation was that the CIE distribution functions $\bar{x}, \bar{y}$ and $\bar{z}$ have reached quite low levels by 660 nm. Moreover the spectral reflectance of most objects does not change appreciably within the range 660 to 700 nm. It therefore appears profitable to concentrate the red analysis around 600 nm (which is the position of the peak of $\bar{x}$) and to adjust the multiplying factor within the matrix to make some allowance for the deep red part of the spectrum that is not analyzed. The error introduced by this procedure would, in most cases, be extremely small; colors whose spectrum was zero magnitude until 660 nm would, of course, produce no response, but such colors are outside not only the color gamut but also the contrast range of present-day television displays.

Figure 11 shows (curve (a)) the equivalent luminance characteristic obtained using the proposed analysis; it should be compared with curve (b) which is the ideal or photopic curve.

Optimum Characteristics for Use in Cameras Fitted With Plumbicon Tubes and Used With Interior Lighting

The optimum transmission characteristics derived assuming these conditions are shown in Fig. 12. They are intended to be used in conjunction with the following linear matrix:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix}_{\text{out}} = \begin{bmatrix} 1.14 & -0.18 & 0.04 \\ -0.06 & 1.23 & -0.17 \\ -0.03 & 0.02 & 1.01 \end{bmatrix} \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}_{\text{in}}$$

This combination gave a minimum error figure n of 1.66 *jnd*. The resulting effective analysis characteristics are shown in Fig. 13, curves (a). These should be compared with the ideal characteristics reproduced as curves (b).

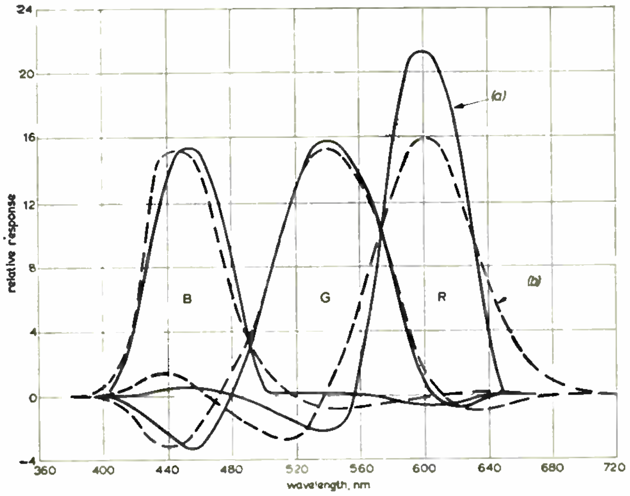

Fig. 13. Comparison of effective analysis characteristics obtained using characteristics shown in Figs. 8 and 12 together with the associated matrix, and ideal analysis characteristics for NTSC primaries: (a) effective analysis; (b) ideal analysis; error figure n = 1.66 jnd.

Comparison With Present-Day Camera

It is interesting to assess how the color accuracy achieved using the above analysis and matrix compares with that which can be attained if a matrix is incorporated in a present-day Plumbicon camera. The result quoted in the first part of this paper is not directly comparable with that given above, however, because it was obtained using different test colors and a different illumination. Using the same method, therefore, a matrix was optimized to suit a typical Plumbicon camera working in illuminant 3000 K and viewing test color sets 1 and 2. It was found that without the matrix the error figure *n* was 5.81 *jnd*, and that this figure was reduced to 2.07 *jnd* when the optimum matrix was inserted. The potency of the matrix is clearly demonstrated by this result. It is clear also that the primary analysis carried out by this particular camera is close to the optimum for use with a matrix. An inspection of the optical transmission characteristics confirmed this point.

Matrices have been optimized to suit a wide range of primary analyses. In each case a marked improvement in color rendering was produced. Therefore, if a matrix is used, the shape of the optical transmission characteristics becomes much less critical, and differences in the color rendering of cameras having differing transmission characteristics may be substantially reduced. It is therefore proposed that after an attempt has been made to instrument the above optimum characteristics a matrix be computed to work with the characteristics actually achieved.

Noise Performance Attainable Using Recommended Analyses

It is of interest to determine what change in SNR would be incurred by using the recommended transmission characteristics with their matrices instead of the optimum positive-only analysis shown in Fig. 1, curves (b), or instead of the typical camera analysis just considered.

In practice, the change in SNR depends not only on the shapes of the analysis characteristics used but also on the optical efficiencies achieved and on any differences in the sensitivities or noise performance of the three receptors. The comparisons made here are therefore based on certain assumptions that may not apply in a given practical situation, nevertheless the results obtained are believed to give a reasonable indication of the changes to be expected.

The rms noise voltage present at the output of Plumbicon tube head amplifiers rises almost linearly with frequency. Moreover the coding system by which the color signal is transmitted to the viewer contains low-pass filters which limit the bandwidth of the chrominance components. Thus the noise visible to the viewer is almost entirely conveyed by the luminance component. In this discussion no account is taken of the results of the sharing of the luminance band by the modulated chrominance signal.

Calculation Relating to Characteristics Determined for Use With an "Ideal" Camera Tube

It is here assumed that the photoelectric devices have combined responses that are rectangular and equal for each color channel and independent of wavelength within the channel and that a given peak transmission is achieved in each of the optical paths irrespective of which characteristic is being implemented. It is further assumed that the three channels generate noise signals having magnitudes that are equal and independent of the light incident on the receptors.

When normalized with respect to illuminant C, the characteristics shown in Fig. 9 have peak heights of 1.87 units (red), 1.42 units (green) and 1.51 units (blue). If the same normalization procedure is applied to the optimum positive-only characteristics (Fig 1, curves (b)), the resulting peak heights are 2.40 units (red), 2.15 units (green) and 1.74 units (blue).

Therefore if equal peak optical efficiencies are maintained in each channel, the output signals R_1, G_1 and B_1 resulting from the analysis of a white in the scene according to the characteristics given in Fig. 9 are proportional respectively to:

$$\frac{1}{1.87}\text{ units, }\frac{1}{1.42}\text{ units, and }\frac{1}{1.51}\text{ units}$$

The channel gain controls are now used to make $R_1 = G_1 = B_1 = 1$ for white. Therefore the noise signals observed at the outputs of the gain controls are proportional to:

1.87 units, 1.42 units, and 1.51 units

Similarly if the optimum positive-only characteristics are used, noise signals proportional to:

2.40 units, 2.15 units, and 1.74 units.

respectively, are produced.

These figures indicate that prior to matrixing, the broader analysis characteristics shown in Fig. 9 give SNR improvements of 2.2 dB (red), 3.6 dB (green) and 1.2 dB (blue) as compared to the optimum positive-only analysis, assuming the above conditions. The matrix, however, reduces these advantages.

The "red" signal R obtained from the matrix is given by:

$$R = 1.06R_1 - 0.09G_1 + 0.03B_1$$

The noise signal present in the "red" channel at the output of the matrix is therefore proportional to:

$$[(1.06\cdot 1.87)^2 + (-0.09\cdot 1.42)^2 + (0.03\cdot 1.51)^2]^{\frac{1}{2}}$$

i.e. to 1.99 units.

Similarly the noise signals present in the "green" and "blue" channels at the output of the matrix are proportional to:

1.72 units and 1.59 units

respectively.

Therefore when the matrix is connected, the analysis shown in Fig. 10 gives SNR improvements of 1.7 dB (red), 2.0 dB (green) and 0.8 dB (blue) as compared with the optimum positive-only analysis (Fig. 1 (b)) assuming the above conditions.

These are the differences in SNR that would be measured in the three color channels at the inputs to the gamma correctors. If gamma correction were not necessary, the above figures would indicate also the improvements in luminance noise observed when saturated colors are displayed. In practice, however, the luminance noise at the output of a color

Table II. Summary of Results.

Analysis	Signal-to-noise ratio (*in dB*), relative R	G	B	White	Color error, *n, jnd*
"Ideal" camera tubes, original scene in illuminant C					
Optimum positive-only analysis . .	0	0	0	0	6.92
Optimum analysis incl. matrix . .	1.7	2.0	0.8	2.5	1.50
Plumbicon camera tubes original scene in illuminant 3000 K					
Optimum positive-only analysis . .	0	0	0	0	5.81
Typical camera with optimized matrix	1.8	1.4	2.3	2.0	2.07
Optimum analysis incl. matrix . .	1.0	1.7	0.8	2.6	1.66

camera in regions of saturated color is caused predominantly by noise originating in the channels carrying low-level picture signals because this noise is considerably amplified by the relatively little excited gamma correction circuits. The amount of noise actually observed depends on the characteristics of the circuits used. Calculations made assuming typical circuit parameters have indicated that a reduction in luminance noise of about 2 dB would be observed in high saturation regions if the recommended analysis characteristics were used in place of the optimum positive-only characteristics.

We now calculate the luminance noise associated with desaturated regions. Assuming that no matrix is present, the luminance of the output display is given by:

$$0.299R_1 + 0.587G_1 + 0.114B_1$$

Therefore if the optimum positive-only analysis is used the luminance noise present in a displayed white is proportional to:

$$[(0.299\cdot 2.40)^2 + (0.587\cdot 2.15)^2 + (0.114\cdot 1.74)^2]^{\frac{1}{2}}$$

i.e. to 1.47 units.

If the recommended analysis were used without the matrix, the luminance noise in a white would be proportional to:

$$[(0.299\cdot 1.87)^2 + (0.587\cdot 1.42)^2 + (0.114\cdot 1.51)^2]^{\frac{1}{2}}$$

i.e. to 1.02 units.

When the matrix is used, however, it modifies the proportions of R_1, G_1, and B_1 that make up the luminance of the displayed color. Thus the luminance becomes:

$$0.298R_1 + 0.673G_1 + 0.029B_1$$

Therefore if R_1, G_1 and B_1 are generated using the characteristics shown in Fig. 9, the luminance noise present in a displayed white is proportional to:

$$[(0.298\cdot 1.87)^2 + (0.673\cdot 1.42)^2 + (0.029\cdot 1.51)^2]^{\frac{1}{2}}$$

i.e. to 1.11 units.

Thus the matrix causes a loss of 0.7 dB in the SNR corresponding to white. This deterioration in SNR is small because the signals from which the luminance component is composed are accompanied by noise signals which, when a matrix is used, are no longer completely uncorrelated. For example, the noise present at the green signal output terminal of the matrix contains a component contributed by the blue camera channel. When the luminance component of the composite signal is subsequently composed, there is a partial cancellation of such antiphase noise components. If this cancellation had not occurred, the SNR for white would have deteriorated by 1.4 dB.

Comparing the above noise levels of 1.47 units and 1.11 units, we find then that the proposed analysis, including the matrix, gives an improvement of 2.5 dB in the SNR in desaturated areas as compared with the optimum positive-only analysis.

Calculation Relating to Characteristics Determined for Use With Plumbicon Tubes

This calculation was based on the previous one with the exception that the three receptors were now assumed to have spectral responses subject to the characteristic shown in Fig. 8. Having been normalized so as to have equal areas when multiplied by this characteristic, the recommended transmission characteristics shown in Fig. 12 have peaks of 6.78 units (red), 1.90 units (green), and 6.00 units (blue). The transmission characteristics, which when multiplied by the characteristic shown in Fig. 8 give the optimum positive-only analysis similarly normalized, where found to have peaks of 8.68 units (red), 3.14 units (green) and 6.66 units (blue). The optical transmission characteristic of the typical camera for which a matrix was optimized assuming the use of illuminant 3000 K had peaks of 6.70 units (red), 2.20 units (green) and 4.42 units (blue) when similarly normalized.

This data was used in a calculation similar to that just described. It was deduced that the characteristics shown in Fig. 12 together with the associated matrix would give SNR improvements as compared with the optimum positive-only characteristics (Fig. 2) of 1.0 dB (red channel), 1.7 dB (green channel), 0.8 dB (blue channel), and 2.6 dB (white). If the typical camera were used with its optimized matrix, the corresponding improvements would be 1.8 dB (red channel), 1.4 dB (green channel), 2.3 dB (blue channel) and 2.0 dB (white). The latter includes an impairment of 0.3 dB in the SNR associated with white due to the linear matrix.

The above results are summarized in Table II.

Conclusions

A substantial improvement in the color rendering obtained from a television camera employing three receptors may be gained by the inclusion of a linear matrix in the signal processing. Optimum optical transmission characteristics for use when a linear matrix is envisaged have been recommended. These characteristics are much broader than those giving best color fidelity when a matrix is not included. Their use, therefore, results in an improvement in noise performance also. Nevertheless, the addition of a linear matrix produces a marked improvement in the color fidelity of devices having wide range of primary analysis characteristics, and in so doing greatly reduces the differences in color rendering observed when switching from one such device to another.

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Analysis of Color Errors in Color Television Cameras

By I. C. ABRAHAMS

In the configuration of color television cameras, at least three systems have been used. The first, and most familiar, makes use of three tubes whose spectral response corresponds to the red, green and blue components, respectively, of the scene. A second type substitutes a tube having a spectral response proportional to the luminosity curve, $\bar{y}$, for the green tube. Still a third makes use of four tubes which correspond to the three primaries as well as the luminosity curve. Due to the gamma correction, the latter two systems theoretically result in chromaticity and luminance errors in the reproduced picture. An analysis is made of the nature of these errors. Calculation is also made of the chromaticity shading which results from shading of the output of one of the three (or four) tubes. Experimental results are also described.

Introduction

Most color television cameras have until now been designed using three camera tubes, having color filters in front of them corresponding to red, green, and blue, respectively. These have been fairly satisfactory; the necessity, however, of providing good registration produces an operational problem. In order to alleviate this problem, variations have been made in which one of the tubes has a spectral sensitivity proportional to the luminosity curve of the human eye. The output of this tube is then used to provide the luminance component of an NTSC-encoded signal. The result is a sharper picture, since the luminance component comes from only a single tube, instead of three registered tubes. Because of the inability of the eye to discern fine detail in chromaticity patterns, the registration tolerance of the tubes is increased.

There are, in turn, two approaches to the design of a color camera having a luminance tube. One is to substitute the luminance tube for the green tube; the other is to use four tubes, one of which is the luminance tube, and the other three of which pick up the red, green and blue components of the scene. Tests were made in which the sharpness of a picture from a luminance-tube system was compared with that of a picture from a red-green-blue system. The luminance-tube system proved to be clearly superior in this regard.

The choice between the two luminance-tube systems lies in their respective colorimetric performance. Two criteria of colorimetric performance exist. One is simply the accuracy of reproduction of chromaticities; the other is the relative sensitivity of the two to chromaticity shading, caused by amplitude shading in one or more of the tubes.

A colorimetric analysis was made for the two types of luminance-tube cameras. Using both of the above criteria, the four-tube camera was found to have superior performance over the three-tube camera. In addition, experimental tests were consistent with the conclusions of the analysis.

Colorimetry of a Television Camera

To a first approximation, a color television camera is a form of colorimeter; that is, its function is to produce three signals whose values represent, either directly or indirectly, the color coordinates of objects in its field of view.

However, certain additional characteristics immediately complicate the problem of colorimetric design. In the first place, the camera must measure the color, not merely of a single object, but, if necessary, of thousands of objects (i.e., picture elements) in a very rapid succession. This introduces problems of bandwidth, noise, shading, and registration. Moreover, the output signals are not merely connected to a meter, but must be transmitted, received, and displayed as an image in which the reproduced chromaticities should be the same as those in the original scene. This gives rise to problems involving the use of taking and reproducing primaries, as well as considerations of non-linearities or gamma. It is only the unwitting tolerance of the human eye and mind that permits a satisfactory solution to the problem of transmitting colored images! A corollary to this statement is that a knowledge of the nature and degree of this tolerance is helpful if not essential in the successful design of a color television system. Such was indeed the case when the NTSC system was specified.

If the camera is considered as a form of colorimeter, it is desirable that at least three camera tubes be used. The respective spectral responses should be adjusted by means of colored filters, so that each one is some linear combination of the CIE tristimulus response curves ($\bar{x}$, $\bar{y}$, and $\bar{z}$). In particular, if the chromaticity coordinates of the three reproducing colors are given, then the curves given by the following matrix should preferably be used:

$$\begin{bmatrix} S_R \\ S_G \\ S_B \end{bmatrix} = \begin{bmatrix} (y_G z_B - y_B z_G) & (x_B z_G - x_G z_B) & (x_G y_B - x_B y_G) \\ (y_B z_R - y_R z_B) & (x_R z_B - x_B z_R) & (x_B y_R - x_R y_B) \\ (y_R z_G - y_G z_R) & (x_G z_R - x_R z_G) & (x_R y_G - x_G y_R) \end{bmatrix} \begin{bmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{bmatrix} \qquad (1)$$

In this matrix, (x_R, y_S, z_R), (x_G, y_G, z_G), and (x_B, y_B, z_B) are the chromaticity coordinates of the three primaries (red, green, and blue, respectively), and S_R, S_G, and S_B are the spectral responses of the three color filters. For the FCC primaries, the coordinates are as follows:

	x	y	z
Red	0.67	0.33	0.00
Green	0.21	0.71	0.08
Blue	0.14	0.08	0.78
White	0.310	0.316	0.374

(Note that $x + y + z = 1$.)

While it is theoretically permissible to use spectral responses which are

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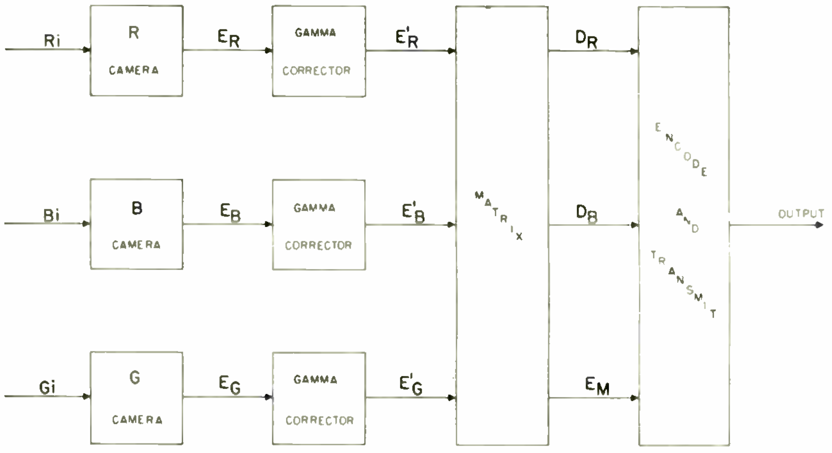

Fig. 1. RGB transmission system.

identically $\bar{x}$, $\bar{y}$, and $\bar{z}$, and then make the matrix transformation electrically, the signal-to-noise performance would suffer. This is because of the necessity of subtracting some of the signals since some of the coefficients in Eq. (1) will be negative. By the same token, the curves S_R, S_G, and S_B will have negative values for some portions of the spectrum. Thus, in choosing color filters, some compromise must be made; the filters can never be made theoretically correct. The chromaticity errors resulting from such a compromise have been analyzed and tabulated by Epstein.[1]

For a camera which is to be used only for televising transparent slides and films (a film chain), more freedom of choice of spectral response of the filters is possible. This is because the spectral distribution of the film dyes is known; and while these distributions will differ among the various color films, there is still far less variation in the spectral distribution for a given color than may be encountered in "live" material. This is to say that fewer (if any) metamers will be encountered with transparencies than with the original source of light. The colorimetric characteristics of such a film chain will then be mainly determined by the spectral response of the film emulsions. This is probably fortunate, since most color film manufacturers have given great attention to this problem, in order to obtain pictures which are pleasing to the viewer, an endeavor which transcends (but nevertheless includes) the principles of pure colorimetry.

The subsequent analysis in this paper assumes that the "red," "green" and "blue" signals from the camera are colorimetrically correct; that is, in a linear system in which each of the three signals controls a respective primary light, the color of the resulting light would be an accurate reproduction of the corresponding color in the scene. Thus, while the results of this analysis may not completely describe the colorimetric performance of the color TV camera, they will comment on possible errors due to the special configurations which are being used or proposed in the system design.

RGB Camera

As a start, it is instructive to analyze the case of a camera using three pickup tubes, corresponding to red, green and blue, respectively (*RGB* Camera). Figure 1 is a simplified block diagram of a transmission system which uses such a camera. The transmission of an NTSC signal is assumed, although the analysis could be adapted for other types of encoding. The gamma correction may be partially or even completely in the camera tubes themselves; for purposes of this analysis, it makes no difference.

Then,

$$E_R = k_1 R_i \qquad (2a)$$

$$E_G = k_1 G_i \qquad (2b)$$

$$E_B = k_1 B_i \qquad (2c)$$

where R_i, G_i and B_i are the input lights and k_1 is a constant. It should be noted that k_1 may be different for each of the three channels if the reference white of the transmitted signal is to differ from that of the original scene. For purposes of this analysis, however, a reference white corresponding to Illuminant C at both scene and receiver is assumed, so as not to obscure the figures to be derived concerning chromaticity errors.

The output of the matrix circuit will be assumed to be given by

$$D_R = E'_R - E'_Y \qquad (3a)$$

$$D_B = E'_B - E'_Y \qquad (3b)$$

where

$$E'_Y = 0.30\, E'_R + 0.59\, E'_G + 0.11\, E'_B \qquad (3c)$$

and

$$E_M = E'_Y \qquad (3d)$$

The primes indicate that gamma-corrected signals are being considered; that is, $E'_R \equiv E_R{}^{1/\gamma}$, $E'_G \equiv E_G{}^{1/\gamma}$ and $E'_B \equiv E_B{}^{1/\gamma}$. It should be noted also that expressing D_R and D_B as in Eqs. (3a) and (3b) instead of in terms of *I* and *Q*, causes no error or lack of generality in the analysis, since only large areas of color (lower frequencies of video) need be considered for the analyses given in this paper. The advantage of this approach is that it simplifies the algebra.

A block diagram of a standard receiver is shown in Fig. 2. The three signals, D_R, D_B and E_M are recovered by the decoder. The matrix must perform the following transformation:

$$E''_R = D_R + E_M \qquad (4a)$$

$$E''_G = E_M - 0.51\, D_R - 0.19\, D_B \qquad (4b)$$

$$E''_B = D_B + E_M \qquad (4c)$$

Whence, using Eqs. (2)

$$E''_R = E'_R \qquad (5a)$$

$$E''_G = E'_G \qquad (5b)$$

$$E''_B = E'_B \qquad (5c)$$

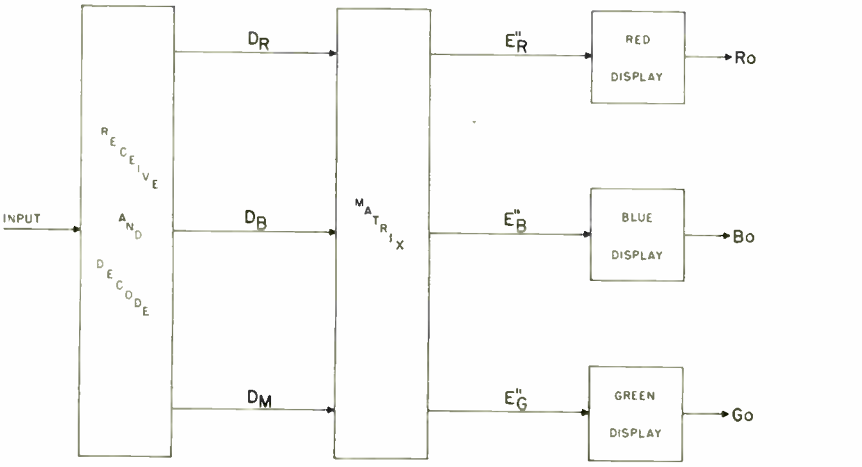

Fig. 2. Receiver for standard FCC signal.

Due to the power-law response of the color picture tube grids, the output lights are given by

$$R_o = k_2(E''_R)^p \qquad (6a)$$

$$G_o = k_2(E''_G)^p \qquad (6b)$$

$$B_o = k_2(E''_B)^p \qquad (6c)$$

Under the FCC standards, γ is chosen to be equal to p. Hence, it can easily be shown that

$$R_o = k\,R_i \qquad (7a)$$

$$G_o = k\,G_i \qquad (7b)$$

$$B_o = k\,B_i \qquad (7c)$$

where $k \equiv k_1{}^{\gamma}\,k_2$

Therefore, since the output lights are each proportional to the corresponding input light, there would be no color error in the system. Note that the term "color" refers to both luminance and chromaticity.

RBY Camera Errors

A similar analysis can be made for certain other proposed camera configurations. One system which has been proposed[2] is the "*RBY*" camera. In this arrangement, one of the three camera tubes has a filter which gives it a spectral response corresponding to the luminance of the scene, rather than the green component. (The filters of the red and blue tubes remain the same.) The purpose of this approach is to permit obtaining a luminance signal which comes from a single tube, rather than all three, and is therefore independent of registration. The result is a luminance signal having greater sharpness, for pictures reproduced either on a color receiver or a monochrome receiver, when using an NTSC or similar system. The luminosity curve is shown in Fig. 3. The filter used must be such as to give this spectral response to the luminance tube, when the spectral characteristics of the camera tube and the light source are taken into account. The green signal is then derived by subtracting the red and blue components from the luminance signal. A block diagram of this system is shown in Fig. 4. In this case, the three signals are given by

$$D_R = E'_R - E_Y{}^{1/\gamma} \qquad (8a)$$

$$D_B = E'_B - E_Y{}^{1/\gamma} \qquad (8b)$$

and $E_M = E_Y{}^{1/\gamma}$ (8c)

where $E_Y{}^{1/\gamma}$ is the gamma-corrected signal from the luminance tube.

Also, due to the luminance filter,

$$Y_i{}^{\cdot} = 0.30\,R_i + 0.59\,G_i + 0.11\,B_i \qquad (9)$$

and $E_Y = k_1\,Y_i$ (10)

The receiver, of course, must be assumed to be the same as before (Fig. 2), and hence, Eqs. (4) and (6) still hold.

Whence, it can be shown that

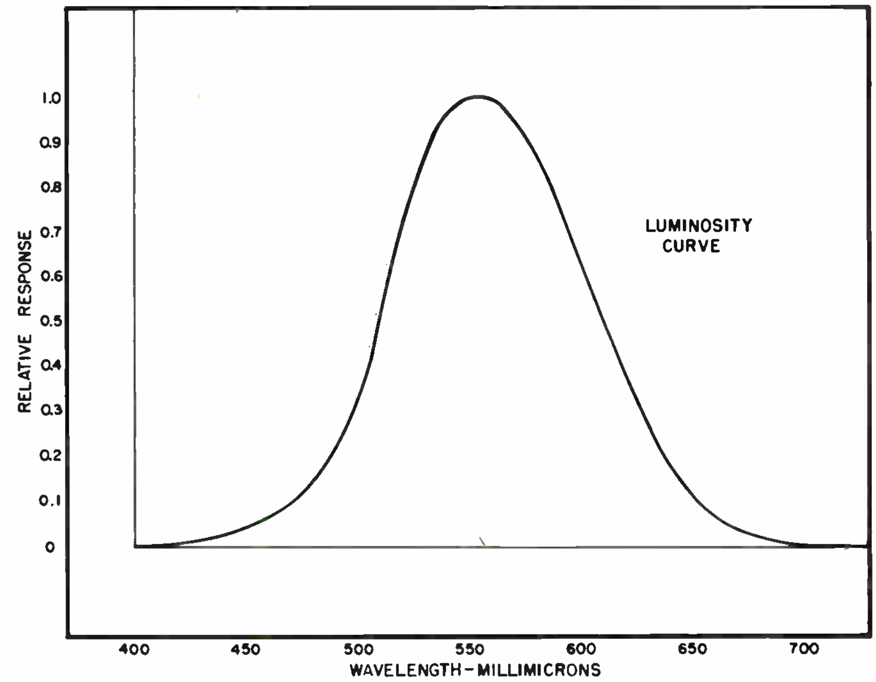

Figure 3

$$E''_R = E'_R \qquad (11a)$$

$$E''_B = E'_B \qquad (11b)$$

and $E''_G = 1.70\,E_Y{}^{1/\gamma} - 0.51\,E'_R - 0.19\,E'_B$ (11c)

Thus, the relation between input and output lights for each of the three primaries is

$$R_o = k\,R_i \qquad (12a)$$

$$B_o = k\,B_i \qquad (12b)$$

$$G_o = k\,[1.70\,(0.30\,R_i + 0.59\,G_i + 0.11\,B_i)^{1/\gamma} - 0.51\,R_i{}^{1/\gamma} - 0.19\,B_i{}^{1/\gamma}]^{\gamma} \qquad (12c)$$

As might be expected, for a linear system ($\gamma = 1$), there would be no color distortion, since each output primary light would be proportional to the corresponding input light. In practice, however, $\gamma = 2.2$, according to FCC standards. Hence errors will be present both in luminance and chromaticity.

In order to compute these errors, one starts with the desired CIE chromaticity coordinates (x_i, y_i) of the input light. An input luminance of Y_i is also assumed. Then, the values of R_i, G_i and B_i will be given by

$$\begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix} = Y_i \begin{bmatrix} 1.910 & -0.533 & -0.288 \\ -0.985 & 2.000 & -0.028 \\ 0.058 & -0.118 & 0.896 \end{bmatrix} \begin{bmatrix} \dfrac{x_i}{y_i} \\ 1 \\ \dfrac{1 - x_i - y_i}{y_i} \end{bmatrix} \qquad (13)$$

These values of R_i, G_i and B_i may then be inserted into Eqs. (12), giving the values of R_o, G_o and B_o. Also, Y_o may be computed from the equation

$$Y_o = 0.30\,R_o + 0.59\,G_o + 0.11\,B_o \qquad (14)$$

The resulting output chromaticity (x_o, y_o) can now be computed from

$$x_o = \frac{0.607\,R_o + 0.174\,G_o + 0.201\,B_o}{0.906\,R_o + 0.827\,G_o + 1.432\,B_o} \qquad (15a)$$

$$y_o = \frac{0.299\,R_o + 0.587\,G_o + 0.114\,B_o}{0.906\,R_o + 0.827\,G_o + 1.432\,B_o} \qquad (15b)$$

The Luminance Error Factor is the ratio of Y_o to the luminance of a distortionless system having the same luminance input, Y_i.

Hence

$$\text{L.E.F.} = \frac{0.30\,R_o + 0.59\,G_o + 0.11\,B_o}{k(0.30\,R_i + 0.59\,G_i + 0.11\,B_i)} \qquad (16)$$

The chromaticity errors are defined as

$$\Delta x \equiv x_o - x_i \qquad (17a)$$

$$\Delta y \equiv y_o - y_i \qquad (17b)$$

In order to give some assessment of the importance of the values of Δx and Δy, it is desirable to take into account the ability of the eye to detect small differences in chromaticity. Figure 5 gives a CIE chromaticity diagram, showing the perceptibility of chromaticity differences, as a function of chromaticity.[3] Each ellipse represents a shift of 100 times the minimum perceptible difference. The diagram shows that the detectable error depends on both the starting chromaticity and the direction (as well as magnitude) of the error. These data refer mainly to perceptible differences in two side-by-side colored areas. Nevertheless, the data serve as

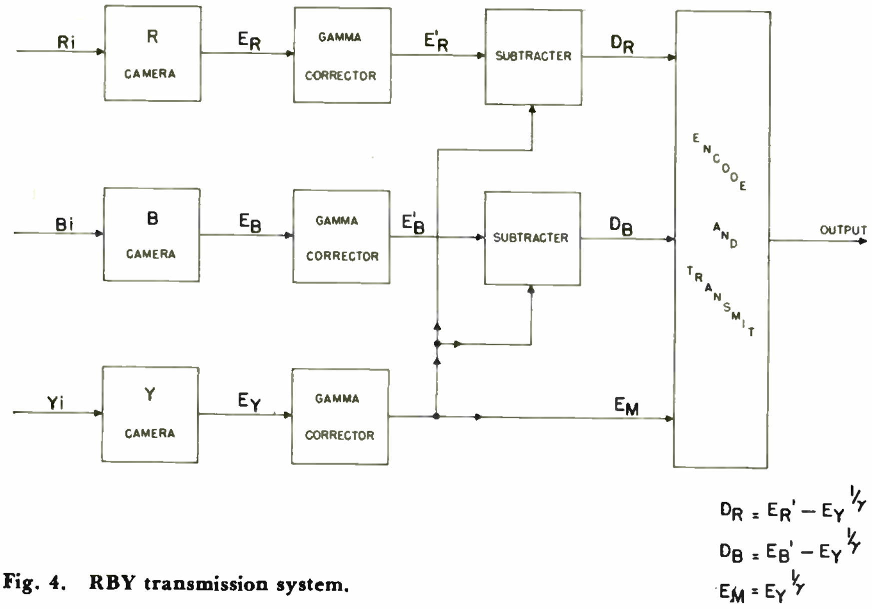

Fig. 4. RBY transmission system.

Table I. Errors in Chromaticity Points in RBY Camera.

Color	Δx	Δy	Δs	Luminance Error Factor
Red	−0.07	+0.03	49	1.37
Green	0	0	0	1.89
Blue	+0.01	+0.05	65.7	1.87
White	0	0	0	1.00
Skin	−0.001	+0.002	1.8	1.02

a useful guide for determining perceptibility of reproduction errors. A series of diagrams[4] has been provided by MacAdam, permitting determination of the equations of the ellipses representing the minimum perceptible color difference. This makes it possible to compute Δs, the number of units of minimum perceptible difference, when x, y, Δx, and Δy are specified.

Table I is a chart of the errors in some of the more important chromaticity points for the *RBY* camera. A value of Δs of 10 or 20 is probably permissible for color reproductions. The actual value depends on a number of psychological as well as psychophysical factors. Some idea of the permissible maximum in Δs can be obtained from Epstein's paper.[1] In calculating chromaticity errors in cameras due to omission of negative lobes in the color filters, a range is given in Δs of 4.1 to 18.2 for the red (depending on the spectrum of the original); 5.6 to 17.7 for the green; and 27.0 to 80.1 for the blue. This type of performance has been found to be quite satisfactory since all past and present designs perforce omit the negative lobes on the color filters. The *RBY* system, however, does exhibit rather large errors in the red, in the direction of orange, as shown in Table I. Similarly, blue is pulled in the cyan direction by a rather large amount.

The skin color has coordinates $x_t = 0.38$, $y_t = 0.33$, as given by MacAdam.[5]

YRGB Camera

In view of the rather large chromaticity errors in the *RBY* camera, another system has been suggested, and is now being used by the General Electric Company in a film chain. This is a four-tube system (*YRGB* camera) in which all three primaries, as well as luminance, are utilized.

A schematic diagram of the optical arrangement of this system is shown in Fig. 6. The color image from the projector is focused onto the relay lens, 2. (The image target is used only to facilitate focusing, and is not part of the normal operation.) The light is then split achromatically, in such a manner that part is transmitted in the direction of the luminance tube, and the remainder in the direction of the other three (chromaticity) tubes. An equal split has been used, although other choices of filters could require a different ratio. The trimming filter, 6, of the luminance camera is chosen to have the characteristics described above. The dichroic mirror, 4, reflects the blue component of the light in the direction of the blue camera and transmits the remainder (essentially yellow light). The dichroic mirror, 5, reflects the red component of this remainder to the red camera, and transmits the remainder (essentially green light) to the green tube. The respective trimming filters, 6, are chosen as described above.

A simplified block diagram of this system is shown in Fig. 7. In this case

$$D_R = E'_R - E'_Y \qquad (18a)$$

$$D_B = E'_B - E'_Y \qquad (18b)$$

and

$$E_M = E_Y{}^{1/\gamma} \qquad (18c)$$

Again, the receiver is the same as before, as shown in Fig. 2. Thus, by the same algebraic procedure as shown for

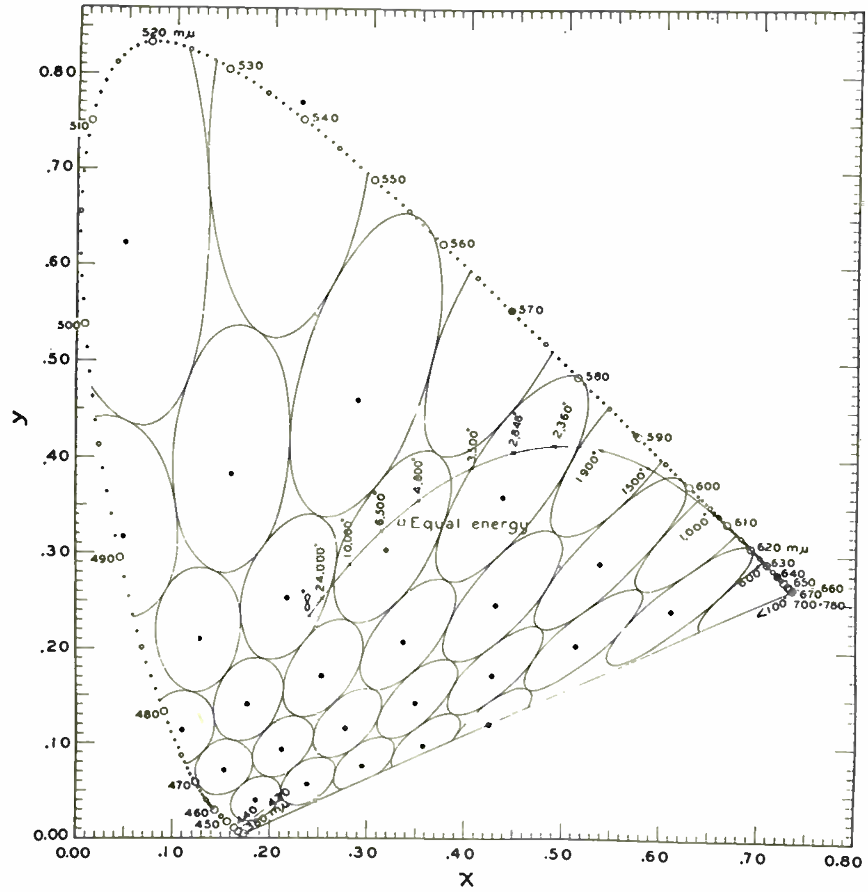

Fig. 5. Approximate perceptibility of differences on the (x,y)-chromaticity diagram.[3]

the *RBY* case, the input and output lights are related as follows:

$$R_o = k\,[0.70\,R_i{}^{1/\gamma} - 0.59\,G_i{}^{1/\gamma} - 0.11\,B_i{}^{1/\gamma} + (0.30\,R_i + 0.59\,G_i + 0.11\,B_i)^{1/\gamma}]^{\gamma} \qquad (19a)$$

$$G_o = k\,[-0.30\,R_i{}^{1/\gamma} + 0.41\,G_i{}^{1/\gamma} - 0.11\,B_i{}^{1/\gamma} + (0.30\,R_i + 0.59\,G_i + 0.11\,Bi)^{1/\gamma}]^{\gamma} \qquad (19b)$$

$$B_o = k\,[-0.30\,R_i{}^{1/\gamma} - 0.59\,G_i{}^{1/\gamma} + 0.89\,B_i{}^{1/\gamma} + (0.30\,R_i + 0.59\,G_i + 0.11\,B_i)^{1/\gamma}]^{\gamma} \qquad (19c)$$

Using the technique for calculating color errors which has been already described, Table II has been derived.

Table II.

Color	Δx	Δy	Δs	Luminance Error Factor
Red	−0.04	0.00	16.7	1.85
Green	+0.01	−0.02	3.6	1.50
Blue	+0.01	+0.01	21.6	2.06
White	0	0	0	1.00
Skin	−0.001	−0.002	0.9	1.02

The chromaticity errors shown for the primaries represent only a very slight shift in dominant wavelength; most of the shift (such as there is) is in the direction of white; this is much less objectionable than the shifts occurring in the *RBY* system. Also, the values of Δs are smaller, except for saturated green. For greens actually likely to be encountered, the chromaticity shift would be much smaller. It should also be emphasized that for only slightly desaturated chromaticities, the Luminance Error Factor falls to less than 1.5 for red and blue.

A method for reducing the chromaticity shift to zero has been suggested to the CCIR by the Japanese. This calls for multiplying the chrominance signal, D_R and D_B, by a factor, F, in which

$$F = \frac{E_M}{E_Y}$$

where E_M is the output of the fourth camera tube (which can have any spectral response, not merely luminance), and E_Y' is defined by Eq. (3c), in which E_R', E_G', and E_B' have been derived from the other three camera tubes. In this case, the Luminance Error Factor will be larger than that shown in Fig. 9, even though Δx and Δy are reduced to zero. It remains to be seen whether the technical difficulty of deriving a signal representing the ratio, F, is warranted by the possible improvement in performance.

Considerable experimental work has been done with the four-tube color camera. Results have shown that the color fidelity, using a large variety of slides, is equal to that of a three-tube camera. At the same time, the sharpness of the pictures, as viewed on both a color and a monochrome receiver, was noticeably improved.

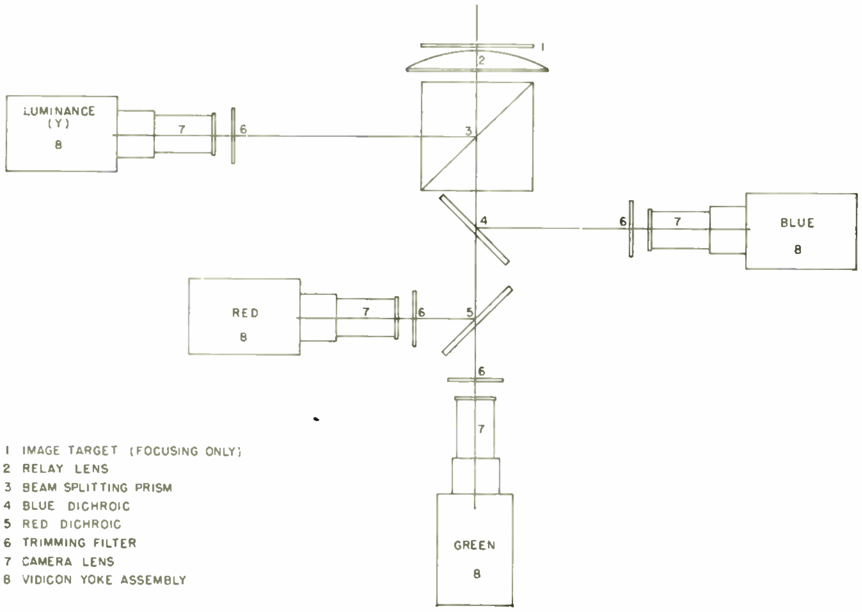

Fig. 6. Optical schematic of 4-vidicon color camera.

This is illustrated in Figs. 8 and 9. Figure 8 is a monochrome reproduction of a photograph of the picture on a color monitor, in which the green tube was deliberately mis-registered. An *RGB* system was used. When the system was switched over to use the luminance tube (in addition to the three color tubes), the picture in Fig. 9 resulted. (The green tube was still mis-registered.) Although some color fringing was still present, the picture was much sharper with the four-tube system.

The situation for the monochrome image is illustrated in Figs. 10 and 11. These were taken from a monochrome monitor, using conditions of extreme mis-register of all three color tubes. Figure 10 shows the picture from an *RGB* camera, and Fig. 11 that from a *YRGB* camera.

While the examples given are for cases of mis-register in order to show the relative performance of the two systems, the four-tube system has superior performance even when a "reasonable" or "normal" degree of registration is used. Such is the case in Figs. 12 and 13. A monochrome reproduction of a color monitor, fed by a three-tube system having good registration, is shown in Fig. 12. The same conditions, but using a four-tube system, are shown in Fig. 13. The increase in sharpness, especially at the edges, is definitely noticeable. The difference is much more striking when the screen is viewed directly, rather than in a photographic reproduction.

Effects of Shading and Unbalance

Another question which arises in connection with the colorimetry of cameras is the sensitivity to slight amounts of

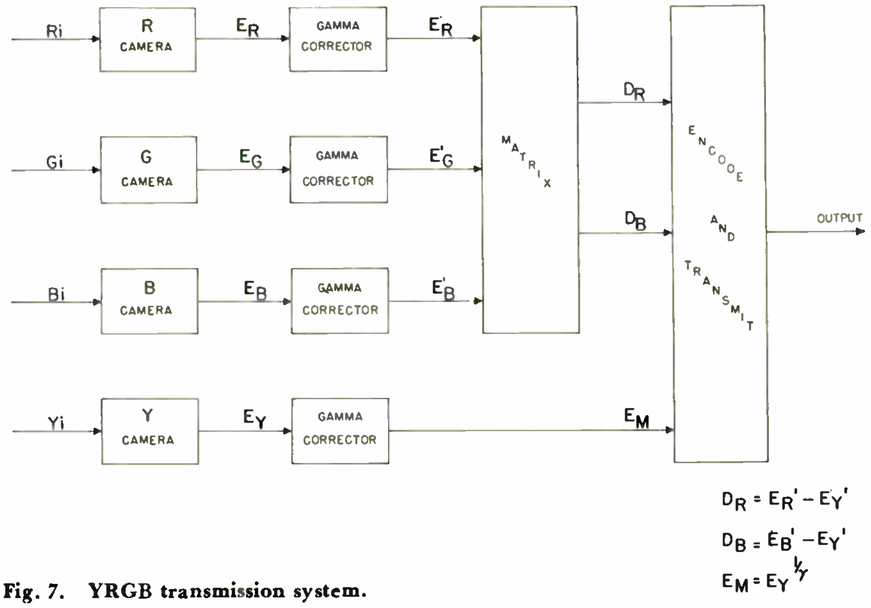

Fig. 7. YRGB transmission system.

Fig. 8. A picture taken from a color monitor using the RGB system with green tube of camera mis-registered.

Fig. 9. Same condition as in Fig. 8, using the YRGB system.

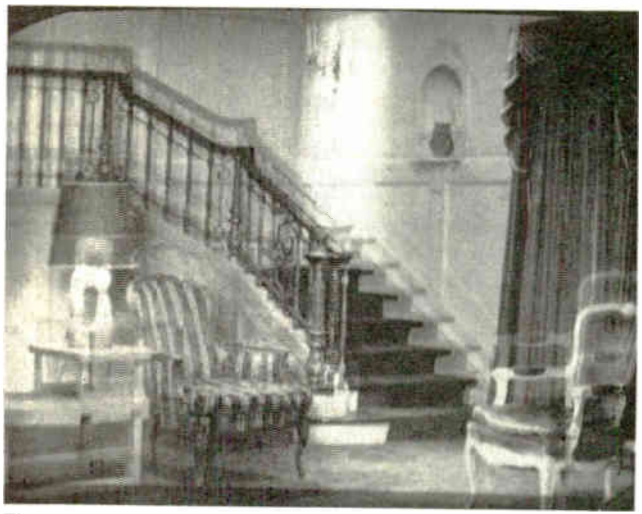

Fig. 10. A picture taken from a monochrome monitor using the RGB system with green tube of camera mis-registered.

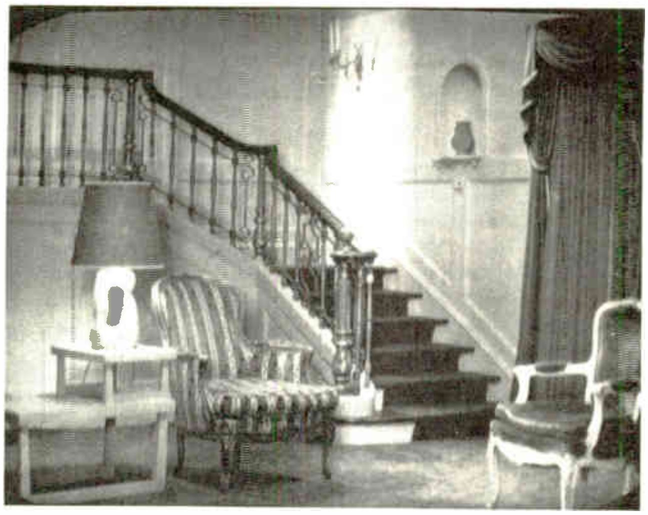

Fig. 11. Same condition as in Fig. 10, using the YRGB system.

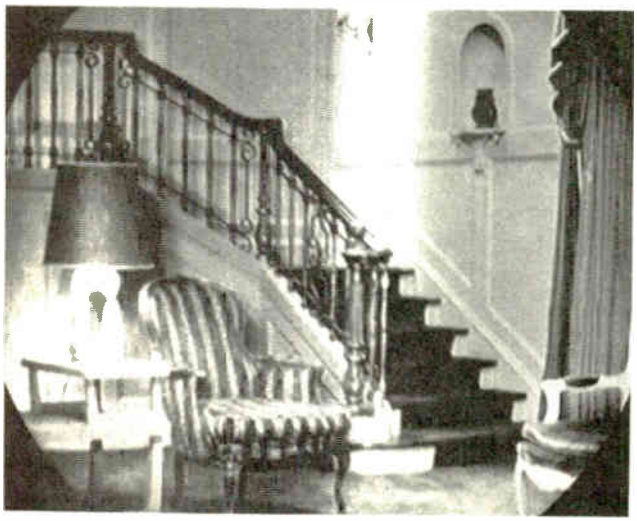

Fig. 12. A picture from a color monitor using the RGB system with normal registration of camera.

Fig. 13. Same condition as in Fig. 12, using the YRGB system.

Table III. Effect of Drift and/or Shading

For a 1% change in	*RGB* or *YRGB* Δx_0 (× 10⁴)	Δy_0 (× 10⁴)	Δs	*RBY* Δx_0 (× 10⁴)	Δy_0 (× 10⁴)	Δs
Red	10.3	0.4	1.08	11.6	− 4.9	1.40
Green	− 2.6	10.3	0.89	—	—	—
Blue	− 7.7	−10.7	0.58	− 7.2	−12.7	0.62
Y	0	0	0	− 4.4	17.5	2.20

unbalance and/or shading, in the region of white. Thus, for example, if there is a slight amount of shading in one or more of the camera tubes, there will be a shading of chromaticity in the reproduced picture, which is apt to be quite noticeable. It is useful to know the magnitude of this effect, especially to permit comparison of the several camera systems. For purposes of this paper, a linear system will be assumed. This will permit the desired comparison, while maintaining reasonable simplicity of the calculations.

It can be shown that, for chromaticities in the region of Illuminant "*C*," i.e., where E_R', E_G' and E_B' are about equal, and for a linear sytem,

$$\Delta x_o = 0.103 \frac{\Delta E_R}{E_R} - 0.026 \frac{\Delta E_G}{E_G} - 0.077 \frac{\Delta E_B}{E_B} \quad (20a)$$

$$\Delta y_o = 0.004 \frac{\Delta E_R}{E_R} + 0.103 \frac{\Delta E_G}{E_G} - 0.107 \frac{\Delta E_B}{E_B} \quad (20b)$$

where ΔE_R, ΔE_G, and ΔE_B are small changes in E_R, E_G, and E_B, respectively. Using Eqs. (20), it is possible to compute the change in chromaticity due to shading or unbalance in either the *RGB* or *YRGB* systems, *in the vicinity of white*. It should be noted that, for the four-tube camera, no chromaticity shading is caused by the luminance camera in this case.

For the *RBY* system, by invoking the equation for E_Y in terms of E_R, E_G and E_B, it can be shown that

$$\Delta x_o = 0.116 \frac{\Delta E_R}{E_R} - 0.044 \frac{\Delta E_Y}{E_Y} - 0.072 \frac{\Delta E_B}{E_B} \quad (21a)$$

$$\Delta y_o = 0.049 \frac{\Delta E_R}{E_R} + 0.175 \frac{\Delta E_Y}{E_Y} - 0.127 \frac{\Delta E_B}{E_B} \quad (21b)$$

The change in chromaticity due to shading or unbalance in the *RBY* camera can be computed by the use of Eqs. (21).

Again, by using the methods described by MacAdam,[4] the chromaticity shift can be calculated in terms of Δs, the number of minimum perceptible units. In the case of shading errors, the value of Δs is particularly significant, since a side-by-side comparison of chromaticity difference appears on the screen. Table III gives the computed results for a few special cases. For example, for one percent shading in the green tube for the *RGB* or *YRGB* cameras, a chromaticity shift of 0.89 minimum perceptible units results. A similar amount of shading in the luminance tube of the *RBY* camera gives a shift of 2.2 units. Therefore, the latter system is 2.5 times as sensitive as the former to shading in the green (or luminance) tube. For the nonlinear case, the ratio would probably be even higher, especially if some of the gamma correction took place within the camera tube itself.

Actual experiments have confirmed these results qualitatively. It was found that green-magenta shading was a problem in a camera using the *RBY* system.

Therefore, from a colorimetric point of view, both in terms of accuracy of chromaticity and shading or drift effects, the four-tube (*YRGB*) camera is preferable to the three-tube (*RBY*) camera. Both analytical and experimental results confirm this statement.

At the same time, a system using a luminance tube is to be preferred over the conventional *RGB* system, since the picture obtained has greater sharpness and less susceptibility to mis-register.

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Discussion

David M. Taylor (*Radio Corp. of America*): Have you ever made an analysis of the four-tube camera using gamma correction in only the monochrome channel?

Mr. Abrahams: No, but it might be very pertinent. The results would probably be worse, because the four-tube system really isn't much of a departure from the three-tube system in practical operation. I mean that gamma-correction is required in the red, green and blue, as well as the monochrome for proper results.

H. N. Kozanowski (*Radio Corp. of America*): Would you comment on the applicability of this system to the live-camera program?

Mr. Abrahams: It certainly is applicable to the live camera work. The point has been made that there is a question of how good register you can get in a color camera. In other words, theoretically, if you can get perfect register anyway, then there's no advantage in using four tubes; but, as a practical matter, when do you get perfect register? It's one of the difficulties we have in proving the advantage, because actually, the register *can* be made good with enough effort. Thus, in connection with a system like this, the question naturally arises: Why don't you just get good register, and then you won't need a four-tube camera? The answer is that, in actual practice, the registration may be somewhat less than perfect.

Dr. Kozanowski: How does it meet the spirit and letter of the NTSC specifications for color and the FCC specifications?

Mr. Abrahams: A very good question. Of course, the purpose of this paper was to discuss the adherence of the four-tube system to the NTSC standards; there is no question but that it does. The manner of deriving the color signals is not the important point in judging adherence to the standards. Only possible color or luminance errors in the picture reproduced on a standard receiver need be considered. I have shown that these errors (due to the use of four tubes, I mean) are far less than those encountered due to the color filters presently used in color cameras. In addition, the slides and films may have considerable color error, some of it deliberately introduced to improve the picture. In other words, the transmitted signal from a four-tube system is entirely standard. There can be negligible distortion of colors due to its use, between the original scene and the image reproduced on a standard receiver.

Frank Marx (*Session Chairman*): It just seems to me that what we are buying in another tube, either in live or film chain, is a much easier operating tool in turning out day-to-day color. And those of you who have had experience with the 3-tube monsters I'm sure will agree with that.

Review of Work on Dichroic Mirrors and Their Light-Dividing Characteristics

By MARY ELLEN WIDDOP

During World War Two, the application of thin films to glass surfaces progressed from experimental laboratory work to practical application in optical devices. At present, virtually all lenses are coated to reduce reflection. Plates coated with multilayer films, known as dichroic mirrors, are also being applied as efficient light dividers. The recent use of dichroic mirrors in experimental color television equipment is one of the best known applications. The purpose of this paper is to review briefly the interference phenomenon involved and to describe the results obtainable with several dichroic mirror designs.

About fifteen years ago scientists began to experiment with the application of very thin multilayer films to glass, in order to reproduce the effects of color selective reflection and transmission strikingly exhibited in nature by certain crystals. Since that time, the use of this method to produce mirrors which efficiently divide light has become well known. One of the first applications of interference mirrors was in photocell monitoring of sound recording for motion pictures. During World War Two, quantities of dichroic interference mirrors were used in range finders and radar cameras. They are now used in both military and civilian products. In the RCA compatible system of color television, dichroic mirrors are used to divide light into primary colors and to combine the primary colors for monitoring.

Like the colors of soap bubbles, thin films of oil on water, oxide films on heated steel and certain crystals such as chlorate of potash, the light-dividing characteristics of dichroic mirrors result from interference in reflected and transmitted light. Interference films are also used to produce neutral light dividers, or to reduce reflection from glass. The films are applied to glass by the deposition of vaporized material on the glass surface, in a vacuum. The thickness of a deposited film may be controlled by observing the changes in intensity of a beam of light reflected from the glass, through a filter, into a photocell. The intensity fluctuates, reaching a maximum or minimum whenever the thickness of the deposited film is effectively equal to a multiple of $\frac{1}{4}$ of the wavelength of the control light.

To review the interference effects of thin films, we will first consider the effects produced by single thin films, as shown in Fig. 1. These diagrams represent plane parallel, nonabsorbing films on glass surfaces, and their effect on an incident light ray. The film thickness in both cases is effectively equal to $\frac{1}{4}$ of the wavelength of the incident light ray. The film in diagram (a) has an index of refraction higher than that of glass, while the film in diagram (b) has an index of refraction lower than that of glass.

Any light ray incident on such a film becomes the source of two sets of almost superimposed parallel rays. These rays tend to cancel or reinforce each other by destructive or constructive interference. The type of interference which occurs depends on the relative phase of the interfering rays. The phase of the reflected and transmitted rays is determined by the optical path through the film and by phase reversals which occur on reflection from a denser medium. In these diagrams, phase is indicated by solid and broken line segments. For simplicity, the angle of refraction is ignored.

The high-index film produces reinforcement for a specified wavelength in the reflected light and cancellation in the transmitted light. Here, the only phase change due to reflection from a denser medium occurs at the air-film boundary.

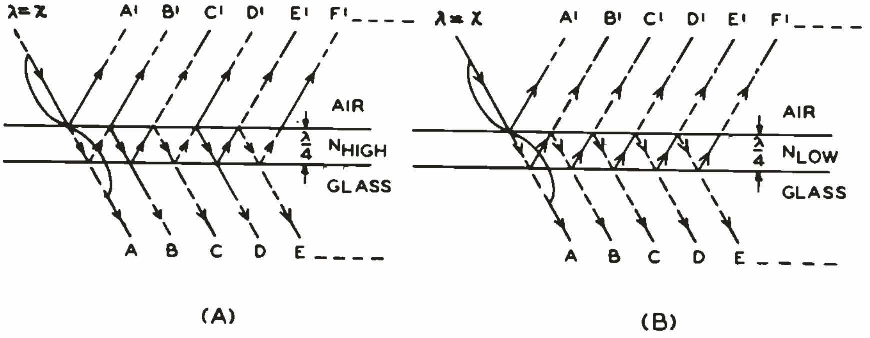
The successive rays, proceeding toward the right, are less and less intense; hence the effects of the first two reflected rays, and the first two transmitted rays, are dominating. The phase reversal of alternate succeeding rays modifies the effect of the first two rays, therefore neither cancellation nor reinforcement is complete.

In the low-index film, there is a phase change in the initial reflection from the air-film boundary and at each reflection from the film-glass boundary. As a result, an effective film thickness equal to $\frac{1}{4}$ of the wavelength here produces cancellation in the reflected light and reinforcement in the transmitted light.

The amplitude of the reflected rays, for a specified angle of incidence, is determined by the relative indices of refraction of the materials on either side of the boundary from which reflection occurs. Therefore, if the relative indices of refraction of the air, film and glass were of such value that the amplitude of the ray initially reflected at the air-film boundary equalled the sum of the amplitudes of the other reflected rays, no light of the specified wavelength would be reflected from the film in diagram (B), since the rays are 180° out of phase.

The maximum reflectance obtainable from a single film is determined by the index of refraction of the film. In order to increase the reflectance for a certain wavelength, multiple alternate layers of high- and low-index materials are applied. The film thickness for each layer is controlled so that the initial reflected rays, of the control wavelength, from each film boundary are in phase when they leave the film. The reflected intensity for that wavelength is then equal to the square of the sum of the amplitudes of the reflected rays.

A diagram representing a seven-layer film and its effect on an incident light ray is shown in Fig. 2. In this film, each layer is effectively equal in thickness to $\frac{1}{4}$ wavelength. The initial reflected rays from each boundary emerge from the film exactly in phase. The strongest



(A) (B)

Fig. 1. Interference effects in single $\frac{1}{4}$ λ films on glass.

Presented on October 7, 1952, at the Society's Convention at Washington, D.C., by Mary Ellen Widdop, Radio Corporation of America, RCA Victor Div., Engineering Products Dept., Camden 2, N.J.

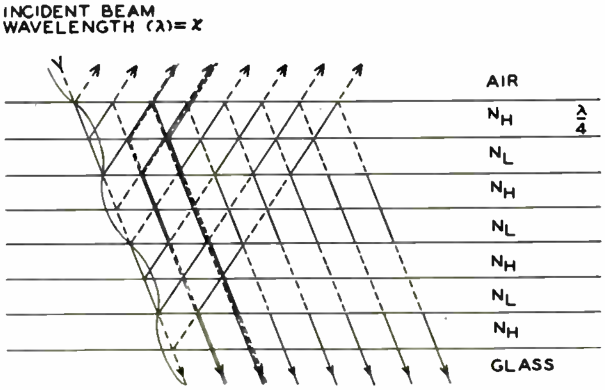


Fig. 2. Interference effects in a multilayer film on glass.

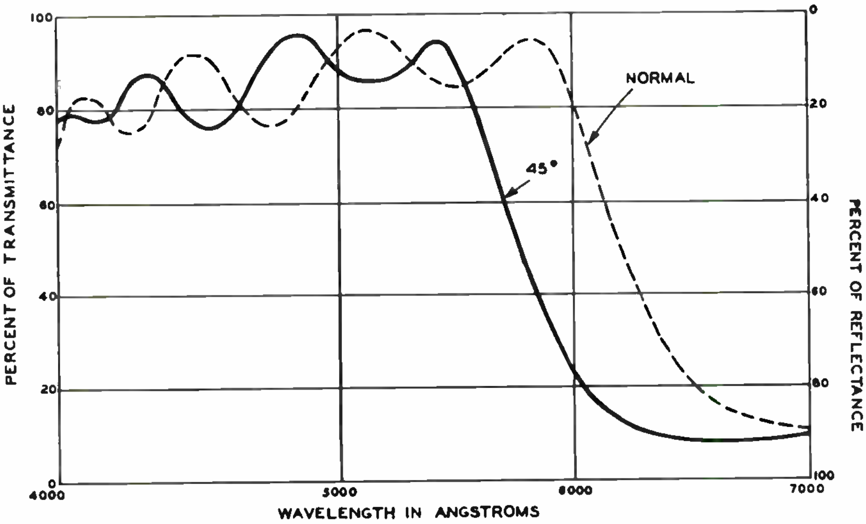


Fig. 3. Characteristics of a seven $\frac{1}{4}$ λ-layer dichroic.

transmitted rays resulting from interfilm reflections are 180° out of phase with the initial transmitted ray. In addition to the strongest set of reflected and transmitted rays, there are many weaker rays resulting from interfilm reflections. Some of these rays are out of phase with the stronger rays but since they are so much weaker they, of course, cannot cancel the effect of constructive interference in reflected light and destructive interference in transmitted light for wavelength X.

The film design shown in Fig. 2 is a standard design which, when composed of the materials most commonly used, reflects over 90% of the light at the control wavelength. The effect of this film on light of other wavelengths is determined by the relative phase of the reflective rays and of the transmitted rays as they leave the film. Transmission characteristics in the visible range for a film of this design, controlled for maximum reflectance at 6350 A at 45° angle of incidence, are shown in Fig. 3. There is no appreciable absorption: therefore, all light not transmitted is reflected. A dichroic of this type is used to reflect red light in the color-television camera.

As shown in Fig. 3, the transmission curve shifts toward the short wavelength end of the spectrum when the angle of incidence is increased. This shift is due to the change of path difference with change of angle, making the film effectively thinner as the angle of incidence is increased. The path difference produced by a film is greatest at normal incidence. The diagrams in Fig. 4 represent two light rays incident on a thin film in air, and illustrate the factors which determine path difference. If a ray strikes the film at normal incidence, the path difference between the ray reflected from the first surface and those reflected from the second is equal to the product of the index of refraction of the film and twice the film thickness. Diagrams 1 and 2 represent rays incident on the film at two different angles. In both cases, dotted lines AC and DB represent successive positions of a wavefront. Therefore, the optical paths AD and CB must be equal, AD (in air) = N (CB), and the difference in optical path at wavefront DB, where the reflection from the second surface leaves the film, is equal to N (AFC). It can be shown that the path difference = N (2d cos r), thus as the angle of incidence increases, the angle of refraction increases, the cosine of r decreases and the path difference decreases.

Such a shift of light-dividing characteristics with change of angle of incidence is sometimes objectionable because of resultant shading in transmitted and reflected images. Shading from one side of an image to the other, due to large field angle, can be compensated for by tapering the deposited film. To do this, the glass is placed in the evaporating equipment at an angle to the plane of the evaporator, rather than parallel to it. The films deposited are then wedge shaped instead of plane parallel. The resultant mirror is then positioned in use so that the thickest part of the film receives light at the greatest angle.

By varying the number of deposited layers, the thickness of each layer, the control wavelength and the angle of control, a wide variety of dichroic

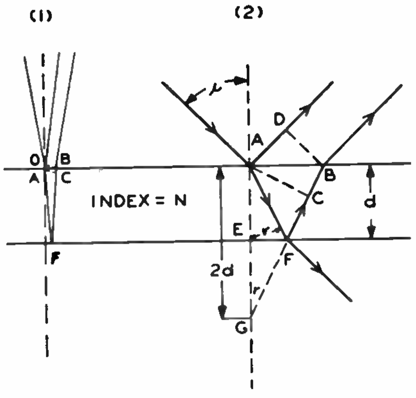


Fig. 4. Path difference of rays reflected from the two boundaries of a thin film.

mirrors is obtainable. In Figs. 5 and 6, transmission characteristics are shown for a number of designs used to fulfill various light dividing or combining requirements. These designs consist of various combinations of $\frac{1}{4}$-, $\frac{1}{2}$- and $\frac{3}{4}$-wavelength film thicknesses.

In general, designs made with layers thicker than $\frac{1}{4}$ wavelength have a narrower band of reflection than $\frac{1}{4}$-wavelength designs. The heavy solid line in Fig. 5 is the transmission curve for a mirror of the type used to reflect blue light in the color camera.

To illustrate a way in which the interference mirrors are used, a diagram of the optical system of an RCA Color-Television Camera is shown in Fig. 7. When light entering the camera through the lens system reaches the dichroic cross, red light is reflected from mirror J to totally reflecting mirror M and then to the image orthicon in the red channel. Blue light is reflected from mirrors I and K, totally reflecting mirror L and then to the image orthicon in the blue channel. Green light passes through both mirrors to the image orthicon in the green channel. Each reflector efficiently transmits the other two primary colors. In this application, the dichroics are assembled in sandwiches with the reflecting surface on the inside, covered by another plate of the same thickness as that on which the dichroic film is deposited. The light path through the glass is then equal for all channels. The blue reflecting mirrors are carefully aligned so that the reflecting surfaces are in one plane and perpendicular to the red reflecting surface. With this arrangement, astigmatism introduced by the glass can be compensated for by placing two plates, E and F, at right angles to each other in

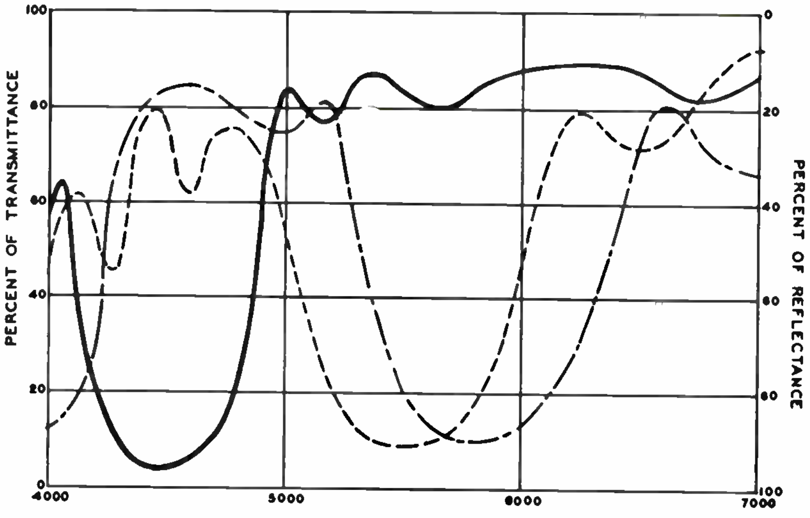


Fig. 5. Light-dividing characteristics of several dichroics.

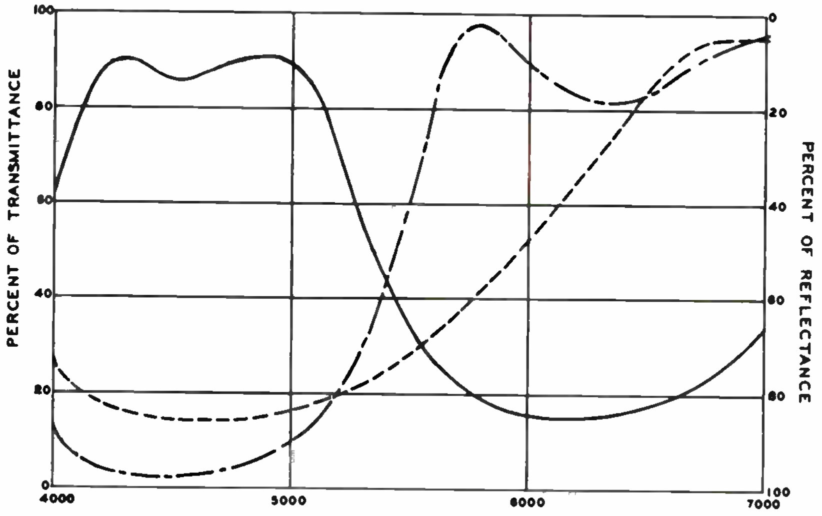


Fig. 6. Light-dividing characteristics of several dichroics.

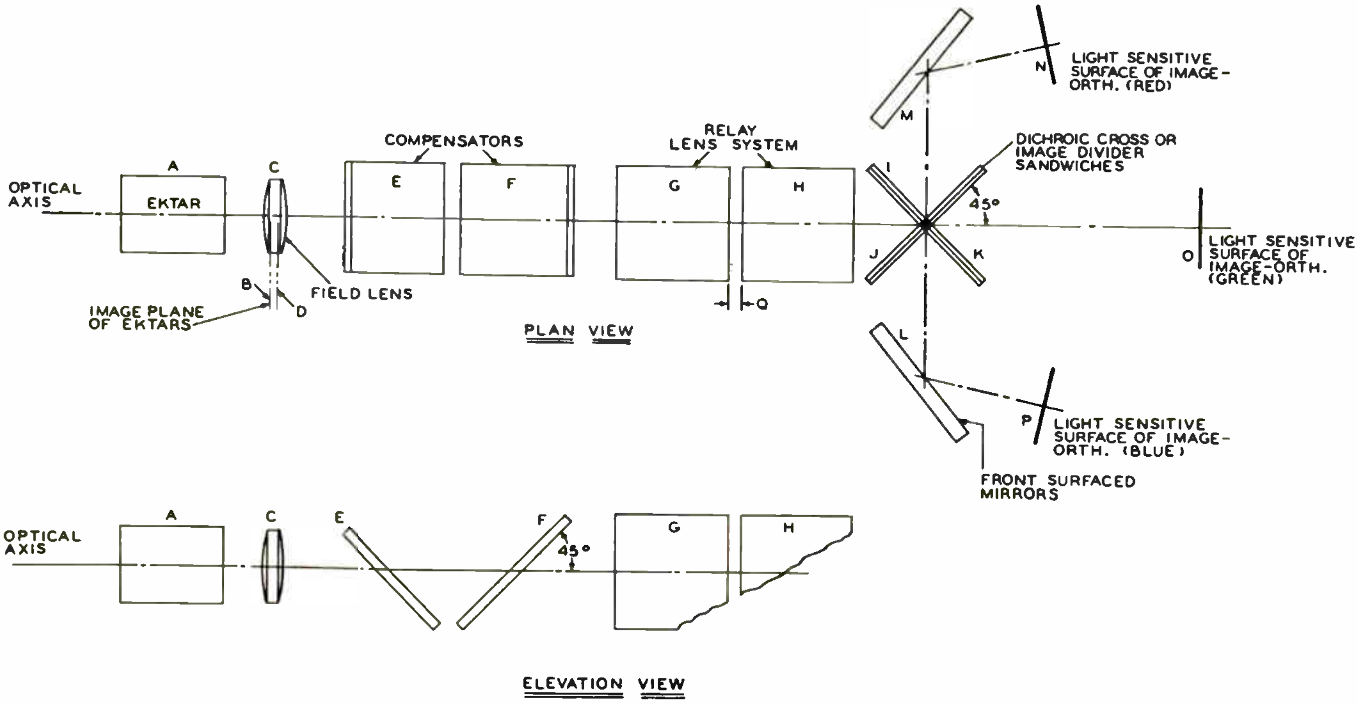


Fig. 7. Optical system of color camera.

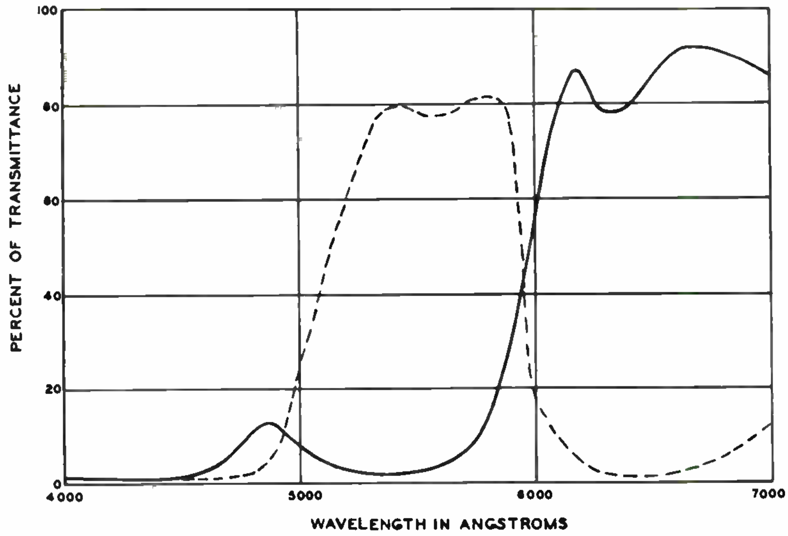


Fig. 8. Transmission characteristics of absorption-interference filters.

front of the relay lens. The line of intersection of these plates is at right angles to the center line of the optical system and to the line of intersection of the dichroics.*

Materials which absorb light can sometimes be used advantageously in interference films. In Fig. 8, transmission characteristics of efficient red and green transmission filters are shown. These filters are made by depositing alternate layers of high- and low-index materials on glass, but in this case one of the materials used has the combined properties of very high index of refraction and strong absorption in the blue region of the spectrum. In the resultant films, blue light is removed by interference and absorption while the red and green portions of the spectrum are efficiently divided by interference.

When the reflected and transmitted light is to be divided in a way which is difficult, or impossible, to achieve with any single film design, sets of layers may be combined on one plate. For the final characteristics of a film to be the product of two different designs, the sets of layers must be separated from each other sufficiently to prevent much of the interference between the sets. The curve shown by the broken line in Fig. 9 is that of a plate coated with two sets of layers, one having peak reflectance for blue light and the other having peak reflectance for red light. In this case, the sets of layers were separated from each other by a thick evaporated layer of material. The solid-line curve in Fig. 9 is the resultant characteristic of two similar sets of layers deposited on opposite surfaces of a plate. Here the elimination of interference between the sets of layers is more nearly complete. Highly reflecting films can be applied to both surfaces of a glass plate advantageously in many cases; however, this scheme cannot be used in any case where double images are undesirable.

Transmission characteristics for an interference mirror which reflects efficiently through the visible spectrum and efficiently transmits infrared radiation are shown in Fig. 10.* In this case, several sets of layers controlled for maximum reflection at different positions in the visible range, are deposited on one surface of a plate. In this case, no attempt is made to prevent interference between the sets of layers. Interference between the sets of layers improves the efficiency of the film.

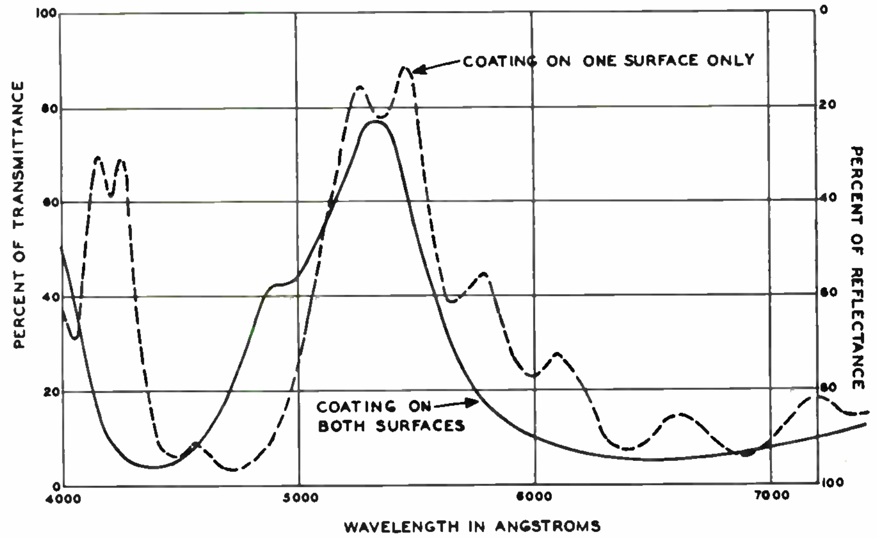


Fig. 9. Light-dividing characteristics obtained by depositing two sets of dichroic films.

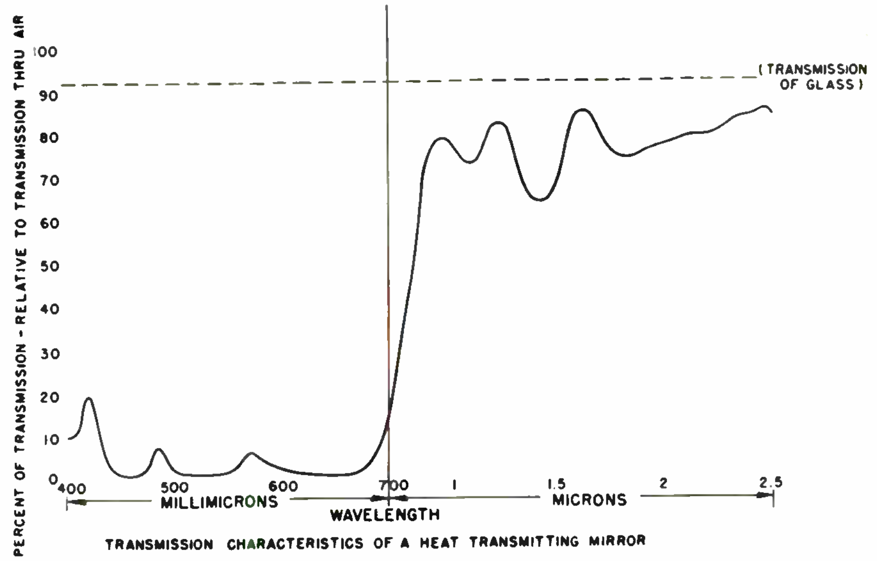


Fig. 10. Transmission characteristics of a heat-transmitting mirror.

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* L. T. Sachtleben, D. J. Parker, G. L. Allee and E. Kornstein, "Image orthicon color television camera optical system," *RCA Rev., 13, No. 1:* Mar. 1952.

* G. L. Dimmick and M. E. Widdop, "Heat transmitting mirror," *Jour. SMPTE, 58:* Jan. 1952.

Interference mirrors can be made which reflect all wavelengths of the visible spectrum with approximately equal intensity. Such mirrors can be made to reflect as much as 45% of the incident light. A relatively thin layer of low-index material is first deposited on the glass surface, followed by a thicker layer of a material with a high index of refraction. The interference effects of such a film design cause all wavelengths of the visible spectrum to be reflected with approximately equal intensity because of the relative thickness of the component layers for each wavelength. The reflectivity of such a film is plotted with respect to the film thickness in Fig. 11.

The low-index film is slightly less than $\frac{1}{4}$-wavelength thick for blue light. The high-index material is deposited until a reflection maximum is passed and the reflection drops to about 85% of the maximum. Since the low-index layer is not $\frac{1}{4}$-wavelength thick at the point of maximum reflectance, the interfering rays are not exactly in phase. This maximum is, therefore, not as high as it would have been if the low-index film had been $\frac{1}{4}$-wavelength thick.

For longer-wavelength green light, the effective thickness of the low-index film is less than for the blue light. The maximum intensity obtainable for this wavelength is, therefore, less than it was for blue. For these film thicknesses then, the reflected intensity for green light has just passed its maximum point, and is approximately equal to the intensity for the blue. And for the red light, having the longest wavelength, the interferring rays are at a point of maximum reinforcement, but the resultant intensity is equal to that of the green and blue.

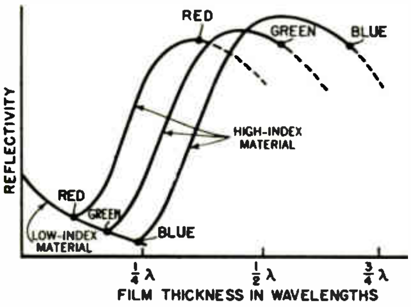


Fig. 11. Design of an achromatic film.

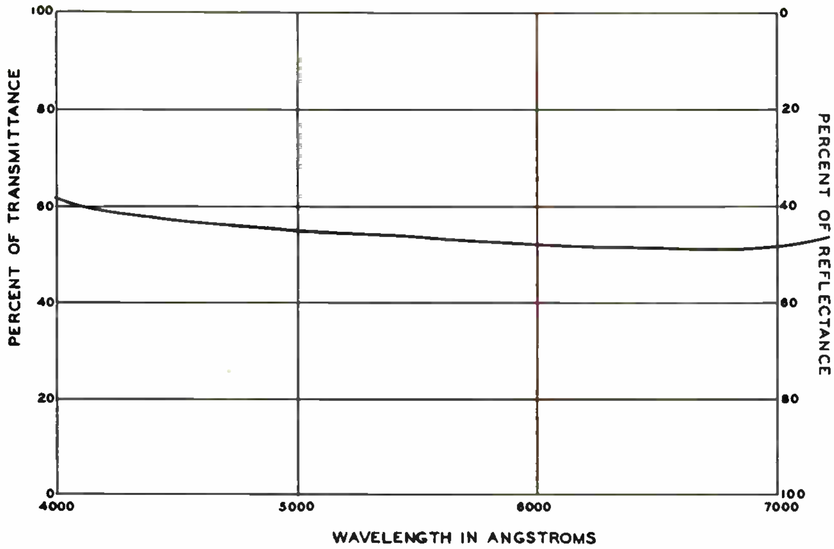


Fig. 12. Characteristics of an achromatic light divider.

The transmission characteristics of a mirror of this type are shown in Fig. 12.

Discussion

A. V. Loughren, Chairman of the Session (Hazeltine Corp.): The importance of these dichroic mirrors in the development work, which has been going on recently both at RCA and many other places in color television, is something to which I can certainly testify personally. Our own developments at Hazeltine came along far faster than they would have otherwise because it was possible to make arrangements to get some of the dichroic mirrors designed by Miss Widdop and use them in our own work. I have no doubt myself as to their importance.

L. L. Ryder (Paramount Pictures Corp.): Is any work being done in conjunction with these mirrors for high-intensity light levels, for instance where they're used in conjunction with arcs and similar light sources?

Miss Widdop: Well, the heat-transmitting mirror which was the last design shown, was developed primarily with that idea in mind, that it would efficiently reflect the visible light and transmit heat, but it never has actually been applied to that purpose.

Mr. Ryder: The real question is will the coating material stand up against these extreme heats of the arc?

Miss Widdop: We don't feel that the films could be used as front surface mirrors. If they were on the back of the mirror or if they were protected, the heat would not bother them, as far as our experience has shown. We haven't actually had such a mirror in use for a long period of time in a high-intensity arc, but we have made tests with it when it has been in a number of hours. I realize this wouldn't compare with the number of hours a mirror would be used in practice. The difficulty with putting such a coating on the back surface of a curved mirror is that it has to be very uniform or a pronounced color will be reflected. But the coating could be put on the inside surface and another glass put in front to protect it. Or a projector could be redesigned so that the beam is reflected at an angle from a flat mirror and then through the film.

Mr. Ryder: A question pertaining to the resolving power of lenses or lens systems which have the dichroic mirrors: How do lens systems using dichroic mirrors compare with lens systems with no reflection mirror? My interest is lens systems for motion picture or television cameras.

Miss Widdop: I'm not sure that I can answer that question. The glass on which the films are deposited has to be very flat, and compensating plates are used to correct for astigmatism introduced by the thickness of the glass and the angle of the mirrors. The films themselves do not introduce any distortion.

Ralph Heacock (RCA Victor Div., Camden, N.J.): In answer to Mr. Ryder's comment on heat-reflecting mirrors from a practical field viewpoint, we made use of some heat-reflecting mirrors and found that they would not satisfactorily stand up in the field under high-intensity arc light projection. More recently, however, we find with the heat-reflecting, inclined mirror, that if a draft of cool air is directed over the reflector, it operates satisfactorily over long periods of time. The maximum amperage that they have used them under, as far as I know, has been about 105 amp with a 10-mm positive carbon.

CBS Color-Television Staging and Lighting Practices

By RICHARD S. O'BRIEN

Color-television program production requires more stringent studio practices than does monochrome television. Camera and system adjustments must be made more precisely, the maximum scenery reflectance level must be reduced, the color balance of the studio illumination must be controlled, a higher light level must be provided and effects light ratios must be reduced. Careful attention to these aspects, in accordance with procedures outlined in this paper, together with an understanding of the fundamental difference between color and luminance contrast, makes possible satisfactory simultaneous reproduction in both color and monochrome.

COLOR TELEVISION transmission of live performances requires an extension of those studio practices which have proven effective in monochrome operation.[1,2] The color signals transmitted must provide satisfactory reproduction in monochrome as well as in color in keeping with the scanning compatibility of the present U.S. standard (National Television System Committee) color-television system.[3] This calls for the direct application of most of the well-established monochrome practices together with meticulous attention to several aspects which are especially important in color. Spectral balance, transfer characteristics, and image sharpness require the well-informed, cooperative efforts of all production personnel to achieve high quality, truly compatible color-television programs. These and other more specialized aspects are discussed in this paper under three divisions of technical production: camera operations, staging and lighting.

Color Television Camera Operation

In a color television camera, the optical image is divided by means of filters into red, green and blue images. These are converted to video signals which are handled through three parallel channels in the camera equipment. These signals are encoded, for transmission, into a luminance signal which contains all brightness information (luminance) and into a chrominance signal which contains all color information (hue and saturation). The two signals are combined by means of frequency multiplexing within the normal television broadcasting channel bandwidth. In a monochrome receiver, only the luminance signal is used. In a color receiver, the luminance and chrominance signals are decoded to obtain counterparts of the original red, green and blue signals. These are applied to a color picture tube wherein they excite red, green and blue phosphors. Combinations of these three "primary" colors enable reproduction of a wide gamut of colors.

To achieve satisfactory performance, camera facilities must be adjusted to provide proper spectral response, accurate matching of red, green and blue channel amplitude-transfer characteristics, accurate registration of the three images and sharp focus. The same basic requirements apply with surprising similarity to the two types of color studio-camera systems in use at the outset of color broadcasting. As shown in Fig. 1, one of these is the tri-tube camera in which the primary color images are applied directly to three image-orthicon tubes.[4] The other is a field-sequential camera[5] whose sequential signals are subsequently converted in the CBS-Chromacoder (a device equivalent to a tri-tube camera) into parallel, red, green and blue signals. In this paper, practices are outlined and rules stated which apply to both camera systems, specific requirements for a particular system being noted as they arise.

Spectral Balance. The red, green and blue signal voltages produced by a color-television camera are influenced by the spectral distribution of the illumination, by the spectral reflectance of the scenery surfaces, and by the spectral response of the camera tube and color-filter combi-

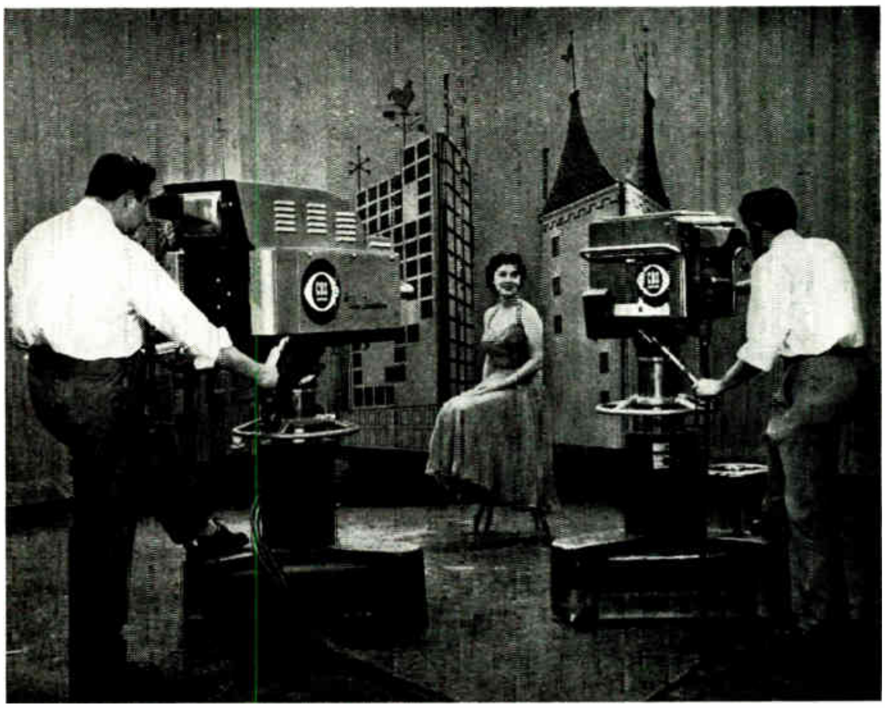


Fig. 1. A tri-tube color television camera on the left is compared with a field-sequential camera used in conjunction with the CBS-Chromacoder system. Both camera systems produce color signals conforming to the FCC color standards.

Presented on May 7, 1954, at the Society's Convention at Washington, D.C., by Richard S. O'Brien, CBS Television, 485 Madison Ave., New York 22.
(This paper was received on May 21, 1954.)

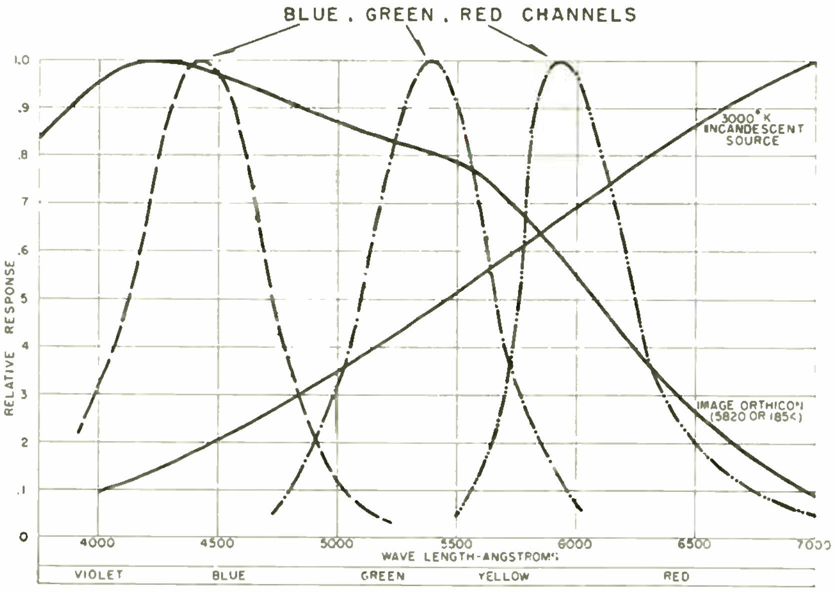


Fig. 2. Camera Spectral Response Characteristics. The spectral response of a typical image-orthicon camera tube is essentially complementary to the spectral energy distribution of a typical incandescent source as shown by the solid-line curves. The relative response of the taking primary channels of a tri-tube camera are shown by the broken-line curves.

nations. In order for the several cameras in a studio to produce matching images, it is necessary that the camera spectral response be carefully balanced against the spectral distribution of the studio illumination. It is the practice to adjust the relative response of the red, green and blue channels to produce equal video voltages from a gray test object placed in the normal studio illumination. To insure uniformity in amplitude-transfer characteristics, such spectral-response adjustment must be undertaken optically, ahead of the image-orthicon tubes, rather than by video-channel adjustments.

The spectral-response characteristic of presently available image-orthicon tubes, although sufficiently uniform among tubes for monochrome operation, must be individually corrected for color operation. In the tri-tube camera, each of the three tubes is required to respond to only a limited portion of the visible spectrum as shown in Fig. 2. In this case, spectral balance may be obtained by inserting neutral-density (colorless) filters in the optical paths of the more sensitive colors, until, as a convenient comparison, each channel reaches saturation at the same exposure level. Densities should be balanced to within a density step of 0.05 (10% transmission). Alternately, color-correction filters may be inserted at a point in the optical path common to all three channels, this being the practice in adjustment of field-sequential cameras.

It should be noted that a change in the color balance of the illuminant (as would be encountered in taking a studio camera outdoors) requires a different choice of neutral-density or color-correction filters. For example, to correct a camera initially adjusted for 3000 K studio illumination for use under a range of typical outdoor conditions, Wratten filters Nos. 83, 85B, 86B and the 81EF series together with a No. 2 haze filter may be found useful.

Transfer Characteristics. As implied above, uniformity in amplitude-transfer characteristics among the three channels of a color camera is essential. If the characteristic of one channel differs from the other two, the reproduced colors will vary in hue as luminance values change. For example, if the green-channel transfer were too "steep," a performer's face might change from its normal hue toward green as the performer moved into brighter light or toward magenta in shadow areas. It is especially difficult to obtain the necessary uniformity of transfer "tracking" in cameras using image orthicons, since it is well known that the transfer characteristics of these tubes are variable. As a result of the electron-redistribution process, the characteristics may follow anything from a square-root law to an essentially linear curve depending on target voltage setting, average exposure, highlight-to-average exposure ratio and other parameters. To minimize these variations the tubes must be adjusted so that highlights fall below the saturation point or "knee" in tri-tube devices rather than above as is common in monochrome operation. This minimizes electron redistribution and provides a fairly stable, almost linear, transfer, but reduces the output-signal level. This in turn requires that the close-spaced target, type-1854 tube be used in tri-tube devices in place of the familiar type 5820 to obtain a satisfactory signal-to-noise ratio.[6]

Also, to maintain the best possible signal-to-noise ratio, careful monitoring and adjustment of overall exposure must

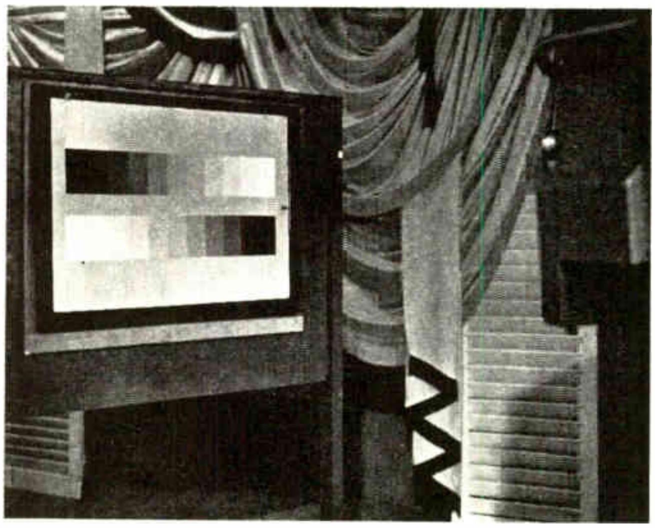


Fig. 3A. A typical, linear reflectance step gray-scale test chart placed in the normal studio illumination for observation through a camera system.

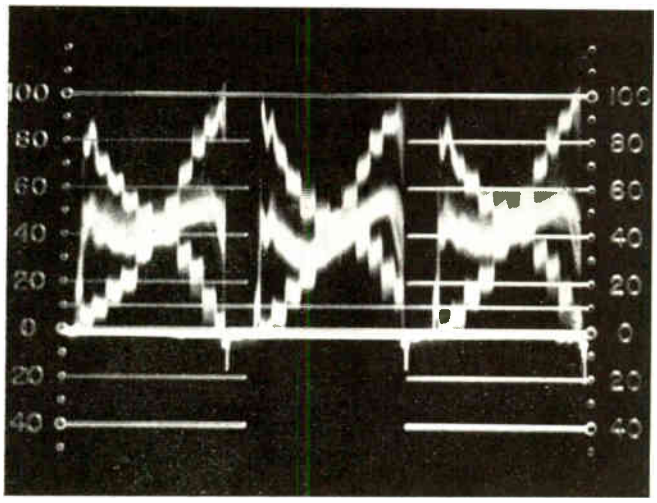


Fig. 3B. The red, blue and green video signals from the chart shown in Fig. 3A as seen on a gated waveform display. Color-balancing filters are inserted to cause the top steps of each signal to reach saturation concurrently.

be carried on throughout a performance. For this purpose, a remote-controlled iris or equivalent must be provided in the common optical path of each camera.

As outlined in the preceding section, the three channels of a color camera may be adjusted to reach saturation at the same exposure level (common-path iris adjustment). In making this adjustment, the target voltages of the three image orthicons must first be carefully set by means of a voltmeter to a chosen potential above cutoff. Higher voltages (e.g., 3.0 v) than used in monochrome are recommended to further minimize electron redistribution effects. Saturation may be observed by noting the concurrence of compression of the top steps of the signals from a gray-scale test chart (see Fig. 3A) as the exposure is varied equally in the three channels. After this adjustment is made, the top steps may be set just below saturation and the shape of the step-wave signal obtained from the gray scale observed on the camera-control waveform monitor. The monitor should include an electronic gating system whereby the three camera channel signals may be "overlaid" or placed side by side as in Fig. 3B to facilitate tracking adjustment. Small departures at lower levels may be compensated for by slight readjustment of one or two of the target voltages, and by careful adjustment of parameters affecting flatness of fields and shading. Large departures require selection of one or more replacement image-orthicon tubes. Shading adjustments must be made to achieve flat shading on neutral gray backgrounds of 15 to 20% luminance reflectance and also to achieve symmetry of the crossed gray-scale waveforms.

As noted, the tri-tube camera transfer characteristic is essentially linear. Thus, a linear reflectance gray scale, Fig. 4, is desirable as it provides an almost linear step-wave display on the camera waveform monitor. However, it is a specification of the National Television System Committee (NTSC) that the camera system be corrected to an overall gamma of 0.45 (1/2.2) to compensate for the nonlinearity of the reproducing picture tube. A gray scale which follows the inverse of this law (gamma = 2.2) is useful where a linear waveform display is desired at a point in the system which follows the electrical gamma-correction device. This scale is also of value in scenery-reflectance calibration and in direct visual observation on a picture monitor because its steps appear nearly equal to the eye. Observation of either of these gray scales on a well-adjusted color monitor provides a critical check of transfer tracking which can be made quickly and easily. Proper reproduction of a neutral gray scale is among the most severe tests for transfer tracking in a color system.

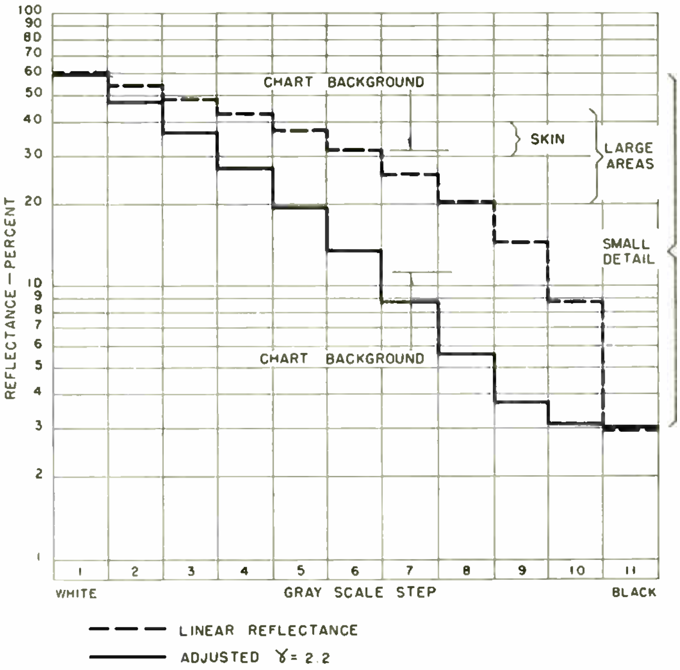


Fig. 4. Gray Scale for Color Camera Adjustment. The broken-line scale is a linear reflectance gray scale suitable for camera adjustment. The solid-line gray scale is arranged to produce a linear wave-form display after gamma correction and is recommended for use in scenery luminous reflectance calibration.

In connection with overall system gamma, it is to be noted that the unity gamma relation between input light and output light values which is theoretically necessary for the best color fidelity produces rather low contrast, washed-out monochrome reproduction. As a compromise, an overall gamma of up to 1.5 may be used requiring an electrical gamma correction of 0.7 to 0.8.

Image Resolution. The three images in a tri-tube device must be held in excellent registration to achieve good resolution and to avoid color fringing. In making adjustments it is common, first to adjust the scanning size and linearity of the green channel which contributes the largest portion of fine detail information to the luminance signal. The red and the blue channels are then adjusted to overlay the green channel throughout the raster. As an indication of the accuracy required, Fig. 5 shows that a 0.1% horizontal misregistration of the red channel results in a 20% reduction in

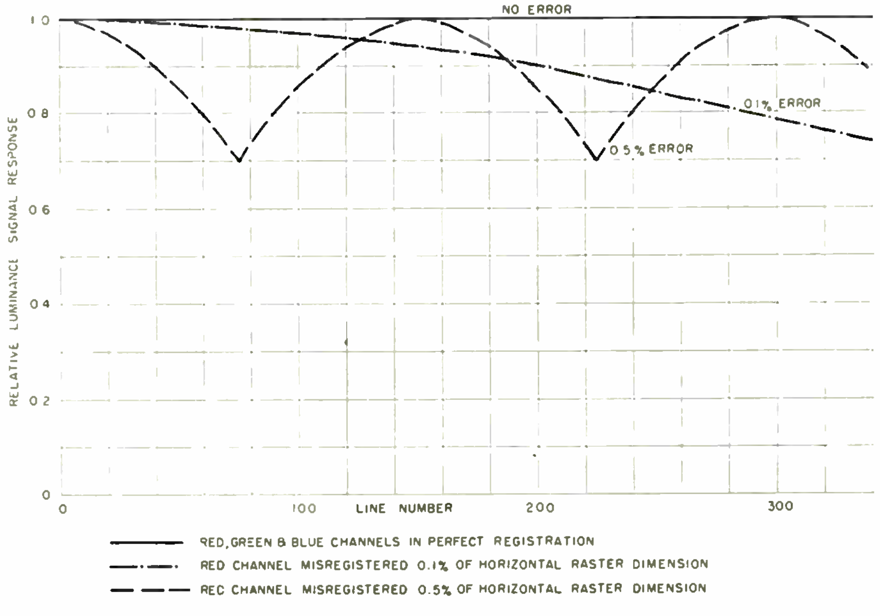


Fig. 5. Effect of Misregistration on Resolution. The response of tri-image devices to fine detail is influenced by the accuracy with which the three images are scanned in proper registration. Ideal aperture correction is assumed in this plot to clearly show the relative loss in detail response caused by misregistration.

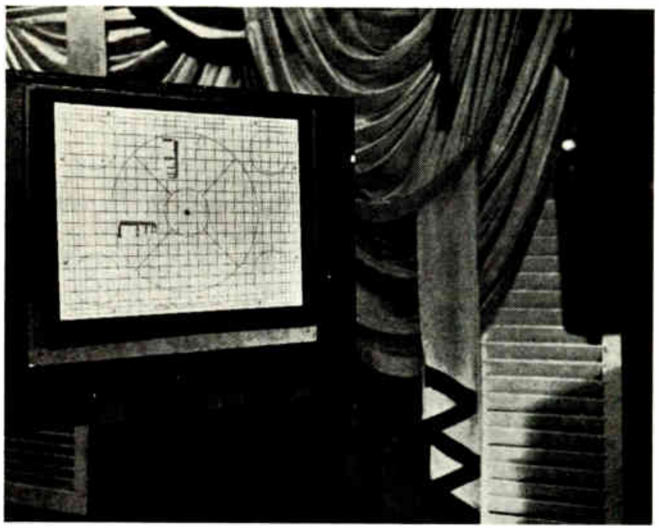


Fig. 6. Coarse camera registration is accomplished by overlaying the three images of the rectangular grid pattern. Fine adjustment must seek to obtain the maximum resolution on the fan-shaped resolution wedge over the major portion of the raster.

luminance signal response for a 280-line resolution test pattern, while a 0.5% misregistration produces a loss of 30% at line numbers 75 and 255. The rectangular grid pattern on the test chart shown in Fig. 6, may be used for coarse adjustments, the lines being 0.031 in. wide (whereas 0.1% is only 0.024 in. on the chart). The resolution wedges, however, must be used for fine adjustment, resolution of at least 450 lines being necessary. Registration adjustments may be observed on monochrome monitors, the camera monitoring equipment being equipped if possible to display camera channels singly, in pairs or all superimposed.

The same procedure applies to the tri-tube portion of the Chromacoder, the test chart being transmitted to the translation unit through a sequential camera.

In addition to the loss in resolution incurred by slight misregistration, further degradation occurs in tri-tube devices from the operation of image orthicons with highlights below the knee. Operation above the knee which is normal in monochrome applications tends to enhance edge contrasts through electron redistribution. These enhancing effects cannot be achieved in tri-tube color devices, because the conditions of operation whereby they are obtained also produce intolerable nonlinearity and variability in transfer characteristics.

In place of these effects, the effective sharpness of a color camera is improved by the introduction of aperture correction which boosts the higher video frequencies. The intent of aperture correction is to compensate for the inherent loss in fine detail which occurs when the image is scanned by an electron beam having a diameter (effective scanning aperture) which is only slightly smaller than the image detail structure. Over and above correct adjustment of the aperture correction amplifiers, it is essential in color camera operation that all optical and electrical focus adjustments be monitored with great care.

Suggested Camera Operating Rules.

1. Operate image orthicons in tri-tube devices below the "knee," riding exposure control to hold highlights at the proper level.
2. Accurately set image-orthicon target-screen voltages to equal voltages above cut-off, (e.g., 3.0 v) varying from this only slightly to improve transfer-characteristic matching as determined by reproduction of a gray-scale chart.
3. Balance exposures at the image orthicon "knee" on the three color channels to be coincident within a 0.05 density step.
4. Adjust for flat shading of backgrounds on a gray surface having a 15 to 20% luminance reflectance value.
5. Adjust image registration prior to making final transfer-characteristic adjustments, using the green channel as a reference. Adjust to obtain detail resolution to at least 450 lines.
6. To compensate for limited resolution, be meticulous in adjusting and monitoring optical and electrical focus.
7. To the greatest possible extent make all adjustments correctly in advance of an operation and make only emergency changes during operation.

Color Television Staging

Whereas it is an objective of camera operation to generate signals which faithfully reproduce the hue, saturation and brightness of the original scene, it is the purpose of staging and lighting to achieve prescribed artistic effects. Intentional distortions may be required to obtain a certain effect. For example, enhancement of color contrasts may be required, as is true also in photography and pictorial painting, to create the illusion of a three-dimensional scene on a flat viewing surface. The practice of such compensations requires a mutual understanding of the problems and close cooperation among technical, staging and lighting personnel so that adjustments may be made in the most appropriate way.

Fortunately, the more realistic appearance of color reproduction makes it somewhat easier to predict the end result than in the case of monochrome. However, the idiosyncrasies of the television facilities detract somewhat from this predictability and call for certain allowances in staging practice. Specifically to be avoided are: certain colors which are reproduced inaccurately, conditions wherein colored backgrounds interact on foreground objects and excessively fine detail which is beyond the capability of the system. In addition, there is the ever-present requirement that a balance be achieved between color contrast and luminance contrast to insure satisfactory reproduction in monochrome as well as in color. Proper solutions to these and other staging problems require an understanding of the manner whereby staging materials reflect light of various wavelengths to produce sensations of hue, saturation and luminance.

Reflectance of Surfaces. An opaque surface in a scene appears to have color as a result of the particular way in which it reflects light. Visible light is known to include radiant energy components having wavelengths ranging from 4000 to 7000 A (A = Angstrom unit = 0.1 $m\mu$ = 1/4,000,000,000 in.). If these single-wavelength components were observed individually, they would produce color sensations ranging from violet (about 4000 A) through blue, cyan, green, yellow and orange to red (above 6000 A) — the so-called spectral colors. If the light reflected from a surface contains relatively stronger components in a particular region of the spectrum, it too may produce the sensation of a characteristic color or hue. Such a hue may be identified in terms of the particular or dominant wavelength of a single component which would produce the same sensation. The degree to which the actual reflected light components are concentrated near the dominant wavelength determines the saturation. A highly saturated color has a relatively narrow spectral-energy distribution and may be thought of as having a high purity of the dominant wavelength. The total strength of the reflected light determines its brightness or luminance value.

Luminance value is measured with reference to the amount of radiant energy which falls within the spectral region of the standard luminosity curve. This curve, included in Fig. 7, has been chosen by international agreement to represent a standardized spectral-sensitivity characteristic for the human eye. In monochrome television, the camera spectral sensitivity corresponds approximately to this curve, and the camera output signal thus provides a direct measure of luminance values. In color television, additional steps are involved. To obtain a measure of the hue and saturation of colored surfaces, the color-camera response is broken into relatively narrow portions of the spectrum as indicated in Fig. 2. The relative amplitudes of the video signals obtained from each of these three primary color regions are then compared to obtain video signals representing color differences and thus conveying hue and saturation information. Also, the signals from the three channels are added together in proportions established by their spectral positions on the standard luminosity curve to form a video luminance signal. This luminance signal is essentially similar to that generated directly by a monochrome camera. It is to be noted that the camera basic spectral response combined with the spectral distribution of the incident light may be assumed for the present to be uniformly balanced throughout the spectrum, the staging problem being concerned with the spectral reflectance of surfaces.

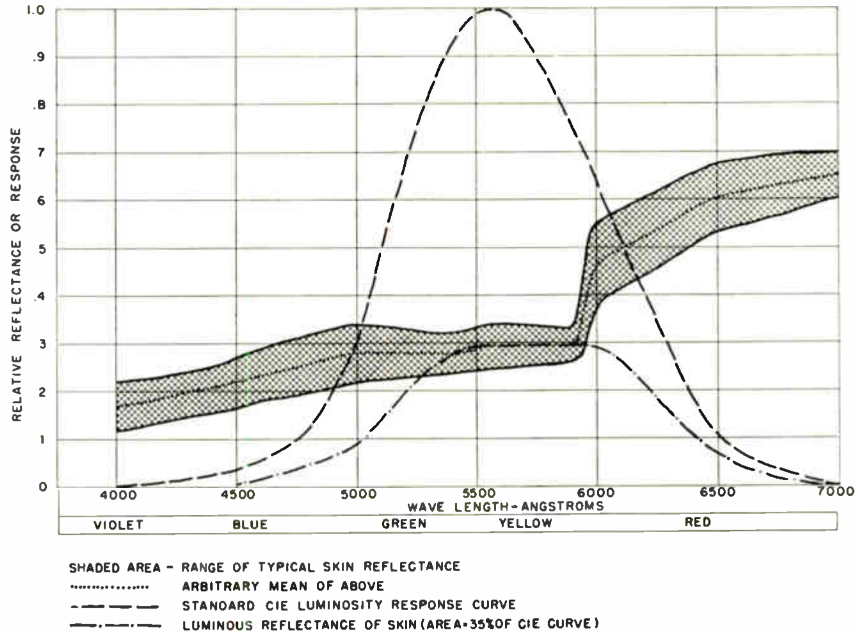


Fig. 7. Spectral and Luminous Reflectance of Skin. The spectral reflectance of human skin varies among individuals, among different areas of each individual and as a function of exposure to the sun. The range shown is representative, but not all inclusive. The luminous reflectance of any surface is its relative reflecting efficiency as measured against the standard luminosity curve and as compared to a perfect reflector.

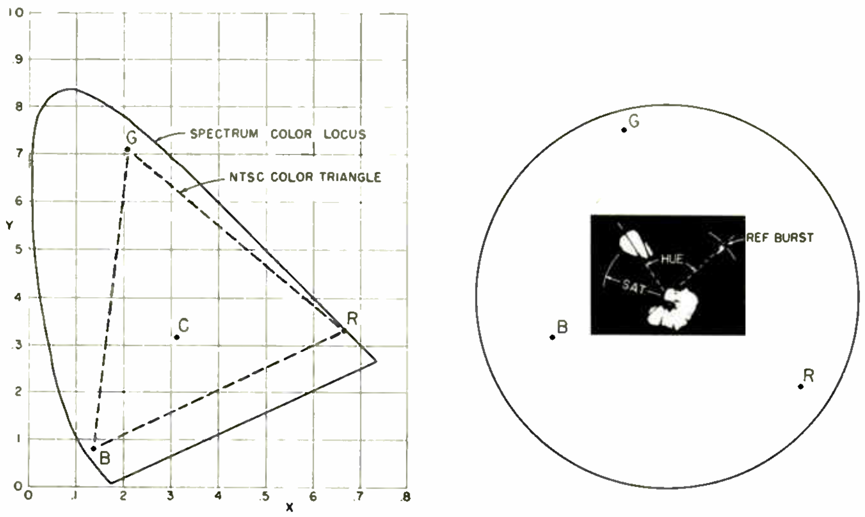
Selection of Colored Surfaces. The selection of materials and paints for a given scene is complicated by the divergent requirements of color and monochrome reproduction. Color reproduction calls for a reduced range of luminance values to allow scope for the color-signal components. In this case, the lack of luminance contrast is more than compensated by color contrast, i.e., differences in hue and saturation. In monochrome reproduction of the same signal, however, the benefits of the color contrasts are not present and the reduced luminance range results in a relatively low-contrast image. This conflict between color and monochrome contrast will be a problem as long as monochrome receivers are in use. It may be resolved by using somewhat desaturated colors, and by making up for reduced large-area luminance values by including small, bright, white highlights in the scene.

As in the case of monochrome studio practice, the luminance-reflectance scale is chosen with respect to the typical reflectance of a performer's skin. The reflectance of skin differs for various spectral wavelengths as shown in Fig. 7. That is, it has color — a desaturated yellow-pink. However, its luminance value of reflectance, measured against the luminosity curve as shown, for typical fair-skinned individuals falls between 30 and 40%. The gray scale shown by the solid line in Fig. 4 has been chosen to have its top step at about 60%, the entire scale having been shifted downward as compared to that recommended for monochrome. Large areas of the scene should not be allowed to exceed this 60% luminance reflectance and preferably should be held between 20% and 50%, a range of 2½ to 1. This applies to areas which appear larger than about one-quarter of the area of a performer's face in the camera image. This restriction is necessary in order to insure that overexposure of the camera tubes may be avoided and that there will be ample headroom available for superimposing the chrominance signal on the luminance component in transmission. However, it is desirable to allow small white highlights to exceed this value in order to enhance the luminance contrast in monochrome reproduction.

Scenic design is facilitated if a catalog of precalibrated samples of scenery materials is made. The samples may be calibrated for luminance reflectance against the color gray scale as observed through the camera system after the manner outlined for monochrome.[2] In making such calibration, the encoded signal should be observed on a monochrome monitor.

Precalibration of samples with respect to their color aspects, hue and saturation, is a little more cumbersome because of the great number of possible combinations of these factors. However, it is possible, by means of an electronic, vector display of an encoded color signal to obtain numerical quantities which specify hue and saturation. Hue is expressed as a vector angle, saturation, as an amplitude in a display which provides a close analogy to the familiar ICI (International Commission on Illumination) chromaticity diagram as shown in Fig. 8. An alternative method for precalibration could be evolved using one of several commercially available, material color standards as a reference for comparison. In the Munsell System, for example, letter and number designations are assigned to over 400 samples covering a wide gamut of hue and saturation and of luminance values as well.[7,8] Actually, if luminance values are held within bounds, very little restriction on hue exists and saturations need be kept low in only a few cases. At this stage of the art, it is felt that any elaborate system for color precalibration is unnecessary, so long as luminance reflectance values are properly controlled. Only a few colors may cause trouble, particularly those having both high luminance and high saturation such as yellows and cyans and occasionally those having very low luminance such as dark blues and reds. Such few colors may be noted and used with due care as to luminance conditions.

Background Surfaces. In large area backgrounds, it is important to avoid high luminance values in highly saturated colors, particularly those having a hue near one of the three camera primaries or its complement. A predominance of energy in one color may



ICI Chromaticity Diagram **Vector Display of Encoded Signal**

Fig. 8. The chrominance portion of an encoded signal obtained from a sample of material (e.g., a green color chip) when viewed on a vector display shows hue as a vector angle and saturation as a radial distance. The NTSC-specified receiver primaries are plotted in their correct positions on this display and also on the ICI chromaticity diagram to show the similarity of the two displays.

cause overexposure and consequent shift in the transfer characteristic in the corresponding camera channel (or during the corresponding period in a sequential camera). The effect is to cause foreground objects to shift in hue as they are moved in front of the background color area or as the camera-lens acceptance angle is changed, changing the relative area covered by the colored background in the final image. A case to be particularly avoided is a high-luminance, high-saturation cyan background which, if it overexposes the green and blue camera channels, may cause faces to turn red. This electronic effect is independent of direct optical contamination of foreground object color by light reflected from nearby colored surfaces.

The use of desaturated or pastel colors, matte surfaces, and medium luminance values will solve part of the background problem. The inclusion of patterns or pictorial details in which a more or less equal amount of reflectance is provided in the three primary colors also will help. Scenic backdrops which include well-distributed, desaturated, primary colors usually reproduce well in both color and monochrome. Excessively busy backgrounds should, of course, be avoided. In general, tan, beige or pink areas reproduce satisfactorily and have a minimum effect on the most important foreground object — a performer's face. Uniform gray areas which contain equal amounts of energy in the three primaries are somewhat difficult to use because slight departures from an intended neutral gray are easily noted by a viewer. Gray may be used in smaller areas. Low key effects may be used if the dark areas are partially filled in with objects or areas providing a reasonably high though not necessarily continuous reflectance in all three primary color regions. Outdoor scenes should avoid using the open sky with its very high luminance as a background, a building, trees or other less luminous areas being more satisfactory.

Clothing and Make-up. Clothing, which appears adjacent to a performer's skin is subject to the same general considerations as backgrounds. Where the clothing is intended to be colored, care must be taken to avoid saturated colors which might cause differential overexposure and adverse effects on adjacent skin areas. Where clothing is intended to appear white, "tattle-tale gray" must be substituted for the light blue or tan garments used to achieve reduced luminance in monochrome practice. The "white" clothing should have a luminance reflectance which does not exceed the 60% step of the gray scale. With respect to the texture of woven material, the swirl pattern which results from the beat between the texture pattern and the camera scanning lines may show up in distracting rainbow effects in the color system. To avoid this, the material may be replaced or the picture composition altered to change the relative dimensions of the texture as compared to the camera raster.

In addition to being influenced by surrounding areas in a scene, the reproduction of skin color is complicated by the variation of the spectral reflectance of skin among individuals (see Fig. 7). Also, the color will vary from one part of a person to another depending on sun tan and other factors. Thus, the objectives of make-up for color television are to make all visible areas of each performer look the same and to achieve reasonable uniformity of coloration among the several performers. The principal correction required among individuals involves slight variations along a green-to-magenta axis. The amount of make-up required is normally small enough so that the appearance of the performer is quite natural on direct observation. In applying make-up, any direct visual judgments should be done under illumination of the same type and color balance as that used in the studio. A final, on-camera observation is desirable.

Identifiable Surfaces. The familiar and easily identified packages and trademarks of well-known products may require particular attention to insure their reproduction with good color fidelity. In some cases, retouching may be required to achieve the desired final result. A number of packages include high-luminance white areas which may have to be toned down toward gray to conform to the luminance range limitations. Colors can usually be accommodated satisfactorily although in some cases it will be desirable to raise or lower the relative luminance of a particular color by retouching with black or white paint. In addition to the use of direct retouching of the packages, slight errors in color rendition can sometimes be rectified by the use of color filters on the camera lens or on the light source. This is, of course, restricted to cases where the package is viewed alone. In general, it is not advisable to attempt corrections by camera adjustment although this, too, may be required in special cases.

Image Sharpness. It has been recommended in monochrome practice[1] that close-up views be used where facial or other fine detail is important. In color, the need for this is even greater because the system imposes a slightly lower limiting resolution than that of monochrome. The present-day camera and receiver equipment further degrades signal transmission, the overall resolution limit being about 15% lower in typical operation than for the monochrome system. This figure should be kept in mind as a guide to how much larger a given object should be made in the final image to insure detail rendition commensurate with that expected in the familiar monochrome system. It should also be noted that resolution and sharpness will be further enhanced if color saturation is kept low, particularly for viewing on monochrome receivers.

Slight additional detail degradation will accompany motion because of relatively long storage time in the camera tubes (operating without redistribution) and because of the slow decay times of certain of the color picture-tube phosphors. Another factor relating to image sharpness is the practice of opening the camera lens aperture one stop wider than in the case of monochrome, to compensate partially for the losses in camera sensitivity. This causes a reduction in depth of focus making it a more critical matter to keep the camera in focus and reducing the depth of playing area which may be kept in focus simultaneously. The increased importance of this problem makes it desirable to examine proposed scenes with a view to using shallow playing areas.

Suggested Staging Rules.

1. For optimum color reproduction, large area surfaces should have a luminance reflectance not over 60% and preferably between 20% and 50%.
2. Small white highlights may be allowed to exceed these limits in order to achieve acceptable luminance contrast for monochrome viewing.
3. Samples of colored materials and paints should be precalibrated as to luminance value against a gray scale.
4. Backgrounds should be low in saturation, matte-surfaced and of medium luminance. Patterns or pictorial material which provide reflectance in all three primary colors should be distributed through a scene — particularly in low-key backgrounds.
5. White clothing must not be worn, gray shirts should be used to represent white, in place of blues or tans used in monochrome practice.
6. Make-up should be judged "on-camera" or at least under lighting of the same type used in the studio. Care should be taken to make all exposed skin match.
7. Identifiable product packages may require slight corrective retouching, particularly in high luminance whites, in order to reproduce correctly in both color and monochrome.
8. Close-up shots should be tightened about 15% as compared to monochrome to retain equivalent fine detail, when it is desired, in the image. Also, scenes may have to be designed with shallow playing areas.

Color Television Lighting

As noted, the hue, saturation and luminance signals derived from a colored surface depend on the character of the incident light as well as the reflectance characteristics of the surface itself. Color television reproduction, like color photography, is influenced by the color quality of the light used in the studio. Whereas, in monochrome television, the color balance of the studio lighting has only secondary effects on the gray rendition of colored objects, in color television, variations in illuminant color can result in drastic changes in color reproduction. Therefore, in addition to the careful adjustment of the base light levels and effects-to-base light ratios, particular care must be given to the nature of the light source itself. The problems, however, are in no way mysterious and are amenable to straightforward solutions.

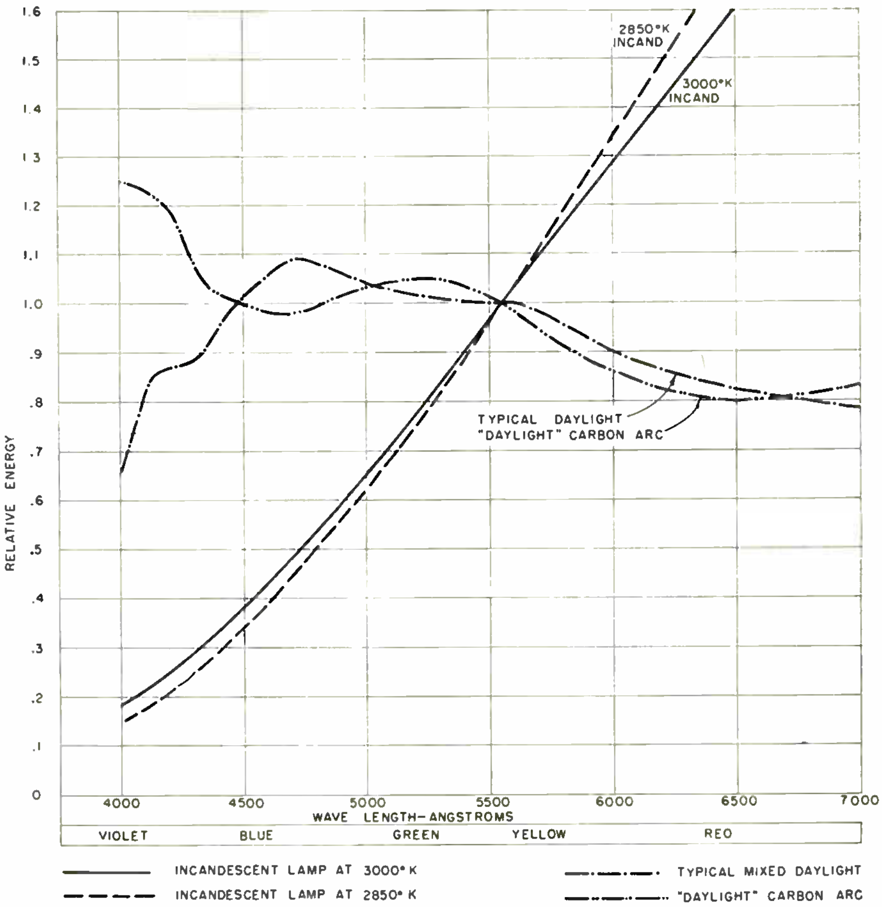


Fig. 9. Spectral Energy Distribution of Typical Light Sources. The spectral energy distribution of the typical light sources shown are sufficiently smooth for use in color-television lighting. Intermixture of incandescent lamps and carbon arcs or daylight requires filter-correction of one of the two sources.

Sources of Light. Sources of light in color television studios must be capable of producing relatively high illumination levels, must be easily adjusted to the same color balance among different units and, above all, must have a spectral energy distribution which follows a smooth curve. The narrow, high-amplitude peaks which are contributed by the low-pressure mercury arc which excites the phosphor in fluorescent lamps, for example, can cause serious distortion in the rendition of certain colors. Although fluorescent lamps have been used in some color television demonstrations and for industrial applications, sharply peaked, discontinuous spectra of this type should be avoided where color fidelity is important.

Sources which have sufficiently smooth spectral-energy distributions include incandescent lamps, sunlight and some carbon arcs. Representative spectra for these sources are compared in Fig. 9. If sources having widely differing spectral distribution are to be intermixed, they must, of course, be corrected by means of filters to match in relative energy level throughout the visible spectrum. Incandescent sources are the most suitable for present-day television-studio operation because, in addition to a smooth spectrum, they are convenient to handle and maintain, they are readily available in a wide range of sizes and types and they may be easily adjusted to obtain a spectral match among units.

Incandescent Lamps. Although the spectral distribution of incandescent lamps follows a smooth curve, there is not an equal amount of energy in all parts of the spectrum. In general, the energy is higher at the red end of the spectrum and includes components in the invisible, infrared region. There is, however, ample relative energy in the blue end of the spectrum to enable color correction to be introduced optically at the camera to give the effect of an equal energy distribution. The correction is facilitated because the camera pickup tube has its highest sensitivity in the blue region so that the camera response and the illuminant distribution are somewhat complementary (Fig. 2). It is of greatest importance that the spectral distribution be made essentially the same for all light sources so that the correction introduced

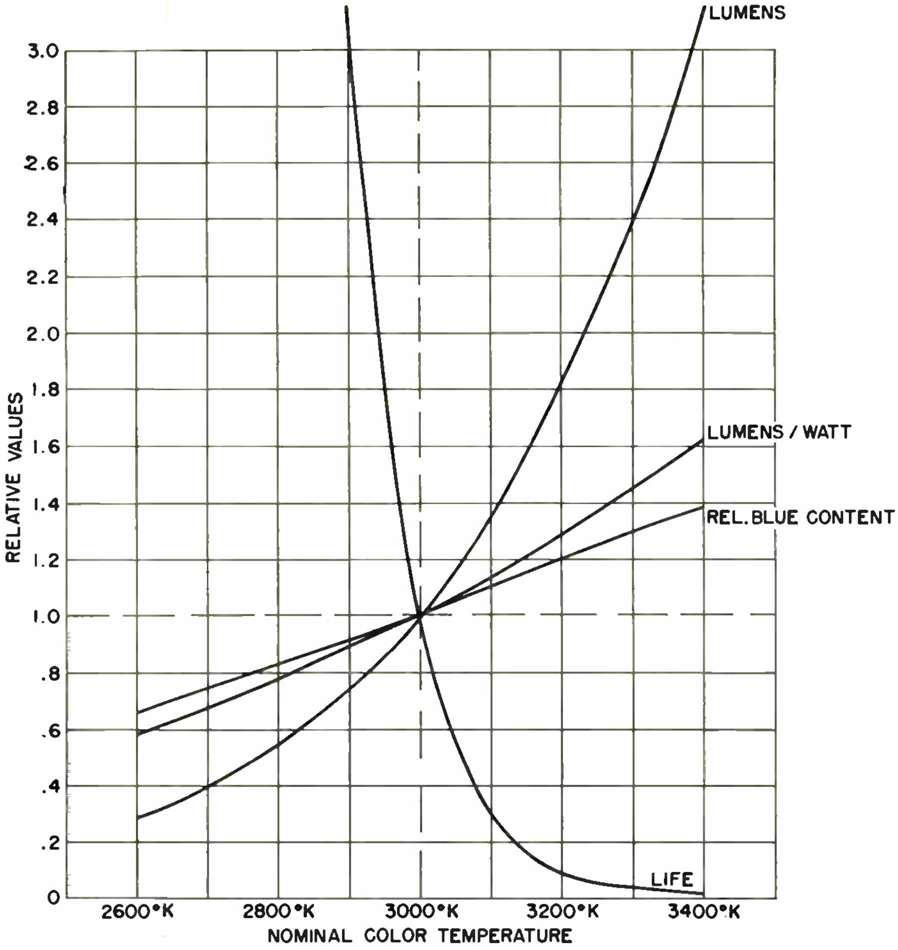


Fig. 10. Incandescent Lamp Parameters. Relative values of incandescent-lamp parameters are arbitrarily set at unity for a nominal lamp color temperature of 3000 K to show the relations between total light output (lumens), efficiency (lumens/watt), the relative energy at the dominant wavelength of the camera blue primary compared to that at the red primary (relative blue content) and (life) as the lamp color temperature is varied.

at the camera will be usable throughout the studio area. This places some restrictions on the choice of lamps and on dimming adjustments.

Light is produced in an incandescent lamp by passing an electrical current through a small filament of tungsten wire, heating the wire to the point where it glows. As the current flow is increased, the heat of the filament is increased and the metal progresses from being "red-hot" to being "white-hot." As it is characteristic for the spectral distribution of the radiated energy of glowing, incandescent material to follow a discrete curve for any particular temperature of the material, it is common practice to describe energy spectra for incandescent lamps in terms of "color-temperature." Thus, a 2850 K lamp has a spectrum similar to that which would be produced by a sample of idealized radiating material heated to a temperature of 2850 K. The Kelvin scale of temperature has degree units equal to those of the Centigrade scale, but has its zero at −273 C. As the temperature is increased, the relative energy level in the blue region increases somewhat, causing the progression from a reddish toward a whiter color balance as noted above.

There are intrinsic relations for a given size of lamp (size and shape of filament wire) among the total light output, the efficiency, the color temperature (and thus spectral distribution) and the life of the lamp.[9] These relations are plotted with respect to color temperature in Fig. 10, from which it is apparent that the higher color-temperature lamps (such as the 3200 K color photography series) produce more and somewhat "whiter" light with a drastically reduced life. In color television studios there appears to be no reason to use other than the general service series of lamps which range from 2870 K to 3000 K in color temperature, there being ample blue energy present to enable the camera to be properly color balanced even with color temperatures as low as 2300 K. The important point is to hold all lamps in a studio within a limited range which permits them to be intermixed.

As a rule of thumb, the color temperature of a lamp may be assumed to change about 10 K for every volt departure from normal applied line voltage (120 v). In practice, it is possible to intermix lamps which are within a range of ±100 K, requiring voltage to be held within ±10 v for a given type of lamp. This allows a reasonable range of dimming adjustment for purposes of balancing levels and ratios, a 10-v reduction in applied voltage corresponding to a 30% reduction in light level. However, greater amounts of dimming adjustment should be used sparingly because they produce a large enough change in color balance to be noticed through the television system. The relative spectral energy distributions for several lamp operating conditions are compared in Fig. 11. Dimmer adjustments may be used within limits to balance out differences among lamps of different wattage ratings which have different normal color temperatures, to compensate for aging effects (a drop off of as much as 50° sometimes taking place), or to compensate for color changes introduced by the fixtures (as much as ±50°). In critical work, such adjustments may be made by noting relative photocell meter readings through red and blue filters, such as Wratten No. 25, red; and No. 47, blue. Color-temperature meters have been described[10] which provide a convenient, calibrated means for making this type of measurement. Meters capable of reading red, green and blue spectral reflectance are useful where these three regions of the spectrum are desired to be measured.[11]

Some improvement in light-to-heat energy ratio on the stage area may be obtained by fitting all incandescent fixtures with infrared absorbing filters. For example, Aklo #3962, cut into 1-in. strips and held loosely in frames to prevent fracture from heat-induced strains is suitable for this purpose. The nuisance of the added element on each light fixture must be weighed against the slight improvement in comfort for the performers. There is no advantage with respect to camera performance.

Lighting Levels. The primary color filters in the color television camera reduce the amount of light energy reaching the camera tube for any one color to less than $\frac{1}{3}$ the amount which reaches the tube in a monochrome camera. Additional losses occur in added optical elements and in the compensating filters used to achieve balanced spectral response. The net result is to make the color camera sensitivity for correct exposure conditions about $\frac{1}{5}$ that of a monochrome camera. This applies to both the Chromacoder field-sequential camera and to the tri-tube camera. Although a less sensitive pickup tube is used in the latter it is operated at a relatively lower exposure with respect to its saturation point and thus requires a similar light level. It is recommended that about half of this decrease in sensitivity be made up by opening the camera lens one stop and the remainder by increasing the light level by a factor of 2.5:1. As compared to the recommended monochrome lighting level[1] of 120 ±10 lm/sq ft (footcandles) with a lens stop of $f/8$ the color lighting level should be 300 ± 20 lm/sq ft with a lens stop of $f/5.6$. For areas which are intended to be reproduced similarly, the tolerance should be observed over the entire playing area including the background and due consideration should be given to uniformity for all camera angles.

It is worth noting that this increase in base-light level requires an increase from 60 w/sq ft of actual studio playing area to 150 w/sq ft for color. It is suggested that a minimum of 50 w/sq ft of total studio floor area be provided in color studios, playing area normally utilizing ⅓ of the total floor space.

Effects light should be employed as in monochrome except that ratios of effects-light components such as back light, modeling light, key light and eye light to the base light must be reduced slightly over those used for monochrome although at some sacrifice in the contrast of the monochrome reproduction from the color signal. Compromises must be made in individual cases on an artistic-judgment basis, observing the result on both monochrome and color-picture monitors. As target values for effects-light components, it is recommended that back light be set between ½ and 1 times base light and that modeling light, key light or other side light be set between 1 and 1½ times base light. Eye light and other specular highlight sources must be adjusted to achieve the desired effect, small, sharp highlights serving to enhance the apparent monochrome contrast. Care must be taken to maintain the level of the light reflected from background areas within a range from ⅔ to 1 times the light reflected from performers' faces, requiring that the incident light level on the background be about equal to that on the performer for normal scenes.

The relative incident light levels may be measured with ordinary photoelectric exposure meters in the manner used in monochrome television. That is, base light should be measured first and the effects lights added and measured individually. In cases where unusual care is required, supplementary measurements of reflected light may be made, the ratio of the lightest to the darkest areas of the scene being held to not exceed 5:1 for large areas and 20:1 for small areas.

Special Effects. The possibilities for special effects in color lighting are almost unlimited. The few precautions which must be observed include: (1) Effects should be avoided which, although satisfactory in color, are meaningless or even confusing in monochrome reproduction; (2) Care should be taken to prevent purposely colored effects-light from optically spilling into adjacent areas of the scene thus distorting the color rendition of familiar objects; (3) As in the case of staging, strong saturated background colors which might interact on camera tube transfer tracking should be avoided.

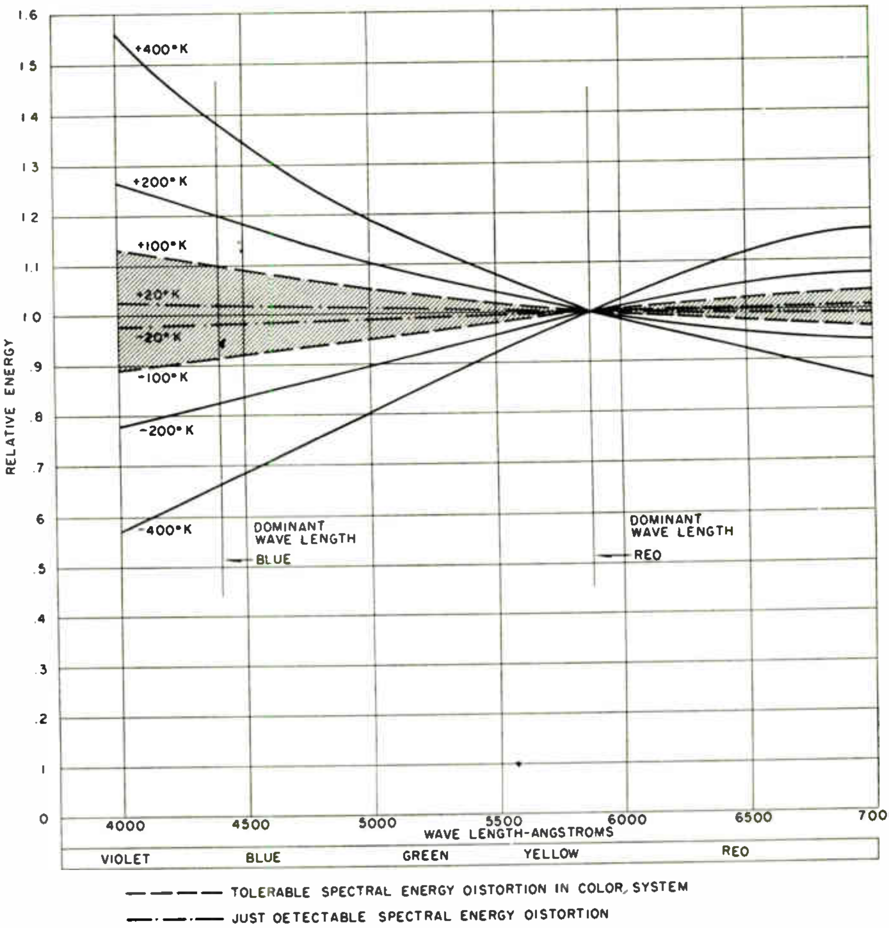


Fig. 11. Spectral Distribution vs. Color Temperature. The curves of the relative spectral distribution of incandescent lamps as a function of color temperature have been normalized to unity at the dominant wavelength of the camera, red-taking primary and plotted so the camera response is equally balanced throughout the spectrum for the reference value. The minimum detectable variation refers to carefully controlled test conditions. The tolerable distortion limits correspond to conditions found not noticeable in typical operation.

Fixtures equipped with dyed-gelatin filters (stage "gelatins") may be used to provide readily changed background colors on a gray cyclorama backdrop. Three sets of fixtures fitted with red, green and blue gelatins and so positioned as to have overlaying coverages, may be differentially dimmed to produce almost any desired color at any desired level of luminance. It is to be noted that there is almost no shift in color as a filtered lamp is dimmed because the filter passes only a very limited bandwidth within which lamp spectrum variations are negligible. Dimming of color-filtered lamps may, therefore, be done without restriction.

Low key effects may be handled by the color television system although it is desirable to avoid large dark areas because very slight differences in camera shading signals may show up as color-shading effects. A "fade-to-black" may, if shading and setup adjustments are not very precisely made, become a fade-to-magenta; on the other hand, if camera adjustment is correctly done, the tri-tube camera will be less subject to the spurious effects often encountered in monochrome operation. To be safe, lighting and staging should be arranged to insure the presence of at least some luminous area in all parts of the picture raster. The dark areas may be allowed to go as low as 100 lm/sq ft in incident light.

Spotlight effects can be used if they are adjusted to produce a total front light—including base light — which does not exceed 1½ times the normal base-light level. Also, the background which appears behind the performer in the picture should be lighted to have a reflected luminance between ⅔ and 1 times that of the performer's face. Arc spotlights, of course, must be color corrected with filters or gelatins to produce a color match, as observed visually, with the incandescent lamps used in the studio unless a colored effect is desired. The carbon-flame arc and high-intensity arc have sufficiently uniform spectra to make such correction and intermixing possible.[12]

Similarly, the light from rear-projection devices using arc lamps must normally be filtered to match the studio illumination in color balance. As an example, a 90-amp carbon-arc slide projector used with a neutral screen has been found to be satisfactorily corrected with the equivalent of a Wratten No. 86B filter. In rear projection, arc sources will generally be required for the coverage of any area larger than 20 sq ft because of the high ambient studio light and the need to balance foreground and rear-projection luminance levels more closely for color. Precautions must be taken to obtain steady, flicker-free illumination from arc sources. Additional color correction will often be required to obtain the desired effect from any particular color slide being used.

Suggested Lighting Rules.

1. Use light sources which have smooth spectral energy distribution curves, such as incandescent lamps.
2. The standard service series of incandescent lamps, having spectral distributions corresponding to color temperatures of between 2800 K and 3000 K, are recommended.
3. Maintain the color balance among source units and fixtures within ±100 K (corresponding to ±10 v).
4. Do not dim unfiltered lamps to lower than 90% of rated voltage (which corresponds to 70% of rated lumen output).
5. Use a base-light level of 300 ±10 lm/sq ft.
6. Use a back-light level of $\frac{1}{2}$ to 1 times the base-light level.
7. Use a side-light level (modeling or key) of 1 to $1\frac{1}{2}$ times base-light level.
8. Measure reflected-luminance levels with a spot brightness meter in critical work and hold large areas of the scene within a 5:1 range.
9. Use "gelatin" filters on three intermixed sets of background or cyclorama lighting fixtures to obtain a wide gamut of background colors.
10. Correct with light filters the light from carbon arcs used in rear projection or spotlights to match the light from the incandescent studio lights.

Summary

As compared to monochrome practices, color-television live-studio operation requires a much more careful and critical approach. Cameras and associated equipment must be carefully adjusted as to spectral response, transfer characteristics, tri-channel registration and resolution. Staging must be designed to make the most out of the present facilities in order to produce artistic results in both color and monochrome. Luminance values must be relatively lower than in monochrome studios and color saturation must be played down in large areas. However, color can be used almost without limit in smaller areas and objects. Lighting, in turn, must be controlled as to spectral energy distribution and a higher and more evenly distributed base level must be provided. Effects-light ratios are slightly reduced. Dimming is restricted somewhat except in the case of color-filtered fixtures used for special effects. Almost unlimited color effects are possible through combinations of staging and lighting control so long as the transmitted signal provides the luminance contrast required for monochrome reproduction as well as the color contrast (with reduced luminance range) desirable in color reproduction.

Future progress in color-television studio operation depends to a large degree on the development of cameras having better resolution, improved stability of transfer characteristic and a greater luminance acceptance range. Improvements in color picture tubes are also needed to realize the full potentiality of the NTSC system of transmission. However, even with present equipment, good results can be obtained through careful attention to details in camera operation and in studio staging and lighting practices.

Acknowledgment

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Discussion

Stuart M. Cadan (Naval Photographic Center): As in the case of monochrome television, when you increase target voltage you must increase the beam current proportionately to discharge the target. This increases the noise level. What is the effect of this on the color television image?

Mr. O'Brien: One must achieve a compromise adjustment. Because noise is increased, it is common to run beam current at the lowest value which will just discharge highlights. Incidentally, the use of a limited range of luminance values in the stage setting, by holding highlights down, makes it possible to keep beam current low.

An interesting additional point to note is that the noise components from the three camera channels add in quadrature, whereas the luminance portions of the signals are combined linearly providing a gain in effective signal-to-noise ratio. Also, the close-spaced (target to target-screen spacing) type image orthicon used in tri-tube devices has an inherently better signal-to-noise ratio than the tube more commonly used in monochrome cameras.

Discharge Lamps and Color Television

By R. E. PUTMAN, J. F. WIGGIN,
C. N. CLARK and H. G. WILLIAMS

New types of high-efficiency discharge lamps are being used increasingly to light many areas, including sports stadiums and arenas where color TV pickups are often made. Colorimetric calculations and live TV tests show that, despite some color distortion due to the light-source spectra, TV color quality is adequate for remote pickups of sports and other events. Suggestions are given for lighting-system design and for meeting operational problems related to remote pickups under discharge lamps.

New types of high-intensity discharge lamps are being used more and more for general lighting in areas where color-television pickup occurs. Mercury vapor lamps have long been accepted in street lighting and industrial lighting applications. Now the introduction of high-pressure sodium and metal-halide discharge sources, plus better color correction for mercury lamps, has brought these sources to sports arenas, stadiums and exhibition halls. Their high efficiency, good optical control and long life result in lighting systems that produce more light, less heat and a lower overall cost per lumen-hour than incandescent lamp systems.

Color television requires higher levels of illumination — particularly on vertical or near-vertical planes — than general lighting systems usually supply. Levels in the range of 200 to 300 fc maintained in service are presently suggested for sports events in several reports published by Illuminating Engineering Society committees and members.[1–3] Satisfying these requirements with incandescent lighting alone could result in excessive heating loads for air-conditioning equipment and the possibility of uncomfortable radiant heating effects even if the air is cooled. An all-incandescent lighting system also involves relatively expensive wiring and high electrical energy costs because of the wattage required. The discharge sources, then, are particularly desirable for supplying high levels of illumination over large areas where lighting will be designed for color television as well as for the seeing requirements of the spectators present.

Questions remain of what effect these sources will have on picture color quality and of what practices to follow to insure best results when televising with light from those sources. The effects of the color properties of three important discharge sources (Fig. 1) on a color television system are examined and compared with the effects of incandescent lamps. The results of both theoretical calculations and live tests are reported. Suggestions for lighting system designs and operational considerations for televising with these sources are given.

A contribution submitted on October 14, 1968, and in final form on February 20, 1969, by Richard E. Putman and Joseph F. Wiggin, Visual Communication Products Dept., General Electric Co., Electronics Park, Syracuse, NY 13201; Charles N. Clark and H. G. Williams, Large Lamp Dept., General Electric Co., Nela Park, Cleveland, OH 44112.

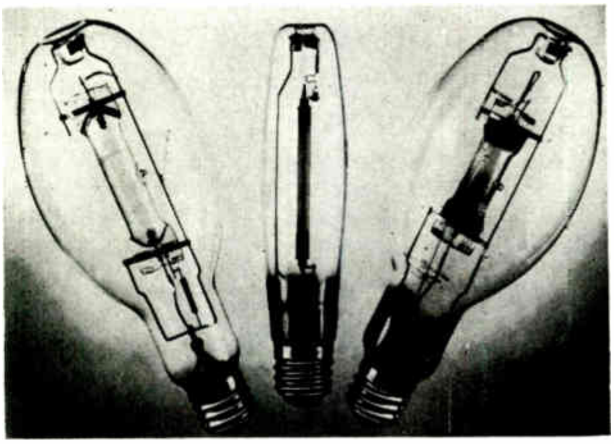

Fig. 1. Examples of 400-W high-intensity discharge lamps. Left: clear mercury lamp (Deluxe White mercury lamp has phosphor coating of outer bulb); center; Lucalox™ high-pressure sodium lamp; right: Multi-Vapor™ metal-halide lamp.

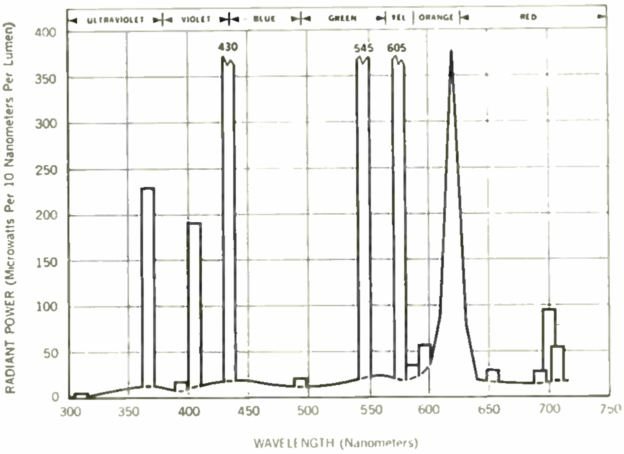

Fig. 2. "Deluxe White" phosphor-coated mercury lamp — initial spectral power distribution of typical 400-W size.

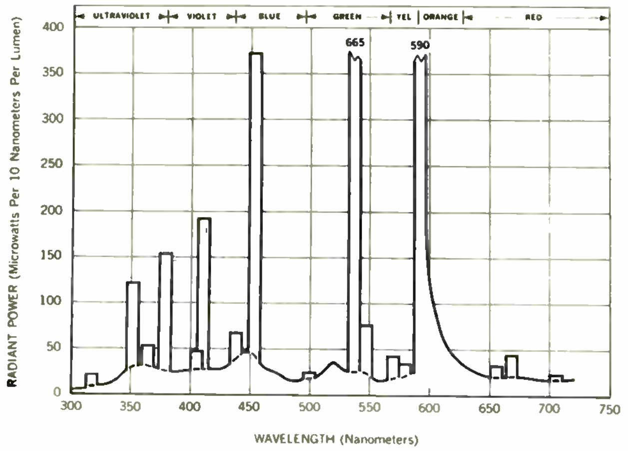

Fig. 3. Metal-halide lamp — initial spectral power distribution of typical 400-W size.

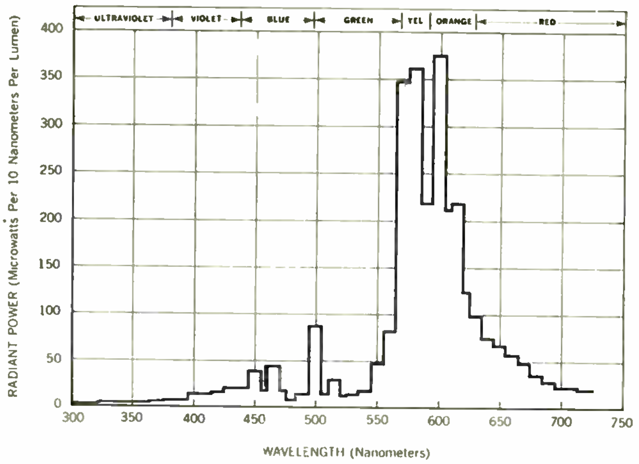

Fig. 4. High-pressure sodium lamp — initial spectral power distribution of typical 400-W size.

The Sources

The arc in a mercury vapor lamp generates "lines" of energy in the ultraviolet, blue, green and yellow portions of the spectrum. In the newest mercury lamps (called "deluxe white"), an europium-doped yttrium-vanadate phosphor coating of the outer bulb converts the ultraviolet energy to red light. The result of the added red is a white light that, to the eye, is fully as acceptable in color quality as that from any of the standard white fluorescent lamps. The efficacy of deluxe white mercury lamps in the 400-W size is 54 lumens per watt (lm/W) initially. In service, the average efficacy is 39 to 48 lm/W depending on whether lamps are group replaced or allowed to burn out. Efficacy of the 1000-W size — often used in high-mounted installations — is about 8% higher initially. Apparent color temperature of the light is about 3600° K. Figure 2 shows the spectral power distribution.

A second discharge lamp type (called "Multi-Vapor"*) uses metal halides in addition to mercury to produce a large number of spectral lines. These lines are located throughout the spectrum, producing white light with an apparent color temperature of about 5000° K. Initial efficacy of 400-W metal-halide lamps is 79 lm/W; average in-service efficacy is 58 lm/W. Initial lm/W of the 1000-W size is about 14% higher. Figure 3 shows the spectral power distribution.

High-pressure sodium lamps (called "Lucalox"*) are the most efficient of the high-intensity discharge sources. Operating a sodium-vapor arc at high pressure results in white light but requires an arc tube material that will not be corroded by the sodium. The quartz used in mercury and metal-halide arc tubes is attacked by sodium vapor, so a new material — a pure form of aluminum oxide — is used to contain the arc. Initial efficacy of the 400-W lamps is 105 lm/W; in service the mean efficacy is 96 lm/W. Apparent color temperature of the lamps is about 2200° K. Their spectral power distribution is shown in Fig. 4.

Incandescent tungsten and tungsten-halogen (Quartzline*) lamps have an efficacy of about 21 lm/W when operated at 3000° K, and about 27 lm/W at 3200° K. Typical spectral power distributions are shown in Fig. 5. In comparing the efficacies of incandescent vs. discharge lamps, power consumption of the discharge lamp ballasts should be taken into account; they were not included in the efficacies cited earlier. A broad general comparison of incandescent and tungsten-halogen lamps with all types of discharge lamps suitable for television lighting was made in an earlier paper.[4]

Color Calculations

The effect of these three types of discharge lamps on the televised colors of eight test objects was investigated. The intent was to predict the type and size of color shifts resulting from the use of these lamps alone and in combination with tungsten lamps, when viewed on the monitor of a TV chain adjusted for white balance in each case. The reference for color shift was tungsten illumination.[3]

Such predictions, combined with actual viewing under laboratory and field conditions, should provide helpful guidance in application of the lamps and operation of the TV system. Furthermore, such a calculation procedure could possibly lead to a "TV Color Rendering Index" analogous to the Color Rendering Index[6] now being applied to

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* Registered trademark, General Electric Co.

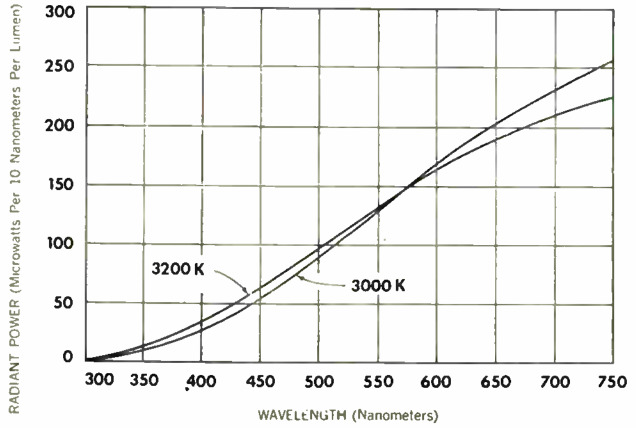

Fig. 5. Incandescent or tungsten-halogen lamps — spectral power distribution at various apparent color temperatures.

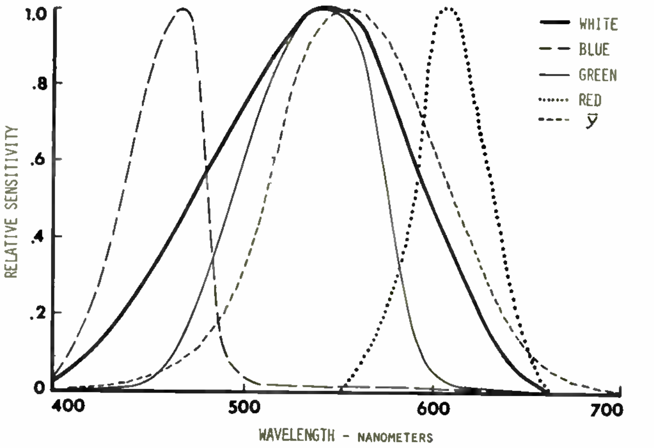

Fig. 6. Relative spectral sensitivity of the three color channels plus the white (or luminance) channel for a typical 4-tube color camera. The $\bar{y}$ curve is the spectral luminous efficiency of the normal human eye (USAS Z7.1-1967). Curves are all normalized to peak at 1:00; therefore, differences in absolute sensitivity are not depicted.

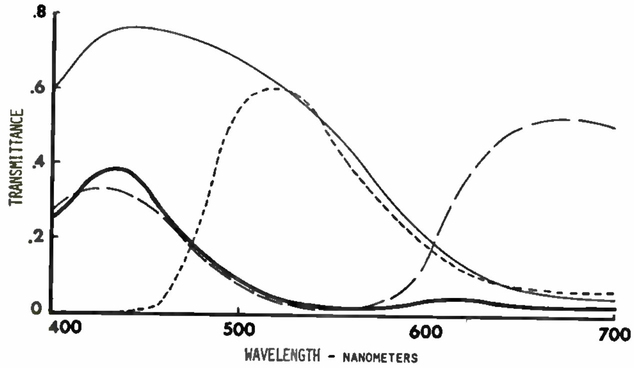

Fig. 7. Spectral characteristics of four test colors.

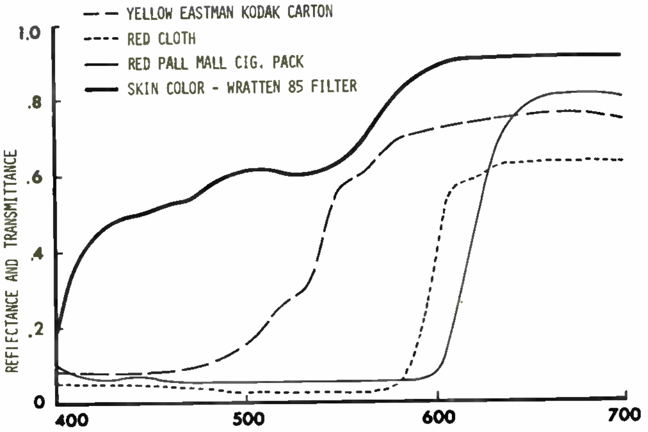

Fig. 8. Spectral characteristics of four test colors. Wratten #85 is only a moderately good approximation to skin color, but is useful as a convenient, reproducible laboratory representation of the color of human skin.

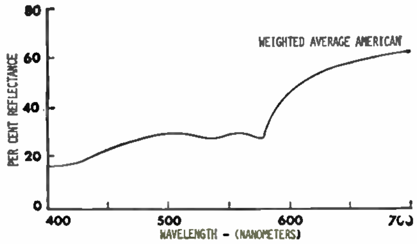

Fig. 9. Spectral reflectance of human cheek, without makeup. Data are for a weighted average of the U.S. populace in 1948, including variations in geography, race, occupation and sex.[5]

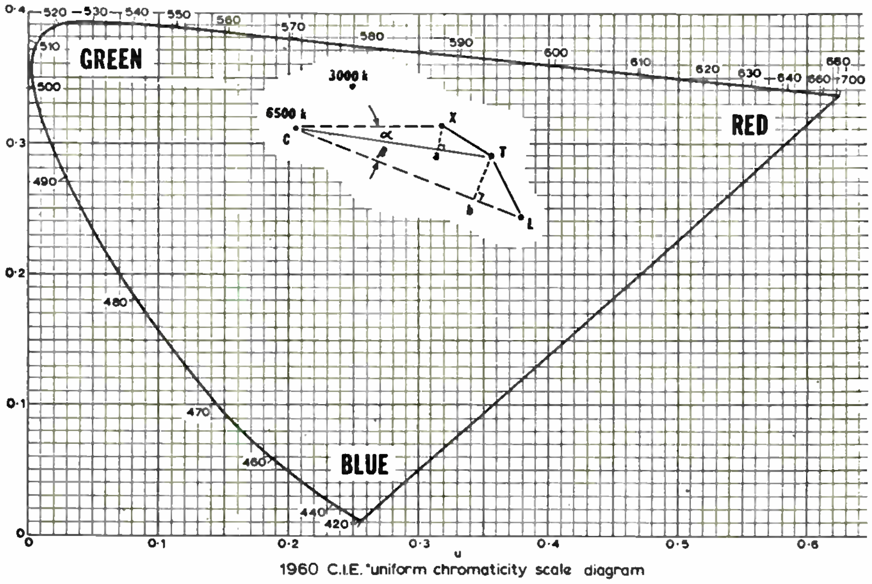

Fig. 10. 1960 CIE Uniform Chromaticity Scale diagram.

L = object color under 6500°K blackbody source, viewed directly.

T = object color under 3000°K tungsten lamp, viewed on color monitor trimmed at 6500°K white.

X = object color under test lamp or combination of lamps, viewed on color monitor trimmed at 6500°K white.

aX = measure of hue shift of color sample under test source vs 3000°K tungsten, both viewed on monitor

bT = measure of hue shift when color sample under 3000°K tungsten source is viewed on monitor at 6500°K white, vs same sample viewed directly under 6500°K blackbody source. In effect, this is a measure of the inherent hue shifts due primarily to the color transfer characteristics of the TV chain.

aT = a measure of saturation change due to test lamp vs 3000°K tungsten lamp.

bL = a measure of saturation change inherent in the TV system.

TX = vector chromaticity shift of color sample under test lamp vs 3000°K lamp, viewed on monitor.

LT = vector chromaticity shift of color sample viewed on monitor vs viewed directly.

Luminance changes are not shown in this diagram.

light sources for ordinary visual situations.

The camera-response curves used are shown in Fig. 6, and spectral data on the test objects are shown in Figs. 7, 8 and 9. The skin color used was the "weighted average American."[5]

The chromaticities of the eight colors were calculated as reproduced on a color monitor adjusted for a chromaticity equivalent to D_{6500} and fed from a four-tube color camera using 55875 tubes. The electronic processing equipment was assumed to be error-free so that gamma correction, encoding, decoding and tracking would introduce no errors in color reproduction. The computations were based on the assumption that the camera was adjusted for white balance — that is, all four signal voltages would be at the reference level of 100 IRE units on the waveform monitor when the camera was viewing a white card. This implies that there is plenty of reserve gain in the processing amplifiers and that no signal-to-noise ratio or lag problems exist due to shortage of light of any color.

The reproduced chromaticities of the colors were computed for the CIE Uniform Chromaticity Scale color triangle (the so-called "*u,v*, diagram")[12] in order that chromaticity shifts would have nearly equal weight for all the test objects, no matter where they fall in the triangle. The standard of comparison used was a system with the monitor set to match the chromaticity of Illuminant D_{6500} and the scene illuminated by 3000° K tungsten light alone. These conditions are used as a base of comparison, because we felt that reproduction by the camera and monitor would thus be acceptable by most observers. We recognize that this system is not perfect, but we believe that it does provide the most direct and readily understandable base.

For purposes of comparison, we assigned numerical values to the computed chromaticity shifts. The units are based on distances on the *u,v* diagram — each unit representing 0.001 in any direction on the diagram (Fig. 10) or 1/10 the width of one of the small squares. In terms of perceived color, a shift of 5 units would approximate the amount of color change introduced by a Wratten color-correcting (CC) filter of 0.05 d to 0.10 d, depending on the exact chromaticity involved. We believe that, for average observers, a hue shift of 10 units or a saturation shift of 15 units would represent the threshold of significant color change of typical scenes on a TV monitor. Color shifts less than these would, in many cases, not even be noticed.

The results of the calculations are shown in Table I and can be summarized as follows: The most significant effect is the relative weakness of the red signal when the colored subjects are illuminated by any of the discharge lamps. As a result, magenta colors are shifted toward blue, yellows toward green and reds are desaturated by significant amounts as compared to tungsten illumination. In addition, cyans are shifted toward blue, greens toward yellow and blues toward magenta, but these shifts are generally small enough so that the resulting color reproduction would be judged good. Hue shifts in the red region are all very slight. As would be expected, an equal-lumen mixture of tungsten with a discharge lamp approximately halves the size of the shifts, so that only the desaturation in the reds would be considered a significant effect on color reproduction.

Table I. Calculated Chromaticity Shifts of Eight Color Samples. (Units are thousandths on *u,v* diagram.)

Lamp	Hue Shifts		Saturation Shifts		Vector Shifts
	Average absolute shift	Samples shifted over 10 units	Average absolute shift	Samples shifted over 15 units	Average absolute
Sodium	8.8	Mag Cyan → Blue Yellow → Gr	20.2	Blue + Red-Yellow-	24.8
Metal-Halide	9.3	Mag → Blue	18.5	Red-	23.8
Deluxe Hg	9.9	Gr → Yel, Yel → Gr Mag Cy → Bl, Bl → Mag Mag → Blue	7.6	Blue + Yellow-	13.4
Tungsten	5.2	Blue → Cyan	32.5	All but Yellow	33.1

Perhaps most significant of all the calculated results are those obtained for the skin color of Fig. 9 which are shown in Table II.

Table II. Calculated Chromaticity Shifts of Weighted Average American Complexion. (Units are thousandths on *u,v* diagram.)

	Hue shift of skin	Sat. shift of skin
Sodium........	2 → yellow	7 –
Metal Halide...	4 → yellow	6 –
Deluxe Mercury.	5 → yellow	1 –
Tungsten.......	0.7 → red	16 –

Although in all cases reproduced color was shifted in hue slightly toward yellow and was slightly desaturated compared to tungsten, the shifts were so small as to be considered of negligible importance.

The choice of 10 units in hue and 15 units in saturation as the limits for significant color shifts is, of course, arbitrary. Seeking confirmation of their appropriateness, we set up colors similar to the test colors in the laboratory and televised them under conditions approximating those assumed for the calculations. The opinion of several observers was that the color shifts observed on the monitor matched the predicted directions, and that only the larger shifts were noticeable. Complexions observed at the same time appeared acceptable under all the lamps, confirming the calculated prediction that complexion shift would be relatively small.

The vector shifts in Table I represent the total chromaticity change (hue and saturation combined) for each color. Averaging the vector shift gives a rough measure of the total "color distortion" of the source. It is interesting to note the vector shifts for tungsten light, which indicate the color distortion inherent in the TV system. The average hue shift for tungsten is 5.2, the saturation shift is 32.5 and the vector shift is 33.1. The shifts for the discharge lamps are *in addition* to these shifts, and are generally smaller. It should be noted that the shifts for tungsten light only represent the TV system as we know it now. All calculations and results are based upon the phosphors that are similar to what is being used in color kinescopes today. The coordinates used were:

	u	v
R	0.489	0.351
B	0.181	0.107
G	0.122	0.373

This compares with the NTSC phosphor coordinates of:

	u	v
R	0.477	0.352
B	0.156	0.134
G	0.076	0.384

If the original NTSC values had been used the errors for tungsten light would have been reduced. The use of electronic masking will greatly reduce the shift in hue and saturation, and improvements in spectral sensitivity of the pickup tubes will further reduce the shift. A combination of improved spectral response of the system and the use of electrical masking will give much-improved system performance.

The exact values obtained by the calculations discussed here will obviously depend on the television system spectral sensitivity, transfer characteristics, monitor adjustments and tolerances on all elements. The test colors used are of great importance. The influence of such other factors as luminance shifts and observer adaptation when viewing the monitor, has not been explored, and may need to be taken into account in any future studies. Thus, the calculations should probably be taken as indicative, but not conclusive.

Lighting Experiments

To help define the requirements for color televising of indoor sports in arenas and gymnasiums using discharge sources, informal experiments were conducted using a four-tube color camera system, a monitor and various types of light sources. The work was done in an industrial lighting demonstration area, where various discharge lamps are used in ceiling-mounted industrial lighting equipment of the type frequently used for lighting arenas and gymnasiums (see Fig. 11).

Live subjects were televised under "deluxe white" mercury, metal halide and high-pressure sodium sources in the overhead luminaires, both with and without supplementary lighting from tungsten-halogen incandescent lamps in portable lighting equipment.

The camera chain was balanced for each lighting condition and a photograph was taken of the subjects on the monitor for that condition. Daylight negative color film (Ektacolor CPS) was used without camera filters; when slides and prints were made from the negatives, each was processed equally. Figures 12 and 13 illustrate the types of photos obtained.

The tungsten-halogen supplementary lighting was used in anticipation of the dual problem of insufficient vertical-surface illumination and poor modeling effects when overhead lighting is used alone. Figure 12 shows the subjects under the first row of overhead fixtures, simulating a sideline location on a basketball court that has lighting equipment only over the court. Adding supplementary lighting at 45° was necessary to eliminate the deep shadows and make the vertical surfaces properly visible (Fig. 13). The problem is, of course, not as serious at locations within the court. The ratio of horizontal-surface illumination to vertical-surface illumination for the various scenes tested was between 3 to 1 and 10 to 1 without supplementary lighting, between 1 to 1 and 3 to 1 with it. The ratio varies according to subject location within the court. Horizontal-surface illumination from the overhead discharge sources alone varied from 200 to 500 fc depending on the source. Vertical surface-illumination from the overhead and

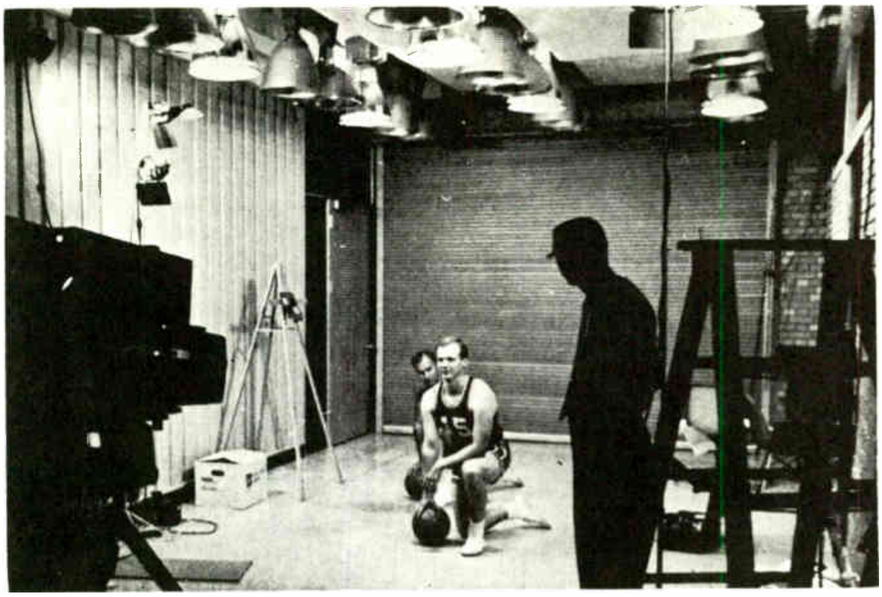

Fig. 11. An overall view of the test site. Discharge sources were used in overhead industrial-type lighting equipment, with supplementary lighting from portable tungsten-halogen units seen at upper left.

supplementary sources together varied from 100 to 400 fc.

The reactions of those observing the test were that all the televising under the discharge sources, both with and without supplementary lighting, produced pictures with color quite acceptable for indoor sports coverage. This checks with the results of the calculations and laboratory observations noted above. Furthermore, lighting with different sources from different directions did not produce noticeably unnatural color effects on the subjects. This should not be surprising, because we are accustomed to seeing key and fill light of different colors outdoors.

It was also concluded that supplementary lighting should be added to typical arena overhead lighting systems to achieve good modeling and sufficient vertical-surface illumination — particularly for sideline locations.

The desirable levels of illumination were found to agree with those stated by others.[1-3] While a picture, of sorts, could be obtained with about 50 fc on vertical surfaces, a latitude of at least two additional aperture stops (four times the footcandles) is desirable for close-ups using lens-extenders, for variable field conditions such as low-reflectance scenes, for better depth of field, and to overcome variations in camera sensitivity and depreciation of electronic equipment.

Lighting System Design Considerations

Lighting system requirements for color televising sports events has been documented elsewhere,[1-3] and installations have been described.[7-10] Specific lighting design considerations will be presented here — particularly as applied to indoor sports.

The overhead lighting system in the typical gymnasium, arena or field-house supplies insufficient quantity and quality of illumination for color television. When high-intensity discharge sources are used, they are generally in typical industrial luminaires which concentrate light downward. The resulting vertical-surface illumination within the lighted area will be one-fourth to one-third the horizontal illumination. If lighting is located only over the playing area, the illumination at the sideline on a vertical surface facing outward can be less than one-tenth the horizontal-surface illumination.

For an existing installation using overhead lighting or a proposed installation where televising will be infrequent, a separate supplementary lighting system is suggested, based on the tests described above. The best choice is probably a system employing tungsten-halogen lamps, because of its low initial cost — the major consideration where televising is infrequent. If televising will be frequent, a discharge source should be considered because of its lower operating cost. Here, the high-pressure sodium or metal-halide lamps may be more appropriate than phosphor-coated mercury lamps because of their better optical control.

The supplementary lighting system must control light accurately so as to produce maximum illumination where it is needed most (usually at the sideline) and to prevent glare. Figure 14 shows a suggested location for supplementary lighting equipment. An elevation of about 45° above the near sideline will permit effective amounts of light to be directed to this area without excessive glare. Shielding of the lamps should be provided

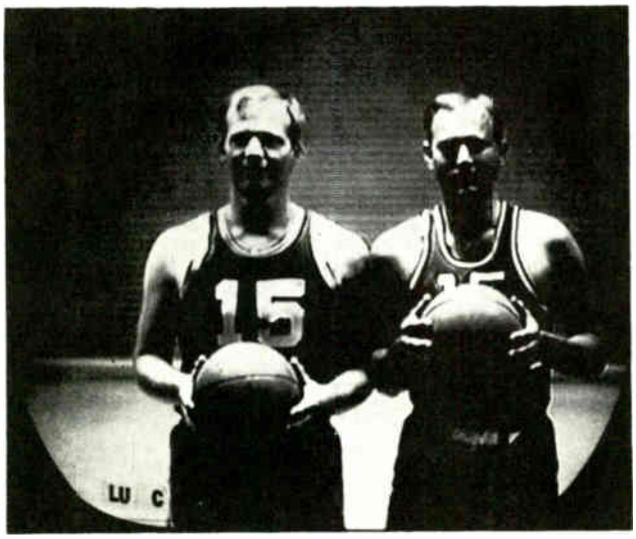

Fig. 12. A photograph of the monitor with lighting in the scene coming from overhead discharge sources alone. This simulates a sideline position of players with no lighting equipment located ahead of the subjects. The ratio of horizontal to vertical surface illumination is about 10:1.

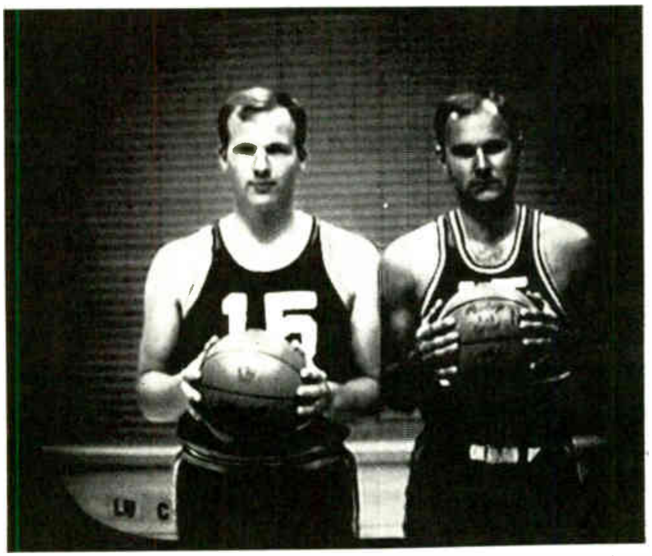

Fig. 13. A photograph of the monitor with overhead lighting from discharge sources as in Fig. 12, and with added front lighting at 45° elevation from tungsten-halogen lamps. The ratio of horizontal- to vertical-surface illumination is about 1.5:1.

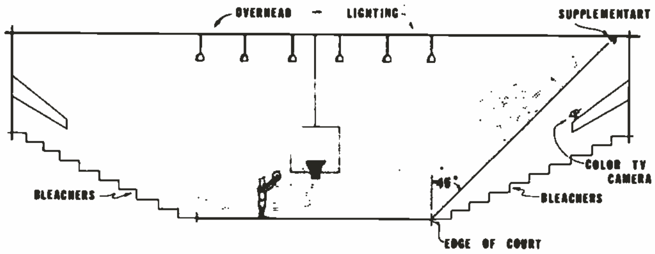

Fig. 14. A suggested approach to lighting a gymnasium for television pickup. Light from supplementary equipment, added to light from the overhead system, solves problems of low illumination level and poor modeling effects. Care needs to be taken to shield the supplementary equipment, to prevent glare for spectators on the opposite side of the gymnasium.

for spectators on the opposite side. Some light should be provided toward one or both end zones if camera sight lines are through the ends of the court.

If lighting is desired for televising the spectators, additional lighting equipment should be located at an angle of about 45° above the spectators' eyes.

If an overhead lighting system produces too little light relative to that coming from a supplementary system at the side, the results can be strong shadows of the players cast across the floor, flat lighting with no highlights and a low visual adaptation level for spectators and players, making them more conscious of the supplementary lighting. Proper quantities of illumination from overhead lighting both for spectator enjoyment and television pickup will probably require discharge lamps because of operating cost and heat considerations. A ratio of horizontal to vertical surface illumination between 1:1 and 3:1 is generally appropriate.

Consideration should be given to lighting indoor sports areas, particularly where color televising is frequent, in a manner similar to that used in stadium lighting. Directing light into the playing area from several sides will improve visibility of the game both for spectators and television. Care must be taken to shield the sources and keep the equipment at an angle high enough to prevent glare. Light should come from both sides of the playing area for proper highlighting and shadow fill. Discharge sources would be a logical choice for such an approach.

Minimum illumination level recommendations for color television generally assume the use of incandescent sources, and will not necessarily be applicable for discharge sources. A factor should be applied that accounts for sensitivity of the camera to the spectrum of the particular source. In the typical four-tube camera system studied, the following relative luminance-signal-per-lumen figures were obtained by calculation:

Incandescent (3000° K)	1.00
High-pressure sodium	0.72
Metal halide	1.05
"Deluxe White" mercury	0.91

Footcandle recommendations based on incandescent lighting should be divided by the appropriate figure to find the footcandles needed from discharge lamps to provide an equal video luminance signal. The exact figures will, of course, vary among different brands and types of cameras.

Uniformity of spectral quality throughout a scene is desirable, especially on close-ups of people, as at conventions; it may be a less severe requirement at sports events. Spectral uniformity throughout a scene is also important when a camera is panned. Therefore, the lighting designer should plan for as intimate and uniform a mixture of light as possible when combining different sources in the same installation.

Where daylight will be an appreciable factor in the lighting system at times when color TV will be used (as in skylighted arenas and outdoor stadiums), there may be advantages in using discharge lamps of relatively high apparent color temperature. This would minimize color shifts during the transition from day to night and also would reduce the color contrasts that could result from uneven mixtures of daylight and electric light within the televised scene.

Operational Considerations

Lag and Noise

In all the calculations discussed earlier, the procedure used automatically balanced the color camera for white. In other words, if there was a deficiency in blue light, the blue gain was increased to compensate for it. From a colorimetry point of view, this is correct; the camera is balanced. However, from a practical point of view, this changes many of the operating parameters of the camera chain.

Table III. Camera Signal Currents for Constant TV Luminance. (3000°K Tungsten = 1.00; Typical 4-tube camera.)

Lamp	Red	Green	Blue
Sodium........	1.69	0.84	0.55
Metal Halide...	0.74	0.92	1.75
Deluxe Mercury	0.85	0.89	1.59

Table III gives the camera signal currents for the red, blue and green channels for the three discharge lamps. In the camera design, the three signal currents are made as nearly equal as possible for tungsten light, in order to minimize color lag. When the spectral quality of a lamp results in reduced color signal current, there is a tendency to introduce two unfavorable effects:

First, since gain must be raised to balance for white, there will generally be a decrease in signal-to-noise ratio in that channel. This is because the primary source of noise is that of the input stage, and not the pickup tube.

Second, since signal current is lower, lag will be greater for this color channel. Thus, in the case of the sodium lamps, there would be blue (or yellow) lag on fast-moving subjects. The reverse is true for the metal-halide and mercury lamps where red (or cyan) lag would occur. When discharge sources are blended with each other or with tungsten, the signal unbalance is reduced.

However, despite the theoretical problems with lag and noise, no serious problems were observed in the laboratory tests referred to earlier. Obviously though, the objectionability of such effects is subjective and would also depend on the program quality level required. The effects are also dependent on the particular camera design — three-tube vs four-tube, design values of color-channel signal current, etc.

Camera color filters to balance the discharge lamp spectrum nearer to tungsten could eliminate any possibility of noise or lag problems. (This is generally done to balance the camera for daylight.) But such filters would, in effect, reduce the light level and offset some of the advantages of the high-efficiency discharge sources.

Scene Shifts

One of the common TV field problems results when the same camera is used to cover both an announcer from close-up and the field or arena, either simultaneously or successively. Obviously, if the camera is balanced for the discharge lamps lighting the large arena, ordinary incandescent supplementary lighting on the announcer will be out of balance. One possible answer is to use similar lighting on the announcer. Discharge lamps can generally be put in scoop-type units and could be adapted into other types of portable lighting equipment. A second possibility is the use of color-compensation filters, which can be incorporated into the camera filter wheel. The specific filter would have to be selected by trial or calculation to fit the lighting condition. Finally, suitable filters could be used over the incandescent lighting units to approximately balance their color to that of the discharge lamps.

This problem is very similar for an arena or stadium at night and for an outdoor scene in daylight. In the first case, the playing area and announcer may be lighted by lamps of different spectral quality; in the second case, part of the field may be in full sun and the announcer lighted only by skylight and/or artificial fill. However, with all-electric illumination, there is a good opportunity for controlling the differences. A little advance planning will help ease the problem, if not eliminate it.

Gray Scale

One of the common problems in field pickups is lack of a readily available gray scale for white-balancing the camera chain to the actual lighting in use. Having such a known reference available is a definite aid in compensating for color shifts during daylighted scenes, and is a necessity for preliminary balancing with either daylight or electric lamps. A large-size black-and-white target (or a black, a white and a gray) is recommended to be used under the actual scene illumination during the initial setup. It would be desirable to incorporate a gray scale into the televised scene so that it receives average illumination, to be used for rebalancing from time to time, especially if the lighting is variable (such as daylight). Failing this, some neutral object in the scene receiving the general illumination should be selected as a reference. Where electric light sources — discharge or incandescent — are in use, it may be practical to build a lightbox or lighted gray scale using the same lamps, and use it close to the camera for white balancing.

Color Photography

The still photographer, in general, uses the same illumination as the television cameras, although he may at times supplement and even override the general illumination with his own flash. He does not have a great problem if his flash overrides the discharge lamp general illumination. However, if he only supplements the general illumination, then differences in color quality may become apparent in his finished product. With experimentation, the photographer can find suitable filters for his flash equipment to approximately match the color quality of its supplementary light to the general area lighting. If he is not using flash, then camera filter recommendations are available[11] to balance his reversal-type color film to the discharge lamps. Of course, color-negative films can be compensated in printing, provided the scene lighting is uniform in color quality.

The motion-picture photographer will have the same difficulties as the still photographer. If he uses supplementary lighting, it would be desirable to color-correct it to match the discharge lamps, since it is not likely that he can override them outside a very limited area. If he works with available light, filter recommendations are available[11] for balancing reversal-type color motion-picture film to discharge lamps. Some experimentation is generally necessary. Mutual cooperation between TV people, photographers and the management of arenas, stadiums, etc., could be very helpful in providing filter recommendations for a particular installation to all interested parties.

Warm-up and Restrike

Most types of discharge lamps require a few minutes after turn-on to reach full output. Furthermore, after turn-off they require up to several minutes of cooling before they will "restrike" and begin warming up again. These lamp characteristics should be taken into account in planning the timing of programs, especially if any on/off cuing of lighting is required. Some types of lamps may not reach color stability until a few minutes after the light output has stabilized. There are differences in timing depending on lamp type, wattage, ballasts and fixtures, so the characteristics of each installation should be checked. For safe crowd-handling, many discharge lamp installations include some incandescent or fluorescent lamps that will relight immediately after any momentary power interruption.

Strobe Effects

On single-phase power systems, discharge lamps may have objectionable stroboscopic effects for both players and spectators in case of fast-moving action. However, we have heard of no cases where strobe effects show up on video.

Conclusions

Based on our calculations and test observations, plus experiences reported in actual installations,[1,7–9] it appears that the three new discharge sources can provide acceptable color quality for television remote coverage of sports and other events. When the camera chain is balanced for each of the discharge sources separately or in combination with incandescent lamps, the magnitudes of color shift do not appear to be great enough to cause problems where color rendition is not highly critical. For color-critical applications in studio work, the suitability of discharge sources would need to be investigated thoroughly.

Because lighting for sports areas is usually not designed specifically for television coverage, problems occur in regard to sufficient vertical-surface illumination, modeling effects and uniformity of illumination, as well as spectral qualities of light sources that are unfamiliar to television technicians.

Lighting advice needs to be given to the operators of arenas and stadiums for adding to existing lighting or for the design of new lighting. Television technicians and technical directors need to anticipate possible problems involved with lamp restrike and lamp warm-up characteristics, and scene shifts that involve changes in light source.

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5

Color Television Broadcasting Facilities and Measurements

Modification of the Pulse-and-Bar Test Signal With Special Reference to Application in Color Television

By PETER WOLF

It is proposed to modify the pulse-and-bar test signal, which has been used in England to measure linear waveform distortion in TV systems, by a special 20T sine-squared pulse. This pulse is formed by the linear addition of a 20T-pulse to the pulse modulated on the color subcarrier. Transmission distortions can thus be recognized at the upper end of the video band. The deformation of the envelope of such a pulse indicates various transmission distortions of the luminance and chrominance channels. The combination of this 20T-pulse with the elements of the existing pulse-and-bar test signal is also suggested.

THE TV TRANSMISSION TECHNIQUE has to solve the problem of leading the electric signals of a pickup system to the home receivers without substantial impairment of picture quality. The allowable waveform distortions on the way from the TV pickup system to the home receivers primarily depend on the allotted degree of picture quality impairment.

Pulse-and-Bar Test Signal in Use up to the Present

In recent years the so-called pulse-and-bar test signal has been introduced for measuring the linear transmission characteristics of TV equipment.[1–6] This test signal consists of a sine-squared pulse with a half-amplitude duration of 2T (2T-pulse) and a line bar waveform with a rise-time also of 2T (Fig. 1). T is the so-called transient time constant of the TV system and is defined as $T = 1/2f_u$ where f_u is the upper video-frequency limit. In the 525-lines standard f_u is approximately 4 MHz and T = 0.125 μsec. The pulse-and-bar test signal is composed of the essential elements of a TV picture which are lines, edges and areas of constant brightness. This is the main reason why this signal has proved extremely useful: Distortions of actual TV pictures can be recognized directly by the distortions of the pulse-and-bar test signal.

Figure 2 shows that the spectra of the 2T-pulse and the bar waveform do not exceed the upper video-frequency limit. The amplitude/frequency spectrum of the line bar waveform has an especially large amount of energy at the lower frequencies. Therefore that signal indicates transmission distortions up to some hundred kilocycles per second. In that frequency range transmission distortions produce a very disturbing smearing when large areas of constant brightness are transmitted. The 2T-pulse, which can be seen as a small vertical line on the TV screen, indicates clearly transmission distortions up to 60 to 80% of the nominal upper video-frequency limit. The spectra of the 2T-pulse and the bar waveform show that these two signals are not sensitive to transmission distortions at the upper end of the video band. This fact is not of great consequence when black-and-white TV is considered, because the spectra of usual black-and-white TV signals have a small amount of energy near the upper video-frequency limit. An experiment has been made to demonstrate this fact (Fig. 3): A very small vertical line was taken by several 625-lines TV cameras and the output signal was observed. Care was taken that the shape of the output signal depended only on the transmission response of the camera. The output signals of the TV cameras have a nearly sine-squared shape with a half-amplitude duration of about 0.13 μsec. This experiment was made under laboratory conditions. Certainly the pulses will be wider if the cameras are tested under TV studio conditions. In this case they may reach the width of a 2T-pulse that is shown at the bottom of the figure (on the right). Therefore the 2T-pulse represents in a good approximation the details which occur in usual black-and-white TV pictures.

Occasionally there are also black-and-white TV signals which — compared to the majority of signals — have an unusually high amount of energy at the upper end of the video band. In all cases color TV signals have high energy at the upper video-frequency limit. All these signals are distorted by transmission errors at the upper end of the video band, and they are not indicated by the 2T-pulse-and-bar test signal.

In order to recognize waveform distortions at the upper video-frequency limit, English authors have proposed the use of a sine-squared pulse of a half-amplitude duration of T.[1–3] This T-pulse, which in the 525-lines standard has a half-amplitude duration of 0.125 μsec, has spectral components up to twice the upper video-frequency limit (Fig. 2). Therefore the T-pulse has the fundamental disadvantage that it is also distorted by an ideal TV-transmission system (that has the characteristic of an ideal 4.2 MHz low-pass filter). In a TV transmission system whose waveform response is not ideal, the distortion of the T-pulse has two different

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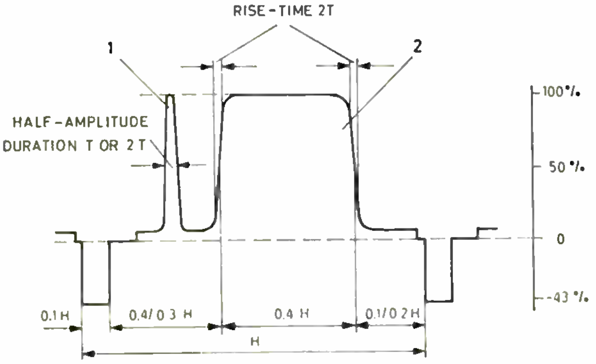

Fig. 1. The existing pulse-and-bar test signal.

1 = T or 2T sine-squared pulse
2 = bar waveform
T = $^1/_2 f_u$ = transient time constant of the TV system
f_u = upper video-frequency limit
(when f_u = 4 MHz, T = 0.125 μs; when f_u = 5 MHz, T = 0.100 μs)
H = line period

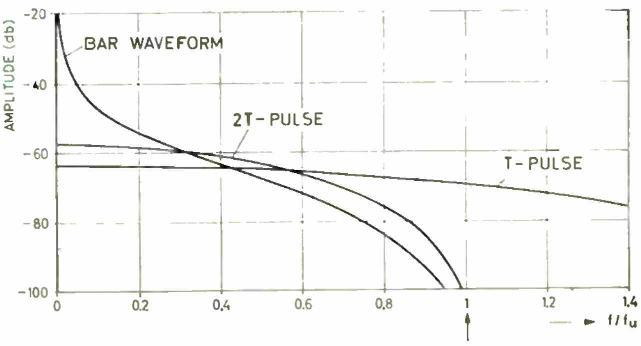

Fig. 2. Amplitude/frequency spectrum of the pulse-and-bar test signal. Zero dB corresponds to the peak amplitude of the test signal.

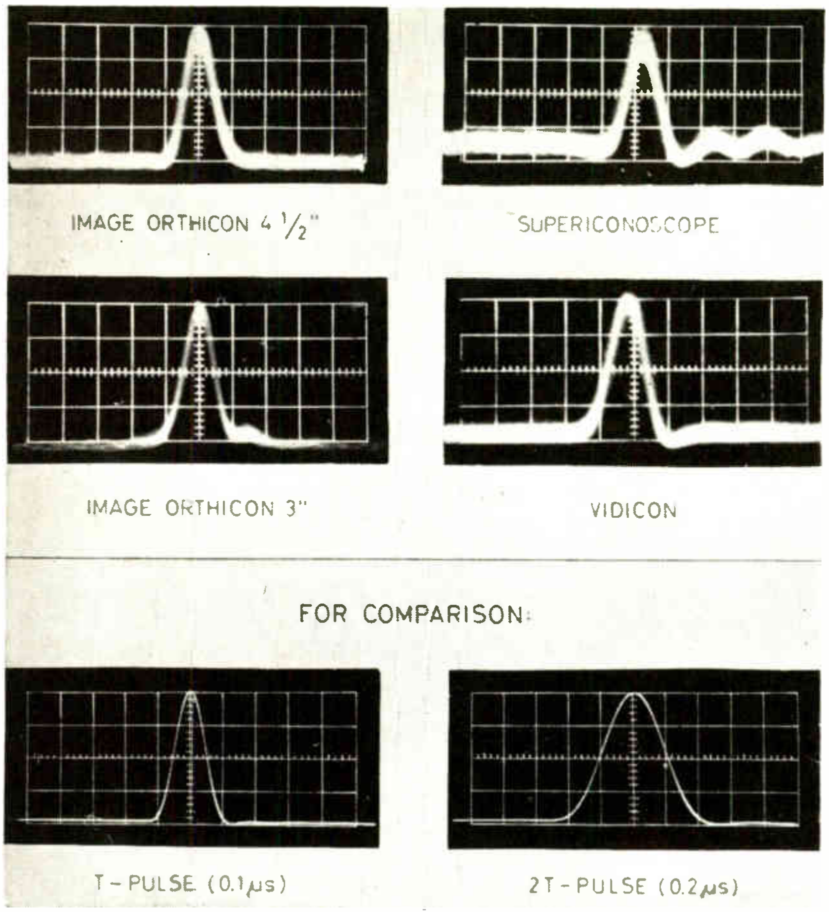

Fig. 3. TV-camera transmission of a very small vertical line (625-line standard). Smallest pulses produced by several 625-line TV cameras under laboratory conditions.

causes: transmission errors inside the video band and transmission distortions outside the video band. The result is that one cannot derive immediately the distortion of real TV signals from the distortion of the T-pulse.

Modulated 20T-Pulse

If practically a high amount of spectral energy appears near the upper video-frequency limit, then it is caused by frequency bursts which result from scanning very small graticules—for example, scanning a strip pattern—or, if color TV is concerned, it is caused by the modulated color subcarrier.

The waveform distortions of such frequency bursts can be detected immediately if the test waveform is similar to these signals. For example, such a test waveform would be the color subcarrier which is modulated by a sine-squared pulse. The half-amplitude duration of the modulating pulse has to be chosen so that the sum of the highest spectral frequency of the pulse and the color subcarrier frequency does not exceed the upper video band limit. When these conditions are met, then the test signal is transmitted by an ideal TV transmission system without distortions. If transmission errors appear, the test waveform is distorted in the same way as black-and-white TV signals with high spectral energy near the upper video-frequency limit and in the same way as color TV signals.

Figure 4 shows a test waveform with the features just described (proposal of the IRT).[7] The color subcarrier is modulated positively to a depth of 100% by a 20T sine-squared pulse. The half-amplitude duration of the 20T-pulse is 2.5 μsec. The 20T-pulse has an amplitude/frequency spectrum up to 10% of the video band width, that is, 400 kHc in the 525-lines standard. This modulated signal is added linearly and in proper phase to the unmodulated 20T-pulse. The right-hand side of the figure shows the resulting waveform: a 20T-pulse filled out with cycles of the color subcarrier. In the following text we will call this test waveform a modulated 20T-pulse, although this term is not completely correct. On the TV screen the modulated 20T-pulse is displayed as a strip pattern with lines of different brightness if it is transmitted in every TV line and if the carrier frequency is phaselocked with the line frequency. But the locked phase relation between carrier frequency and line frequency is not desirable, because in this case the oscilloscope display does not show the envelope of the modulated 20T-pulse clearly. The amplitude/frequency spectrum of the modulated 20T-pulse is shown in Fig. 5 in a linear scale. Because the unmodulated 20T-pulse is added to the modulated waveform there are two spectral ranges of the modulated 20T-pulse: the first one reaches from nearly zero up to 10% of the whole video band (that is, 0 to 400 kHc in the 525-lines standard); the second one is color subcarrier frequency plus or minus 10% of the whole video band (that is, 3.58 ± 0.40 MHz in the 525-lines standard).

Hence the spectral lines of the modulated 20T-pulse cover the frequency ranges, in which the main information of the luminance channel, on the one hand, and the chrominance channel, on the other hand, are situated; different transmission responses in both channels are

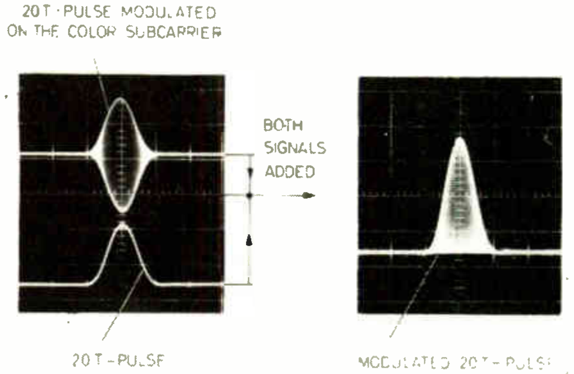

Fig. 4. Generation of the modulated 20T-pulse.

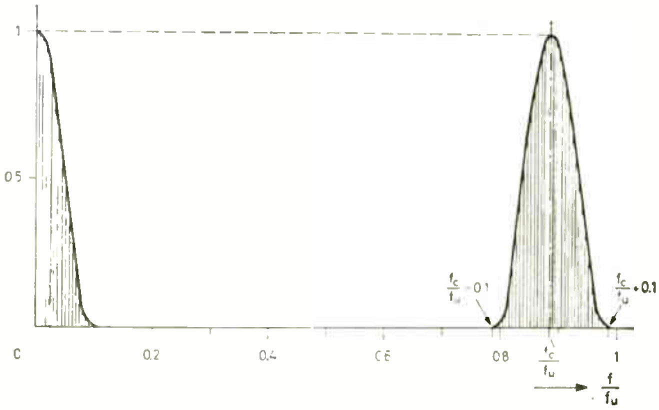

Fig. 5. Amplitude/frequency spectrum of the modulated 20T-pulse. f_u = upper video-frequency limit; f_c = color subcarrier frequency.

indicated by characteristic deformations of the envelope of the modulated 20T-pulse. Some examples may demonstrate this fact. Figure 6 shows what happens if there is some gain difference between luminance and chrominance or, otherwise expressed, if there is some gain difference between low and high frequencies: The lower envelope of the modulated 20T-pulse is bent symmetrically with respect to the vertical axis of the pulse. (The continuous line at the top indicates the amplitude of the corresponding undistorted waveform.) The amplitude of the cosine-shaped lower envelope indicates directly the gain difference of the chrominance channel with regard to the low frequencies of the luminance channel. The relative amplitude of the color subcarrier (η) is given by

$$\eta = 1 - 2a \qquad (1)$$

where a is the relative amplitude of the cosine-shaped lower envelope (referred to the amplitude of the undistorted waveform—continuous line at the top).

A 10% loss of gain at the color subcarrier frequency produces a 5% amplitude cosine-shaped deformation of the lower envelope of the modulated 20T-pulse.

Figure 7 shows what happens if there is some time delay between luminance and chrominance or between low and high frequencies: The lower envelope of the modulated 20T-pulse is bent asymmetrically with respect to the vertical axis of the pulse. (The continuous line at the top indicates the amplitude of the corresponding undistorted waveform.) The amplitude of the sine-shaped lower envelope corresponds to a definite envelope delay difference between the chrominance channel and the low frequencies of the luminance channel. This envelope delay difference (Δt_{ed}) is given by Eq. (2).

$$\Delta t_{ed} = 0.1 \frac{b}{0.06} \text{ (in } \mu\text{sec)} \qquad (2)$$

where b is the relative amplitude (pp) of the sine-shaped lower envelope (referred to the amplitude of the undistorted waveform). Equation (2) is valid up to delay time differences of some 0.1 μsec and only for the 525-lines standard where the 20T-pulse has a half-amplitude duration of 2.5 μsec. Equation (2) shows that a 0.1 μsec envelope delay difference produces a sine-shaped deformation of the lower envelope of 6% amplitude. Finally, Fig. 7 indicates that a mere delay time error causes no change in the amplitude of the upper envelope of the modulated 20T-pulse.

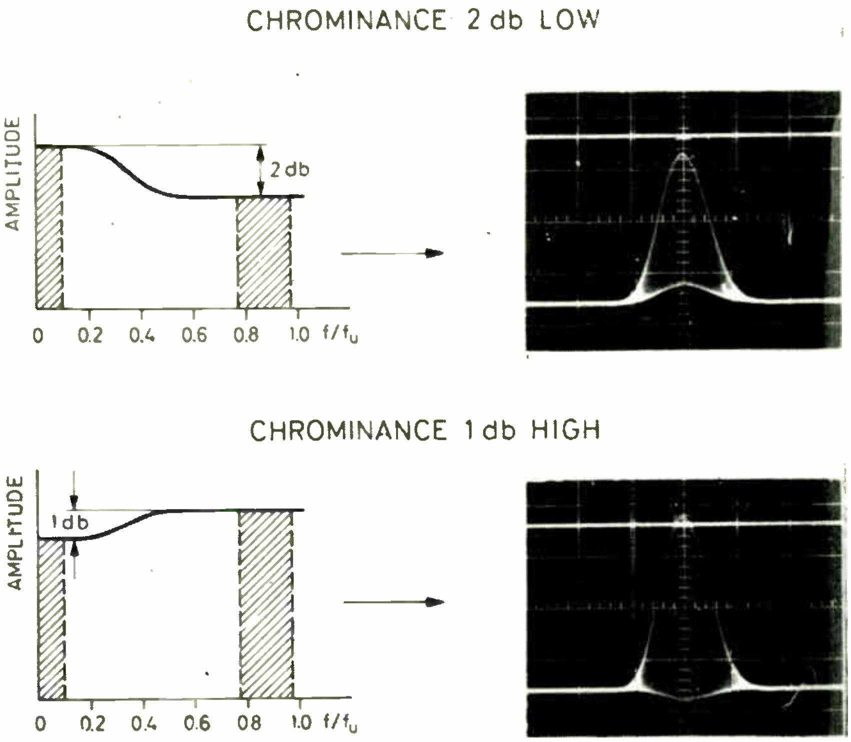

Fig. 6. Distortion of the modulated 20T-pulse caused by gain difference between luminance and chrominance. The amplitude of the deformation of the lower envelope corresponds to the change in the amplitude of the upper envelope.

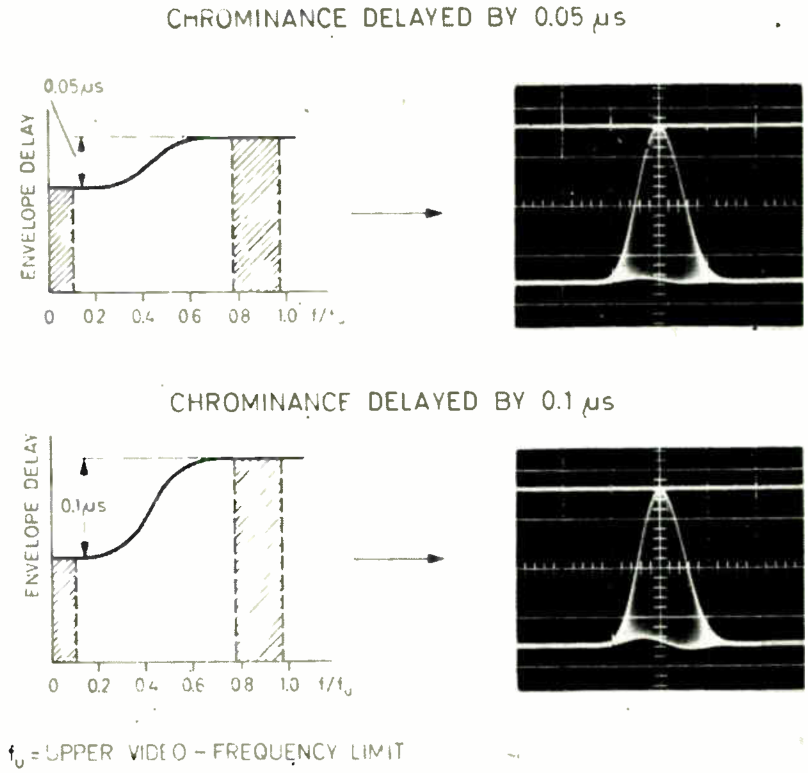

Fig. 7. Distortion of the modulated 20T-pulse caused by time delay between luminance and chrominance (625-lines standard).

Modified Pulse-and-Bar Test Signal

These two examples have shown that the waveform distortions of the modulated 20T-pulse indicate very clearly linear transmission errors at the upper end of the video band. To get a test signal which enables the detection of waveform distortions in the whole video band, the modulated 20T-pulse has to be combined in a suitable way with the elements of the existing pulse-and-bar test signal. Figure 8 shows a proper combination of the 2T-pulse, the modulated 20T-pulse and the bar waveform—the modified pulse-and-bar test signal. The three signals are carried on successive lines. During one line the bar waveform is transmitted and during the next line the modulated 20T-pulse and the 2T-pulse are transmitted. If the oscilloscope is

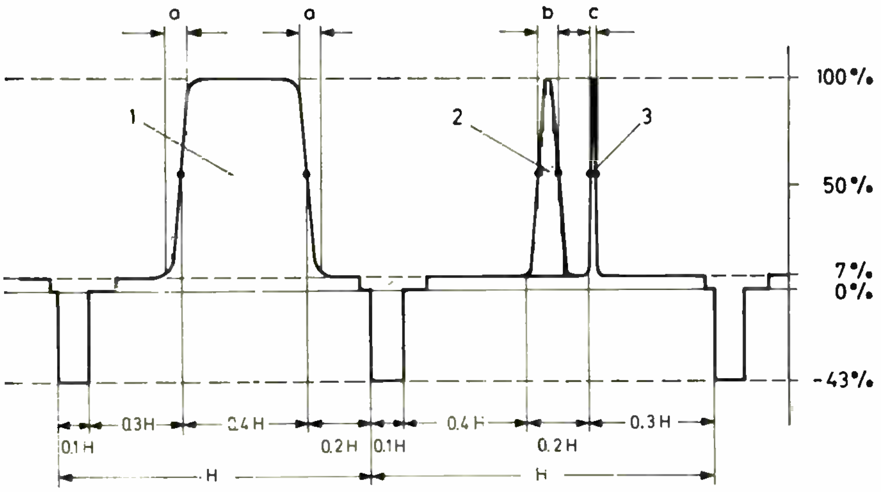

Fig. 8. Modified pulse-and-bar test signal.
1 = bar waveform, a = rise-time 2T
2 = modulated 20T-pulse, b = half-amplitude duration 20T
3 = 2T-pulse, c = half-amplitude duration 2T
$T = {}^1/_2 f_u$, f_u = upper video-frequency limit
(when f_u = 4 MHz, T = 0.125 μs; when f_u = 5 MHz, T = 0.100 μs)
H = line period

triggered by every successive line synchronizing pulse, the bar waveform is displayed above the modulated 20T-pulse and the 2T-pulse (Fig. 9). This oscilloscope display is very suitable, because the amplitudes of the two sine-squared pulses are referred usually to the bar amplitude. Figure 10 shows the amplitude/frequency spectrum of the modified pulse-and-bar test signal in a semi-logarithmic scale. It can be seen that the spectral lines cover the whole video band and do not exceed the upper video-frequency limit.

The modified pulse-and-bar test signal also indicates linear transmission errors in the chrominance channel. Transmission distortions of this kind produce cross-talk between the Q- and I-signal which cause disturbing color edges in color TV pictures.[8-10] In Fig. 11 a network which consists mainly of a resonant circuit tuned to the color subcarrier produces a linear transmission distortion in the chrominance channel. At the top, Fig. 11 shows the amplitude/frequency and phase/frequency responses of the network. In the middle, the lacing of the envelope of the modulated 20T-pulse suggests that the modulated part of the signal is distorted considerably. In the modified pulse-and-bar test signal only the modulated 20T-pulse clearly indicates this transmission error in the chrominance channel.

If linear transmission characteristics are to be measured, care must be taken that nonlinear transmission characteristics do not falsify the result. Before linear transmission characteristics are tested, another measurement has to be carried out which ensures that nonlinear effects are negligibly small in the chosen range of the video signal. The modified pulse-and-bar signal indicates very clearly by the distortions of the modulated 20T-pulse nonlinear gain errors (Fig. 12). If linear gain errors appear, the amplitude of the cosine-shaped deformation of the lower envelope corresponds to the change in the amplitude of the upper envelope (Fig. 12 at the top). If nonlinear gain errors are involved—for example, SSB-distortion—this correspondence no longer prevails (Fig. 12 at the bottom). But it is a precondition for the discerning of nonlinear gain errors with the modulated 20T-pulse that in each case, the bar waveform is transmitted as reference amplitude. It may be mentioned that an experienced observer is able to detect nonlinear transmission characteristics by the distortions of the bar waveform too.

Conclusion

Summing up, it can be said that the modified pulse-and-bar test signal has the advantages of the existing pulse-and-bar test signal without its disadvantages. If the T-sine-squared pulse is replaced by the modulated 20T-pulse, the whole test signal is transmitted by an ideal TV transmission system without distortions. Because the spectral lines of the modulated 20T-pulse cover the frequency ranges in which the main information of the luminance and chrominance channels is situated, the waveform distortions of that pulse indicate the characteristic distortions of color TV signals. Because the modified pulse-and-bar test signal is composed of the essential elements of a TV picture, it is distorted in the same way as all actual TV signals.

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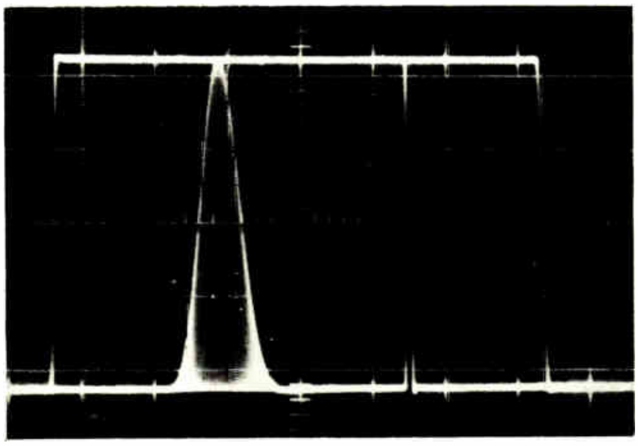

Fig. 9. Oscilloscope display of modified pulse-and-bar test signal. The bar waveform is displayed above the modulated 20T-pulse and the 2T-pulse.

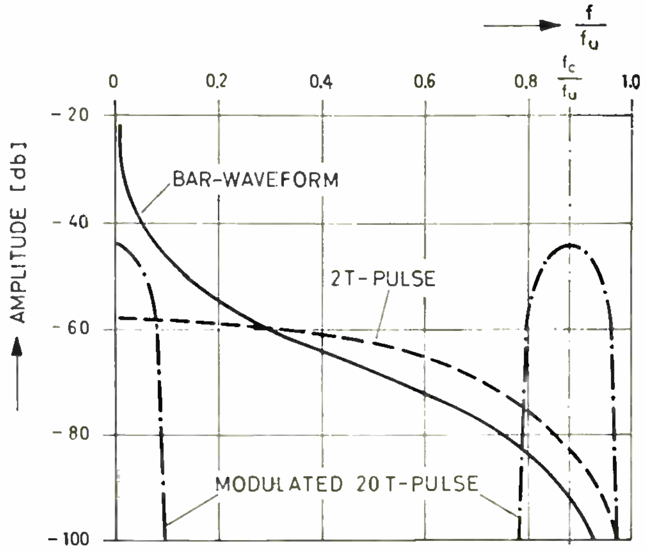

Fig. 10. Amplitude/frequency spectrum of the modified pulse-and-bar test signal. Zero dB corresponds to the peak amplitude of the test signal. f_u = upper video-frequency limit; f_c = color subcarrier frequency.

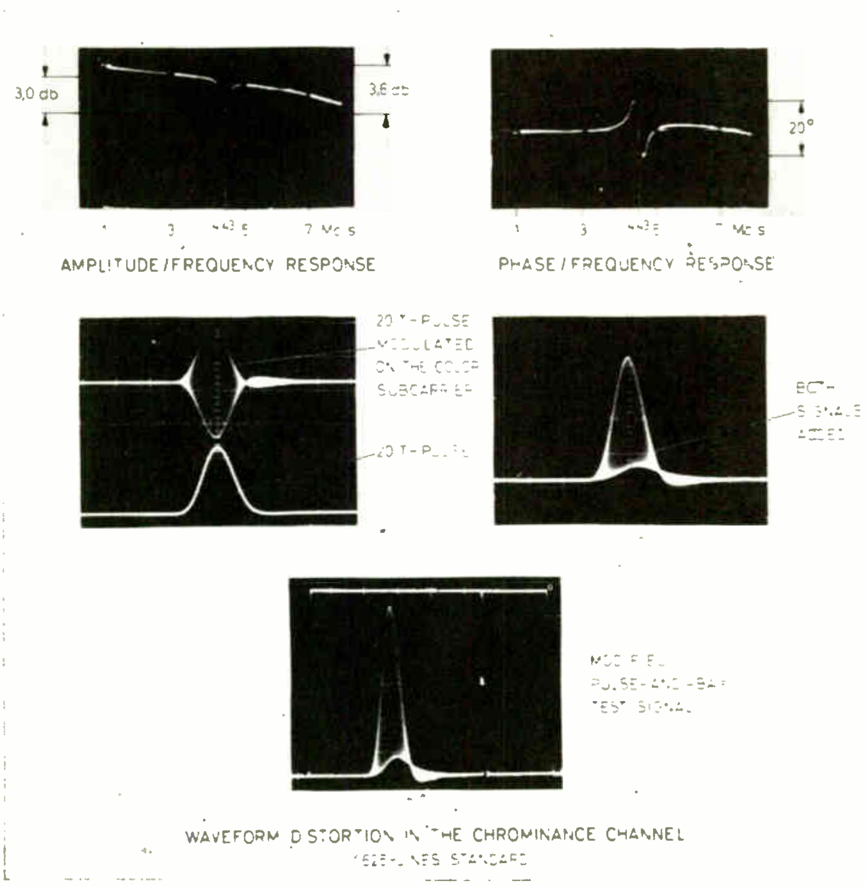

Fig. 11. Waveform distortion in the chrominance channel (625-lines standard). A hole of 3 dB in the amplitude/frequency response and a phase shift of 20° in the phase/frequency response (at the color subcarrier frequency) cause a lacing of the envelope of the modulated 20T-pulse. 2T-pulse and bar waveform are not distorted.

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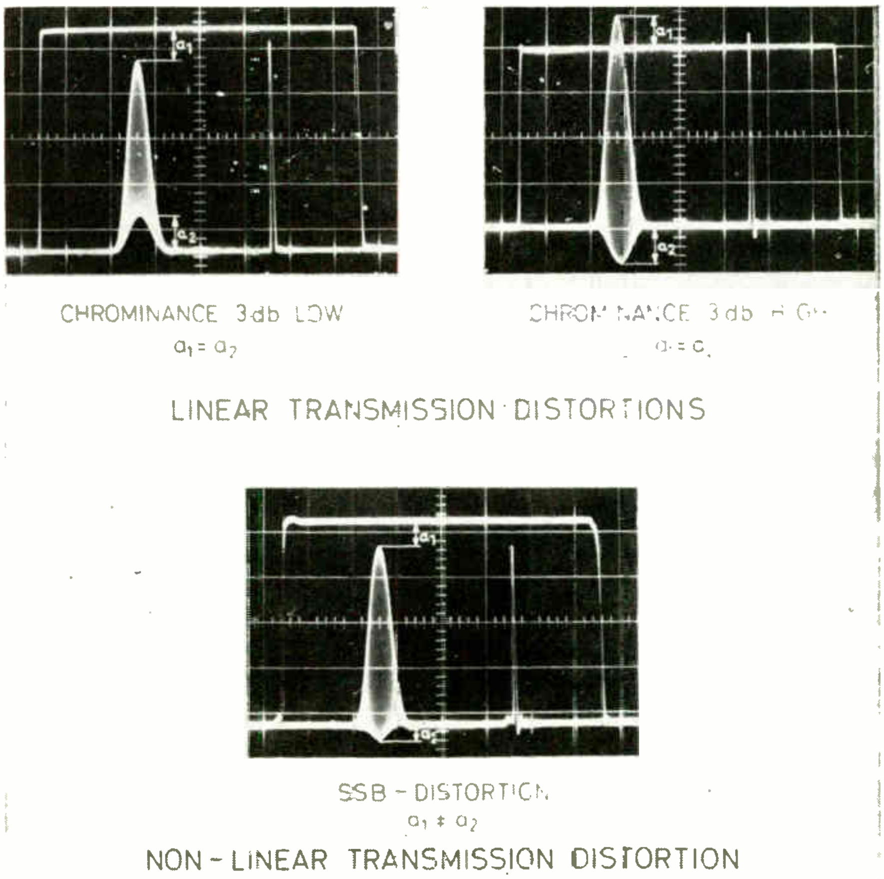

Fig. 12. Distortion of the modified pulse-and-bar test signal caused by linear and nonlinear gain errors.

Testing of Television Transmission Channels With Vertical Interval Test Signals

By R. E. MALLON
and A. D. WILLIAMS

The choice and use of test signals for in-service testing of video transmission facilities during the vertical interval (VITS) are based on several considerations. The sine-squared pulse, having a half-amplitude duration of 1/8 μs, often called a *T* pulse, is not a good choice for the quality rating of a television channel. Computed results from transmission response of actual facilities and echo-rating theory show that this signal may fail to detect poor channels and will on occasion indicate that a good channel is bad. The *T* pulse correlates poorly with the results of subjective tests. Alternative signals analyzed as to their spectrum and application include the 2*T* pulse, a step function having a controlled rise time and the 20T modulated pulse for evaluating the color-carrying capabilities of a channel. On the basis of results of measurements made on operating transmission systems the next steps are recommended in the development of an optimum set of vertical interval test signals.

Introduction

Many papers[1] have appeared throughout the television world in the past few years discussing waveform testing of television facilities. The more recent papers have been concerned not only with waveform testing, but waveform testing on an in-service basis using test signals placed in the vertical interval of a composite video signal. This paper will discuss the use of these waveforms, particularly with respect to facilities used for the transmission of video signals over an extensive intercity network.

The choice of an individual vertical interval test signal (VITS) should not be made without a consideration of the other signals in the set. While this paper will use this principle in discussing vertical interval signals, it will limit its discussion to those signals used for determining the linear distortion in a transmission path. This paper does not provide a definitive answer as to the "best" set of signals to be used, but hopefully sets up a basis for continuing work in the field, work that will lead to a choice of satisfactory signals.

Waveform testing on a full-frame basis has been used since the start of intercity television service. The first Bell System signal generator used in the testing of commercial video channels provided a 60-Hz square wave and a rectangular waveform occurring at a 15.75-kHz rate. These waveforms were used to quickly evaluate the performance of a channel in the low- and middle-frequency range. Sinewave measurements were then used in correcting the trouble. As color transmission became more dominant throughout the network, the waveforms available from the original generator were supplemented by a *T* pulse and a multiburst signal.

These full-frame signals were only used on an out-of-service basis. As network usage increased it became desirable to monitor the condition of a channel on an in-service basis. Fortunately, the use of vertical interval test signals had been implemented in Europe. Since the 1950's these VIT signals (Fig. 1) were applied to U.S. facilities by the Broadcasters. The occurrence of these signals on a horizontal line limits their usefulness to evaluations of the middle- and high-frequency response of a channel.

This use of waveform testing, i.e., to examine the gain and phase response of a facility, assumes that the gain and phase response is directly related to picture quality and that corrective measures on these parameters will lead to good pictures. As waveform testing evolved the concept of directly relating picture quality to waveform response itself, without a definitive examination of the gain and phase response, came into being.[2]* Waveforms could then be chosen for one of two criteria, i.e., either as a direct measure of the frequency response or as a direct measure of picture quality. This duality has led to some inconsistencies in the choice and evaluation of test signals, particularly with respect to the *T* pulse.

Presently Used Test Signals

The characteristics and capabilities of the test signals presently used to measure linear distortion will now be discussed.

T Pulse

The *T* pulse is a sine-squared pulse identified by its half amplitude duration expressed in terms of *T* microseconds. *T* is related to the nominal cutoff frequency of the television system under discussion by the expression $T = {}^1/_2 fc$ (MHz). For the U.S. 525-line NTSC

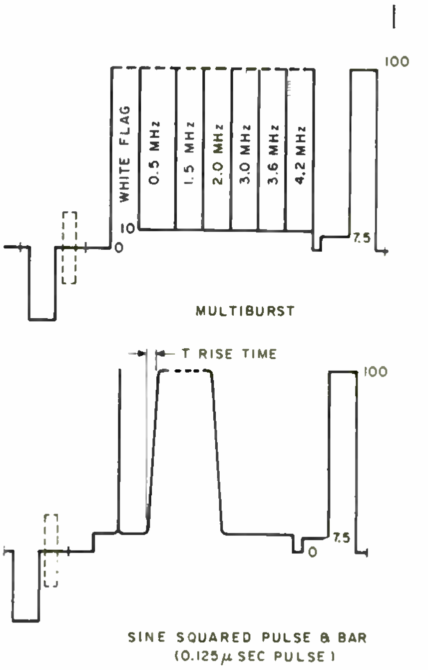

Fig. 1. Vertical interval test signals (the multiburst and bar signals).

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* A test set based on this concept was developed by the Bell Telephone Laboratories in 1961. The 9A set determines the echo rating of a channel by measuring the distortion produced by a channel on a rectangular pulse occurring at a 15.75-kHz rate.[3]

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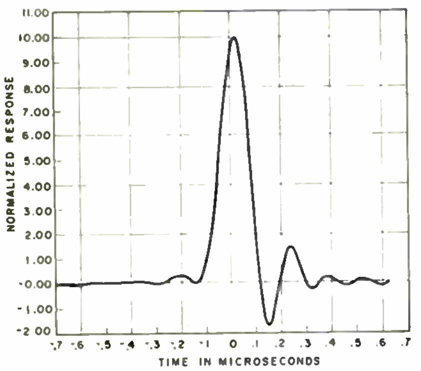

Fig. 2. T pulse response, with K rating equal to 2.1% and echo rating equal to −40 dB.

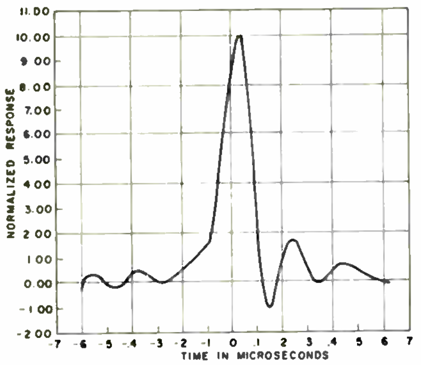

Fig. 3. T pulse response. Here K rating equal to 7.9% and echo rating equal to −30 dB.

system f_c is 4.0. The T pulse can be written as

$$f(t) = \frac{1}{2} + \frac{1}{2}\cos\frac{\pi t}{T} \qquad |t| \leq T$$

$$= 0 \qquad \text{otherwise}$$

Transmission information can be obtained by measuring parameters of the received pulse. These parameters include the timing and amplitude of its overshoots, its height, width and symmetry. The present practice in using the T pulse is limited to the measurement of the undershoot and overshoot of the response. These measurements are used as a good–bad test of the channel. Presently used Broadcaster limits suggest that a transmission channel having a pulse response with a first overshoot greater than 15% (negative) and/or a second overshoot greater than 10% (positive) is bad. This evaluation can lead to misleading results about the quality of a video channel because the T pulse has about 30% of its energy above the nominal video band. T pulse response is thus the result of channel characteristics outside the video band as well as those within the band. In many channels the characteristics outside the band are the controlling factors in determining the ringing amplitude of the T pulse. Therefore, the T pulse should not be used to measure channel quality without removing the extraneous information in the pulse response.

Figures 2 and 3, which show the T pulse response of two actual video channels, give an example of the misleading results obtained when T pulse ringing amplitude is used to measure quality. Both channels show large ringing amplitudes. When evaluated in terms of equivalent echo performance, channel A (Fig. 2) has an echo rating of −40 dB while B (Fig. 3) has a 10-dB worse echo (−30 dB). Bell System intercity facilities are designed to have an echo rating of −40 dB or better. The significant difference between the channels is that A has major deviations *outside* the video band while B has major deviations *within* the video band. Ringing amplitude of the T pulse does not detect this 10-dB difference and indicates that both channels may be bad.

Any measure of good or bad should be based on the results of subjective testing. Preliminary tests have been completed on the correlation of picture quality to T pulse response. Table I gives the results of these tests.

The tests were made under standard conditions[4] using the comment scale shown in Table I. Home color receivers would give results equivalent to those of the color monitor and it can be seen that overshoots that would be rated excessive by current tolerances do not subjectively impair a picture beyond the "Just Perceptible" comment.

Although the T pulse, as used in this country, is not desirable as a quality rating test signal it can be used to determine quality utilizing a method suggested by Lewis.[5] This method requires a detailed analysis of the T pulse response. In this analysis the out-of-band energy is eliminated mathematically. Quality is then determined in terms of a K rating factor. A channel having a rating of K% is subjectively equivalent to a channel with a well displaced echo of K%. Application of this method to the T pulse responses of Figs. 2 and 3 results in K ratings of 2.1% and 7.9%.† This shows that if properly used the T pulse can show up the differences in quality between channels. The work involved in this method is too difficult to do on a routine basis.

The K rating was calculated for a number of video channels and compared to the T pulse response of the channel. The results are shown in Fig. 4 as a scatter plot of K rating vs. overshoot of the T pulse. This figure shows the lack of correlation between the quality rating of the channel in terms of K rating and the T pulse response.

Bar Signal

The bar signal (Fig. 1) has most of its energy within the video band; therefore it does not have many of the problems of the T pulse. Through the use of a properly designed graticule the bar response can be used to directly measure the quality of a video channel in the middle-frequency region. Evaluation of the bar response is usually accomplished by measuring its tilt. The leading edge of the bar contains information about the high-frequency region of the channel and many European countries use this fact in evaluating that region.[6]

Multiburst

The multiburst signal (Fig. 1) gives information about the gain response of the channel. This test signal complements the others and can be used as a check on conclusions drawn from them. It has the further advantage of being easy to understand. While the information in the multiburst is somewhat redundant, it seems reasonable to continue its use until a more urgent need develops for the lines on which it is placed.

Alternative Test Signals

Examining the presently used test signals in terms of measuring the quality of a video channel shows that: (1) the T pulse is not a good pulse for measuring the quality of the channel in the high-frequency region because of the tedious calculation required to properly account for the effects of out of band energy; (2) the bar signal can directly give information about the quality of a channel in the middle-frequency region and may also be used to measure the high-frequency region; and (3) the multiburst, while not a quality rating test signal, can be used to give supporting information to the quality test signals.

If the T pulse is not acceptable as a test signal to directly measure the quality it is necessary to consider alternative waveforms. There are two possibilities that have received much attention in the literature and these are the leading edge of the bar and the $2T$ pulse. Both of these test signals have been adopted by European countries in conjunction with the K rating method and should be good test signals for the high frequency region. The bar signal has the advantage of having the reference white level well defined, while the $2T$ pulse shows how a narrow pulse would be transmitted.

An objection that has been raised to the $2T$ and the bar signal is that both test signals have little energy in the region of the color subcarrier. They are not particularly sensitive to transmission deviations in that region. This objection apparently led to the initial choice of the T pulse over the $2T$ pulse because of the high energy content of the T pulse around 3.6 MHz. Any attempt to find a baseband test signal having energy around 3.6 MHz and also little out-of-

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† K ratings as determined by the Lewis method are based on the properties of the British 405-line system. As a result of this these K ratings differ from echo ratings computed for 525-line U.S. systems.

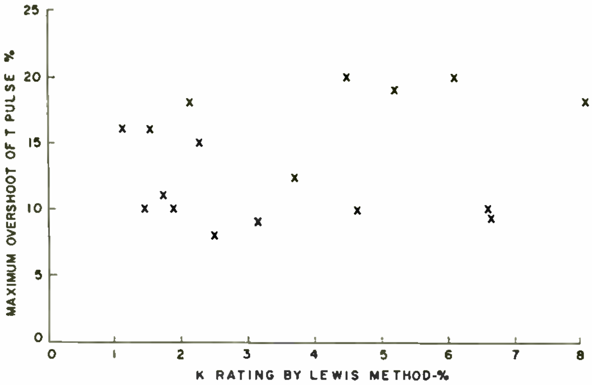

Fig. 4. Comparison of K rating and T pulse for a number of video channels.

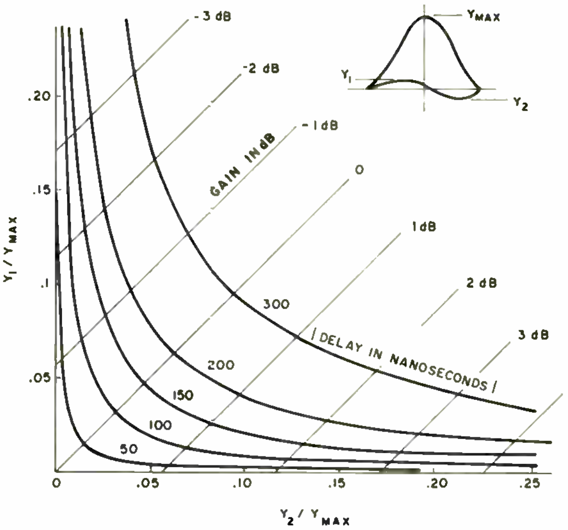

Fig. 6. A method of determining the gain and delay differences between the luminance and chrominance channels from the baseline response of the 20T modulated pulse.

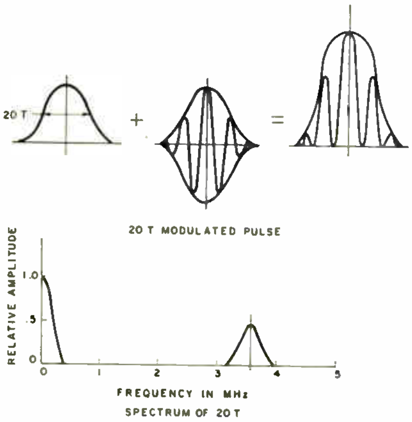

Fig. 5. The 20T modulated pulse signal and its spectrum.

band energy leads to a complicated time function for the test pulse.

A different approach to satisfying the need for determining the transmission performance in the color subcarrier region has been taken recently.[7] This approach is to develop a separate test signal for the color channel. When testing the chrominance channel it is sufficient to determine the gain and delay differences between the chrominance and the luminance channels. They are a direct measure of the effect of linear distortion on the chrominance signal. Note that in this case the objective of the test is to measure the transmission characteristics of the channel and not to directly measure quality.

The chrominance test signal receiving the most attention is the 20T modulated pulse.[7] This signal is generated by adding a baseband 2.5-μs sine-squared pulse to a color subcarrier modulated by a 20T pulse. The composite signal and its spectrum are shown in Fig. 5. Gain and envelope delay differences between the luminance and chrominance channels will distort the baseline of the 20T modulated pulse.

Rosman[8] has developed a method of determining the gain and delay differences between the luminance and chrominance channels from the baseline response of the 20T modulated pulse. Curves used in this process are given in Fig. 6‡ Y_1 represents the maximum positive deviation of the baseline envelope of the 20T modulated pulse. Y_2 represents the maximum negative deviation of the same envelope. Y_{max} represents the received pulse height. The determination of these three parameters allows the use of the curves of Fig. 6 to determine the desired gain and delay differences. A positive gain difference indicates that the chrominance channel experiences more gain than the luminance channel. The order of occurrence of Y_1 and Y_2 determines whether or not the chrominance channel leads or lags the luminance channel. In the example given in Fig. 6 Y_1 occurs first. This indicates that the chrominance channel is delayed with respect to the luminance channel. Note that when the gain difference is 1 dB or greater the method is very insensitive to small delays.

Another approach to finding the gain and envelope delay difference from the 20T pulse response is to measure the baseline envelope at $\tau/2$ μs (X_1) and $-\tau/2$ μs (X_2) from the peak. τ is the half amplitude duration of the 20T pulse and is 2.5 μs for the NTSC system. This method is described in the Appendix. Curves for determining the gain and delay differences using X_1 and X_2 normalized to the 20T pulse height, X_{max}, are shown in Fig. 7. This method has a better sensitivity to delay for large gain differences than using the peaks of the deviations as described earlier. An example using both methods is shown in Fig. 8 for a channel with 1.3-dB gain difference and 43 ns delay difference.

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‡ The curves of Fig. 6 have been calculated for the NTSC 525-line system. Those presented by Rosman[8] were for a 625-line system.

Table I. Subjective Test Results.

T-Pulse response		Average comment (3 Pictures)	
Ringing frequency MHz	First overshoot − %	Color monitor (color picture)	Monochrome monitor (monochrome picture)
4.3	10	1.4	1.7
4.3	25	1.4	2.3
5	35	1.9	3.1

Comment Scale

1. Not perceptible
2. Just perceptible
3. Definitely perceptible, but only slight impairment
4. Impairment, but not objectionable
5. Somewhat objectionable
6. Definitely objectionable
7. Extremely objectionable

Table II. Comparison of 20T Modulated Pulse and Frequency Domain Measurements.

Frequency domain measurements				20T modulated pulse measurements	
Slope across the chrominance band*		Gain and delay difference†			
Gain, dB	Delay, ns	ΔG, dB	ΔD, ns	ΔG, dB	ΔD, ns
0.13	80	0.30	105	0.28	104
0.22	170	0.42	160	0.45	157
0.30	200	0.55	210	0.58	208

* Slope across the chrominance band is the gain or delay at 4.2 MHz minus the gain or delay at 3.0 MHz.

† Gain and delay difference is the gain or delay at 3.6 MHz minus the gain or delay at 15.75 kHz.

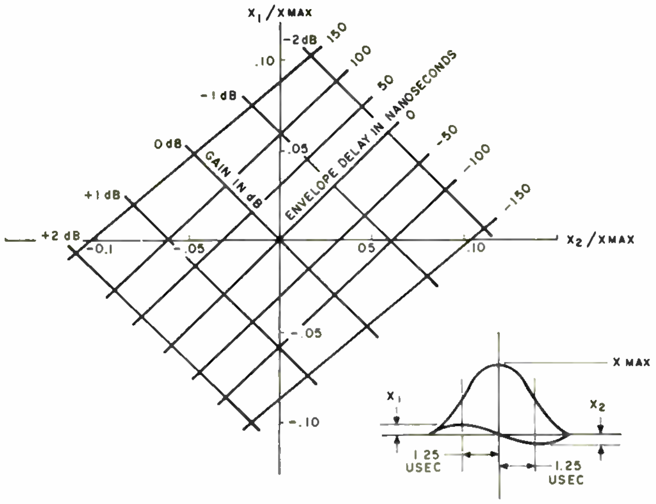

Fig. 7. Another approach to finding the gain and envelope delay difference from the 20T pulse response.

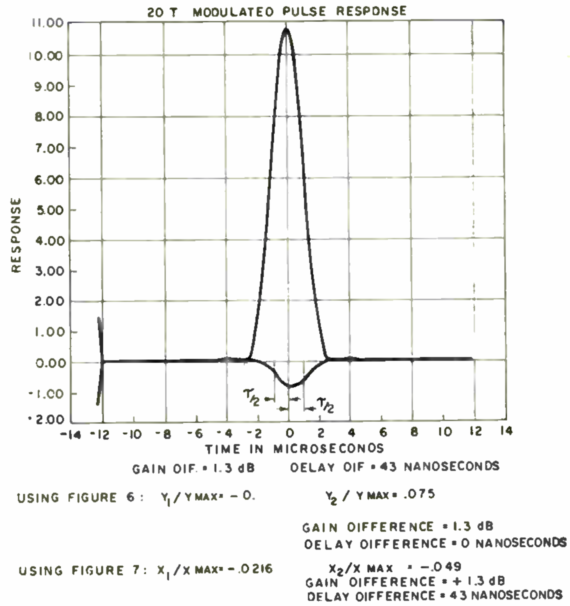

Fig. 8. An example using both methods illustrated in Figs. 6 and 7.

Test Results

To determine the feasibility and operating characteristics of the 20*T* modulated pulse as a test signal, a series of tests were made using passive networks and actual video transmission channels. Figures 6 and 7 are based on the assumption that the luminance and chrominance components of the test signals are only displaced in time and changed in amplitude with respect to one another. In an actual video channel there may also be other linear distortions that will effect the received waveshape in addition to the assumed deviations. Calculations of 20*T* response have shown that even for deviations up to 3 dB and 300 ns across either the luminance or the chrominance band Figs. 6 and 7 can still be used.

When there is distortion across the band there is a question as to how to define the gain and delay differences between the two bands. Gain and delay differences were defined, for the purposes of calculations, as the difference between the 15.75-kHz and the 3.6-MHz values. To check the calculations the 20*T* modulated pulse response was measured for various combinations of 5-MHz sharp cutoff filters and compared with frequency domain measurements. For each combination Fig. 7 was used to determine the gain and delay differences from the 20*T* pulse response. Frequency domain parameters, gain and envelope delay, were measured with a 36B set.[9] This set measures gain and envelope delay from 0.2 to 10.0 MHz. Table II shows the gain and envelope delay difference between luminance and chrominance found with the 36B set and the 20*T* modulated pulse as well as the gain and delay deviations across the chrominance channel. There was no measurable distortion in the luminance band.

Table II shows good agreement between the 20*T* pulse results and the frequency domain measurements which indicates that linear distortion across the band will not seriously affect results obtained from the 20*T* modulated pulse.

Other factors of concern in the use of the 20*T* modulated pulse are channel characteristics such as nonlinear distortion and noise. Intercity video facilities are intended to have a delay difference of less than 50 ns between the chrominance and luminance channel and a gain difference of less than 0.75 dB. This means that the distortion of the 20*T* modulated pulse baseline will usually be less than 3% of the peak amplitude. It is possible that noise and nonlinear distortions could affect the baseline of the 20*T* pulse. In tests on four 2000-mile video channels with the 20*T* modulated pulse, the gain and delay differences between the luminance and chrominance channels as measured with the 20*T* pulse changed by about 0.3 dB and 30 ns for a 4-dB change from nominal testing level. These variations of the 20*T* pulse responses with level are comparable with the linear distortions to be measured. The tests were made on a full-frame basis so that the average level of the test signal was constant. If the 20*T* pulse is used in the vertical interval of a video signal the average picture level changes could cause the 20*T* baseline to vary with picture content and mask the desired results. Additional work is needed to determine how the 20*T* modulated pulse behaves as a VIT signal and at what level it should be used.

Although lowering the level of the 20*T* modulated test signal may reduce the effect of nonlinear distortion it would increase the effect of noise. Consider a channel having a 40-dB SNR and using a one-volt 20*T* modulated test pulse. The SNR at the baseline of the 20*T* pulse for 3% distortion will be only 10 dB. Any reduction in signal level reduces this value, making the baseline envelope difficult to evaluate. The 20*T* pulse generator used in these tests did not have gain and delay networks to determine the characteristics of the channel. Such a 20*T* pulse receiver would probably increase the precision of the measurements, but would still be subject to the problems of noise and nonlinear distortion.

Since baseline distortion depends on the test signal pulse width it is apparent that the noise performance can be improved by narrowing the pulse. A reduction in pulse width by a factor of two can increase the baseline distortion by a factor of two. The gain in baseline distortion magnitude with a reduction in pulse width may be enough to overcome the problems of noise and nonlinear distortion in the video channel. The disadvantage in reducing the pulse width, say from 20*T* to 10*T*, is an increase in the bandwidth of the test signal. This makes the signal more susceptible to linear distortion across the band and allows energy to occur outside the nominal chrominance channel bandwidth. However, looking at the spectrum of the 10*T* pulse shows that its spectrum is down 6 dB at about 400 kHz; therefore most of its energy is still within the chrominance band. In addition, the deviations that are to be measured are so small that they should not affect the accuracy of the method.

Further measurements of the 20*T* modulated pulse response on video channels and correlation with frequency domain measurements are needed to fully evaluate the 20*T* pulse. In addition, other pulse widths should be considered to make the test pulse less susceptible to other channel deviations.

Conclusions and Recommendations

Vertical interval testing is used to directly measure the quality rating of equipment and facilities on a routine real-time basis. The test signals used in the vertical interval should be chosen so their response is easy to interpret and is directly related to the quality of the channel. The T pulse does not meet these requirements and therefore should not be used as a vertical interval test signal. A possible replacement is the $2T$ pulse. Another alternate would be the bar signal.

Evaluation of the test pulse response should be in terms of the K quality rating factor. K rating graticules are not universally applicable to all television systems, but must be designed to fit each individual system's characteristics. Therefore, K rating graticules should be developed which are directly applicable to the U. S. 4.2-MHz system.

Characteristics of a channel in the color subcarrier region of the frequency band should be measured with a test signal separate from the luminance test signals. Although the $20T$ modulated pulse seems like a good test pulse for this purpose, more information must be known about it before it is adopted as a standard test signal. Particularly important is the susceptibility of the $20T$ pulse to nonlinear distortion in the channel. Narrower pulses such as the $10T$ pulse also have merit and should be evaluated. Further investigations should be carried out on both a full-frame and a vertical interval testing basis on actual video facilities.

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APPENDIX

Analysis of 20*T* Modulated Pulse Response

In this Appendix a method of obtaining the gain and envelope delay difference between the luminance and chrominance channels will be discussed. The upper and lower envelopes of the $20T$ modulated pulse can be written as the sum and difference of a baseband $20T$ pulse passed through the luminance and chrominance channels. Let $f(t)$ represent the baseband $20T$ pulse, $u(t)$ the upper envelope, and $l(t)$ the lower envelope of the $20T$ modulated pulse. If the gain of the chrominance channel with respect to the luminance channel is k and the envelope delay is τ, the upper and lower envelopes are:

$$u(t) = f(t) + kf(t-\tau) \qquad (1)$$

$$l(t) = f(t) - kf(t-\tau) \qquad (2)$$

The baseband $20T$ pulse, $f(t)$, can be written as

$$f(t) = \frac{1}{4} + \frac{1}{4}\cos\frac{\pi t}{T_c} \qquad |t| \leq T_c$$

$$= 0 \qquad \text{otherwise}$$

where $T_c = 2.5$ µs for the NTSC system. Then

$$u(t) = \left[\frac{1}{4} + \frac{1}{4}\cos\frac{\pi t}{T_c} + \frac{k}{4} + \frac{k}{4}\cos\frac{\pi(t-\tau)}{T_c}\right] \qquad (3)$$

$$l(t) = \left[\frac{1}{4} + \frac{1}{4}\cos\frac{\pi t}{T_c} - \frac{k}{4} - \frac{k}{4}\cos\frac{\pi(t-\tau)}{T_c}\right] \qquad (4)$$

Consider $l(t)$ at $\pm T_c/2$ normalized to the upper envelope at $t = 0$, $u(0)$. Let $u(0) = X_{\max}$, $X_1 = l(-T_c/2)$, and $X_2 = l(T_2/2)$. Then

$$X_{\max} = u(0) = \frac{1}{2} + \frac{k}{4} + \frac{k}{4}\cos\frac{\pi\tau}{T_c}$$

$$\approx \frac{1+k}{2} \quad \text{for} \quad \tau/T_c \ll 1 \qquad (5)$$

$$X_1/X_{\max} = l(-T_c/2)/u(0) = \frac{1}{1+k}\left[\frac{1}{2} - \frac{k}{2} + \frac{k}{2}\sin\frac{\pi\tau}{T_c}\right] \qquad (6)$$

$$X_2/X_{\max} = l(T_c/2)/u(0) = \frac{1}{1+k}\left[\frac{1}{2} - \frac{k}{2} - \frac{k}{2}\sin\frac{\pi\tau}{T_c}\right] \qquad (7)$$

Taking the sum of Eqs. (6) and (7) and solving for k yields;

$$k = \frac{1 - X_1/X_{\max} - X_2/X_{\max}}{1 + X_1/X_{\max} + X_2/X_{\max}} \qquad (8)$$

Taking the difference of Eqs. (6) and (7) and solving for τ yields for $\tau/T \ll 1$

$$\tau \approx \frac{2T_c}{\pi}\left(\frac{X_1/X_{\max} - X_2/X_{\max}}{1 - X_2/X_{\max} - X_1/X_{\max}}\right) \qquad (9)$$

Letting $\Delta = X_1/X_{\max} - X_2/X_{\max}$ and $\Sigma = X_2/X_{\max} + X_1/X_{\max}$ Eqs. (8) and (9) can be rewritten as

$$k = \frac{1-\Sigma}{1+\Sigma} \qquad (10)$$

$$\tau = \frac{2T_c}{\pi}\,\frac{\Delta}{1-\Sigma} \qquad (11)$$

To summarize, this method yields the gain and delay of the chrominance channel with respect to the luminance channel by taking two measurements and using Eqs. (10) and (11). Note that for pure gain distortion $l(t)$ is an even function about $t = 0$ $(\Delta = 0)$ while for pure delay distortion $l(t)$ is an odd function $(\Sigma = 0)$.

Equations (6) and (7) were used to derive Fig. 7. For no distortion the peak of the upper envelope and $u(0)$ are equal while for expected value of channel they are close enough for measurement purposes.

Discussion

Frank Davidoff (CBS TV Network): You mentioned that you had difficulty in using the 20 *T*-pulse because of channel nonlinearity. Did you investigate the effect of nonlinearity on other test signals such as the sine-squared pulse and multi-burst?

Mr. Mallon: No, we did not.

Mr. Davidoff: Should linear test signals possibly be transmitted at half amplitude to isolate the effects of nonlinearity?

Mr. Mallon: Reduction of the testing level might reduce the effects of nonlinearity. There are problems in general correlating the results of linear distortion test signals, and apparently the problems stem from the nonlinearities of the channel. In particular, we use the *T*-pulse response of a channel to find the gain and envelope delay characteristics of the channel. These results should have correlated with other measurements such as the 20-*T* modulated pulse results and frequency domain measurements. There were difficulties in correlating these different methods of measuring essentially the same thing. The nonlinearities seem to contribute to this problem.

James Walter (Radio Corp. of America, Camden, N.J.): In your evaluation of the signals you referred to the *T*-pulse as not being suitable for use as a vertical interval test. What about the use of these signals as 100% on-line testing when the line is available to transmit them line by line? What is their usefulness then?

Mr. Mallon: I think it depends on what you want to get out of the test. The *T*-pulse is a very valuable test signal if you have enough time to evaluate the response properly. The *T*-pulse response contains information about the channel from zero to about 7 or 8 MHz. However, to obtain this information requires a rather detailed analysis to find the channel characteristics. In the vertical-interval testing method, the main objective is to determine — on a real-time basis — how good the channel is for transmitting video information. One of the objectives is to have a relatively simple testing signal and evaluation method, so that a trained observer is not needed. In the case of the *T*-pulse, because of all its extra energy and extraneous information, you cannot do this very simply. However, the *T*-pulse, if properly used, is a good testing signal. We use it now through a Fourier transform to obtain the gain and the envelope delay characteristics of the channel, which we could not do with 2-*T*.

Mr. Walter: Do you ever resort to the direct on-line testings, such as a Wandel and Goltermann test set? Or something of that variety that will measure envelope delay?

Mr. Mallon: Yes, we have measuring systems that were developed by the Bell System that give visual or oscilloscope presentations of gain and envelope delay characteristics of the channel. For these, of course, you have to have the channel full time.

Mr. Walter: Do you find these more acceptable than the *T*-pulses?

Mr. Mallon: It depends on what you want to measure on the channel. The frequency domain test sets give you information such as gain and envelope delay characteristics of the channel. If channel quality is of interest the step from frequency domain characteristics to actual channel quality is not an easy one. To find out something about the quality of the channel it is usually necessary to use waveform testing, such as transmitting signals representative of actual video signals and see how much they are distorted.

Integration of Technical Facilities in Black-and-White and Color TV Programming

By EDWARD P. BERTERO

In a television plant, Technical Operations is frequently asked to provide facilities for handling programs involving the integration of combinations of film, video tape, live and outside or field program sources. In order to avoid picture disturbances when switching to these various program sources, horizontal and vertical synchronization must be maintained between the sources at all times. In-plant-timing, genlock, audlok, frequency standard lock, and standards conversion are all methods and procedures used to realize this synchronization both in color and black-and-white television.

In-plant-timing

It is normal procedure in the final stages of the installation of a TV studio plant to establish "in-plant-timing." This procedure times the TV synchronizing pulses in the plant to each camera and switcher so that switching between cameras and studios does not create picture disturbances in home receivers tuned to the station.

Color TV requires six synchronizing pulses which must be timed. These pulses include: (1) 3.58-MHz (Mc/s), (2) vertical drive, (3) horizontal drive, (4) kinescope blanking, (5) synchronizing pulses, and (6) burst flag. These pulses are generated by the TV synchronizing generator and are all time-related to each other. In distributing these synchronizing pulses throughout a plant, varying delays between pulses are encountered, since the path lengths, and thus delays, are different. The color subcarrier 3.58 MHz signal is a sinusoidal wave that is easily corrected in delay by a 360° phase control. Vertical drive, a 60-Hz (c/s) signal, ordinarily does not require cable length correction because of its relatively long duty cycle. The timing of horizontal drive, horizontal blanking, horizontal sync and burst flag pulses, require accurate delay correction to comply with FCC requirements. Very accurate relationships must be maintained between all pulses to realize the proper width of front and back porches (Fig. 1).

Since studio and switching systems differ both electronically in delay and physically in distance from the input to output terminals, a pulse distribution system must provide in-plant-timing so that the various video signals originating at different locations in the plant arrive, or are timed to be the same, at a particular reference location. Timing is difficult if the facilities are different. One studio may have a special-effects amplifier, whereas others may not. Furthermore, similar components, such as a special-effects amplifier made by different manufacturers, do not all have the same delay. In short, the pulse timing and video delay of various equipment components in a signal path must be compensated for in each studio.

To time a TV plant, the longest pulse and video path lengths must first be determined to establish a reference time basis for the entire plant. Then, lump delays must be introduced in the pulse distribution system so that the path lengths in the shorter studios and switching systems match the pulse and video time reference initially established. In practice, in-plant-timing for black-and-white TV is established using the kinescope blanking pulse. The timing of the blanking pulse and the position of the edges of this pulse must be very accurately positioned by the use of proper delays, since these edges are what primarily time the TV plant with the home receiver. In color TV the same procedure must be followed as in black-and-white TV, and it is also necessary to time the 3.58-MHz color subcarrier within the plant. A simple two-studio plant is shown in Fig. 2.

In-plant-timing is at best a time consuming, laborious task. It becomes more complicated when piggyback operation must be provided (i.e., when the output of Studio A which integrates live and tape segments must go through Studio B, which integrates the output of Studio A with live program and film commercials).

Piggyback operation must be designed into the plant. Means must be provided for switchable pulse delays. The approach of in-plant-timing for piggyback operations is again to first establish maximum stacking of studios and thus pulse delays. A practical piggyback limit for a large network station is three studios. Beyond three-studio stacking, the switching of the pulse delays and possibly video delays becomes inordinately complicated and expensive.

A simplified version of a TV plant

Presented on May 5, 1966, at the Society's Technical Conference in Washington, D.C., by Edward P. Bertero, National Broadcasting Co., 30 Rockefeller Plaza, New York, N.Y. 10020. (This paper was received on March 10, 1966.)

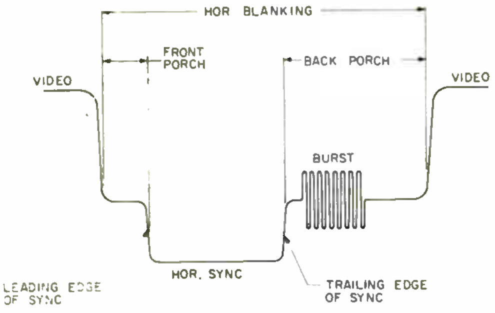

Fig. 1. The position of the horizontal sync pulse during horizontal blanking time is specified by the FCC. The leading edge of the sync pulse is used in receiver locking circuits. The trailing edge of sync is frequently used to trigger clamp circuits in broadcast equipment.

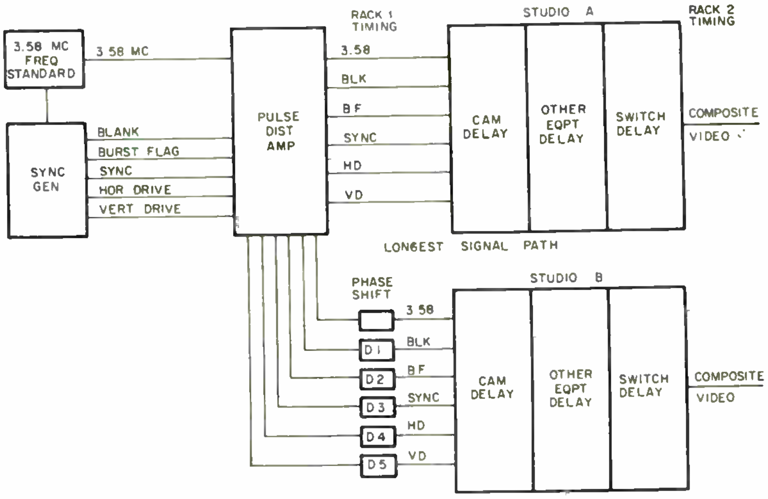

Fig. 2. Studio A Composite Video Output is the longest signal path time of plant. Studio Composite Video Output must be made equal to Studio A by adding D_1 through D_5.

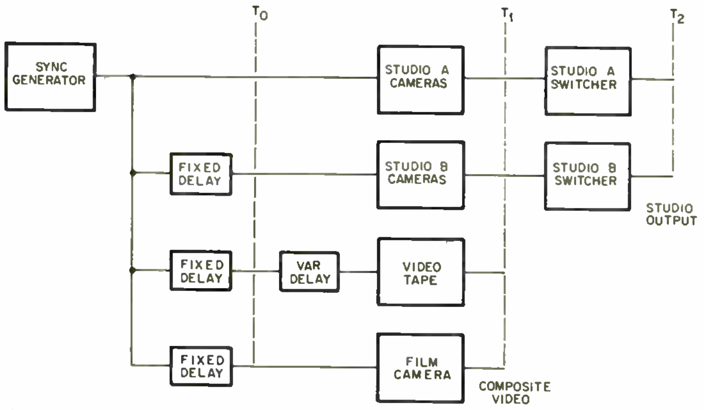

Fig. 3. Two studio timing.

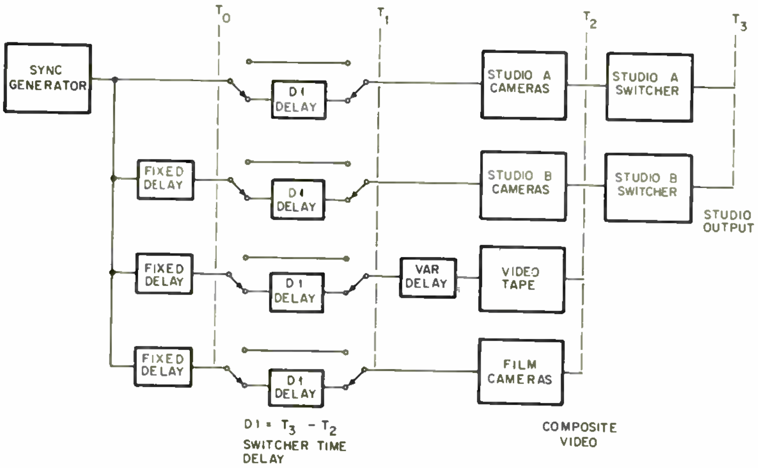

Fig. 4. Two studios timed for piggyback operation.

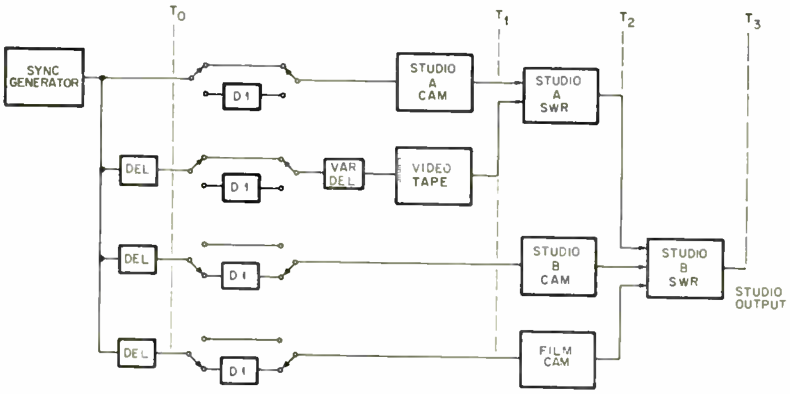

Fig. 5. Two studios piggyback operated.

with video-tape and film facilities is shown in Fig. 3. If piggyback operation is anticipated, switchable pulse delays are required as shown in Fig. 4. The plant ordinarily can operate either with all delays in or all delays out.

A hypothetical TV plant timed to operate in a two-studio piggyback mode is shown in Fig. 5. It should be noted that the pulse signals fed to switcher A are not delayed. Delay is added to the Studio B video source so that the output of Studio A and all the video sources of Studio B arrive at the input to Studio B switcher at time T_2.

In-plant-timing is not something done only at the time of the installation of a TV plant. It is a continuing job. A change in switching systems, the addition of distribution amplifiers, new cameras or film chains, or any other change that will affect pulse or video timing must be carefully studied before integration into a plant. The mixing of cameras of different manufacture, or the integration of black-and-white and color cameras in a plant can create knotty problems. In general, the older the TV plant, the more difficult it becomes to expand facilities.

Genlock

The subject of remote timing comes up whenever the Program Department requires mixing, fading or dissolving from the TV studio to a mobile field pickup. Then it is necessary to time-lock the TV plant sync generator to the mobile unit sync generator so that there is no picture disturbance when switching from studio to mobile unit or vice versa during a broadcast. A technique known as genlock is used to operate two sync generators in series (or synchronism). In principle, the plant sync generator is locked to the mobile unit sync generator. A single line drawing of a genlock system is shown in Fig. 6A. The TV plant is made available to the mobile unit, in a time sense, so that the TV picture can originate at either the studio or the mobile unit with no disturbance in picture during switching or dissolving to and from either program source. The system works equally well in black-and-white or color TV. In color, of course, accurate phasing of the color subcarrier is required at the plant sync generator. This particular function is not required in black-and-white operation.

In practice, genlock adjustments between studio and the remote program sources are always done during the test period prior to the time of broadcast. It is not uncommon for a news program to consist of a local commentary and several remote program sources. In this case, genlock is not feasible except to one of the remote program sources. A vertical roll may be visible in switching to and from the remote program source not in the genlock mode.

Superlok

The technique of inserting names or subtitles in a television picture which is frequently done during a news program is called superlok. Superlok is a form of genlock but has the inherent advantage of always being genlocked with the program source being viewed at the time of title insertion, even though the program source is not genlocked to the studio.

A line diagram of technical facility requirements of a news program is shown in Fig. 6B. It is to be noted that no attempt is made to genlock to the remote program sources. A vertical disturbance may be viewed in switching. Shortly after switching, however, sync generator B is genlocked to the remote program source. The projected title or name to be used on the news segment being viewed is televised by the superlok camera. Energizing the superlok relay transfers the program output from the video amplifier to the special-effects amplifier output. On cue the title can be dissolved, or inserted and removed from the televised picture. Upon completion of title insertion the superlok relay is de-energized and program is routed in the normal fashion. Superlok title insertions can be done either in black-and-white or in color.

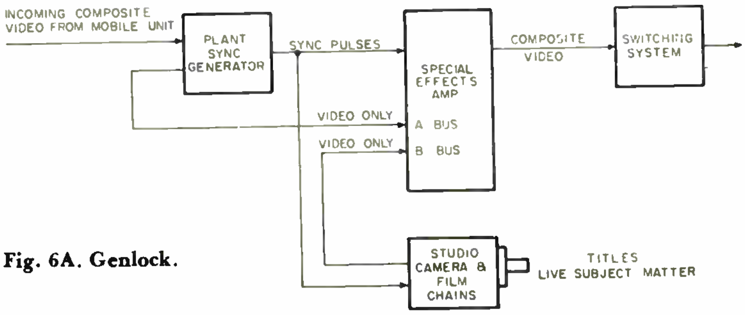

Fig. 6A. Genlock.

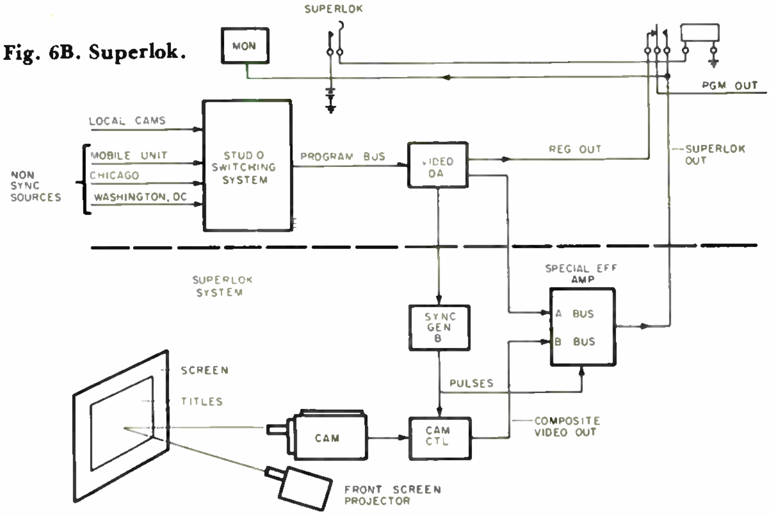

Fig. 6B. Superlok.

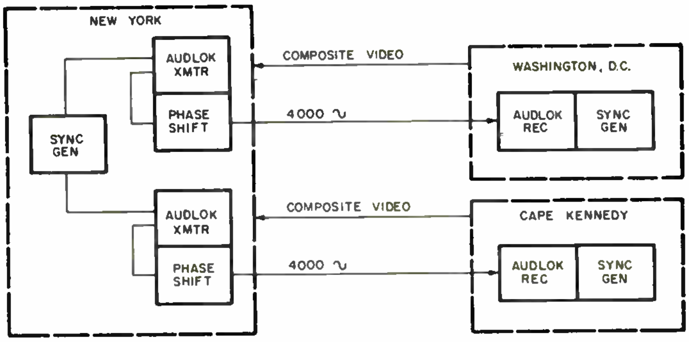

Fig. 7. Audlok.

Audlok

In a large TV plant, it often happens that video-tape recording, kinescope recording and TV broadcasting occur simultaneously. The TV plant may also be in genlock mode for a mobile unit pickup to be taped. The next program might, for instance, require integration of a show with program control in New York, with portions of the program from Washington, D.C., and Cape Kennedy. In such a situation it is necessary to switch, dissolve, etc., to each pickup point without picture disturbances.

The problem is to time the program sources from Washington and Cape Kennedy to arrive at the same time in New York and be coincident with New York sync pulse time. Stated in another way, with New York as a basis of reference, Washington must be timed in advance of New York by the transit time of the signal between Washington and New York. Likewise Cape Kennedy must be timed in advance of New York by the transit time of the signal between Cape Kennedy and New York.

It is not possible to use ordinary genlock of pulse synchronization in this problem. Genlock is a forward type of locking and is the condition whereby the control studio locks to the outside program source. Genlock might be used to synchronize New York to Washington, but it could not be used simultaneously to lock New York with Cape Kennedy.

A system known as audlok has been devised to solve this type of synchronizing problem. Audlok might be described as a backward type of genlock that synchronizes both Washington and Cape Kennedy to a New York time base. As the term implies, an audio frequency is used to time-lock synchronizing generators. In the system shown in Fig. 7, an audlok transmitter is located at Master Control in New York, and an audlok receiver to be synchronized with New York is located in Washington, D.C. Another audlok transmitter and associated receiver are located in New York and Cape Kennedy, respectively. Each audlok transmitter and associated receiver is interconnected by means of a rented telephone circuit. The horizontal line frequency of the New York synchronizing generator is processed by the audlok transmitter to produce a submultiple audio-frequency sine wave of about 4000-Hz which can easily and quickly be phase-shifted by any desired amount. The audlok receiver in Washington processes the 4000-Hz tone from New York and multiplies it to lock the Washington sync generator. Then, by superimposition of New York and Washington pictures and by means of phase control the Washington sync generator can be accurately timed, both horizontally and vertically, so that the Washington pulses are coincident with New York pulses at arrival in New York. With another audlok system the sync generator at Cape Kennedy can be similarly adjusted so that the Cape Kennedy pulses are coincident with New York pulses. Thus, the timing problem between New York, Washington and Cape Kennedy is solved. Audlok has worked very successfully in black-and-white TV.

Frequency Standard Locking Technique

The success of audlok has suggested several other schemes to eliminate the need for time control circuits between pickup points and control location. One such scheme would use very stable 3.58-MHz oscillators to control TV sync generators. The stability must be in the order of one part in 10^{11}. It is reasoned that if a stable 3.58-MHz oscillator is used to time a New York sync generator, and another 3.58-MHz oscillator is used to time a sync generator in the Washington, D.C., studio, it should be possible for New York, on viewing a TV picture from Washington, to arrange by telephone for framing adjustment at one end or the other. Such a system is now in operation in black-and-white TV and requires only daily checking and minor adjustment of phase each morning. Tests in color TV indicate that at this stage the technique does not provide sufficient stability of color subcarrier reference to permit dissolves and special effects due to lag and short time phase delays in the intercity circuits.

Translator

Several systems of time locking two or more television synchronizing generators have been described. In all these systems, timing is the common denominator of the synchronizing process. Time syn-

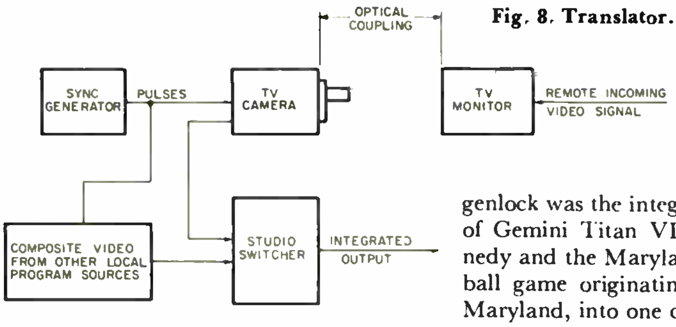

Fig. 8. Translator.

chronization is possible only when the horizontal line frequency and the picture frame rates are the same between two or more synchronizing generators and time is the only parameter that requires synchronization.

Many other disciplines have been confronted with the problem of time synchronization. In those instances where the timing differential has not been too large, some form of energy or information storage has solved the problem. Such a system of video information storage, where time synchronization cannot be used, has been developed for use in television. The system is known as picture translation. That is, a TV picture on one time base is translated to a TV picture on a different but compatible time base by video information storage. Translation is accomplished in a device called a translator (Fig. 8), which consists of a high-quality TV monitor and a TV camera. The camera is adjusted for full monitor scanning. The monitor displays the nonsynchronous program televised from some distant source. The translator camera, operated on the local sync generator pulses, views the monitor. The reading and writing rates are the same in this optically coupled system, but differ in time reference. However, because of the information storage in this system, i.e., storage characteristics of the kinescope phosphor and the information storage of the camera tube, the difference in time reference or phase of the system is no longer a problem. In short, by means of video information storage, two time systems that differ only in phase can be coupled. Therefore, the translator camera can be integrated with any other program source originating in New York without any picture disturbance during switching time.

The translator must be a unity device to avoid picture degradation. It is also necessary to keep noise to a minimum to minimize picture degradation. Such a system has been used by several major broadcasters for some time and has proven very successful in black-and-white TV. It has been employed with some success in color TV using a tricolor kinescope and a color camera. However, considerably more development is required to realize optimum translation in color. One recent example of the use of this system in conjunction with color genlock was the integration in New York of Gemini Titan VII from Cape Kennedy and the Maryland-Penn State football game originating in College Park, Maryland, into one composite picture to permit the viewer to observe the critical actions of both events without interruption.

Standards Converter

With the advent of video tape, the TV broadcaster has been faced with a more difficult timing problem: the integration of a video-tape recording made on any of the several European standards into a program to be broadcast on American TV standards. In this instance one must contend not only with a difference in horizontal line frequency but also with a difference in frame rate. The problem is handled by use of a specialized device called a standards converter. As the title implies, the device is used to convert from one TV frequency standard to another. In concept it is similar to the translator previously described. It differs from the translator in that instead of reading and writing on the same TV standard, it reads on one standard and writes on another. Storage minimizes the problem of reading and writing at different horizontal frequencies.

There is a problem, however, in reading and writing at frame rates which differ by large time increments. If you read or write at a 60-Hz rate, and write or read at 50-Hz rate, the resultant difference of 10-Hz manifests itself as an annoying flicker. Circuits have been developed to minimize this 10-Hz flicker but it has not as yet been completely eliminated. Multi-standard video-tape machines and standards converters have been in use for many years in black-and-white TV. As yet a color TV standards converter has not been made available to the broadcasting industry. Color translators and color standards converters can be made using the same approach used in black-and-white TV. But the complexity of demodulating a color signal to display the red, green and blue components of the signal on three kinescopes and the reconstitution of the picture on the new standards results in serious degradation with currently available techniques.

Successful translation of monochrome signals by wholely electronic means has been accomplished in Europe for horizontal timing differences only, (e.g., translation of a 625-line, 50-Hz TV picture to a 405-line, 50-Hz TV picture). There is reason to believe that in the future a similar electronic approach will be developed to convert from European to American TV standards in color.

Summary

The average TV receiver can accept some minor discontinuity or timing error in synchronizing pulses both vertically and horizontally, which may occur during the course of switching a program. When not tuned to a TV station, the TV set will scan a raster and utilize the synchronizing signal from a station only to "lock in" the receiver vertical and horizontal oscillators. Many components of equipment used in a broadcast plant, however, are "driven" by the synchronizing generator, and any discontinuity or timing error of the pulses can result in a serious discontinuity in the TV picture. The video-tape machine is one such device that is very sensitive to any synchronizing pulse discontinuity or timing error. Experience indicates that synchronizing pulse timing must be maintained within certain limits. The maximum timing error of vertical framing that can be tolerated during a program switch, cannot exceed the time of half a TV line or ±32 μsecs. On special effects, dissolves, wipes, etc, the timing tolerance of kinescope blanking must be maintained to ±.05 μsec to avoid visible picture shift on the home screen. Finally, in color TV the phase of the 3.58-MHz color subcarrier during such an operation must be maintained to ±3 degrees or approximately 3 ns to avoid a noticeable shift of color. These tolerances which must be maintained not only during a program originating from a local TV plant but between all other program sources (including local mobile unit, intercity pickup, or a coast-to-coast pickup) that are synchronized by any of the methods described for color or black-and-white TV.

In timing TV synchronizing signals that are not identical in line rate or frame rate, a more fundamental problem in time is encountered. Standards conversion, as described, is only a report on the state of the art. The technique for monochrome conversion is adequate but not considered the ultimate solution. Some thorough investigations have been made of this problem. Information theory offers some possible solutions. A solution is to sample or quantize video information on one standard and reconstitute a picture on the desired standard. Results of such approaches have been encouraging and are useful in some disciplines, such as space and military applications. As yet, however, the results have not been considered acceptable for commercial TV broadcasting.

The author wishes to express his gratitude to various members of the Audio-Video and Maintenance Groups of the National Broadcasting Co. for assistance in the preparation of this

paper. Special thanks are extended to R. Butler, J. Crampton and E. Boisvert for their assistance.

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System Designing of Color Television Facilities

By YUTAKA ITOH

The number of color receivers was greatly increased in Japan in 1966. The Tokyo Broadcasting System had predicted the necessity for a thorough redesign of facilities and established the detailed design targets by the end of 1962. The overall transmission characteristics were first set up by using eight parameters which affect the quality of the pictures received. These overall characteristics are divided into program production facilities, local transmitter and intercity microwave linkages. The program production facilities are divided into seven blocks and these are further divided into each individual unit of equipment to complete the entire system design targets. These design targets have proved very helpful for the further development of high-standard equipments. The methods of establishing the design targets are described.

As THE LARGEST commercial broadcasting organization in Japan, the Tokyo Broadcasting System had to be prepared for the many requirements associated with adapting its facilities to color and the complexity of program production techniques. By the end of 1962, the TBS Engineering Dept. had predicted the necessity for a thorough redesign of facilities and established the detailed design targets of every unit equipment, such as synchronizing pulse generator, pulse and video distribution amplifiers, cable equalizer, stabilizing amplifier, pulse and video delay lines and microwave link. These design targets have proved helpful for further development of high-standard equipments.

Overall Transmission Characteristics

The overall transmission characteristics were first set up from color encoders, where NTSC color picture signals are originated, to the RF output of a television transmitter by using the following eight parameters which will affect the quality of the pictures received: (1) dynamic gain and insertion gain variations, (2) frequency response, (3) pulse response, (4) sine-squared pulse response, (5) differential gain, (6) differential phase, (7) envelope delay and (8) signal-to-noise ratio (SNR). The overall characteristic are set as shown in Table I. Of course, some of the above parameters are interrelated, but it is not easy to deduce or interpret one parameter from the others.

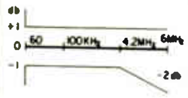
The logic governing the above settings is as follows:

(*1*) *Dynamic gain and insertion gain variation:* less than ±1 dB. Dynamic gain is the gain fluctuation from APL 10% to 90%, taking APL 50% as a reference, and this specifies the gain fluctuation which varies with the amount of the dc component in the video signal. Moreover, this specification includes the gain variation resulting from the ambient temperature, heating of the equipments themselves after being energized, ac power supply voltage fluctuation of ±5%, and therefore the ability of the stabilized power supply unit or units concerning the equipments will also affect this value in some cases.

The figure is deduced from the fact that the just-noticeable change in SNR

Presented on April 20, 1967, at the Society's Technical Conference in New York by Yutaka Itoh, Television Engineering Dept., Tokyo Broadcasting System Inc., Akasaka Minatoku, Tokyo, Japan.
(This paper was received on March 14, 1967.)

Table I. Design Targets of Overall Transmission Characteristics.

<table>
<tr><th>Item \ System</th><th>Program production facilities</th><th>S T L (Coaxial cable 2.9Km)</th><th>Transmitter</th><th>Over-all</th><th>NTT (REFERENCE) Hypothetical reference circuit 2500Km</th></tr>
<tr><td>E Dynamic gain (APL 10~90% Reference APL 50%) Insertion gain variation</td><td>± 0.7 db</td><td>± 0.1 db</td><td>± 0.2 db</td><td>± 1 db</td><td>Short-period variations (1 sec) ±0.3 db
Medium-period variations (1 hr) ±1.0 db</td></tr>
<tr><td>F Freq response (1) (Reference 100 KHz)</td><td>
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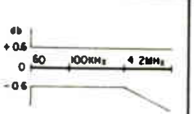
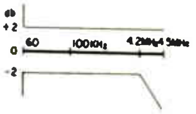
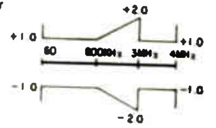
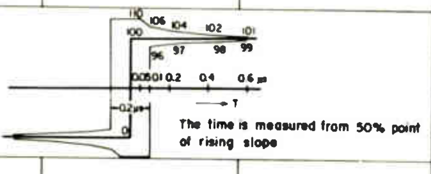
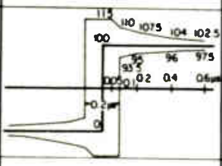
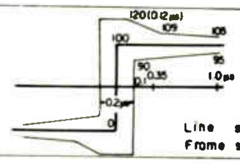
</td><td>
</td><td>
</td><td>Colour
</td></tr>
<tr><td>G Pulse response (2) (15.75 KHz 250 KHz Rise time 0.1μs)</td><td colspan="3">

The time is measured from 50% point of rising slope</td><td>
</td><td>

Line slope ± 5%
Frame slope ±10%</td></tr>
<tr><td>H Sin² response (2T Pulse)</td><td>K = 1</td><td>K = 1</td><td>K = 1</td><td>K = 2</td><td>——</td></tr>
<tr><td>K D G (3) (APL 10~90%)</td><td>10%</td><td>2.5%</td><td>7.5%</td><td>20%</td><td>10%</td></tr>
<tr><td>L D P (4) (APL 10-90%)</td><td>5°</td><td>1°</td><td>4°</td><td>10°</td><td>5°</td></tr>
<tr><td>O Envelope delay (5) (Up to 4.2MHz Reference 15.75KHz)</td><td>± 45 mμs</td><td>± 5 mμs</td><td>as per the Radio Regulation Rule</td><td>± 50 mμs</td><td>30 mμs
Up to 4MHz Reference 15.75KHz</td></tr>
<tr><td>Q S/N {Hum Periodic
Random (6)</td><td>41 db p-p/p-p
41 db p-p/rms</td><td>49 db p-p/p-p
60 db p-p/rms</td><td>49 db p-p/p-p
49 db p-p/rms</td><td>40 db p-p/p-p
40 db p-p/rms</td><td>Periodic noise
• Power-supply hum (including the fundamental frequency and lower order harmonics) ----- 30db (p-p/p-p)
• Single-frequency noise between 1KHz and 1MHz -50db (p-p/p-p)
• Value (db) to which the signal-to-noise ratio for single-frequency noise may decrease linearly between 1MHz and fc ------------ 30db (p-p/p-p) but the signal-to-noise ratio should not be less than 50db at 3.6MHz
Random noise
weighted ------------------ 54db (p-p/rms)
unweighted {Flat noise ----- 40.5db (p-p/rms)
Triangle noise ---- 44.9db (p-p/rms)</td></tr>
<tr><td>e Front porch (7) (Reference Sync gen output)</td><td>±0.1125 μs</td><td>——</td><td>± 0.0125 μs</td><td>0.022H ±0.002H (0.127μs)</td><td></td></tr>
<tr><td>f Pulse width (Reference Sync gen output)</td><td>+ 0
− 5.4 %</td><td>——</td><td>+ 0
− 0.6 %</td><td>H SYNC 0.075H +0 −0.005H (6.6%)</td><td></td></tr>
</table>

(1) The upper limit response of high frequencies shall not exceed that of low frequencies
(2) Beyond 0.6 us points, the tolerance remain the same
(3) Max flat part is taken as the reference and the value shown can be applyed for the both positive and negative direction
(4) The phase of the black level is taken as the reference and the value shown can be applyed for the both positive and negative direction.
(5) The envelope delay with in transmitter is not included
(6) Unweighted.
(7) Measure at ±0.03 V points from black level

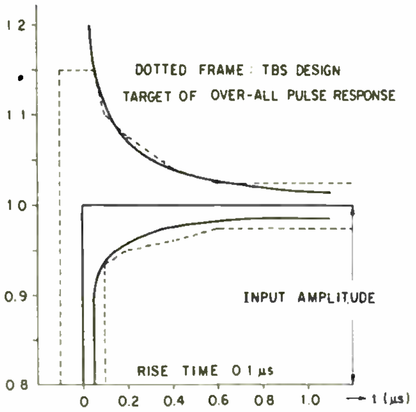


Fig. 1. Just-noticeable limit of transient waveform.

is about 1 dB at a receiver located at just marginal field strength.

(*2*) *Frequency response:* within ±2 dB in the range of 60 Hz to 4.2 MHz taking 100-kHz response as the reference. The frequency response above and below the specified frequencies should be of smooth-roll-off characteristics. Any boost in high frequencies will cause overshoot and ringing, and low-frequency boost will affect the bounce response, so no boost of any kind is allowed. The value of ±2 dB is based upon the Radio Regulations of Japan.

(*3*) *Pulse response:* The framed limits shown in Table I in the overall characteristics column define the pulse response.

+15% at 0.05 μs
+10% and −6.5% at 0.1 μs
+7.5% and −5% at 0.2 μs
±4% at 0.4 μs
±2.5% at more than 0.6 μs

(The time is measured from the 50% point of the rising slope.)

This specification is based upon the experiments of J. Müller and the NHK Technical Research Laboratory, which are shown in Figs. 1 and 2, respectively. Figure 1 shows the just-noticeable limit as to the square waves of the known overshoots and ringings displayed on the picture tube.[1] Figure 2 shows the results of subjective tests on the allowable amount of reflection.[2]

The test pattern signal from a monoscope is displayed on a picture tube 30 cm in diameter, and artificial reflections of known delay-time and amplitudes are added to the original signal.

A number of viewers observed the mixed signal and obtained the just-noticeable and allowable limits of picture deterioration. The dotted curves shown in Fig. 2 are obtained when the SNR of the original picture is 33 dB (which roughly corresponds to the allowable limit for white noise content). Fortunately, the results of the above two tests gave very similar values, and the design target of the pulse response was set as shown by the dotted frame in Figs. 1 and 2. Smears, ringings and reflected waves should be kept within the specified frame.

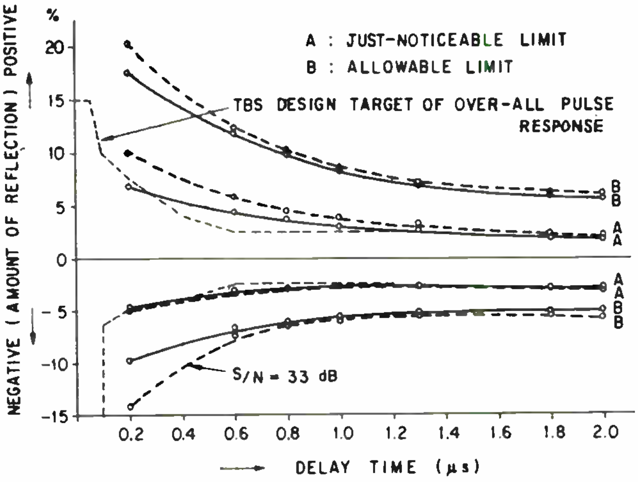


Fig. 2. Subjective test result of allowable amount of reflection.

(*4*) *Sine-squared pulse response:* K = less than 2% with $2T$ pulse. At the moment, the NTT (Nippon Telegraph & Telephone Public Corp.) transmission lines are measured by using a $2T$ pulse, but this method of measurement is not adequate for color transmission characteristics. The new method of employing a modulated $20T$ pulse was recently introduced by Peter Wolf.[3] This modulated $20T$ pulse is being prepared for use by TBS. In this design target, K with $2T$ pulse is prescribed to be less than 2% as the overall response.

(*5*) *Differential gain:* Less than ±20% at APL 10 to 90%.

(*6*) *Differential phase:* Less than ±10 degrees at APL 10 to 90%. As to the above two items, our Radio Regulations recommend that the amplitude and phase of color bar signals at the 75% level shall be within ±20% and ±10 degrees respectively. These figures were specified for the differential gain and differential phase.

(*7*) *Envelope delay:* ±50 ns up to 4.2 MHz taking 15.75 kHz as the reference. These values are taken from the Radio Regulations of Japan, which define the coincidence of $E_{Y'}$, $E_{I'}$ and $E_{Q'}$. The envelope delay characteristics of amplifiers, cables, and such equipment as the stabilizing amplifier which divides picture signals into the luminance and chrominance components, will affect the coincidence of $E_{Y'}$, $E_{I'}$ and $E_{Q'}$. Therefore, this value (50 ns) has to be taken care of by the whole system. The predistortion for color receivers prescribed by the Radio Regulations is not included in this value.

(*8*) *Signal-to-noise ratio:*

(*a*) *Hum, periodic noise:* More than 40 dB (p-p/p-p).

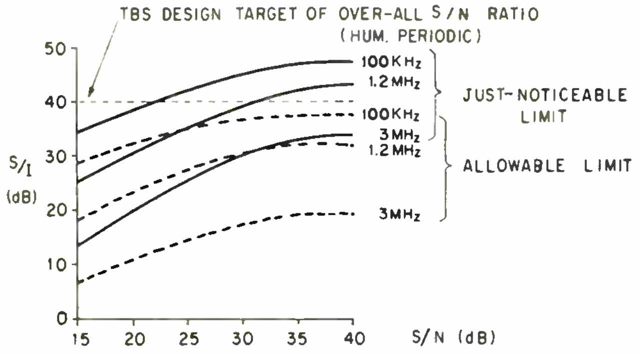


Fig. 3. Just-noticeable and allowable limits of beat interference.

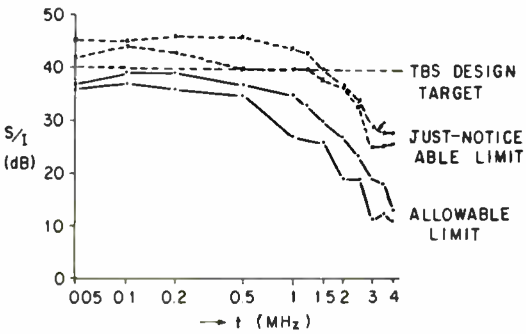


Fig. 4. Just-noticeable and allowable limit of single-frequency interference where SNR = 40 dB.

Figure 3 shows curves of the just-noticeable and allowable limits of the single-frequency interference.[4] The horizontal axis represents the SNR (dB) of a measured video signal and the vertical axis represents the S/I ratio (dB). Where S is a peak-to-peak value of the picture signal of the video signal, N is the rms value of noise and I is the peak-to-peak value of the interfering sinusoidal signal.

Figure 4 shows the variation of the just-noticeable and allowable limits using a single frequency noise up to 4 MHz in the case of a SNR ratio of 40 dB.[4] As there were only three television engineers observing, maximum and minimum values were plotted with straight lines.

From the test results shown in Figs. 3 and 4, the overall design target is determined to be 40 dB (p–p/p–p) at 60 Hz to 4.2 MHz. The amount of crosstalk or leakage of color subcarrier is also defined by this specification. Noise in the blanking period, with leakage of the clamping pulses, is not considered as a periodic noise and not defined by this value. The leakage clamping pulse, however, if superimposed on a burst signal, may cause jitter in color-genlock operation. As for the leakage clamping pulses, 40 dB (p–p/p–p) is considered the target for each unit equipment with clamp circuits (not as the overall specification).

(*b*) *Random noise:* More than 40 dB (p–p/rms), unweighted. When weighted, the above figure should be read as 46.0 dB for flat noise and 49.3 dB for triangular noise.

Figure 5 shows the value of added noise in dB which causes just-noticeable and allowable changes in picture quality vs. the SNR of the original picture.[4] The curve is obtained from the subjective assessment, where 50% of the viewers admitted they noticed the just-noticeable and allowable limits. From these curves, it was found that pictures having a better than 40-dB SNR can be allowed slightly more noise before viewers become aware of the added noise; whereas pictures having a poor SNR cannot be allowed any

Table II. Laws of Addition.

PARAMETERS	EXPRESSED IN	LAWS OF ADDITION
DYNAMIC GAIN & INSERTION GAIN VARIATION	db	r.m.s
FREQ. RESPONSE	db	LOW FREQ ARITH x α HIGH FREQ ARITH
PULSE RESPONSE	%	r.m.s
Sin^2 PULSE RESPONSE	%	r.m.s
D G	%	ARITH x α
D P	°	ARITH x α
ENVELOPE DELAY	mμs	ARITH x α
S/N	mV	r.m.s

$n = 2, \alpha = \frac{5}{6}$ $n = 3, \alpha = \frac{4}{5}$ $n = 4, \alpha = \frac{3}{4}$
n : NUMBER OF BLOCKS OR UNITS

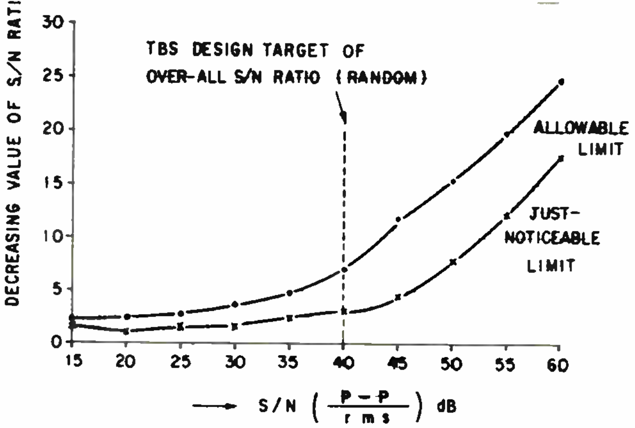


Fig. 5. The values of added noise in dB which cause just-noticeable and allowable picture deterioration vs. original picture SNR.

Table III. Design Targets of Each Block.

System / Item	① VAN SW -μ-STAB -μ OUTSW	② VTR INPUT SW-VTR -VTR OUTSW	③ TELECINE OUTPUT SW	④ STUDIO SW	⑤ CO-ORD SUB SW	⑥ L MASTER	⑦ NETWORK MASTER	Cascading of Blocks						Laws of addition
								④—⑥ ④—⑦	[illegible]	①-5-⑥-⑦ ①-④-⑥-⑦	④②⑤⑥⑦	①-②-⑤-⑥-⑦	①②④⑤⑥	
E Dynamic gain (APL 10~90% Reference APL 50%) Insertion gain variation	±0.3db	±0.35db	±0.1 db	±0.25db	±0.25db	±0.2db	±0.2db	±0.35db	±0.35 db	±0.5db	±0.6db	±0.7db	±0.7db	r m s
F Freq responce (Reference 100KHz)	MHz 60~4.2±0.3db 6 − 0.5 8 − 2.4	MHz 60~4.2±0.5db 6 Roll off	60~6M ± 0.2 10 − 0.4	MHz db 60~6 ± 0.2 8 − 0.5 10 − 1.0	MHz db 60~6 ± 0.2 8 − 0.5 10 − 1.0	MHz db 60~6 ± 0.2 8 − 0.5 10 − 1.0	MHz db 60~6 ± 0.2 8 − 0.5 10 − 1.0	MHz db 60~6 − 0.4 8 − 1.0 10 − 2.0	MHz db 60~4.2 ± 0.5 6 − 0.6 8 − 1.2 10 − 2.4	MHz db 60~4.2 ± 0.8 6 − 1.0 8 − 3.8	MHz db 60~4.2 ± 1 6 Roll off	same as left	same as left	Low Freq Arith x α Higt Freq Arith
G Pulse responce (1575KHz 250KHz Rise time 0.1μs)	0.05μs ($^{+6}_{-4}$ % 0.1 ($^{+4}_{-3}$ 0.2 ($^{+3}_{-2}$ 0.4 (±1 0.6 (0.5	0.05μs (+8 % 0.1 ($^{+6}_{-4}$ 0.2 ($^{+4}_{-3}$ 0.4 (±2 0.6 (±1	0.05μs ($^{+3}_{-2}$ % 0.1 ($^{+1.5}_{-1}$ 0.2 ±0.5	0.05μs ($^{+4}_{-3}$ % 0.1 ($^{+2.5}_{-1.5}$ 0.2 ($^{+1.5}_{-1}$ 0.4 ±0.5	same as left	same as left	same as left	0.05μs ($^{+5}_{-3}$ % 0.1 ($^{+3}_{-2.5}$ 0.2 ($^{+2}_{-1.5}$ 0.4 ±0.5	0.05μs ($^{+6}_{-4}$ % 0.1 ($^{+4}_{-3}$ 0.2 ($^{+3}_{-2}$ 0.4 ±1 0.6 ±0.5	0.05μs ($^{+8}_{-5}$ % 0.1 ($^{+6}_{-4}$ 0.2 ($^{+4}_{-3}$ 0.4 ±2 0.6 ±1	0.05μs (+10% 0.1 ($^{+6}_{-4}$ 0.2 ($^{+4}_{-3}$ 0.4 ±2 0.6 ±1	same as left	same as left	r m s
H Sin^2 responce (T Pulse)	K = 2	K = 4	K = 1	K = 1	K = 1	K = 1	K = 1	K = 2	K = 2	K = 4	K = 1 (2T Pulse)	same as left	same as left	r m s
K D G (APL 10~90%)	3.8 %	3.6 %	0.5 %	2.1 %	2.1 %	1.5 %	1.5 %	3.0 %	3.5 %	7.2 %	8.7 %	9.4 %	9.9 %	Arith x α
L D P (APL 10~90%)	1.5°	2.1°	0.2°	1.2°	1.2°	0.6°	0.6°	1.5°	1.7°	3.2°	4.6°	4.5°	5°	Arith x α
(10) O Envelope delay (Up to 4.2MHz Reference 1575KHz)	±10 mμs (±25 mμs) (8)	±25 mμs	±1 mμs	±1 mμs	±1 mμs	±5 mμs	±5 mμs	±6 mμs	±7 mμs	±18 mμs (±30mμs) (8)	±31 mμs	±37mμs (±46 mμs) (8)	±26mμs (±43mμs) (8)	Arith x α
Q S/N (Hum Periodic) Random	3.5mV 46db (9)Min 45db p-p/rms	3.5mV 46db 45db p-p/rms	1.5mV 53db 67db p-p/rms	2.5mV 49db 62db p-p/rms	2.5mV 49db 62db p-p/rms	2.5mV 49db 62db p-p/rms	2.5mV 49db 62db p-p/rms	3.5mV 46db 59db p-p/rms	4mV 45db 58db p-p/rms	6mV 41db 44db p-p/rms	6.1mV 41db 44db p-p/rms	6.5mV 41db (9)Min 41db p-p/rms	6.5mV 41db (9)Min 41db p-p/rms	r m s
e Front porch (Reference Sync gen output)	±0.025μs	±0.0375μs	—·—	±0.0125μs	±0.0125μs	±0.0125μs	±0.0125μs	±0.025μs	±0.025μs	±0.0625μs	±0.0875μs	±0.100μs	±0.100μs	Arith
f Pulse width (Reference Sync gen output)	+0 −1.2%	+0 −1.8%	——	+0 −0.6%	+0 −0.6%	+0 −0.6%	+0 −0.6%	+0 −1.2%	+0 −1.2%	+0 −3 %	±4.2%	±4.8%	±4.8%	Arith
								$n=2, \alpha=\frac{5}{6}$	$n=2, \alpha=\frac{5}{6}$	$n=3, \alpha=\frac{4}{5}$	$n=3, \alpha=\frac{4}{5}$	$n=4, \alpha=\frac{3}{4}$	$n=4, \alpha=\frac{3}{4}$	

(8) With audio multiplexion (6MHz sound subcarrier)
(9) Varies with relay distances
(10) Tolerance in time of occurrence of corresponding items in E'_Y, E'_Q and E'_I at ENCODER : 5mμs.

additional noise before viewers notice the change in picture quality.

The design target was set at the gradual bend in the curves in Fig. 5. The difference between color and monochrome was found to be only 1 dB.[5] (In color, the random noise is slightly more susceptible.)

Assignment of Tolerances to Entire Television Transmission System

The overall transmission characteristics defined in the above paragraph are divided or assigned to two large sections of the entire system. In the case of local transmission, these are the program production facilities and the transmitter, including associated S-T link.

For the network feed, the two sections are program production facilities and inter-city microwave linkages.

The assignment of tolerances to the above sections is shown in Table I. The first half of the above two cases, or the program production facilities, were further divided into seven blocks, namely: (1) remote pickup block; (2) VTR block; (3) teleciné block; (4) studio subcontrol room block; (5) coordination subcontrol room block; (6) local master block; and (7) network master block, as shown in Table III.

The tolerances assigned to each block are assigned further down to each individual unit equipment and complete the entire system design targets, as shown in Tables IV to VIII.

Law of Addition

To assign tolerances to many sections, blocks or to unit equipments, the arithmetical law of addition for frequency response, D.G., D.P., and envelope delay characteristics, was applied when the same kind of blocks or unit equipments are cascaded. The rms law is applied to the dynamic gain and insertion gain variation, pulse response, sine-squared pulse response and SNR.

When cascading different kinds of unit equipments or blocks, addition of transmission characteristics is made according to the laws shown in Table II, which are based on our experience and were established in 1962.

This setting of the laws of addition was found to be very close to the C.C.I.R. Recommendation Doc. CMTT/1009-E issued in July 1966,[6] and the paper presented by K. H. Potts concerning sine-squared pulse response, issued in April 1963.[7] Suppose a picture taken at a remote location by a remote pickup unit is once taped and played back, then used as an insertion to a studio program with local superimposition of a commercial handled in a coordination sub-control room, the total number of blocks passed would become 5 (n = 5). The blocks that the picture passed would be: Block No. 1 (remote pickup), No. 2 (VTR), No. 4 (studio control room), No. 5 (coordination control) and No. 6 (local master switcher).

As Blocks No. 4 and No. 5 have the same equipment composition in adding the characteristics of these two blocks, we must use the simple arithmetical addition; therefore, the number of blocks passed should be considered as 4 (n = 4) instead of 5, and by using the Table II, the α or discounting coefficient will be found to be 3/4. Or, in other words, 4/3 times tolerances are allowed to the entire picture transmission path, by comparison with the tolerances obtained by using the purely arithmetical addition law.

Other Characteristics to Be Noted for Unit Equipment

(*a*) *Input impedance:* It is important to be acquainted with the characteristics of a 75-Ω coaxial cable. The impedance characteristic curve of cable rises abruptly at frequencies lower than 10 kHz and has a fairly large imaginary part even in the video-frequency band.[8] As an example, where the coaxial cable 5C-2V (RG-6/U) of 100 m is terminated with a pure resistance of 75 Ω ± 1% and the return loss is measured at the sending end, considerably large standing wave is observed in video frequency band, as shown in Fig. 6. This standing wave varies with the length of a cable.

To avoid the visible reflection caused by bridging connections, the length of cable must not extend more than 5 m, as the amount of reflection at frequencies lower than 200 kHz is about 26 dB, and overshoots and undershoots having widths shorter than 50 ns are not visible to the eye, as shown in Fig. 1.

Since the return loss of the cable is about 32 dB at frequencies higher than 200 kHz, the specification for the unit

Table IV. Design Targets of Remote Pickup Block.

Item	Equipment	Van SW'er	Micro wave link	Smear Comp. Amp	STAB input SW'er	STAB	STAB output SW'er		Over-all
A	Input level (V),(S) (P-P)	0.7 V (V)	1.0 V (VS)	1.0 V (VS)	1.0 V (VS)	1.0 V (VS)	0.7 V (V+S)		
B	Input impedance Return loss (to 75Ω)	75Ω ±5% 60~8MHz 32 db	same as left	20kΩ 10PF 60~8MHz 32db (75Ω)	75Ω ±5% 60~8MHz 32 db	same as left	same as left		
C	Crosstalk between input signals	60~8MHz 1mV 57db	same as left	same as left	same as left	same as left	same as left		
D	Gain control range	1V ±3db	1V ±3db	1V ±3db	——	0.7V ±6db	——		
E	Dynamic gain & insertion gain variation	±0.15db	±0.2db	±0.05db	——	±0.15db	——		±0.3db
F	Frequency Response	60~8MHz 0.1db 10 (+0.1 −0.2	60~6MHz 0.2db 8 (+0.2 −2.0	60~8MHz ±0.1db 10 (+0.1 −0.2	60~10MHz 0.1	60~8MHz ±0.2 10 (+0.2 −0.4	60~10MHz ±0.1		60~4.2MHz ±0.3 [illegible] 8MHz
G	Pulse response (rise time 0.05μs)	0.05μs (+2 % −1.5 0.1 ±0.5	0.05μs (+2.5% −1.5 0.1 (+2 −2 0.2 (+2 −1 0.4 ±1	0.05μs +2 % −1.5 0.1 ±0.5	0.05μs ±1 % 0.1 ±0.5%	0.05μs (+2.5% −2 0.1 ±1 0.2 ±0.5	0.05μs ±1% 0.1 ±0.5%		0.05μs +6. −4% 0.1 +4. −3% 0.2 +3. −2% 0.4 ±1% 0.6 ±0.5%
H	$\sin^2$ pulse response (T/2 pulse)	1	1 (T pulse)	1	1	1	1		2 (T pulse)
I	Sag of 60 Hz	1 %	2 %	1 %	——	1 %	——		1 %
J	Bounce (after clamper)	1st half cycle 25% 1 sec 2nd half cycle 7%	1st half cycle 40% 0.25sec 2nd half cycle 15%	1st half cycle 25% 1sec 2nd half cycle 7%	——	1st half cycle 25% 1 sec 2nd half cycle 7%	——		
K	D G	(12) 1 %	3 %	0.25 %	——	0.75 %	——		3.8 %
L	D P	0.5°	1°	0.1 %	——	0.3°	——		1.9°
M	Strength of clamping action	26db	——	——	——	26db	——		
N	White clipper charactristic	110% 60~8MHz (11)	——	——	——	110% 60~8MHz (11)	——		
O	Envelope Delay	±1mμs	±5mμs (±20 mμs) (8)	±1mμs	——	±5mμs	——		±10mμs (±25mμs) (8)
P	Delay time								
Q	S/N Hum, Periodic Random	1mV 57db 70db p-p/rms	(9) 2.5mV 49db Min 45db p-p/rms	1mV 57db 70db p-p/rms	same as left	1mV 57db 70db p-p/rms	same as left		(9) 3.5mV 46db 45db p-p/rms
R	Number of outputs	4	2	3		3			
S	Isolation between outputs	60~4MHz 40db ~8MHz 30db	60~4MHz 40db ~8MHz 30db	60~4MHz 40db ~8MHz 30db	60~8MHz 57db	60~4MHz 40db ~8MHz 30db	60~8MHz 57db		
T	Output level	1V (VS)	1V (VS)	1V (VS)	1V (VS)	0.7V (V+S)	0.7V (V+S)		
U	Output impedance Return loss	75Ω±5% 60~4MHz 32db ~8MHz 26db	same as left	same as left	75Ω±5% 60~8MHz 32db	75Ω±5% 60~4MHz 32db ~8MHz 26db	75Ω±5% 60~8MHz 32db		
a	Sync pulse allowable input level	4V (+1 −2) V P-P or 1V (+1 −0.5)	——	——	——	——	4 V		
b	Input impedance Return loss	20kΩ 10PF 60~4MHz 32db	——	——	——	——	75Ω±5% 60~4MHz 32db		
c	Adjustable output level	0.3V 0~0.6V	——	——	——	4 V 0~6V	——		4 V
d	Rise and fall time	0.19μs	——	——	——	0.19μs	——		0.19μs
e	Front porch	±0.0125μs	——	——	——	±0.0125μs	——		±0.025μs
f	Pulse-width	+0 −0.6%	——	——	——	+0 −0.6%	——		+0 −1.2%
g	Overshoot	2 %	——	——	——	2 %	——		2 %

(8) With audio multiplexion (6MHz sound subcarrier)
(9) Varies with relay distances.
(11) Shall uniformly clips white peak at 110%, over 60~8MHz.
(12) Values up to 90% picture level,

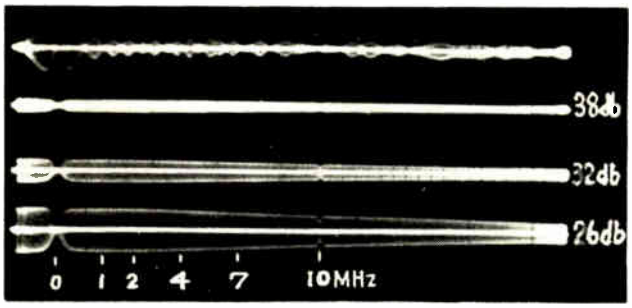


Fig. 6. Return loss characteristic of cable 5C-2V(RG-6/U), 100-m.

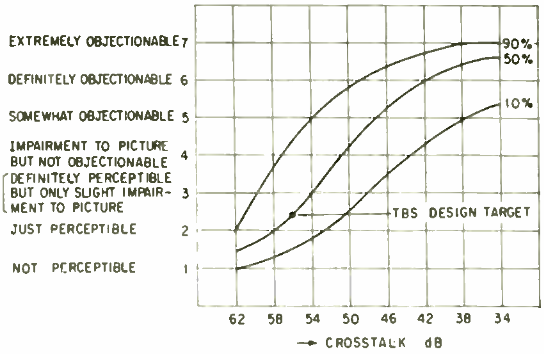


Fig. 7. Subjective test result of picture crosstalk.

equipment is also set at 32 dB up to 8 MHz. Then a loading coil must be used for preventing the mismatching resulting from the stray input capacitance of a unit.[8]

(*b*) *Crosstalk between Signals:* Figure 7 shows the results of an evaluation test on picture crosstalk.[2] The 90% curve is obtained by very sensitive observation and the crosstalk is noticed when it exceeds 61 dB. 50% curve (observation by ordinary people) shows that the viewer noticed the crosstalk at 58 dB. 58 dB was taken as the value of the just-noticeable limit, and set the standard at 57 dB as the value corresponds to 1 mV in a video circuit having 0.7 V peak-to-peak.

This value of 57-dB or 1-mV crosstalk has to be kept up to 4.2 MHz because otherwise the crosstalk of the color subcarrier will cause color contamination. Use is also recommended of 1-V p-p

Table V. Design Targets of VTR block.

Item \ Equipment		Cable Comp.Amp (including Cable)	VTR input SW'er (including Amp.)	Cable Comp.Amp (including Cable)	V T R	Cable Comp.Amp (including Cable)	VTR output SW'er (including Amp.)	Over-all
A	Input level (V),(S) (P-P)	1V (VS)	1V (VS)	1V (VS)	1V (VS)	1V (V)+(S)	1V (V)+(S)	
B	Input impedance Return loss (to 75Ω)	75Ω ± 5% 60~8MHz 32db	same as left	same as left	same as left	same as left	same as left	
C	Crosstalk between input signals	60~8MHz 1mV 57db	same as left	same as left	same as left	same as left	same as left	
D	Gain control range	1V ± 3db	1V ± 1db	1V ± 3db	1V ± 3db	0.7V ± 7db	same as left	
E	Dynamic gain & insertion gain variation	± 0.05db	± 0.05db	± 0.05db	± 0.3db	± 0.05db	same as left	± 0.35db
F	Frequency Response	60~8MHz ±0.1db 10 +0.1 −0.2	same as left	same as left	60~4.2M ±0 db	60~8MHz ±0.1db 10 (+0.1 −0.2	same as left	60~4.2M ±0.5db 6 Rolloff
G	Pulse response (rise time 0.05 µs)	0.05µs +2 −1.5 % 0.1 ±0.5%	same as left	same as left	0.05 (+8 0.4±2 0.1 (±1 0.6±1 0.2 (±3 (rise time 0.1µs	0.05µs (+2 −1.5 % 0.1 ±0.5%	same as left	0.05 (+8 0.4±2% 0.1 (±1 0.6±1 0.2 (±3 (rise time 0.1µs
H	Sin² pulse response (T/2 pulse)	K = 1	same as left	same as left	K = 4 (T pulse)	K = 1	same as left	K = 1 (T pulse)
I	Sag of 60Hz	1%	same as left	same as left	1%	1%	same as left	3%
J	Bounce (after clamper)	1st half cycle 25% 1 sec 2nd half cycle 7%	same as left	same as left	same as left	same as left	same as left	
K	D G	0.25%	0.25%	0.25%	3%	0.25%	0.25%	3.6%
L	D P	0.1°	0.1°	0.1°	2°	0.1°	0.1°	2.1°
M	Strength of clamping action	—	—	—	—	—	—	
N	White clipper charactristic	—	—	—	—	—	—	
O	Envelope Delay	± 1mµs	same as left	same as left	± 25mµs	± 1mµs	same as left	± 25mµs
P	Delay time							
Q	S/N Hum, Periodic Random	1mV 57db 70dbp-p/rms	same as left	same as left	2.5mV 49db 45dbp-p/rms	1mV 57db 70dbp-p/rms	same as left	3.5mV 46db 45dbp-p/rms
R	Number of outputs	3	3	3	2	3	3	
S	Isolation between outputs	60~4MHz 40db ~8MHz 30db	60~8MHz 57db	60~4MHz 40db ~8MHz 30db	60~4MHz 40db ~8MHz 30db	60~8MHz 57db	same as left	
T	Output level	1V (VS)	same as left	same as left	0.7V (V)+(S)	same as left	same as left	
U	Output impedance Return loss	75Ω±5% 60~4MHz 32db ~8MHz 26db	75Ω±5% 60~8MHz 32db	75Ω±5% 60~4MHz 32db ~8MHz 26db	same as left	75Ω±5% 60~8MHz 32db	same as left	
a	Sync pulse allowable input level	—	—	—	—	—	4V	
b	Input impedance Return loss	—	—	—	—	—	75Ω±5% 60~4MHz 32db	
c	Adjustable output level	—	—	—	4V 0~6V	—	4V 0~6V	4V
d	Rise and fall time	—	—	—	0.19µs	—	0.19µs	0.19µs
e	Front porch	—	—	—	±0.025µs	—	± 0.0125µs	±0.0375µs
f	Pulse width	—	—	—	+0 −1.2%	—	+0 −0.6%	+0 −1.8%
g	Overshoot	—	—	—	2%	—	2%	2%

(11) Shall uniformly clips white peak at 110%, over 60 ~ 8MHz

Table VI. Design Targets, Teleciné Block.

Item \ Equipment		Cable Comp.Amp (including Cable)	Relay SW'er (including Amp.)	Over-all
A	Input level (V),(S) (P-P)	0.7V (V)	0.7V (V)	
B	Input impedance Return loss (to 75Ω)	75Ω±5% 60~8MHz 32db	same as left	
C	Crosstalk between input signals	60~8MHz 1mV 57db	same as left	
D	Gain control range	0.7V ± 3db	0.7V ± 1db	
E	Dynamic gain & insertion gain variation	± 0.05db	same as left	± 0.1db
F	Frequency Response	60~8MHz ±0.1db 10MHz +0.1 −0.2	same as left	60~8MHz ±0.2db 10MHz (+0.2 −0.4
G	Pulse response (rise time 0.05µs)	0.05µs (+2 −1.5 % 0.1 (±0.5%	same as left	0.05µs (+3 −2 % 0.1µs (+1.5 −1 0.2µs ±0.5
H	Sin² pulse response (T/2 pulse)	1	1	K = 1 (T pulse)
I	Sag of 60Hz	1%	1%	2%
J	Bounce (after clamper)	1st half cycle 25% 1 sec 2nd half cycle 7%	same as left	
K	D G	0.25%	0.25%	0.5%
L	D P	0.1°	0.1°	0.2°
M	Strength of clamping action	—	—	
N	White clipper charactristic	—	—	
O	Envelope Delay	± 1mµs	± 1mµs	± 1mµs
P	Delay time			
Q	S/N Hum, Periodic Random	1mV 57db 70dbp-p/rms	same as left	1.5mV 53db 67dbp-p/rms
R	Number of outputs	3	3	
S	Isolation between outputs	60~4MHz 40db ~8MHz 30db	60~8MHz 57db	
T	Output level	0.7V (V)	0.7V (V)	
U	Output impedance Return loss	75Ω±5% 60~4MHz 32db ~8MHz 26db	same as left	
a	Sync. pulse allowable input level	—	—	
b	Input impedance Return loss	—	—	
c	Adjustable output level	—	—	
d	Rise and fall time	—	—	
e	Front porch	—	—	
f	Pulse width	—	—	
g	Overshoot	—	—	

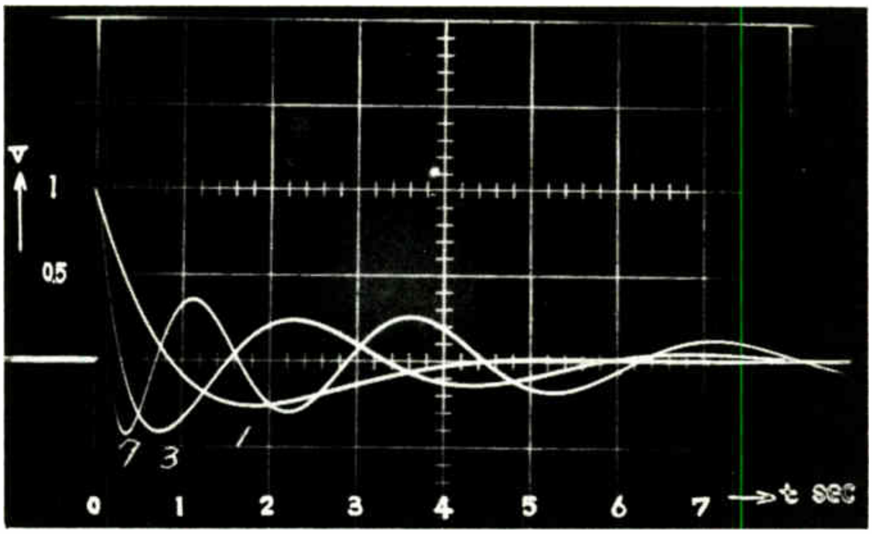


Fig. 8. Step-function response of video distribution amplifiers arranged in tandem.

Table VII. Design Targets of Studio and Coordinate Subcontrol Block.

Equipment / Item	Cable Comp.Amp (including Cable)	Relay SW'er (including Amp)	Mix Amp. I	Mix Amp. II	Burst killer and white clipper	Output Amp		Over-all
A Input level (V), (S) (P-P)	0.7 V (V)	0.7 V (V)	0.7 V (V)	0.7 V (V)	0.7 V (V)	0.7 V (V)		0.7 V (V) 1.0 V (VS) (to master)
B Input impedance Return loss (to 75Ω)	75Ω ± 5% 60-8MHz 32db	75Ω ± 5% 60-8MHz 32db	20kΩ 10PF 60-8MHz 32db	same as left	same as left	same as left		
C Crosstalk between input signals	60~8MHz 1 mV 57db	same as left	same as left	same as left	same as left	same as left		
D Gain control range	0.7v ± 3db	0.7v ± 1db	0.7v ± 3db	same as left	same as left	same as left		
E Dynamic gain & insertion gain variation	±0.05db	±0.1db	±0.1db	±0.1db	±0.1db	±0.05db		±0.25db
F Frequency Response	60~8MHz ±0.1db 10MHz $^{+0.1}_{-0.2}$db	same as left	same as left	same as left	same as left	same as left		60-8MHz ±0.2db 8MHz [illegible] 10MHz [illegible]
G Pulse response (rise time 0.05 μs)	0.05μs $^{+2}_{-1.5}$% 0.1 ±0.5%	same as left	same as left	same as left	same as left	same as left		0.05μs [illegible] 0.1 [illegible] 0.2 [illegible]
H Sin² pulse response (T/2 pulse)	1	same as left	same as left	same as left	same as left	same as left		K = 1 (T pulse)
I Sag of 60Hz	1 %	same as left	same as left	same as left	same as left	same as left		2 %
J Bounce (after clamper)	1st half cycle 25% 1 sec 2nd half cycle 7%	same as left	same as left	same as left	same as left	same as left		
K D G	0.25 %	0.5 %	0.5 %	0.5 %	(12) 0.75 %	0.25 %		2.1 %
L D P	0.1°	(12) 0.2°	0.4°	0.4°	0.4°	0.1°		1.2°
M Strength of clamping action	—	—	26db	26db	26db	—		
N White clipper characteristic	—	—	—	—	(11) 110 % 60Hz ~ 8MHz	—		
O Envelope Delay	±1 mμs	same as left	same as left	same as left	same as left	same as left		±1 mμs
P Delay time								
Q S/N Hum, Periodic Random	1 mV 57db 70db p-p/r.m.s	same as left	same as left	same as left	same as left	same as left		25 mV 49db 62db p-p/r.m.s
R Number of outputs	3		3	3	3	3		
S Isolation between outputs	60-4MHz 40db -8MHz 30db	60 - 8MHz 57db	60-4MHz 40db -8MHz 30db	same as left	same as left	same as left		1 V (V)(S) 0.7 V (V)→ CO-OR Sub
T Output level	0.7 V (V)	0.7 V (V)	0.7 V (V)	0.7 V (V)	1 V (VS)	0.7 V (V)		
U Output impedance Return loss	75Ω ± 5% 60-4MHz 32db -8MHz 26db	same as left	same as left	same as left	same as left	same as left		
a Sync pulse allowable input level	—	—	—	—	4 $^{+1}_{-2}$ or 1 $^{+1}_{-0.5}$ V P-P	—		
b Input impedance Return loss	—	—	—	—	20KΩ 10PF 60-4MHz 32db (75Ω)	—		
c Adjustable output level	—	—	—	—	0.3 V 0 ~ 0.6 V	—		0.3 V
d Rise and fall time	—	—	—	—	0.19 μs	—		0.19 μs
e Front porch	—	—	—	—	±0.0125 μs	—		±0.0125 μs
f Pulse width	—	—	—	—	+0 -0.6 %	—		+0 -0.6 %
g Overshoot	—	—	—	—	2 %	—		2 %

(11) Shall uniformly clips white peak of 110 %, over 60 ~ 8MHz

(12) Values up to 90 % picture level

pulses to distribute all kinds of synchronizing pulses to reduce crosstalk.

(*c*) *Bounce:* Figure 8 shows an example of the step function response of cascaded video distribution amplifiers. As the number of cascaded distribution amplifiers is increased the time to the first half-cycle is shortened and amplitudes of the first and second half cycles are increased. If the time to the first half-cycle is reduced to more than 0.1 s, the sync separators in some picture monitors will not follow properly and will cause picture roll.

The amplitude of the first half-cycle is specified as less than 25%, which is close to the calculated value of the bounce produced by an amplifier having three blocking condensers. Cause of instantaneous color change at the time of picture switching is often found as big bounce.

(*d*) *Strength of clamping action:* A clamping circuit should always be provided at every interconnection point of the seven blocks of the program production facilities. In order to reduce the amplitudes of hum, sag and bounce from 50% to 2.5% (just-noticeable limit), the clamping strength is set at 26 dB.

(*e*) *Output isolation:* When one of the three outputs of an equipment is opened or shorted (even at the receiving end of the output line) the variation of the frequency response of the other two outputs has to be kept within ±0.1 dB, and the reflected color subcarrier at the shorted or open end of the output line shall not affect the phase of the other two outputs. In order to achieve the above, a 40-dB isolation is required.

(*f*) *Output impedance:* Since, as mentioned before, the return loss of a coaxial cable is 32 dB, the same value is applied to the output impedance. If the input and output impedances at each interconnecting point are 32 dB, the reflected signal level at the receiving end is −64 dB compared to the original signal. This reflection is of fairly small value, but we have to consider the case mentioned below.

If there are four long cable connections in the station (for instance, the four cables which connect the encoder to studio switcher, studio switcher to VTR input, VTR output to coordination switcher and coordination switcher to local master switcher) and all four have the same length and same reflection characteristics, the reflected waves may by chance have the same phase relationship all together, so there will be deterioration of the original signal. This means the arithmetical addition of four reflected waves, each having −64 dB level, which in turn creates reflected waves of −52 dB level.

(*g*) *Compensation for attenuation characteristic of cable:* The loss characteristics of the cables are shown in Fig. 9. When the cable is terminated by a 75-Ω resistance at the receiving end, the attenuation characteristics become flat at frequencies lower than 20 kHz in the case of 5C-2V (RC-6/U) and attenuation compensation is required for the higher frequencies only. The step function response is calculated on the assumption that the attenuation characteristics are proportional to root f, and the result is shown in Fig. 10. By applying to this calculation the just-noticeable limit of smear mentioned before, we can find the maximum extendable length of cable without using cable compensation. TBS is using 5C-2V (RG-6/U) cable extensively, for connecting between rooms or racks, and the overall maximum allowable length of this cable without using compensation is only 44 m for the entire transmission system. NEC (Nippon Electric Co.) and TBS together developed a high-standard video distribution amplifier which can take a plug in the cable compensation unit. A cable of any length from 0 to 200 m can be compensated precisely (±0.1 dB) and continuously by turning one control knob. This type of cable compensation is used at various points of the entire system to maintain the design targets.

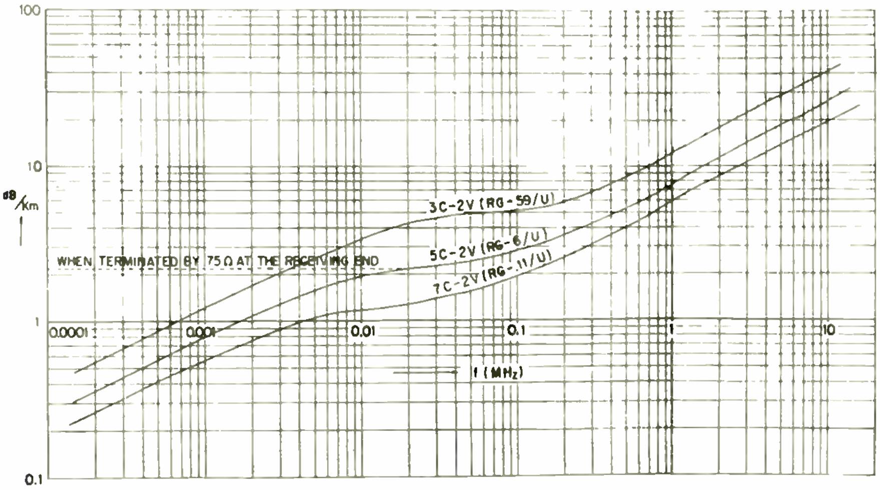


Fig. 9. Characteristics of cable: attenuation vs. frequency.

Table VIII. Design Targets of Local and Network Master Block.

Item \ Equipment	Cable Comp Amp (including Cable)	Relay SW'er (including Amp)	Buffer Amp	STAB input SW'er	STAB Amp	STAB output SW'er	Buffer Amp	Over-all
A Input level (V), (S) (P-P)	1V (VS)	1V (VS)	1V (VS)	1V (VS)	1V (VS)	1V (VS)	1V (VS)	
B Input impedance Return loss (to 75Ω)	75Ω±5% 60~8MHz 32db	75Ω±5% 60~8MHz 32db	20kΩ, 10PF 60~8MHz 32db (75Ω)	75Ω±5% 60~8MHz 32db	75Ω±5% 60~8MHz 32db	75Ω±5% 60~8MHz 32db	20kΩ 10PF 60~8MHz 32db (75Ω)	
C Crosstalk between input signals	60~8MHz 1mV 57db	same as left	same as left	same as left	same as left	same as left	same as left	
D Gain control range	1V±3db	1V±3db	1V±3db	——	1V±6db	——	1V±3db	
E Dynamic gain & insertion gain variation	±0.05db	±0.05db	±0.05db	——	±0.15db	——	±0.05db	±0.2 db
F Frequency Response	60~8MHz ±0.1db 10MHz (+0.1 −0.2)	same as left	same as left	60~10MHz ±0.1	60~8MHz ±0.2 10 (+0.2 −0.4)	60~10MHz ±0.1	60~8MHz ±0.1 10 (+0.1 −0.2)	60~6MHz ±0.2 8MHz (+0.2 −0.5) 10MHz (+0.2 −1.0)
G Pulse response (rise time 0.05 μs)	0.05 (+2 −1.5)% 0.1 ±0.5%	same as left	same as left	same as left	0.05 (+2.5 −2)% 0.1 ±1 0.2 ±0.5	0.05 (+2 −1.5)% 0.1 ±0.5%	same as left	0.5μs (+4 −3)% 0.1 (+2 −1) 0.2 (+1 −1) 0.4 ±0.5
H Sin² pulse response (T/2 pulse)	1	1	1	1	1	1	1	K − 1 (T Pulse)
I Sag of 60Hz	1%	1%	1%	——	1%	——	1%	2%
J Bounce (after clamper)	1st half cycle 25% 1 sec 2nd half cycle 7%	same as left	same as left	——	1st half cycle 25% 1 sec 2nd half cycle 7%	——	1st half cycle 25% 1 sec 2nd half cycle 7%	
K D G	0.25%	0.25%	0.25%	——	0.75%	——	0.25%	1.5%
L D P	0.1°	0.1°	0.1°	——	0.3°	——	0.1°	0.6°
M Strength of clamping action	——	——	——	——	26db	——	——	
N White clipper characteristic	——	——	——	——	110% 60~8MHz (11)	——	——	
O Envelope Delay	±1mμs	same as left	same as left	——	±5mμs	——	±1mμs	±5mμs
P Delay time								
Q S/N Hum, Periodic Random	1mV 57db 70db p-p/rms	same as left	same as left	same as left	same as left	same as left	same as left	2.5mV 49db 62db p-p/rms
R Number of outputs	3		3		3		3	
S Isolation between outputs	60~4MHz 40db ~8MHz 30db	60~8MHz 57db	60~4MHz 40db ~8MHz 30db	60~8MHz 57db	60~4MHz 40db ~8MHz 30db	60~8MHz 57db	60~4MHz 40db ~8MHz 30db	
T Output level	(VS) 1V	(VS) 1V	(VS) 1V	(VS) 1V	(VS) 1V	(VS) 1V	(VS) 1V	
U Output impedance Return loss	75Ω±5% 60~4MHz 32db ~8MHz 26db	same as left	same as left	75Ω±5% 60~8MHz 32db	75Ω±5% 60~4MHz 32db ~8MHz 26db	75Ω±5% 60~6MHz 32db	75Ω±5% 60~4MHz 32db ~8MHz 26db	
a Sync pulse allowable input level	——	——	——	——	——	——	——	
b Input impedance Return loss	——	——	——	——	——	——	——	
c Adjustable output level	——	——	——	——	0.3v 0~0.6v	——	——	0.3v
d Rise and fall time	——	——	——	——	0.19μs	——	——	0.19μs
e Front porch	——	——	——	——	±0.0125μs	——	——	±0.0125μs
f Pulse width	——	——	——	——	+0 −0.6%	——	——	+0 −0.6%
g Overshoot	——	——	——	——	2%	——	——	2%

(11) Shall uniformly clips white peak at 110%, over 60 ~ 8MHz

Specifications for Final Output Waveform Relations

So far, we have been referring only to transmission characteristics; but we have also established a set of specifications concerning all the delay diagrams and pulse widths of the entire system which specifies the final output waveform relations.

Figure 11 shows the horizontal blanking period of a color signal. The color standards specified by the Radio Regulations are indicated. The figures in parentheses ( ) are TBS standard for optimum adjustments. The rise time of the leading and trailing edges of the horizontal blanking signal is not specified by the Regulations and is usually dictated by the camera control unit in use, and the actual value is found to be around 0.002 H.

The minimum number of cycles of burst signal is 8 cycles, and if the rise and fall time of burst flag pulse are taken into account, the width of the burst flag pulse must be 9 cycles of color subcarrier frequency, or 0.04 H. Then the maximum duration left for the front porch is:

$$0.175 - (0.145 + 0.002 \times 2) = 0.026 \text{ H}$$

and the maximum duration between the trailing edge of the horizontal sync and the start of the burst (breeze way) is

$$0.125 - (0.075 + 0.04) = 0.010 \text{ H}$$

From the above values, 0.022 H is assigned to the front porch, and the duration between the trailing edge of the

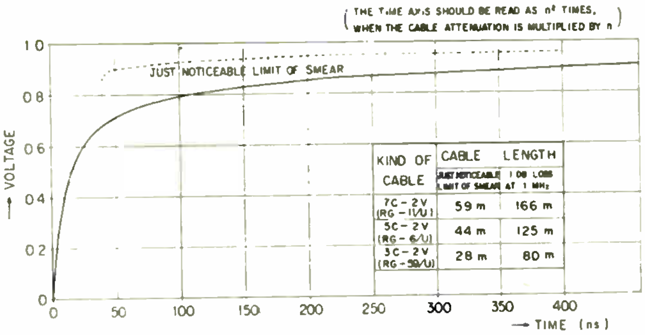


Fig. 10. Step-function response of coaxial cable. The curve shows the waveform where the cable attenuation is 1dB at 1 MHz.

horizontal sync and the start of burst is set at 0.008 H.

The tolerance in the width of the horizontal sync is 0.075 H ± 0.005 H as defined by the Radio Regulations, but the plus side of the allowance is not actually permitted from the above discussion. The allowance for the width of the horizontal sync pulse is then +0 and −0.005 H.

This tolerance must be divided or assigned to the maximum number of equipments cascaded in the entire system handling the distribution, regeneration and mixing of the horizontal sync pulse. Because of the absence of the plus side tolerance, the arithmetical law of addition must be applied. The specifications for variation of front porch and pulse widths are tabulated together with the corresponding transmission characteristics.

Color Subcarrier Distribution System

When we want to mix or wipe two color pictures, the phase of the color subcarriers must be correctly aligned. Table IX shows the just-noticeable limits of phase error for each color of the color bar test signals.[9] From the above subjective test, we set the tolerance of the phase error at ±1 degree.

If we express this phase error by the length of coaxial cable (5C-2V or RG-6/U) it is only 15 cm, and if we want to keep the delay-time of each video distribution amplifier within this tolerance, it may not be possible to keep the frequency responses of the respective amplifiers within the specifications. Therefore, TBS is using the subcarrier distribution system shown in Fig. 12, in which the picture originating block always receives its subcarrier from the block to which the picture is sent.

We are now experimenting with the automatic burst phase detector which can be used with the 360° dc-controlled phase shifter now in use.

Conclusion

When the results from the above work were first derived, some of the figures obtained were thought to be too tight to achieve. But with the help of some Japanese manufacturers, a series of equipments to meet the above specifications have been completed, and the introduction of highband VTR brings the VTR specification much closer to design targets. The following is the list of newly developed high-standard equipment to our specifications.

(1) Video distribution amplifier — with cable length compensator up to 200 m of 5C-2V (RG-6/U) and fixed time delay.

(2) Pulse distribution amplifier — with no pulse width variations and fixed time delay.

(3) Stabilizing amplifier — with no pulse width and front porch variations.

(4) Passive cable equalizer — ±0.05 dB up to 6 MHz at 120 m compensation for 5C-2V (RG-6/U) cable.

(5) D. G. and D. P. compensator — to be used to improve the playback picture quality of the low-band VTR.

(6) Delay boxes — for pulses; 50-ns steps, maximum delay time 2.55 μs for video and pulses; 5-ns steps, maximum delay time 0.605 μs for video; 1° steps at 3.58 MHz, maximum delay time 11°.

(7) 360° phase shifter — constant output amplitude, remote-controlled by dc voltage.

(8) Mixing amplifier — dc-controlled fader amplifier.

(9) Sync pulse generator — with instantaneous genlock (1/30 s), bi-directional slow genlock; when genlocked to a phase modulated vertical serration by which the output will not be affected.

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Table IX. Just-Noticeable Limits of Amplitude and Phase Variation for Each Color in Color Bar Signals.

	AMPLITUDE	PHASE
YELLOW	12 %	2°
CYAN	8	1.5
GREEN	16	3.5
MAGENTA	5	5
RED	16	7
BLUE	16	6

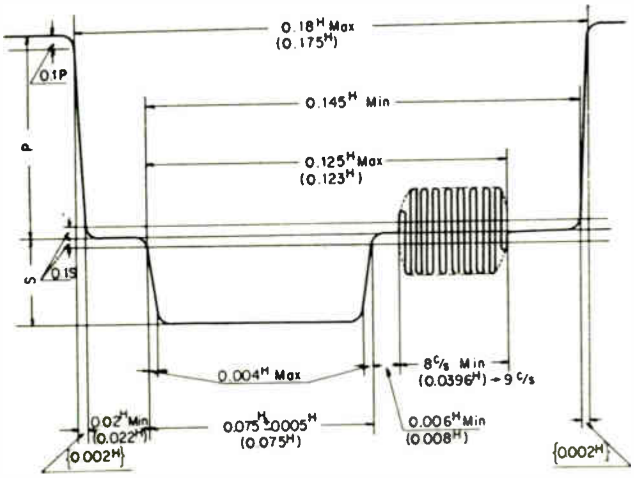

Fig. 11. Horizontal blanking period as to the Radio Regulations.

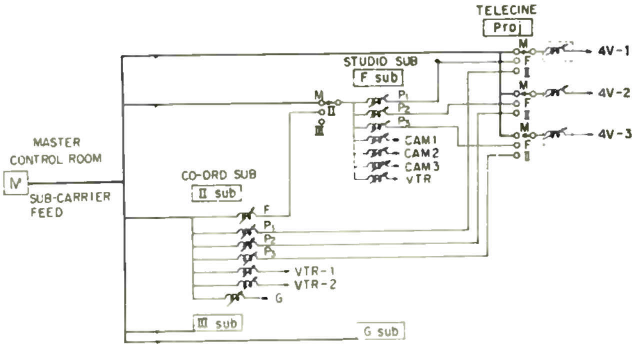

Fig. 12. Subcarrier distribution diagram.

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Discussion

Anon: You indicated that you were working on an automatic phase corrector for a subcarrier. Would this be in the video circuit or would this be in the subcarrier distribution?

Mr. Itoh: The automatic phase corrector is to be inserted in the subcarrier distribution system. At present, we are using the dc-controlled phase shifters in the subcarrier distribution system. We are now developing a phase error detector which feeds the phase correcting dc voltage to the phase shifters.

Television Studio Performance Measurements

By M. W. S. BARLOW

Recent improvements in TV terminal equipment design and stability have enabled a much improved performance to be obtained. The increased accuracy of performance measurements required has shown some deficiencies in present measurement techniques. Improved methods are suggested, together with comments on system design leading to better initial performance with faster and easier maintenance.

The installation of television equipment is normally followed by "acceptance" tests intended to prove that the equipment is performing to specification. After acceptance, routine maintenance tests are made to ensure that the specified performance does not deteriorate. With early equipment, and especially that using vacuum tubes, the performance was not too stable, necessitating wide tolerances in the specification, and correspondingly coarse requirements for the test equipment. Similarly, tests could be made only over short paths of several units in cascade, or the statistical sum of the tolerances became too wide for useful appreciation.

In the last few years, equipment performance and stability have become much tighter, requiring a better grade of test gear to measure the tolerances. At the same time the cumulative effects of many units in cascade has become usefully measurable and reasonably stable. In fact, the performance of individual units may now be so "excellent" that the main system errors come from secondary sources that previously have been ignored. Table I gives a comparison of some parameters for old and new equipment. With this degree of improvement it now becomes worth while to pay attention to the secondary sources of errors, and to bring whole systems to a performance figure that previously could only be maintained over a very short path. Test equipment requirements and routine testing methods need to be reexamined. These in turn call for some extra attention during the original system planning.

Test Signals

If equipment has been thoroughly tested in its design or approval stage, certain routine test signals give a clear idea of present performance. These signals may be applied continuously as Vertical Interval Test (VIT) signals, or used as "full frame" test signals when the equipment is not in use operationally. Two broad types of signal are in current use, the transient test, and the specific detailed, test signal. The former, typified by the sin² pulse in its various forms, tends to give a type of Go/No Go answer: up to a certain degree of distortion, the path being measured is acceptable. It is usually impossible to directly establish exactly what deficiency in the path is responsible for the measured distortion. When the error is unacceptable, the specific test signals are applied to the path and its elements in turn to determine the actual fault. The signals used for these purposes are the familiar modulated stairstep, sweep or multiburst, window and various more specialized signals as necessary. With these signals it is possible to measure the performance of the system by splitting up the modulation spectrum into various parts and using the correct signal for each. Table II outlines how each signal is used.

Table I. Typical Amplifier Characteristics.

Parameter	1957 Value	1967 Value
Freq. Response, dB	+0.2 and −0.3 db at 6 MHz	+0 and −0.1 db at 8 MHz
Differential Gain	2% Max.	0.5% Max.
Differential Phase	0.5° Max.	±0.15°
Vertical tilt	2% Max.	0.5% Max.

Table II. Typical Television Test Signals in Present Use.

Signal	Measurement	Measured with
Modulated Stairstep	Differential gain	Oscilloscope and high-pass filter
	Differential phase	Vectorscope
Multiburst or sweep	Amplitude/Frequency	Wideband oscilloscope
Sin² Pulse	H. F. transients, etc.	Wideband oscilloscope and calibrated graticule
Sin² Window	L.F. transients tilt, etc.	DC oscilloscope

It has been the custom to use these signals at nominally the same level as the video program signal, and to display and measure them at unity gain, especially when photographed, for ease of comparison between input and output. The differences between input and output are now so small, however that this method of comparison is inexact. It may be argued that if the difference is so small as not to be easily visible in this manner, the result on the program signal will also be extremely slight. This is true, but there are sufficient other deficiencies in the overall TV system that every improvement is a help. In the case of TV studio terminal equipment such as switching and routing systems, it is relatively easy to hold the performance to very tight tolerances. This eases the requirements on other parts of the system but gives an overall improvement.

Referring again to Table II, it will be noted that the measuring oscilloscope now has extreme requirements including that of high gain to increase the visibility of errors. No longer is it possible to rely on the ubiquitous Tektronix 524 of yesteryear for anything more than simple level measurements. Modern oscilloscope design is generally ahead of requirements, but no one instrument includes all the features now necessary.

Deficiencies in Present Test Gear

Because the studio broadcasting system is capable of being held to close tolerances more easily than the network connections or transmitter, it is usual for the smallest share of tolerance spreads to be allowed the studio system (see the Appendix). To test any subsection of the studio system, a measurement sensitivity some ten times that required for network testing, for example, is required. This increased accuracy is at the limit of some of the present-day test equipment.

As outlined in Table II, *differential* gain is measured by feeding a modulated stairstep through the unit under test, and looking at the end result via a high-pass filter. Waveform monitors such as the Tektronix 529 have the filter built in for both A and B inputs. But they have barely enough vertical gain to give a sensitivity of 5% differential gain per 10 IEEE units of deflection. Measurements of 0.5% differential gain become a matter of guesswork. It is not possible to dis-

Presented on September 19, 1967, at the Society's Technical Conference in Chicago, Ill., by M. W. S. Barlow, Studio Systems Dept., Canadian Broadcasting Corp., 7925 Côte St. Luc Rd., Montreal 29, Que., Canada.
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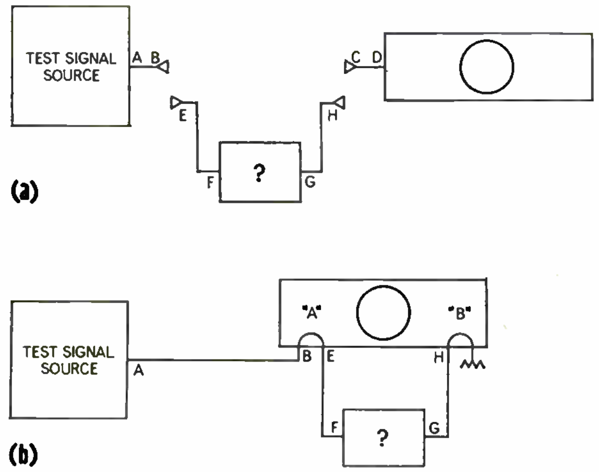

Fig. 1. Typical low-accuracy test methods. At (a) is the case where the test signal is patched or switched directly to the oscilloscope and then via the unit under test. Cables AB, CD, EF and GH all affect the measured response. At (b), cables are "teed" to the oscilloscope input terminals, and the oscilloscope input loading may mis-terminate the test signal source. Both inputs of the oscilloscope must be very accurately matched for this type of measurement.

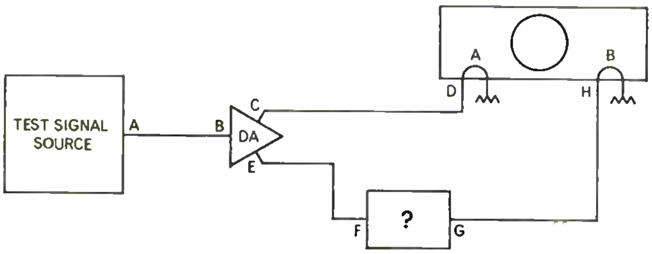

Fig. 2. The preferred method of connection of all test signals. By using a distribution amplifier with identical outputs, and making cable CD equal to EF plus GH in type and length, an exact measurement of the performance between points F and G can be made. As before, the two oscilloscope inputs must be accurately matched, or one input used only for both measurements.

play A and B inputs simultaneously, and it is necessary to photograph the results for comparison. Regular oscilloscopes with sufficient gain lack the built-in filter facility.

Differential phase is measured with the same signal, but displayed on a vectorscope. This requires either a phase-locked burst to give a standard "color sync" signal, or a feed of the stairstep modulation to the vectorscope. A resolution of 0.2 degrees is obtainable with older vectorscopes, such as the Tektronix 526; however, the vertical stability is insufficient for higher accuracy.

Frequency response should not be measured with a multiburst signal except for the crudest indications. If the oscilloscope vertical gain is increased it becomes tedious to measure the peak-to-peak amplitude of each burst because only one end of the trace will be visible at a time. Measuring the positive or negative peaks only is unacceptable because of possible axis shift. A sweep signal generator is preferable, but it may suffer from axis shift which would affect the accuracy at high magnifications. The most accurate method is a differential sweep. This involves detecting both input and output sweeps and displaying the differential output on an oscilloscope as an "A–B" display. A simpler method is the use of a differential sweep generator, such as the Marconi Instruments TF1099, which is designed for this purpose. At a level of about 0.7 V peak-to-peak, a sensitivity of at least 0.05 dB/cm of vertical deflection is obtainable from 100 kHz to 20 MHz. Only one cable is required between the TF1099 and the oscilloscope, and this is carrying only detected (LF) signals. It is therefore possible to use this system to measure physically long video paths and yet have the oscilloscope at a convenient location. Present instruments of this type do not permit detection of composite sweep signals especially if delays due to cable lengths are involved.

With modern equipment the frequency response seems to be the most sensitive performance parameter. It is the one requiring most attention to bring within specification. Other parameters outside specification usually imply a serious fault.

Waveform tests using $\sin^2$ signals are adequately covered by present instrumentation but with marginal sensitivity for the scale of measurements being made in studio systems. Some systems in which luminance and chrominance information are processed separately may require small amplitude signals on a large setup to avoid spurious echoes being generated in filters and black clip circuits. 20T, 2T, T and T/2 pulses are needed to explore the system thoroughly. With modern equipment the pulse shape distortions are likely to be small. The window signal is a sensitive check of equalization in the 100-kHz to 400-kHz region. Extra equalization may be required for long cables to correct these frequencies adequately and reduce picture smear. The pulse-to-bar ratio is a sensitive check of balance between HF and MF equalizers. Low-frequency tilts at line or field rate are unlikely to be noticed unless several systems are cascaded.

Test Methods

The physical interconnection of the test signal generator with the equipment under test requires a closer look if accuracy is to be increased by a factor of, say, 10 times. The precise method in use depends on local circumstances, particularly if the equipment has been removed from its normal operating position to the maintenance shop. Probably one of the two methods outlined in Fig. 1 is in use. At Fig. 1 (a) is the typical case of an *in situ* measurement. The test signals from a central source are routed via switches, relays or patch cords to the oscilloscope, where they are examined for correctness. The circuit path to be examined is now included in the test route, and the scope trace re-examined. It is apparent that cables EF and GH are part of the test circuit. It may not be so obvious that the trace on the oscilloscope is not a true record of either the test generator output or the test signal actually applied to the test path. Allowance must be made for cables AB and CD.

Figure 1 (b) is the popular method in the maintenance shop, using a scope with dual display facilities ("ALT" or "CHOPPED"). The various cables, and the terminating resistor, are connected by "T" adaptors to the oscilloscope inputs. Even if cables EF and GH are exactly identical, the "A" input will only be a true measure of the signal at point B, i.e., neither the generator output nor the input to the unit under test. The "B" input should be a true measure of the output signal if the termination conditions are correct. If cable EF is of any appreciable length (say more than 12 in.) then the input capacity of the oscilloscope will not appear across the termination but somewhere along the cable, thus mis-terminating the signal source. Also, the A and B inputs to the scope, and any internal circuitry involved in processing these inputs, must be very closely balanced for whatever measurement is being made. It is apparent that the "A-B" display is not accurately a measure of the performance of the item under test.

Apart from the oscilloscope performance, the connecting cables contribute the major part of the measurement uncertainties. To avoid this complication, the test arrangement of Fig. 2 is much preferred. This uses a distribution amplifier (DA) to split the feeds to oscilloscope and unit or path under test. By making

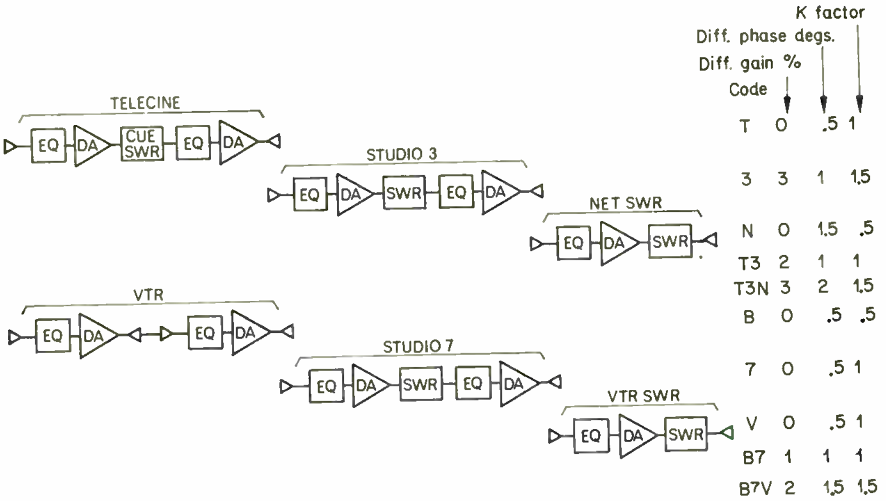

Fig. 3. Part of a typical System Performance diagram. The various inputs, switchers and routing outputs are shown from left to right. The test results are entered at the far right opposite the code for the particular path. As paths are cascaded, the coding is changed and the total results are entered. Note that all jacks at the end of each path are in the same jackfield permitting fast cascading of circuits with standard jack-cords for routine maintenance measurements.

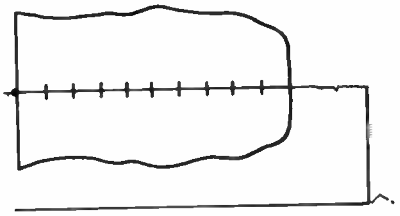

Fig. 4. Tracing of an oscilloscope camera trace showing a 10-MHz sweep (from left to right, 1-MHz markers) through all Toronto color paths in cascade, code B3T12V7N. This is not an operational path but is a quick way of determining whether overall performance has altered since the last routine measurement.

cable CD equal in length and type to EF plus GH, a true measure of the response between F and G can be found. It is necessary that both outputs of the DA are identical, easily checked by connecting F directly to G. The oscilloscope balance requirements are the same as for Fig. 1 (b). Cable AB can be any length, equalized if necessary, but the response of the DA to the test signal must not significantly affect the results.

For high accuracy measurements such a system is essential. It should be included in all plans for monitoring or measuring systems, whether they be VIT or full frame, and whether the equipment is portable or installed in racks.

Application to System Tests

No details have yet been given of what the "test paths" might include. With early, wide-tolerance equipment, the test path might be a single piece of equipment such as a distribution amplifier or a routing switcher. Such tests could be described as "unit tests." System tests were limited to such systems as a complete studio switcher, from input jacks to output jacks. The sum of the tolerances plus the day-to-day drifts in performance made the results of little more than academic interest. With more stable equipment it is now possible to be sure that the measured responses will be maintained. Consequently, it is now worth while to improve the performance as much as possible at the time of installation. It is rare for a single system (such as a studio) to be used alone; it normally has external feeds into it (such as Net, VTR, Telecine), and various other systems being fed by its output (routing switchers, transmitter feeds, etc.). If each subsystem is trimmed for good performance it is possible to cascade them into one large system and to make one set of measurements that will test the performance of the entire equipment via a long but highly practical path. For example, one test from a telecine chain through a studio and a routing switcher, measured at the transmitter input terminals, will provide a complete idea of the true operation of the station under these conditions.

Because a number of identical units such as DA's and equalizers are now in cascade, there begin to appear cumulative errors which otherwise might not be noticed. Finally, by careful choice of cascaded systems, it is possible for the maintenance crew to repeat these system measurements routinely. A minimum number of measurements will then give maximum information quickly and in its most useful form.

The practical details depend on local circumstances. The following example is based on experience at the CBC Toronto studios. It is most convenient if all measurements can be made from the same place with the same oscilloscope. In most stations there is a central jackfield or central monitoring position which is suitable. In Toronto this is in Master Control. A high-grade switcher, presently fitted with 42 inputs, is used to display the outputs of all color sources, plus studio and net feeds, on a vectorscope, an oscilloscope, and a color monitor. Each feed is correctly timed through the switcher back to the jackfield. Any feed which appears to have the same color phase as another, as seen on the vectorscope, will also be in phase at the jackfield and can safely be mixed. These facilities also permit easy measurement and comparison of color burst and other waveform detail. Operator's arguments as to what really is the level are quickly resolved.

A System Performance Diagram, similar to Fig. 3, was drawn up. A recent paper by N. R. Grover[1] shows how this diagram is used for theoretical studies of system performance. It is in a form so useful that it has been used also to record measured results. The Performance Diagram is a type of one-sheet test report. It is used on installation tests and for routine maintenance tests. The various inputs (VTR, telecine, net input) are shown in skeleton form, but detailing exactly which jacks are used for input and output. Where more than one system is available — for instance, there may be several nominally identical telecines — each will be tested exactly on installation. Subsequently, the diagram lists "average" performance. Studio switchers are shown next, and routing switchers and output arrangements to the right. These groups are staggered vertically on the diagram so that the performance figures can be listed in the chart at the right. The chart also lists the CBC acceptable limits as outlined in the Appendix. Each path is given a code (T for telecine, 3 for Studio 3, N for network output switcher, etc.). As each path is cascaded the code is noted and the figures added to the chart. Thus "T3" would indicate a measurement from telecine, which is patched as a regular input to Studio 3 switcher, to the output of Studio 3 appearing in Master Control. "T3N" would indicate that this output is then routed through the Net switcher and measured at its output in Master Control. Long systems can be built up, described and measured very easily. Paths that are not even used in practice can be cascaded to emphasize cumulative system errors. Figure 4 shows the frequency response for every color signal path in the building in cascade: 4 switchers, 4 Proc. Amps., 14 equalizers and 28 DA's. The overall response is not good, being of the order of +0.4 and −0.6 dB. It compares with a single studio switcher response of some years ago. The LF saddle is mainly due to a slightly under-equalized line to

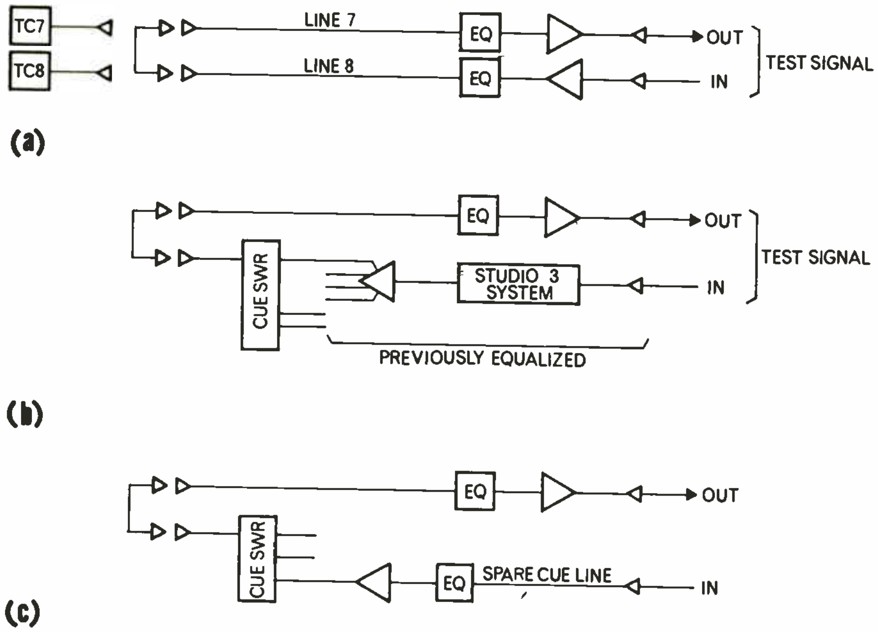

Fig. 5. A method of utilizing a cue circuit to permit a loop measurement where no return path was directly available. At (a), the amplifier of one of two identical program paths to telecine was reversed to allow the line equalizers to be set. At (b), the studio 3 cue system (previously equalized) was selected at the telecine chain to permit the cue switcher equalization to be set. At (c) a spare cue line was corrected so that both ends of the final loop were available on the same jackfield. One loop measurement now checks the telecine cue system and the telecine program lines in cascade.

Studio 7. Operational paths are trimmed to the performance limits shown in the Appendix.

Studios, VTRs and Net input systems are simple and fast to measure because both ends of the system are available on the patchfield and central monitoring system. Allowances may have to be made for the physical lengths of jack cords for accurate measurements. With Toronto telecine, however, only the program output from the chains appears. At first sight there is no easy way of looping a signal up to the chain and back. The telecine chains are on a different floor, and the method of solving the problem may be of interest.

Figure 5 (a) shows one of the telecine chains with its amplifier reversed so that the program lines could be correctly equalized. This is done with the differential sweep, dividing the required equalization equally between the two lines, which are of equal physical length. This method could be used on a routine basis, but is awkward and involves recabling the amplifier for the duration of the test. As no other equalized line was available, an alternative route via the video cue system was used.

At Fig. 5 (b), the sweep was fed into Studio 3 (previously equalized itself) and the Studio 3 output was selected as the Studio Cue feed to telecine. The cue feed was patched back into the program line to master control. The cue switcher output could now be equalized.

At Fig. 5 (c), the spare cue input, which appeared on the master control jackfield, was used instead of the Studio 3 output and this enabled the Spare Cue input line to be equalized. Once these adjustments have been made, it is possible to sweep from the jackfield to telecine and back, checking both cue and program distribution simultaneously. In the absence of color cue facilities, an extra equalized line from master control to the telecine chain would be required to make this test. It should be included on future installations.

Practical Results

First measurements showed that most circuits were displaying a droop in frequency response around 2 or 3 MHz. This has also been reported in a paper by Davidoff of CBS.[2] Tests showed that this was usually due to incorrect cable equalization followed by excessive HF peaking to maintain correct color burst amplitude through the system. A cumulative droop in video DA's was also detected; each DA contributes less than 0.1 dB of droop but always at the same point. With many DA's in cascade, the problem became serious. All DA's were therefore modified to include an adjustment to correct for this droop.

With the DA's eliminated as variables, attention was turned to the equalizers (mainly type WE323 in program paths). These had originally been set either by known cable length or by multiburst measurements. Accurate differential sweep displays showed that in many cases the taps were wrong; there is a tolerance on these equalizers just as for any piece of equipment.The actual setting should always be chosen with a sweep. Because the taps are at 50-ft intervals (representing approximately 0.25 dB loss at 5 MHz), the internal equalization of switchers and certain DA's was varied to give an overall flat response in conjunction with the equalizers. There have been comments that this prevents interchange ability of DA's, but this is not a serious problem because: (1) there have been no recorded failures amongst some 500 DA's in service; (2) each DA is individually marked with its own location identity and always returns there; (3) DA's are individually adjusted for gain, so reducing their interchangeability anyway; and (4) emergency interchange of DA's would only introduce a small fraction of a dB of errors in the frequency response.

When all circuits involving lumped equalizers had been corrected, attention was turned to cascading various paths. It was found that the extra connecting lengths of unequalized cables were ruining the previous equalization. CBC practice is to lump equalize only to the nearest 50 ft. Units connected by short cables to a jackfield were therefore not equalized — but these units in cascade were now contributing to the overall errors. A typical example was a utility DA whose input and outputs appear at the jackfield. Adding this to a circuit dropped the color burst amplitude by 2 IEEE units compared to the direct, equalized, feed. Systems such as these were therefore equalized (with their internal adjustments) for flat response measured between input and output jacks. Some 25 ft of cable compensation is possible with our present DA's. It would be useful if manufacturers would include in their specifications not simply the frequency response of a unit measured in a jig, but also the maximum length of cable that can be added without exceeding the range of the frequency compensating adjustments.

Particular care must be taken with test signal distribution paths, and VIT signal systems, to ensure that the signals reach their destinations without added distortion due to lack of equalization. The practice of putting all the test gear in one rack some distance from the central monitoring point is hazardous. CBC Toronto practice is to use only an equalized test signal selector facility for this purpose, and does not attempt to use unequalized inter-rack trunk lines.

Window signal tests showed that MF compensation of about 0.1-dB boost at 400 kHz per 200 ft of cable was required to correct the shape of the top left and bottom right corners of the window waveform after the HF equalization had been completed. A switchable equalizer box was used to determine the required settings. Again it is emphasized that due to system tolerances, it will be more accurate to measure the required correction rather than to rely on the estimated cable lengths or the settings of the HF equalizers. Davidoff's paper gives an alternative measurement method of greater accuracy. In practice, even at maximum gain on the measuring oscilloscope, it is difficult to judge an exact match of window corner shape. Steps of 0.1-dB boost at 400 kHz appear to be quite near enough. Suitable fixed equalizers could be added. Recent developments in DA's which include full-range equalizers for several hundred feet of cable offer an attractive alternative.

None of the other parameters caused any concern even on the longest paths, as long as the frequency response was good. Indeed the frequency response, at high sensitivity, seems a sensitive indicator of system performance for the upper part of the video spectrum. It may be possible to eliminate some other tests altogether, based on practical experience. A valuable side effect of the accurate system equalization is a reduction in arguments as to which oscilloscope is "correct" when several are available in the same area.

It is possible to go on and on refining the performance but there will often be some little overlooked problem which will bring the purist back to earth with a vengeance. After carefully correcting one studio to have a response flat to +0 and −0.1 dB at 8 MHz, it was a disappointment to find that the Scotch tape seal on the Proc. Amp. chrominance gain control was broken after 24 hr of use. It was finally discovered that the operators were in the habit of patching a utility color bar feed into the switcher for VTR reference purposes. This feed was not equalized correctly and to obtain a "standard" output, the chrominance gain adjustment was altered by some 0.4 dB. Such an error would not be made with a sweep (or possibly multiburst) but is indicative of some of the operational problems that can arise.

APPENDIX

CBC Maximum Tolerance Specifications for Terminal Equipment.

	Distribution Amplifiers	Processing Amplifiers	Mixers	Routing Switchers	VIT Generators	Complete Studio System (via longest operational path)
Differential Gain (at 10–50–90% APL)	0.5%	1.0%	2%	1%	1%	5%
Differential Phase (at 10–50–90% APL), relative to blanking	±0.15°	±0.5°	±0.7°	±0.3°	±0.2°	±4°
Freq. response dB to 8 MHz	+0 −0.1	+0.1 −0.2	+0.1 −0.2	+0.1 −0.2	+0 −0.1	+0.3 −1.0
						(System: +0.3, −0.5 to 4.2 MHz)
Field tilt	0.5%	0.5%	1%	1%	1%	3%
Line tilt (This and items below not individually specified						2%
Window overshoots (T risetime)						+3%, −2%
K rating (T pulse)						1%
Envelope delay (relative to delay at 0.2 MHz)						±25 ns
Signal to crosstalk (p–p values, to 4.2 MHz)						45 dB
Signal (p–p) to random RMS unweighted noise to 8 MHz						60 dB
Signal (p–p to periodic p–p noise) to 8 MHz						40 dB
4 KHz to 4.2 MHz						54 dB
Transient bounce (all black to all white video) first overshoot						30%
second						10%
third						0
Input reflection to 4.2 MHz						5%
above 4.2 MHz						10%
Output reflection to 4.2 MHz						10%
above 4.2 MHz						20%

Conclusion

Careful attention to measuring techniques enables systematic errors to be reduced considerably in television systems. Some test equipment is at the limit of its performance and must be improved to obtain increased accuracy. Cascading television systems permits a rapid test of many units at once; the measurements can be made more easily by doing them from one central location. The test procedures are equally useful for acceptance or maintenance tests. Some equipment may have to be individually treated to obtain system performance of very close tolerance.

Acknowledgments: The author has drawn freely upon the experience of many of his colleagues, and wants to thank them for suggestions and assistance. Thanks are due to the Chief Engineer for permission to publish this paper.

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Limitations of Nonphased Color Video-Tape Recording Systems in Television Broadcasting

By A. J. BUXTON and C. P. GINSBURG

The earliest method of broadcasting color television programs from magnetic tape attempted to preserve the time-base stability of the chrominance information with respect to a stable color subcarrier by treating the off-tape chroma information separately from the luminance. This method has commonly been known as nonphased color because it characteristically fails to preserve the relationship between subcarrier and sync. The relevant FCC specifications and a typical nonphased color system are described; an analysis of the output components shows the subcarrier to undergo full correction while the quadrature modulation is left uncorrected. A number of subjectively disturbing effects are identified, including loss of dot cancellation, loss of luminance resolution and impairment of hue quality.

VIDEO-TAPE RECORDING became a part of television broadcast operations in 1956, but was restricted to black-and-white pictures. Two years later, a method for handling color programs on tape was introduced and put into use. This method, which had two variants and which has been aptly called "nonphased" color, gave reasonably good results by the standards of the late 50's, but did not conform to the intent of the NTSC specifications for color television transmission. Possibly because the method was the only way to use tape for the recording of color at that time, the FCC did not issue citations to stations which aired color programs from video-tape recorders.

By 1962, a series of major technological breakthroughs culminated in the introduction to the broadcast industry of a new system for recording and reproducing NTSC color from tape. This new method, referred to as the "direct color" system, as opposed to the nonphased method, resulted in substantially better pictures on the screens of both monochrome and color receivers, and conformed to the intent of the NTSC specifications.

It is possible today to design a color video-tape recorder employing either the direct or the nonphased method. A recorder using the nonphased color system can be produced at considerably lower cost than one using the direct color system. This applies to both the four-headed transverse-scan configuration and the helical-wrap diagonal-scan arrangement. The purpose of this paper is to explain why the NTSC specifications read as they do and what significance actually exists in the deviation from these specifications through the use of a nonphased color video-tape recorder, and to draw a conclusion in regard to the present and future use of nonphased color in U.S. television broadcasting practice.

Key Specifications in Broadcast Color Recording

On December 17, 1953, the Federal Communications Commission approved a set of technical signal specifications formulated by the National Television System Committee as the technical transmission standards for commercial color TV broadcasting in the United States.* These standards were chosen by the NTSC in accordance with the philosophy that the quality of the signal transmitted should be as good as, but not substantially better than, the quality which a TV receiver could utilize.

The NTSC specifications which are of concern in video-tape color recording are those which define the exact value which the color subcarrier must have relative to the picture carrier, the maximum permissible deviation from this stipulated color subcarrier frequency and its maximum permissible rate of change, and the relationship of the horizontal scanning frequency to the color subcarrier. A tolerance is given for the horizontal frequency, but it is the same tolerance given for the accuracy of the color subcarrier frequency, since the intent of the NTSC specifications is that the horizontal scanning frequency be derived by direct countdown from the color subcarrier frequency. Finally, limits are defined for the phase error (relative to burst) in the modulated carrier.

The color subcarrier frequency is specified to be 3.579545 MHz ±0.0003%, with a maximum rate of change not to exceed 1/10 Hz/s. The horizontal scanning frequency is specified at 15,734 ± 0.047 Hz, exactly 2/455 times the color subcarrier frequency, and the maximum permissible phase error of the modulated subcarrier referred to the burst phase is ±10°.

The specification then quotes, "Closer tolerances may prove to be practicable and desirable with advance in the art." Since ±10° error does cause visible hue change, it has now become common practice to interpret the above specification as ±5°. The purpose of these relationships, including the extremely stringent tolerance on color subcarrier frequency accuracy and rate of change, is:

(1) to transmit a color subcarrier whose frequency is sufficiently accurate to stay within the lock-in range of the local oscillator in a color receiver, and whose rate of change is slow enough so that it can be followed by the local oscillator;

(2) to minimize the effect of the dot pattern caused by the presence of the color subcarrier and its sidebands in the luminance channel;

(3) to minimize the hue distortion caused by the presence of the high-frequency luminance components in the chrominance channel; and

(4) to keep hue distortion due to quadrature modulation phase shift within acceptable visual limits.

Even with time-base error component rates as low as 10 Hz, the corresponding peak-to-peak time-base error has to be

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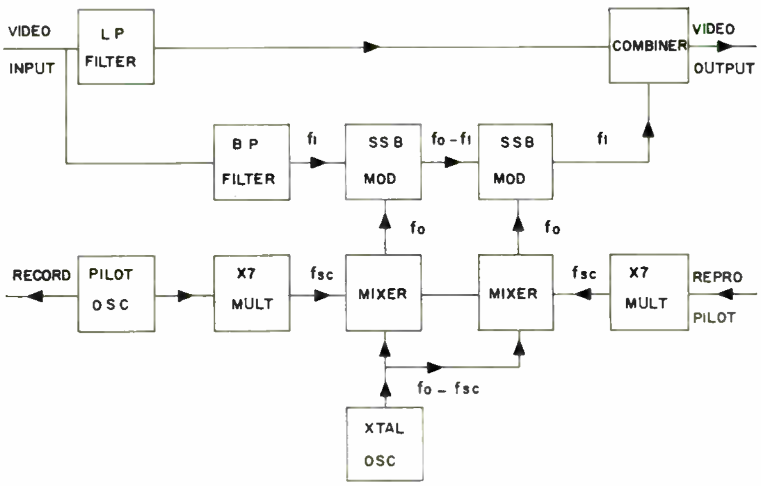

Fig. 1. Schematic of nonphased color corrector.

kept to a fraction of a nanosecond to meet a subcarrier stability of 1/10 Hz/s. This severe requirement is clearly beyond the capabilities of direct time-base correction of the subcarrier with conventional recorders. Time-base correction of the chroma signal to within four nanoseconds permits the error burst to be erased and replaced by a burst from a stable source without causing more than 5° of relative phase error, but this paper will concern itself with an alternative approach, i.e., nonphased color correction.

Basic Principle of NonPhased Color Corrector

The reproduced signal containing the time-base error is applied to a complementary pair of high- and low-pass filters, with a crossover at approximately $2\frac{1}{2}$ MHz (Fig. 1).

The chrominance signal is applied to a double modulation circuit in which the chroma signal is frequency-shifted to a higher frequency (using the single sideband multiplex principle) and then shifted down again to its original place in the frequency spectrum.

The pseudo time-base correction occurs by virtue of the choice of carriers driving the SSB modulators. While one modulator is driven from a stable source, the other is driven from a multiplier derived from a lower frequency pilot recorded and reproduced together with the color signal.

It is arranged that the frequency modulation pattern (and degree of deviation) carried by this modulator carrier, resulting from time-base error, is identical with the modulation pattern (due to time-base error) of the subcarrier burst. Since this particular SSB modulator selects the difference product, the modulation is cancelled out in its output signal. It only remains to add the luminance and corrected chrominance together to complete the heterodyne corrector system.

There are variants of this basic scheme. In one alternative, the time-base modulated carrier applied to the modulator is generated in a start-stop oscillator (one designed to be phase-corrected by the color burst at the beginning of each line) locked to the subcarrier burst. The resulting carrier will not, however, carry the continuous time-base shift during scan lines; it will continue to oscillate at a fixed frequency in phase with the burst that initiated the oscillation.

In another variant, the double modulation circuit is replaced by a demodulator/modulator combination, this time applying the cancellation technique to the demodulator via the necessary demodulating carrier.

As these variants do not change the main characteristics of the device to a marked degree, the heterodyne scheme will be used to demonstrate and clarify the limitations of this technique.

Analysis of the Time-Base Characteristics of the Output Components

Mathematical Treatment

Except where indicated otherwise, the symbols used herein have the following significance:

C_m = subcarrier modulated with chrominance
$g(t)$ = the I component of the chrominance signal
$h(t)$ = the Q component of the chrominance signal
w_{sc} = the angular frequency of the subcarrier in radians/s
$f(t)$ = time modulation component
C_{mt} = modulated subcarrier C_m further time modulated by $f(t)$
$D_1 D_2$ = constants
E = double modulation carrier containing time-base modulation
H = double modulation carrier with no time-base modulation

Let the modulated subcarrier be represented by:

$$C_m = g(t) \sin \omega_{sc}t + h(t) \sin \times [\omega_{sc}t + \pi/2] \quad (1)$$

Let us inject this signal C_m with time-base error modulation. Let it be represented by C_{mt}

Then $$C_{mt} = g\{t + f(t)\} \sin \omega_{sc}\{t + f(t)\} + h\{t + f(t)\} \sin [\omega_{sc}\{t + f(t)\} + \pi/2] \quad (2)$$

Let one of the double modulation carriers E be derived from pilot (off-tape) multiplier circuits. Let it be represented by:

$$E = D_1 \sin [\omega_m t + \omega_{sc} f(t)], \quad (3)$$

and let the other (H) be derived from a stable source. Let it be represented by

$$H = D_2 \sin \omega_m t, \quad (4)$$

(Note that $\omega_{sc} f(t)$ represents the phase deviation, due to time-base error at the subcarrier frequency.)

As we have a complex signal being frequency-translated and frequency-modulated in two successive mixers, and as we are interested in phase relationships, we will analyze the mixing process based on the concept that the mixer has a second-order nonlinearity creating the upper and lower sidebands. The Appendix shows that if an input A sin $(\omega_1 t + \theta_1)$ is applied to the double mixer, along with the heterodyning carriers B sin $(\omega_2 t + \theta_2)$, and C sin $(\omega_3 t + \theta_3)$, then the required output is proportional to:

$$ABC \sin \{(\omega_3 - \omega_2 + \omega_1)t + \theta_3 - \theta_2 + \theta_1\} \quad (5)$$

Applying the necessary substitutions for A, B, C, θ_1, θ_2, θ_3, based on expressions (2) (3) and (4), we get an output:

$$g\{t + f(t)\} D_1 D_2 \sin \{(\omega_m - \omega_m + \omega_{sc})t - \omega_{sc} f(t) + \omega_{sc} f(t)\}$$
$$+ h\{t + f(t)\} D_1 D_2 \sin \{(\omega_m - \omega_m + \omega_{sc})t - \omega_{sc} f(t) + \omega_{sc} f(t) + \pi/2\}$$

Simplifying we get:

$$g\{t + f(t)\} D_1 D_2 \sin \omega_{sc}t + h\{t + f(t)\} \times D_1 D_2 \sin (\omega_{sc}t + \pi/2) \quad (6)$$

If we replace $g(t)$ by a constant G, and $h(t)$ by zero, in (1) then C_{mt} will reduce to $G \sin \omega_{sc}\{t + f(t)\}$ and expression (6) will now be reduced to $G D_1 D_2 \sin \omega_{sc}t$, and will represent the subcarrier burst output.

This expression obviously carries no time-base error and we can therefore say that the nonphase color corrector effectively stabilizes the subcarrier burst.

Furthermore, examination of the full chroma output expression (6) tells us that the two carrier components (at right angles to each other) now carry no time-base error, yet the quadrature modulation carries the same time-base error modulation as the original signal. We can therefore deduce that the I and Q components will carry the same time-base error as the luminance and will result in no hue distortion at sharp color transitions.

Interprètation

The subcarrier burst is completely stabilized and the IQ components, although still carrying the original time-base error, will still be exactly in phase with the luminance, and will therefore give the correct hue; the only distortion so far is limited to the familiar velocity error displacement pattern, varying from line to line. We will next examine the effect of the nonphased color system on distortions resulting from the frequency interleaving of the chroma and luminance.

Distortion of Sharp Black/White Transitions

Higher frequency luminance components are passed through the chroma channel along with the chroma signals. The following analysis demonstrates the distortion resulting from pseudo time-base correction on such components after recombining with uncorrected luminance components.

Let the luminance signal be that of a stationary object containing a sharp black/white transition (for example, a picture one-half white, half black, with a vertical pattern).

Let this signal be represented by:

$$\begin{aligned} &A_1 \sin \omega_1 t \\ &+ A_2 \sin \omega_2 t + \theta_2 \\ &+ A_3 \sin \omega_3 t + \theta_3 \\ &+ A_n \sin \omega_n t + \theta_n \end{aligned}$$

[where $\omega_2, \omega_3 \cdots \omega_n$ are multiples of ω_1]

After being subject to time-base modulation, it will become:

$$\begin{aligned} &A_1 \sin \omega_1 \{t + f(t)\} \\ &A_2 \sin \omega_2 \{t + f(t)\} + \theta_2 \\ &A_3 \sin \omega_3 \{t + f(t)\} + \theta_3 \\ &A_n \sin \omega_n \{t + f(t)\} + \theta_n \end{aligned} \qquad (7)$$

Let one of the higher frequency components, $A_n \sin \omega_n \{t + f(t)\} + \theta_n$, lie within the chroma channel.

Using the results derived in the Appendix, and substituting modulation carriers of $D_1 \sin (\omega_m t + \omega_{sc} f(t))$ and $D_2 \sin \omega_m t$, we have the wanted output represented by:

$$A_n D_1 D_2 \sin \{\overline{\omega_m - \omega_m + \omega_n t} - \omega_{sc} f(t) + \omega_n f(t) + \theta_n\} = A_n D_1 D_2 \sin (\omega_n t + \overline{\omega_n - \omega_{sc}} f(t) + \theta_n) \qquad (8)$$

In a practical case, $\omega_{sc} = 2\pi 3.58 \cdot 10^6$, and ω_n could equal $2\pi 3 \cdot 10^6$.

In this event, $\omega_n - \omega_{sc} = 0.16$ of ω_{sc} and represents "84%" cancellation. If it had suffered no cancellation, it would still have had the form

$$A_n \sin \omega_n \{t + f(t)\} + \theta_n.$$

and, together with its other associated luminance channel components, it would have created a sharp black/white transition at every line scan.

With such high-frequency cancellation, a dynamic time-base error is developed between these high-frequency components and the main luminance spectrum. This degrades the shape of both sync pulse and any black/white transitions, and edge definition will be lost.

If, for example, the time-base error was one microsecond, the displacement in this case would be 840 ns (equivalent to 170 mils on a 12-in. screen).

Dynamic Variations From the Preferred Dot Pattern

Brief Review of the Correct Dot Interlace and Its Equivalent Frequency Spectrum

The chrominance signal contains concentrated bands of sidebands, spaced symmetrically on both sides of the subcarrier, with a separation equal to the line time.

When these sidebands (plus subcarrier) are considered as spurious products in the luminance channel, they appear as odd-order harmonics of a fundamental equal to a half-line rate. We can therefore say that the composite spurious pattern has a period equal to two lines and, furthermore, as it contains only odd harmonics, will consist of a repetitive waveform in which the second half repeats the first half after inversion.

There will thus be space integration over any one field with the line dot pattern offset by 180° every line. The succeeding field will follow exactly the same pattern except for a vertical offset of half a line. This composite pattern, fully developed over the full frame, is then subject to time integration with each frame containing a dot pattern exactly in antiphase to the preceding frame. (This statement is strictly true only when the color pattern is repeated every line, but with slow changes in color from line to line it can be considered to be a fair representation.)

Modified Dot Pattern After Heterodyne Correction of Time-Base Error

Let us consider a color bar pattern which has been recorded, and is being displayed. At the input to the heterodyne corrector the 525 lines can be split into adjacent pairs with every pair identical, and this identity applies to the chrominance overlay as well as to the luminance. The time-base error will of course modify the individual time bases, such that some are compressed and some are expanded corresponding to the relatively slow rates of change of error, but the intimate relationship between the sync pulse and the following subcarrier is retained, thus preserving both space and time integration. Now let us examine these adjacent pairs after heterodyning and recombining.

The luminance (plus some higher order chroma side-bands) will pass through with no change. The main chrominance signal (together with high-order harmonics of the luminance) will be modified according to expression (6). The two quadrature components no longer carry phase shifts due to time-base jitter and appear completely corrected. Only their amplitudes show the time-base error. If this chrominance signal is now drawn (in the time domain) as an overlay on the unmodified luminance, the requirement for repetition after inversion is now no longer met. Repetition will now occur only at time-base error periods (generally a multiple of the scan lines with a significant servo component whose period is many frames), and effective space and time integration is therefore invalidated.

Crosstalk Within the Chrominance Channel

The correct interleaving of chrominance sidebands and luminance components has other beneficial effects over and above the already mentioned dot pattern cancellation. It performs a similar effect within the chrominance channel. Unwanted luminance harmonics will appear (to the subcarrier) as odd-order sidebands of a basic modulation rate of half the line frequency.

The significance of "odd order" is again that of repetition after inversion during the succeeding line, and will have the effect of minimizing the unwanted hue distortion due to modification of the *I* and *Q* components by the luminance breakthrough.

The heterodyne corrector splits the full-frequency band into two channels. The crossover frequency is generally chosen as a compromise between the desire to contain the full chrominance sidebands within the heterodyned channel (which would in theory require a crossover at 2 MHz) and the need to keep the proportion of the luminance spectrum, subject to heterodyning, as low as possible, and thereby minimize the loss of resolution with sharp transitions. Taking a crossover of 2½ MHz as a typical choice, we have part of the chrominance band (the *I* signal) between 2 and 2½ MHz which will not be subject to heterodyning, and any luminance components in this region will not show the necessary hue distortion cancellation when demodulated against a carrier that has been subject to heterodyning.

The visual distortion generated by this limitation will appear as a hue distortion along the vertical edges of a color bar pattern with a repetitive form depending on the time-base period.

Conclusion

In some respects this simple and inexpensive color corrector performs well: It does indeed stabilize the burst to within the specifications, and does so without developing an erroneous hue, since it corrects not only the burst but also the modulated subcarrier.

On the other hand, it introduces a number of degradations of the original signal:

(1) It offers poor resolution of black/white transitions.

(2) It fails to maintain the optimum dot structure, and the resultant semi-random strengthening and weakening of the dot structure is subjectively disturbing.

(3) It does nothing to reduce the true

time-base error of the sync pulse, the luminance, or the demodulated *I* and *Q* components, and does therefore maintain the time-base error in an equal degree for all three.

(4) The luminance components in the 2- to 2½-MHz region will not be treated in the same way as the luminance components passed through the heterodyne channel (2½–4 MHz) within the chrominance. There will therefore be impairment of the hue error cancellation and pseudo-random color interference patterns will be generated.

The basic techniques and devices employed when the direct color system was first demonstrated in 1962 have not yet been superseded by methods employing less expensive components or devices. When and if such developments occur, they will be applicable to both helical-scan and transverse-scan recorders. In the meantime, the use of nonphased color systems in video-tape recorders for commercial television broadcasting is not yet recommended.

Bibliography

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C. E. Anderson and J. Roizen, "Color videotape recorder," *Jour. SMPTE*, *68:* 667–671, Oct. 1959.

C. E. Anderson, "Conversion to Color Recording Using the Ampex VR-1000 Videotape Recorder," Ampex Corp. document, 1959, 20 pages.

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APPENDIX

Let the mixer characteristic be represented by the expression:

$$i = a + bv + cv^2$$

where a, b, c are constants

Let the two signals applied to the first mixer be:

$A \sin(\omega_1 t + \theta_1)$ and $B \sin(\omega_2 t + \theta_2)$

Selecting the term containing the sum and difference frequencies, we get:

$$2cAB \sin(\omega_1 t + \theta_1) \sin(\omega_2 t + \theta_2)$$

$$= cAB \cos \{\overline{\omega_2 - \omega_1 t} + \overline{\theta_2 - \theta_1}\}$$

(lower sideband)

$$- cAB \cos \{\overline{\omega_2 + \omega_1 t} + \overline{\theta_2 + \theta_1}\}$$

(upper sideband)

Picking out the lower sideband, and mixing it in a second mixer (same characteristic) with a carrier $C \sin(\omega_3 t + \theta_3)$, we get:

$$2cC \sin(\omega_3 t + \theta_3) cAB \cos\{\overline{\omega_2 - \omega_1 t} + \overline{\theta_2 - \theta_1}\}$$

$$= c^2 ABC \sin \{\overline{\omega_3 + \omega_2 - \omega_1 t} + \overline{\theta_3 + \theta_2 - \theta_1}\}$$

$$+ c^2 ABC \sin \{\overline{\omega_3 - \omega_2 + \omega_1 t} + \overline{\theta_3 - \theta_2 + \theta_1}\}$$

The lower sideband output is therefore proportional to:

$$ABC \sin \{\overline{\omega_3 - \omega_2 + \omega_1 t} + \overline{\theta_3 - \theta_2 + \theta_1}\}$$

and it should be noted that this is true even if A, B, C, θ_3, θ_2, θ_1, are themselves functions of t.

Appendices

Standards and Recommended Practices

PH22.55–1966, Specifications for Leaders and Cue Marks for 35mm and 16mm Sound Motion-Picture Release Prints, is a revision of the 1947 issue. The Universal Leader specified in this standard represents the culmination of many years of effort to design a leader which would satisfy both television and motion-picture requirements.

American Standard Specifications for

Leaders and Cue Marks for 35mm and 16mm Sound Motion-Picture Release Prints

ASA
Reg. U.S. Pat. Off.
PH22.55–1966
Revision of
Z22.55-1947
*UDC 778.5

Page 1 of 6 pages

1. Scope

This standard specifies the make-up or assembly of leaders and cue marks for 35mm and 16mm sound motion-picture release prints for use in both motion-picture theaters and television studios.

2. Reduction Ratio

The reduction ratio in the production of the head and foot leaders from 35mm motion-picture film shall be in accordance with American Standard 16-Millimeter Positive Aperture Dimensions and Image Size for Positive Prints Made from 35-Millimeter Negatives, PH22.46-1946 (Reaffirmed 1959).

3. Orientation of Words and Numerals

3.1 Orientation and dimensions of letters and numerals in this standard are with respect to 35mm motion-picture film and are modified proportionally for 16mm prints in accordance with Section 2.

3.2 The third, fourth, and fifth frames of the identification sections containing the title of the film and reel number shall be printed in white letters on a black background so that they are read normally when the reel is uppermost and the leading end or head of the film hangs down ready for threading.

3.3 The words "Type of Sound," "Aspect Ratio," "Picture Title," "Company," "Series," "Reel No.," "Prod. No.," and "Play Date" shall be printed lengthwise with the film in white letters on a black background.

3.4 In sections where information is to be printed lengthwise with the film, light framelines shall be included and all such printing must be placed within the outlined areas so that it can be read on 16mm reduction prints.

3.5 In the trailer (foot leader), the title of the film and the reel number shall be printed so that they appear inverted when the remainder of the reel is uppermost and the film hangs downward as in projection.

4. Head Leader (See Fig. 1)

4.1 Protective Section. The protective section of the 35mm leader shall consist of 8 feet of transparent or raw stock; for 16mm leader, 3¼ feet. When the protective leader has been reduced to a length of 6 feet for 35mm film or 2½ feet for 16mm film, it is to be restored to its original length.

The last frame of this section contains the words "Splice Here" and an arrow pointing to the frameline between this frame and Frame 1 of the identification section. The letters should be at least ⅛ inch high.

Approved February 7, 1966, by the American Standards Association, Incorporated
Sponsor: Society of Motion Picture and Television Engineers, Inc.

*Universal Decimal Classification

Printed in USA
ASA1M366

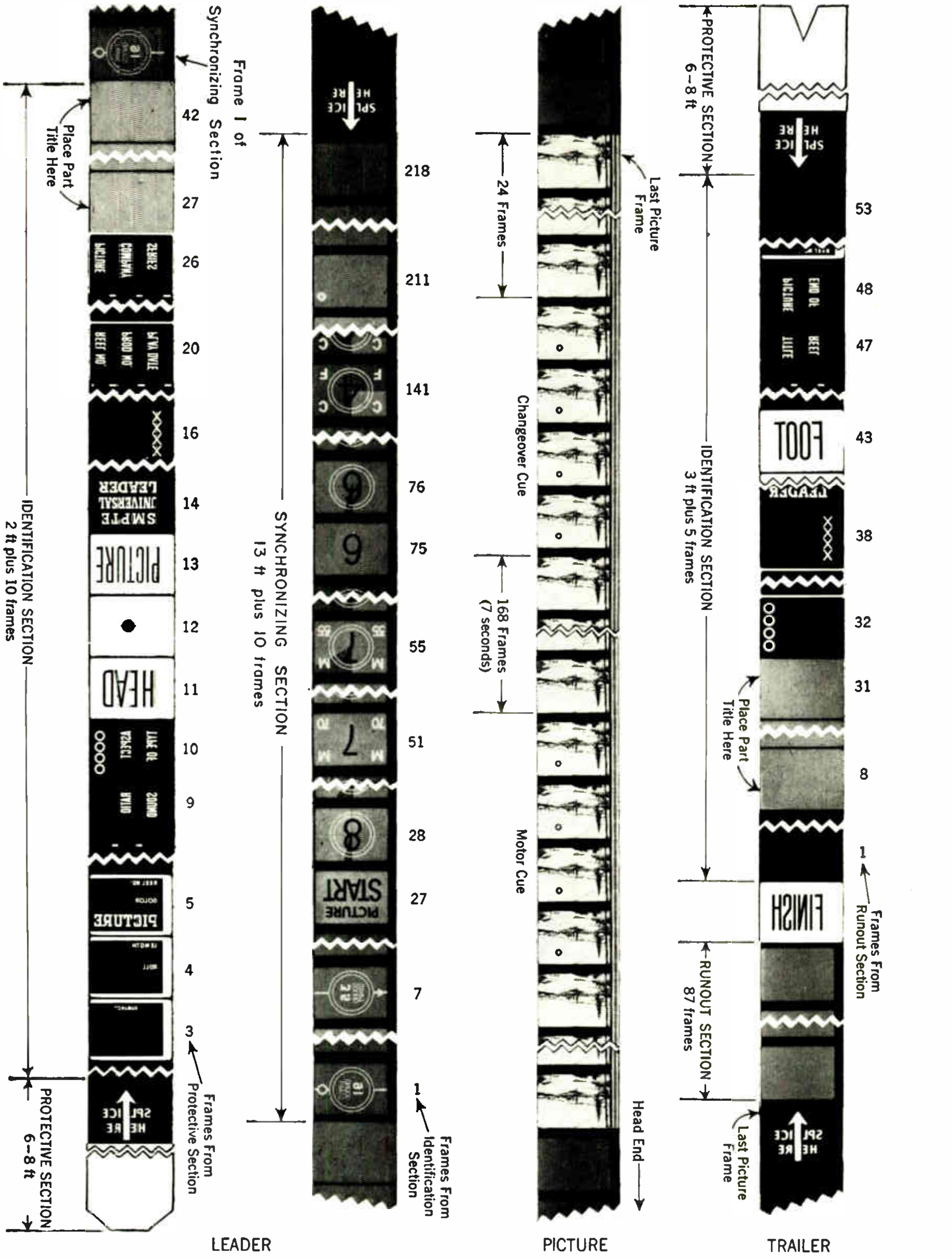


Fig. 1. Figure shows 35mm film with sound track on right edge as seen from the light source in the projector. The sound track is on the left edge of 16mm film.

4.2 Identification Section. The identification section of the leader shall be 42 frames in length. The frames may be of the 4 x 3 format or of a reduced height.

4.2.1 Since many types of film may be used for leaders, exact densities have not been specified. For the purpose of this standard, the following approximate densities are suggested:

White or low density	0.35
Gray or medium density	0.65
Black or high density	1.95

4.2.2 The identification section, when viewed as specified in 3.2, shall be made up as follows:

Frames 1-2—Black.

Frame 3—The printed word "Subject" with letters $\frac{1}{16}$ inch high at top of frame in upright position, white on black background (4 x 3 format).

Frame 4—The printed word "Length" at top left side of frame and the printed word "Roll" at center of frame on left side. Lettering to be comparable to that in Frame 3 (4 x 3 format).

Frame 5—The printed words "Reel No." at top left side of frame and printed word "Color" at center of frame on left side. Lettering, read upright, to be comparable to that in Frame 3. At bottom of frame printed word "Picture" $\frac{1}{8}$ inch high.

Frames 6-10—Five frames of black with light framelines on which the words "Aspect Ratio" and "Type of Sound" are plainly printed lengthwise with the film in $\frac{1}{8}$ inch high white letters. Each group of words starting in the 10th frame and in two separate lengthwise lines reading through base of film from left to right with head end of film at right.

Frame 10—Four letter O's vertically in line and opposite the sound track area approximately $\frac{5}{16}$ inch from the 35mm camera aperture centerline opposite the sound area. Letters to be $\frac{1}{8}$ inch high and $\frac{1}{8}$ inch wide, white on black background (4 x 3 format).

Frame 11—The printed word "Head" not less than $\frac{3}{8}$ inch high in inverted black letters on white or low-density background.

Frame 12—A $\frac{1}{8}$-inch diameter black dot in center of 4 x 3 format. White or low-density background with narrow black framelines.

Frame 13—The printed word "Picture" not less than $\frac{3}{8}$ inch high in inverted black letters on white or low-density background.

Frames 14-15—Two frames in which the words "SMPTE Universal Leader" shall be printed. Letters to be not less than $\frac{1}{8}$ inch high. Inverted white letters on a black background (4 x 3 format).

Frame 16—Four letter X's vertically in line adjacent to sound track area approximately $\frac{5}{16}$ inch from the 35mm camera aperture centerline toward sound area. Letters to be $\frac{1}{8}$ inch high and $\frac{1}{8}$ inch wide, white in black background (4 x 3 format).

Frames 17-18—Same as Frames 14-15.

Frames 19-26—Eight frames of black with light framelines on which the words "Reel No.," "Prod. No.," and "Play Date" are printed lengthwise with the film in $\frac{1}{8}$ inch high white letters in Frame 20. In Frame 26, on three lines lengthwise, reading left to right through film base with head of leader to right, the words "Picture," "Company," and "Series," using the same format as that in Frame 20.

Frames 27-42—Sixteen frames of part titles are to be inserted here. In each frame (1) the reel number (Arabic numeral not less than $\frac{1}{4}$ of frame height) and (2) the picture title shall be printed in black letters on a white background. If part titles are not available, these frames should be black of medium density with narrow framelines.

4.3 Synchronizing Section. The synchronizing section of the leader shall be 218 frames in length.

4.3.1 The cross-hair lines shall be black and the two large circles shall be white. Seconds count-down numerals shall project right side up.

4.3.2 The synchronizing section, when viewed as specified in 3.2, shall be made up as follows:

Frame 1—The 16mm sound start indication shall be printed in white letters on a medium-density background as shown in Fig. 2.

Frames 2-6—Five frames of medium density.

Frame 7—The 35mm sound start indication shall be printed in white letters on a medium-density background as shown in Fig. 3.

Frames 8-26—Nineteen frames of medium density.

Frame 27—The words "Picture Start" shall be printed in black on a low-density background, the letters in the word "Picture" to be not less than $\frac{1}{8}$ inch high and in "Start" not less than $\frac{1}{4}$ inch high. Visual count-down begins with this frame.

Frame 28—The visual count-down continues with the figure "8" in black within a circle of low density on an over-all low-density background with a 15-degree wedge of medium density on the right of top center, as projected. In each succeeding frame, the wedge increases in 15-degree steps, moving clockwise when projected. See Fig. 4.

Frame 50—All background, except for a 15-degree wedge at the top left center, is of medium density.

Frame 51—The numeral changes to "7" in black on a low-density background. On each side of the "7," there shall be in letters $\frac{1}{8}$ inch high, white on a low-density background, "M" and "70" vertically to indicate 70mm magnetic sound start.

Frame 52—The wedge again appears.

Frame 55—The white "M35" appears in the same format as the "M70" appears in Frame 51. See Fig. 5.

Frames 56-140—The sequence of numerals marking the seconds of film running time at 24 fps (frames per second) continues to Frame 140.

Frames 141-146—The moving wedge and numeral appear on Frames 141-146 but with the addition of the Gothic letters "C" and "F" on the left- and right-hand side of the circle, respectively, to indicate the position in the leader where one to six frames may be removed and a similar number of control frames spliced in.

Frames 147-170—The sequence of numerals and moving wedge marking the seconds of film running time continues through to Frame 170.

Frame 171—The numeral "2" in black on a low-density background appears ending the visual count-down.

Frames 172-210—Thirty-nine frames of diffuse density 1.0 to 1.2 maximum.

Frame 211—A single transparent dot shall be located as specified in 5.2.

Frames 212-218—Seven frames of diffuse density 1.0 to 1.2 maximum.

4.3.3 One additional frame follows with the words "Splice Here" and an arrow pointing to the frameline between Frame 218 and this frame. The letters should be at least $\frac{1}{8}$ inch high.

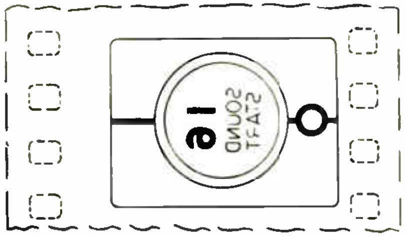


Fig. 2. 16mm Sound Start Identification Frame.
NOTE: Section within frame lines as seen when projected.

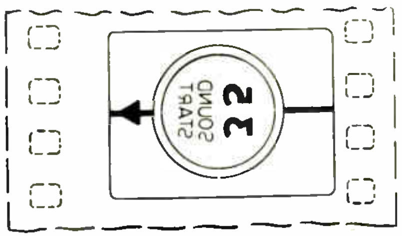


Fig. 3. 35mm Sound Start Identification Frame.
NOTE: Section within frame lines as seen when projected.

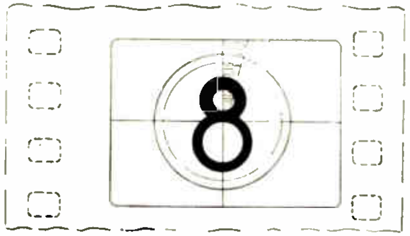


Fig. 4. Example of Visual Count-down.

NOTE: Section within frame lines as seen when projected.

5. Picture Section (See Fig. 1)

5.1 Picture. It is recommended that picture action start and finish on fades wherever possible. Otherwise, significant sound should be kept at least five feet for 35mm prints and two feet for 16mm prints from the start and finish of the picture.

5.2 Motor Cue. The motor cue shall consist of an opaque circular dot with a transparent outline or a transparent circular dot with an opaque outline, printed from a 35mm negative which has had four consecutive frames punched with a die 0.094 inch in diameter. The position of this cue mark for release prints with aspect ratios up to 1.85:1 shall be as shown in Fig. 6. The position of the cue mark for release prints with aspect ratios from 2.35:1 to 2:1 shall be as shown in Fig. 7.

Following the four frames containing the motor cue, there shall be 168 frames, or seven seconds running time, to the beginning of the changeover cue.

5.3 Changeover Cue. The changeover cue shall consist of four frames containing circular dots of the same dimensions and position on the frame as those in the motor cue.

Following the four frames of the changeover cue, there shall be 24 frames, or one second running time, to the beginning of the runout section of the trailer.

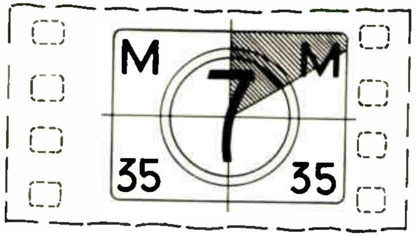


Fig. 5. 35mm Magnetic Sound Start.

NOTE: Section within frame lines as seen when projected.

6. Trailer (Foot Leader) (See Fig. 1)

6.1 Additional Frame. One additional frame follows with the words "Splice Here" and an arrow pointing to the frameline between the picture section and the trailer. The letters should be at least ⅛ inch high.

6.2 Runout Section. The runout section of the trailer shall consist of 88 frames, 87 of which are to be of diffuse density 1.0 to 1.2 maximum. Frame 88 shall have the printed word "Finish" not less than ⅜ inch high in upright black letters on white or low-density background.

6.3 Identification Section. The identification section of the trailer shall consist of 53 frames.

6.3.1 The identification section shall be made up as follows:

Frames 1-7—Seven frames of black opaque without framelines.

Frames 8-31—Twenty-four frames of part titles are to be inserted here. In each frame (1) the end of reel, (2) the reel number (Arabic numeral not less than ¼ of frame height), and (3) the picture title shall be printed in black letters on a white background. If part titles are not available, these frames shall be blank of medium density with narrow framelines.

Frame 32—Four letter O's vertically in line and opposite the sound track area approximately 5/16 inch from the 35mm camera aperture centerline opposite the sound area. Letters to be ⅛ inch high and ⅛ inch wide, white on black background (4 x 3 format).

Frames 33-37—Five opaque frames with light framelines for reproduction of information written on the negative.

Frame 38—Opaque with four X's adjacent to the sound track, similar to Frame 16 of the head leader identification section.

Frames 39-40—Similar to Frames 14-15 of head leader identification section with words "SMPTE Universal Leader," except that the words are upright.

Frame 41—Similar to Frame 13 of head leader identification section, except that the word "Picture" is upright (not inverted).

Frame 42—Dot similar to that in Frame 12 of head leader identification section.

Frame 43—Similar to Frame 11 of head leader identification section, except printed word is "Foot" which is upright (not inverted).

Frames 44-48—Five blank frames of opaque with light framelines upon which the words (1) "Picture Title" and (2) "End of Reel" are printed lengthwise with the film in ⅛ inch high white letters on black background.

Frames 49-51—Three frames identical to Frames 5, 4, and 3, respectively, of head leader identification section, except that the letters are inverted.

Frames 52-53—Two black frames.

6.3.2 One additional frame follows with the words "Splice Here" and an arrow pointing to the frameline between this frame and Frame 53 to indicate where the protective section joins the trailer.

6.4 Protective Section. The protective section of the trailer shall consist of 8 feet of transparent or raw stock for 35mm prints and 3¼ feet for 16mm prints.

NOTE: The Society of Motion Picture and Television Engineers makes available leaders in accordance with this standard. Supplied on master positive motion-picture stock in 16mm and 35mm sizes, intended for reproduction as negatives, they are identified as SMPTE Universal Leaders.

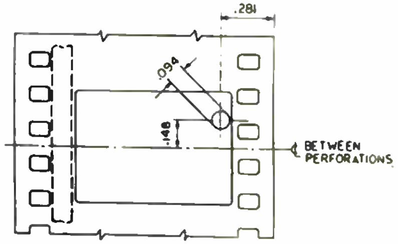


Fig. 6. Position of Cue Marks for Release Prints with Aspect Ratios up to 1.85:1.

NOTE: Image as seen on the screen.

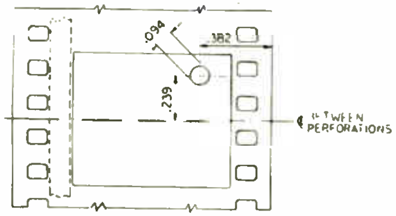


Fig. 7. Position of Cue Marks for Release Prints with Aspect Ratios from 2.35:1 to 2:1.

NOTE: Image as seen on the screen.

Appendix

(This Appendix is not a part of American Standard Specifications for Leaders and Cue Marks for 35mm and 16mm Sound Motion-Picture Release Prints, PH22.55-1966, but is included to facilitate its use.)

A1. The difference between projection rates of 24 and 25 frames per second is negligible in the normal usage of the leader.

A2. Logos, trademarks, or other extraneous material, if absolutely necessary, should be inserted in the leader prior to the 16mm sound start cue or just preceding Frame 32 of the trailer identification section or both.

A3. The outside diameter of the large white circle indicates the height of the television safe action area specified in SMPTE Recommended Practice RP 13-1963, Safe Action Area for TV Transmission, Society of Motion Picture and Television Engineers.

A4. The outside diameter of the small white circle is equivalent to the height of a projector aperture having an aspect ratio of 1.85:1.

USA standard

Approved October 16, 1967

USAS
PH22.148–1967

UDC 771.537:778.5:771.523

Sponsor
Society of Motion Picture
and Television Engineers, Inc.

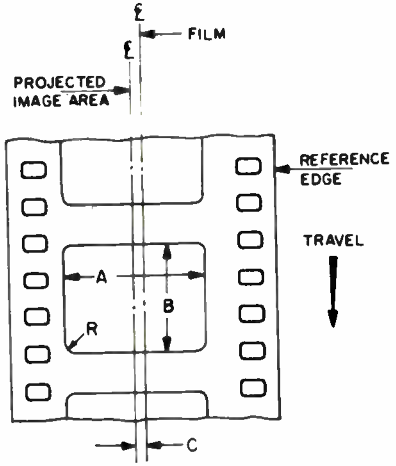
Specifications for Film Image Area Used for Review Room Viewing of 35mm and 16mm Motion-Picture Prints Intended for Television Transmission

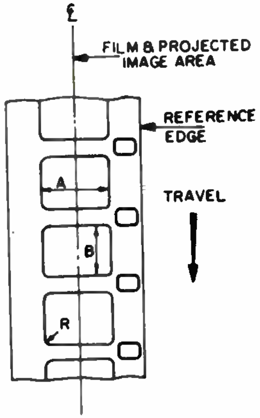
1. Scope

This standard specifies the dimensions of that part of the film image area used for review room viewing of 35mm and 16mm motion-picture prints intended for television transmission, and the placement of this area.

2. Dimensions

2.1 The dimensions shall be as specified in the figures and table.





35mm			16mm	
Inches	Millimeters	Dimensions	Inches	Millimeters
0.713 max	18.11 max	A	0.331 max	8.41 max
0.535 max	13.59 max	B	0.248 max	6.30 max
0.050	1.27	C		
0.143	3.63	R	0.066	1.68

2.2 Dimensions A, B, and R are specified in conformity with SMPTE Recommended Practice RP 8, Safe Action and Safe Title Areas for TV Transmission.

NOTE: Related USA Standards that may be helpful in the application of this standard are:

Projected Image Area of 16mm Motion-Picture Film, PH22.8-1957

Aperture for 35mm Sound Motion-Picture Projectors, PH22.58-1954

Dimensions for Television Image Area on 35mm Motion-Picture Film, PH22.95-1963

Dimensions for Television Image Area on 16mm Motion-Picture Film, PH22.96-1963

Appendix

(This Appendix is not a part of USA Standard Specifications for Film Image Area Used for Review Room Viewing of 35mm and 16mm Motion-Picture Prints Intended for Television Transmission, PH22.148-1967, but is included to facilitate its use.)

A1. Viewing Conditions

During preparation of motion pictures, the producer, the motion-picture film laboratory personnel, and others examine the film many times from the original test shots through many stages to the final release prints. The films are projected in a specialized theater known as a "review room." These installations are designed to permit judgments of projected picture quality and determinations of the suitability and acceptability of release prints, daily and work prints, production tests, printer and processing tests, etc. The rooms are constructed to accommodate a small reviewing group of usually 10 to 20 people. The actual picture size may be large or small, depending upon the space available, but the viewing conditions are chosen to duplicate as nearly as possible actual conditions whether the print is intended for theatrical viewing or television transmission. All viewing conditions are capable of being precisely controlled and should be held to a minimum tolerance.

A2. Action Area

This standard specifies a film area within which all significant picture action should take place, with the intent of ensuring visibility of that action on a properly adjusted home receiver. Projectors used primarily for inspection of prints rather than for reviewing action expected to show in a typical home TV receiver should have apertures at least as large as required to project an image area of 0.792 in. by 0.594 in. from a 35mm motion-picture film (PH22.95) and of 0.368 in. by 0.276 in. from a 16mm film (PH22.96). (These are the areas actually scanned during television broadcasting and, therefore, are available for reception by sets adjusted to this extreme.) For review room purposes, the dimensions of the safe action area should be indicated at the screen and appropriate steps should be taken to ensure that the projected image on the screen is aligned properly so that only that part of the picture image area intended to fall within the safe action area actually does so. Whatever the choice of image area to be projected, the need remains for assurance that projection conditions are maintained so that all action intended to fall within the "safe action area" reaches the projection screen and can be reliably recognized as such, relative to any additional picture information reaching the screen. Consequently, during a screening, a fixed vertical position relationship must be maintained between the film image area and its associated perforations to avoid the need for further framing adjustments.

SMPTE RECOMMENDED PRACTICE RP 5-1964 (Revision of RP 5-1960)

Dimensions of Patch Splices in 2-In. Video Magnetic Tape

Introduction

This Recommended Practice originated in the Video Tape Recording Committee as a Proposed American Standard. At the November 12, 1958, meeting of the Committee it was decided that industry needs could best be met in this instance by an SMPTE Recommended Practice which was subsequently published in the February 1960 Journal. The initiating committee revised the recommendation to include the slower tape speed of 7.5 ips. The proposal, approved by the Video Tape Recording and Standards Committees, was published for trial and comment in the November 1963 Journal. It received final approval by the Society's Board of Governors on February 14, 1964.

Recommendations

1. *Scope*

1.1 This Recommended Practice specifies the dimensions and location of patch-type splices in magnetic video tape of 2-in. width. The recommendations are intended primarily for application in recording and reproducing studio practice.

2. *Location of the Splice*

2.1 The angle of the cut with respect to the guided edge of the tape shall be as given in the diagram and table.

2.2 The cut shall be centered between two recorded video tracks and so located as to maintain continuity of video synchronizing pulse timing (Note 1).

2.3 The separation between the two cut edges after splicing shall not exceed 0.001 in. at any point along the cut.

2.4 The longitudinal distance between corresponding points on the recorded transverse video tracks immediately preceding and following the splice shall not depart from the average distance between successive tracks by more than ±0.0005 in. (Note 1).

3. *Splicing Tape*

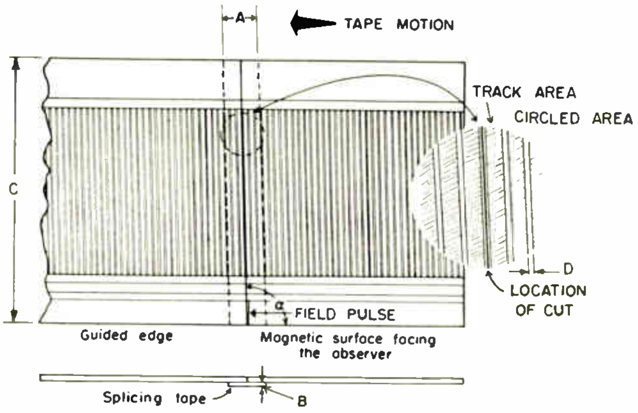
3.1 The dimensions of the splicing tape shall be as given in the diagram and table.

4. *Characteristics of the Splice*

4.1 The splicing tape on a finished splice shall not extend beyond the edges of the magnetic video tape.

4.2 The guided edge of the magnetic tape on the two sides of the splices shall lie on a common straight line when the tape surface is constrained to lie in a plane.

Note 1: Paragraphs 2.2 and 2.4 apply only to recorded tapes.



Note: Drawing not to scale

	Dimensions*	Rate of Tape Travel 7.5 ips		15 ips	
A	Width of splicing tape	0.25	nom	0.25	nom
B	Thickness of splicing tape	0.0007	max	0.0007	max
C	Width of magnetic tape	2.0	nom	2.0	nom
D	Distance between recorded tracks	0.0028	nom	0.0056	nom
α	Angle of cut	90° 17′ ± 3′		90° 33′ ± 3′	

* All dimensions in inches except α.

SMPTE RECOMMENDED PRACTICE RP 6–1967

Reference Carrier Frequencies and De-Emphasis Characteristics for 2-In. Quadruplex Video Magnetic Tape Recording

Introduction

In quadruplex television magnetic recording systems, the level of the reproduced signal is controlled by three factors, viz., (a) adjustment of the playback video amplifier gain setting, (b) the reference frequencies to which the video signal deviates the carrier (at frequencies not affected by pre-emphasis), and (c) the combination of the video pre-emphasis used in recording and the video de-emphasis used in reproduction. In order to achieve uniformity in playback, it is essential that video tape recordings be made in accordance with the practices defined herein. It is also essential that all signals contained in a composite recording made by electronic editing or physical splicing of the recorded tape be recorded in accordance with the same one of the practices defined herein.

1. *Scope*

1.1 This recommended practice specifies the reference frequencies to which the carrier is deviated and the associated video de-emphasis, for each of the recommended modulation practices used in 2-in. quadruplex video magnetic tape recording of U.S. standard color and monochrome television signals. (The video pre-emphasis to be used in recording is specified indirectly by requiring a flat input-to-output video response along with a specified de-emphasis in reproduction.)

2. *Practice HB*

2.1 This practice is suitable for color and monochrome signals.

2.2 Recorded carrier frequencies:

(a) Reference white level	10.0 ± 0.05 MHz
(b) Blanking level	7.9 ± 0.05 MHz
(c) Sync tip level	7.06 ± 0.05 MHz

2.3 The general de-emphasis characteristic is defined in Section 5 below.

2.3.1 Values:

(a) T = 0.600 microsecond
(b) X = 1.5

3. *Practice LBM*

3.1 This practice is suitable only for monochrome signals.

3.2 Recorded carrier frequencies:

(a) Reference white level	6.8 ± 0.05 MHz
(b) Blanking level	5.0 ± 0.05 MHz
(c) Sync tip level	4.28 ± 0.05 MHz

3.3 The general de-emphasis characteristic is defined in Section 5 below.

3.3.1 Values:

(a) T = 0.132 microsecond
(b) X = 4.0

4. *Practice LBC*

4.1 This practice is used for color signals.

4.2 Recorded carrier frequencies:

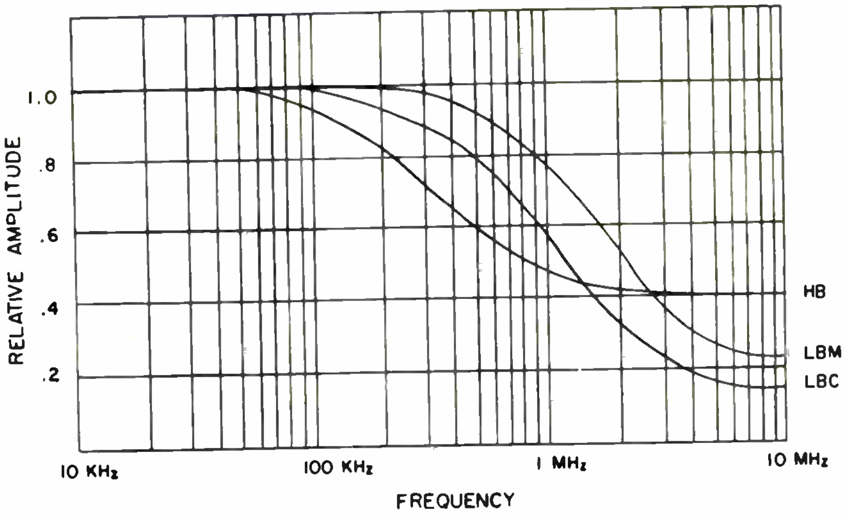
(a) Reference white level	6.5 ± 0.05 MHz
(b) Blanking level	5.79 ± 0.05 MHz
(c) Sync tip level	5.5 ± 0.05 MHz

4.3 The general de-emphasis characteristic is defined in Section 5 below.

4.3.1 Values:

(a) T = 0.240 microsecond
(b) X = 6.56

Revision of
RP 6–1960
Approved March 1967

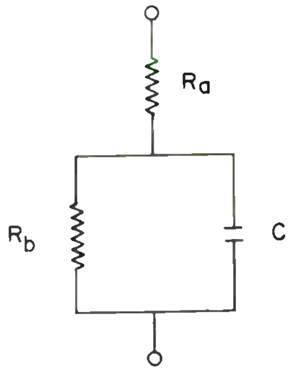


Graph A. Video De-emphasis Curves.

5. *De-emphasis Characteristic*

5.1 The video de-emphasis characteristic curves are described in Graph A.

5.2 The video de-emphasis curves are defined as the normalized impedance of the following two-terminal network:



$R_b = XR_a$
$T = R_bC$

where T is time constant, R is resistance in ohms, and C the capacitance in microfarads.

5.3 The de-emphasis characteristic is introduced following the demodulator in the signal playback circuitry. (To obtain a flat input-to-output video response over the passband of interest, a complementary video pre-emphasis characteristic is introduced ahead of the frequency modulator stage during recording.)

Appendix

(This Appendix is not a part of SMPTE Recommended Practice RP 6-1967, Reference Carrier Frequencies and De-Emphasis Characteristics for 2-In. Quadruplex Video Magnetic Tape Recording, but is included to facilitate its use.)

This recommended practice assumes that all pre-emphasis and de-emphasis is placed in the video portion of the signal path and that the response of the RF portion of the signal path is flat over the passband of interest. Ideally, the magnitude of the remanent flux on a recorded tape should be independent of frequency over the passband of interest, but since there is no practical way of measuring it, the most practical approach is to ensure that record current in the video heads is independent of frequency over the passband of interest.

SMPTE RECOMMENDED PRACTICE RP 7*

Density and Contrast Range of Black-and-White Films and Slides for Television

This Recommended Practice originated in the Subcommittee on Density Requirements for TV Films and Slides of the Television Committee. The proposal, approved by the initiating committee and the Standards Committee, was published for trial and comment in the December 1961 Journal. The recommendation received final approval by the Society's Board of Governors on April 29, 1962.

The purpose of the recommendation is to promote uniform, high, technical quality of television programs on films and slides from any source by specifying density values which are most desirable for effective television transmission. The achievement of optimum picture reproduction requires not only proper print quality and density but also the cooperation of the artist, production directors and technicians in matters such as make-up, composition, lighting and exposure of negative as well as proper adjustment of the television system. It has been the experience of the members of the committee that any attempt to correct for shortcomings in one step by introducing nonstandard techniques in another, will usually result disadvantageously.

Films conforming to this Recommended Practice are intended to provide optimum quality when reproduced through a television system. However, they may not necessarily appear to be optimum when viewed by direct projection.

1. *Scope*

1.1 This recommendation specifies important density values of black-and-white 16mm and 35mm motion-picture films and slides intended for television transmission.

2. *Density Requirements*

2.1 The minimum diffuse density of highlight areas shall have a normal value of 0.4 to 0.3 but not less than 0.3 for optimum reproduction in the television system. This value is not intended to apply to glint, specular highlights or other small areas where details need not be reproduced.

2.2 The maximum diffuse density of lowlight areas shall have a normal value of 1.9 to 2.0 but not greater than 2.0 for optimum reproduction in the television system. This value is not intended to apply to small areas where details need not be reproduced.

2.3 The density of human faces, usually observed more intently than other picture areas, shall be greater than the measured minimum density as specified in Section 2.1 by a value not less than 0.15 or more than 0.5 unless special effects are desired. These density values are important in order to preserve the proper density relationships between face tones and high-lights.

3. *Measurement*

3.1 The method of density measurement shall be in accordance with American Standard Method of Determining Transmission Density of Motion-Picture Films, PH22.27-1960, or the latest revision thereof approved by the American Standards Association, Incorporated.

3.2 Evaluation of the film under normal conditions of television reproduction by means of an oscilloscope calibrated in terms of diffuse density may be used as an alternative method of measuring film density. The oscilloscope used shall be in accordance with the Institute of Radio Engineers Standard Measurement of Luminance Signal Levels, 58 IRE 23.S1, or the latest revision thereof.

NOTES

1. The following Society-sponsored American Standards apply to the dimensional values for films and slides for television:

(a) Picture Area—Motion-Picture Film. The television picture area of 35mm and 16mm motion-picture film shall be in accordance with American Standard Television Picture Area—35mm Motion-Picture Film, PH22.95-1954, and Television Picture Area—16mm Motion-Picture Film, PH22.96-1954, or the latest revisions thereof approved by the American Standards Association, Incorporated.

(b) Soundtrack. The photographic sound record on 35mm and 16mm motion-picture prints shall be in accordance with American Standard Photographic Sound Record on 35mm Prints, PH22.40-1957, and Photographic Sound Record on 16mm Prints, PH22.41-1957, or the latest revisions thereof approved by the American Standards Association, Incorporated.

(c) Film Dimensions. The film width, perforations, etc., shall be in conformance with American Standards or SMPTE Recommended Practices.*

(d) Television Slides. The dimensions of slides to be used for television transmission shall be in accordance with American Standard Slides and Opaques for Television Film Camera Chains, PH22.94-1954, or the latest revision thereof approved by the American Standards Association, Incorporated.

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* A copy of this Recommended Practice may be obtained without charge upon request to SMPTE headquarters. A complete index of American Standards is also available.

SMPTE RECOMMENDED PRACTICE

RP 8–1968

Safe Action and Safe Title Areas for TV Transmission

1. *Scope*

1.1 This recommended practice defines for TV transmission the safe action image area within which all significant action must take place to ensure visibility of the action on the average home receiver.

1.2 The practice also defines the safe title image area within which the more important information must be confined to ensure visibility of the information on the majority of home receivers.

2. *Dimensions*

2.1 The dimensions shall be as given in the figure and table.

2.2 The dimensions are given in terms of the percentage of the nominal height of the scanned area transmitted by the television system. (See Appendix.)

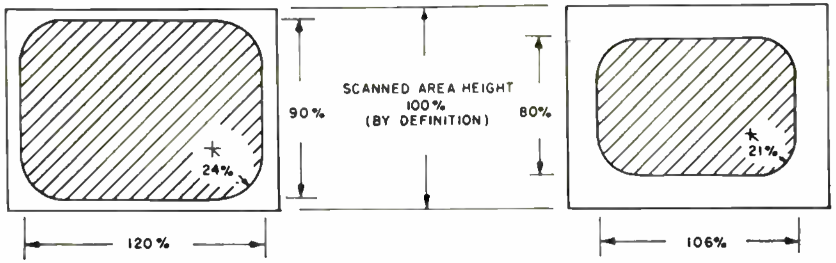
2.3 The height of the scanned area shall be as specified in USA Standards:

Dimensions of Television Image Area on 16mm Motion-Picture Film, PH22.96-1963

Dimensions of Television Image Area on 35mm Motion-Picture Film, PH22.95-1963

Slides and Opaques for Television Film Camera Chains, PH22.94-1954

2.4 Significant action shall be kept within the safe action area defined by the 90 x 120 percent guidelines.



Dimensions of Safe Action Area				Scanned	Dimensions of Safe Title Area		
Width (120%)	Height (90%)	Radius (24%)	Medium	Height (100%)	Width (106%)	Height (80%)	Radius (21%)
0.331 in.	0.248 in.	0.066 in.	16mm Film	0.276 in.	0.294 in.	0.221 in.	0.059 in.
0.713 in.	0.535 in.	0.143 in.	35mm Film	0.594 in.	0.634 in.	0.475 in.	0.127 in.
1.013 in.	0.759 in.	0.203 in.	2" x 2" Slide	0.844 in.	0.900 in.	0.675 in.	0.180 in.

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RP 8–1961 and
RP 13–1963
Approved January 1968

2.5 Essential information shall be kept within the safe title area defined by the 80 x 106 percent guidelines.

3. *Operating Procedures*

3.1 It is recommended that the appropriate area be outlined in camera viewfinders.

3.2 Projectors used for production evaluation of prints intended for television transmission should be equipped with apertures in accordance with USA Standard Specifications for Film Image Area Used for Review Room Viewing of 35mm and 16mm Motion-Picture Prints Intended for Television Transmission, PH22.148-1967.

3.3 The safe title area should be indicated on the review room screen.

Note: Projectors used for print inspection should have apertures at least as large as the scanned area. The dimensions of the safe action area and safe title area should be indicated on the projection screen.

Appendix

(This Appendix is not a part of SMPTE Recommended Practice RP 8-1968, Safe Action and Safe Title Areas for TV Transmission, but is included to facilitate its use.)

It should be pointed out that the dimensions of the two safe areas remain as established in earlier issues. The method of specifying the dimensions in terms of the image height has been adopted to conform with current practices.

SMPTE RECOMMENDED PRACTICE

RP 9–1966

Dimensions of Double-Frame 35mm 2x2 Slides for Precise Applications in Television

Introduction

The use of 2x2 slides has increased enormously in many television stations. The handling of these slides is or will be by automatic or remote methods. Slides containing titles or geometric material must not tilt. In many sequences slides bear related subject matter and it is necessary to lap-dissolve between them. Under these conditions it is important that the material be accurately located on the film clip and that the film clip be accurately located in the mount. This is achieved in this recommended practice by locating the picture information relative to the sprocket holes of the film clip and then using the sprocket holes to locate the clip in the mount. The dimensions and tolerances specified below are based on the fact that information on successive slides will register in a suitable television slide projector within the equivalent of ± 5 television lines in a horizontal and vertical direction when the Datum B and Datum C edges of the mount are against the stops in the projector.

Television scanned area has an aspect ratio of 4:3. The mask dimensions shown in Figure 2 are sufficiently larger than those of the scanned area to permit convenient use.

1. *Scope*

1.1 This recommended practice specifies dimensions and tolerances for a double-frame 35mm film clip and an associated 2x2 inch mount which are intended to ensure that picture information is accurately and consistently positioned in a suitable slide projector.

1.2 The slide mount described in Section 3 represents one suitable method for attaining accurate and consistent positioning of picture information in a suitable slide projector. The use of alternate methods of mounting the film clip to within the same accuracy shall be considered as meeting the requirements of this recommended practice.

1.3 This recommended practice is not intended to replace or to void American Standard Slides and Opaques for Television Film Camera Chains, PH22.94-1954, or American Standard Dimensions for Lantern Slides, Z38.7.19-1950.

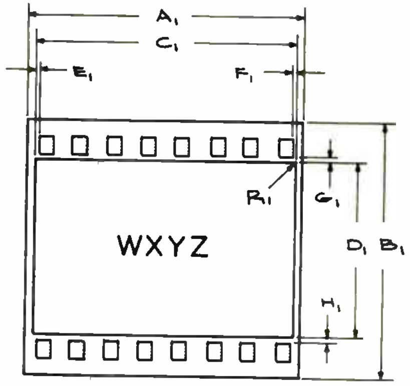

Fig. 1
Location of Image on Film

Table 1

Dimensions	Inches	Millimeters
A_1	1.196 ± 0.004	38.00 ± 0.10
B_1*	1.377 nom	34.98 nom
C_1	1.429 ± 0.012	36.30 ± 0.30
D_1	0.964 ± 0.012	24.49 ± 0.30
E_1-F_1	0 ± 0.004	0 ± 0.10
G_1-H_1	0 ± 0.004	0 ± 0.10
R_1	0.016 max	0.41 max

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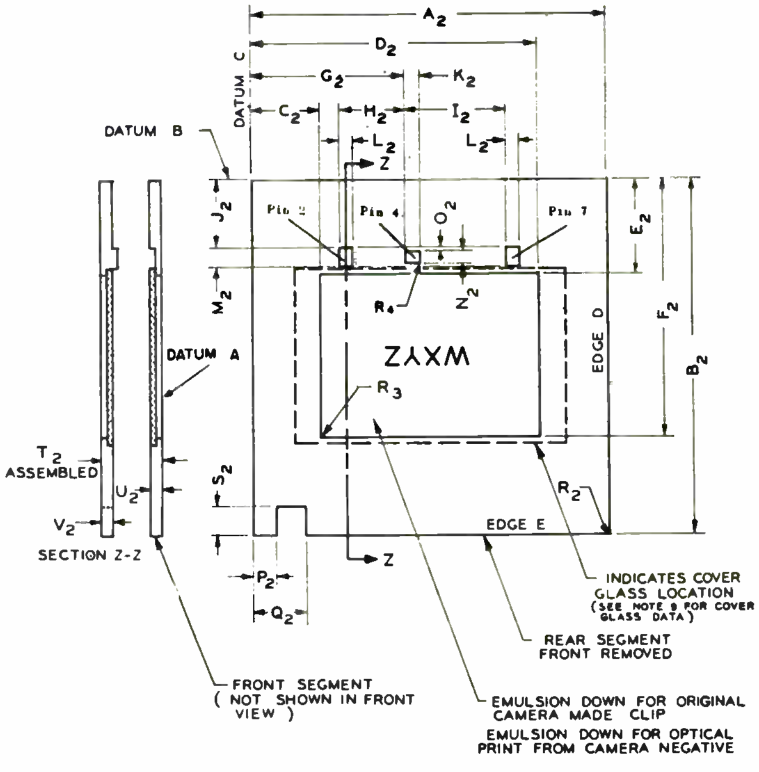

Fig. 2
Slide Mount

Table 2

Dimensions	Inches	Millimeters
A_2	1.984 ± 0.004	50.39 ± 0.10
B_2	1.984 ± 0.004	50.39 ± 0.10
C_2	0.3780 ± 0.0020	9.601 ± 0.051
D_2	1.6060 ± 0.0020	40.792 ± 0.051
E_2	0.5244 ± 0.0020	13.320 ± 0.051
F_2	1.4496 ± 0.0020	36.820 ± 0.051
G_2	0.8602 ± 0.0017	21.849 ± 0.018
H_2	0.3681 ± 0.0020	9.350 ± 0.051
I_2	0.5659 ± 0.0010	14.374 ± 0.025
J_2*	0.3831 ± 0.0025	9.731 ± 0.064
K_2	0.0768 ± 0.0005	1.951 ± 0.013
L_2	0.0656 ± 0.0010	1.666 ± 0.025

Dimensions	Inches	Millimeters
M_2	0.1088 ± 0.0005	2.761 ± 0.013
N_2	0.1000 ± 0.0010	2.540 ± 0.025
O_2	0.0036 ± 0.0020	0.091 ± 0.051
P_2	0.180 max	4.57 max
Q_2	0.330 max	8.38 max
R_2	0.062 max	1.57 max
R_3	0.062 max	1.57 max
R_4	0.018 ± 0.002	0.46 ± 0.05
S_2	0.150 max	3.81 max
T_2	0.115 ± 0.005	2.92 ± 0.13
U_2	0.060 ± 0.002	1.52 ± 0.05
V_2	0.060 ± 0.002	1.52 ± 0.05

*See Note 6

2. *Double-Frame 35mm Film Clip*

2.1 The film for double-frame 35mm film clips to be mounted and used in compliance with this practice shall be in accordance with American Standard Dimensions for 35mm Motion-Picture Film, KS-1870, PH22.36-1964, and shall be of low-shrinkage safety film base.

2.2 The camera used for exposure shall produce an image on the film the dimensions of which are in accordance with American Standard Picture Sizes for Roll and 35mm Still-Film Cameras, PH3.39-1961.

2.3 The location of the image on the film and the length of the film clip shall be in accordance with Figure 1 and Table 1. (See Note 11.)

3. *Slide Mount*

3.1 The mount for the double-frame 35mm film clip shall be manufactured in accordance with Figure 2 and Table 2.

3.2 Slide mounts produced in accordance with this recommended practice shall meet the dimensional tolerances of Figure 2 and Table 2 for at least one year following manufacture.

Notes

1. The surfaces indicated by Datum A shall be plane within 0.002 in. (0.05mm).

2. The edges indicated by Datums B and C and Edge D shall be straight within 0.002 in. (0.05mm).

3. Datums B and C and Edge D shall be perpendicular to Datum plane A within 1 degree.

4. Datum C and Edge D shall be perpendicular to Datum B within 0.002 in. (0.05mm).

5. Dimensions P_2, Q_2, S_2, and V_2 define an area within which a notch may be provided to indicate the proper position of the mount in a magazine or projector. When the film is inserted in the mount as shown in Figure 2 and the mount is placed in a normal film projector to produce a proper image on the screen, the notch will be down and away from the lamp. In this position the notch may be used as a mechanical interlock.

6. Pins 2 and 7 must not depart from Dimension J_2 by more than 0.0020 in. (0.051mm) with respect to each other.

7. The pins must maintain their indicated dimensions at least 0.010 in. (0.25mm) beyond the emulsion position.

8. The pins should extend through the film clip but must not project beyond either exterior surface of the slide mount.

9. Cover glass should be built into the mount on each side of the film surface. This glass should be nominally 0.030 in. (0.76mm) thick and should be treated to reduce Newton's Rings where film contacts the glass. When the mount is assembled, there should be sufficient space between the cover glasses to accommodate a film thickness of 0.006 in. (0.15mm) in a snug manner.

10. Material shrinkage and other practical considerations should be taken into account when choosing dimensions and tolerances for manufacturing purposes. The dimensions and tolerances in Table 2 provide a guide for the final product.

11. The recommended emulsion position is that of an original reversal camera film.

12. Slide mounts manufactured in accordance with the reference edges specified as Datums B and C will have minimum position variations among different mounts when these edges are against the projector stops. When Edges D and E are against the projector stops, slightly poorer positioning accuracy results due to the added dimensional tolerances of A_2 and B_2.

SMPTE RECOMMENDED PRACTICE RP10*

Signal Specifications for a Monochrome Video Alignment Tape for 2-In. Video Magnetic Tape Recording

Early in its deliberations for a monochrome video test tape, the Video Tape Recording Committee established, as one of its objectives, the provision of an *operational* test tape that would permit rapid evaluation and operational adjustment of recording-playback equipment. Consideration was given to a series of tapes each with a separate test signal as well as a single tape with several signals recorded consecutively. Both from an operational and economical standpoint, this approach was dropped in favor of a test tape using a composite signal, made up of signals currently in use by TV broadcasters, arranged in a combination that would produce a kinescope presentation as well as provide a means of obtaining oscilloscope presentation for more minute evaluation of the equipment performance.

A test tape made in accordance with this recommended practice will enable operators of television tape recorders to readily determine accurate quadrature and vacuum guide alignment, thereby establishing most effective operating conditions conducive to obtaining maximum head life and highest degree of tape interchangeability.

The Practice was developed and approved by the Society's Video Tape Recording Committee and accepted by the Standards Committee. It was published in the May 1961 *Journal*, subsequently receiving the approval of the SMPTE Board of Governors in June 1962.

1. *Scope*

1.1 This recommended practice specifies the signals to be recorded on a magnetic video tape for use in evaluating and adjusting the performance of monochrome video tape recording and playback equipment on a routine operational basis. The characteristics which can be checked primarily are related to the video performance although a cursory check of the audio channel is included for operating convenience.

1.2 Specifically, the recorded signals on the tape provide means for check of the following characteristics or adjustments:

(a) video-head quadrature
(b) tape vacuum guide position
(c) video levels
(d) video amplitude-frequency response
(e) video transient response
(f) video low-frequency tilt
(g) video amplitude linearity
(h) video-head playback sensitivity
(i) relative noise banding
(j) r-f carrier deviation frequencies
(k) program and cue track audio levels
(l) control track levels and phase

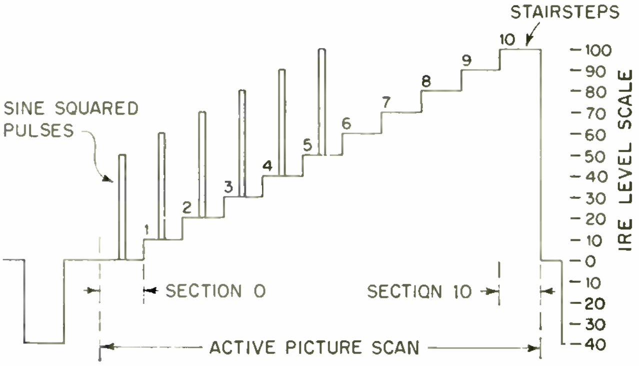

Fig. 1. Bands 1 through 4.

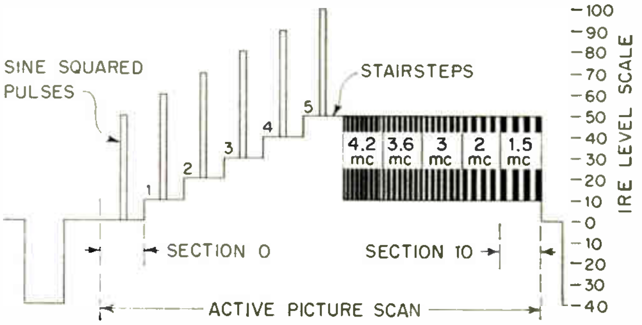

Fig. 2. Bands 5 through 8.

2. *Recorded Signal Characteristics*

2.1 The video signals recorded by the video heads shall occupy sequential bands from top to bottom in the reproduced picture, each of which corresponds to a single traverse of a video head across the tape. For the purpose of identification, these bands are designated as one through sixteen. The first band after that containing the vertical synchronizing pulse interval shall be designated as band one. (Band one will contain fewer active lines than the other bands because it contains a portion of vertical blanking.) The active picture portion of the horizontal scan shall be divided into eleven equal sections. For the purpose of identification, these sections are designated as zero through ten. Information shall be recorded as follows:

	Information	*Bands*
2.1.1	A stairstep signal consisting of a ten-step linear gray scale extending from blanking level to 100 IRE units respectively, as shown in Fig. 1.	1 through 4
2.1.2	A stairstep signal consisting of a	5 through 8

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* A copy of this Recommended Practice may be obtained without charge upon request to SMPTE headquarters. A complete index of American Standards is also available.

	five-step linear gray scale extending from black level to 50 IRE units respectively, as shown in Fig. 2.	
2.1.3	A series of five sine-wave bursts, as shown in Fig. 2, and described as follows: The time sequence of the burst frequencies shall be 4.2, 3.6, 3.0, 2.0 and 1.5 mc. The axis of the multiburst shall be at 30 IRE units, and the peak-to-peak amplitude shall be 40 IRE units. Each burst duration will be at least 75% of the section width.	5 through 8
2.1.4	A window signal at reference white level (100 IRE units) three sections wide and six bands high to be positioned horizontally in sections six, seven and eight, as shown in Fig. 3, and vertically between the centers of the ninth and fifteenth bands. The remaining section shall be at blanking level (0 IRE units).	9 through 15
2.1.5	Vertical synchronizing pulse interval and a portion of vertical blanking.	Band 16 Only
2.1.6	Sine-squared pulses of $\frac{1}{8}$-microsecond width (measured at half level) and 50 IRE units in height at horizontal positions corresponding to the center of each of the first six sections. The base level of each sine-squared pulse shall be as follows: (a) Bands 1 through 8, the same as the accompanying stairstep section level, as shown in Figs. 1 and 2. (b) Bands 9 through 15, at blanking level, as shown in Fig. 3.	1 through 15

2.2 The waveform of the composite signal shall appear as shown in Fig. 4.

2.3 All synchronizing waveforms and signal amplitudes shall conform with EIA Standard RS-170 or the latest revision thereof.

2.4 All video signals shall be within ±1 IRE unit of specified amplitudes.

2.5 Rise and decay time of the stairstep signal shall not exceed 0.003 H (0.3% of the horizontal scanning period). The leading and trailing edges of the window signal shall correspond approximately in shape and rise time to the sine-squared pulses specified in paragraph 2.1.6. such as may result from the use of the same pulse shaping network for both sine-squared pulse and window signals.

2.6 Overshoot of the stairstep signal shall not exceed 5% of the amplitude of transition. An exception is the trailing edge of stairstep (leading edge of horizontal blanking) which is limited to 2% in accordance with EIA Standard RS-170 or the latest revision thereof.

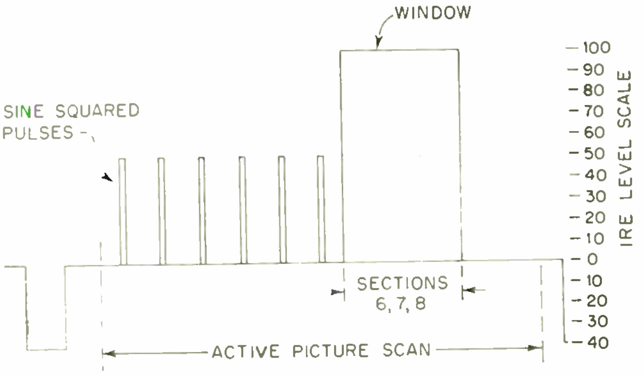

Fig. 3. Bands 9 through 15.

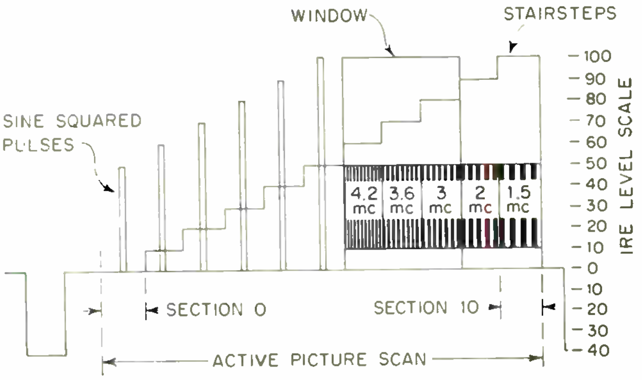

Fig. 4. Composite waveform. Waveforms shown at the rate sweeps.

2.7 Multiburst frequencies shall conform with specified values within 1%. Total harmonic distortion content of the multiburst frequencies shall not exceed 2%.

2.8 The audio tone and cue records shall consist of an audio tone interrupted periodically with voice announcements.

2.9 (a) The audio tone shall be 400 cps ±2% recorded at a level 10 db below that corresponding to a 3% total harmonic distortion at 400 cps.

(b) The audio response-frequency characteristics shall be as specified in Proposed American Standard Characteristics of the Audio Records for 2-In. Video Magnetic Tape Recordings, VTR 16.5, or the latest revision thereof.

2.10 The voice announcements shall be made at one-minute intervals and shall not exceed 20 seconds in duration. The announcement shall provide identification of the tape as regards the applicable SMPTE Recommended Practice, the tape issue number, and the manufacturer of the standard tape. Additional identification (such as serial number) may be included at the discretion of the manufacturer.

3. *Recording Conditions*

3.1 The video alignment tape shall conform with applicable American Standards and SMPTE Recommended Practices.

SMPTE Recommended Practice RP 11*

This Recommended Practice originated in the Video Tape Recording Committee. The proposal, approved by the initiating committee and the Standards Committee, was published for trial and comment in the October 1961 Journal. The recommendation received final approval by the Society's Board of Governors on February 16, 1962.

Tape Vacuum Guide Radius and Position for Recording Standard Video Records on 2-in. Magnetic Tape

1. *Scope*

This recommended practice specifies the tape vacuum guide radius and position for recording standard video records on 2-in. magnetic tape.

2. *Mechanical Dimensions*

2.1 The radius of the tape vacuum guide shall be 1.0334, +0.0000, −0.0005 in. (26.248, +0.000, −0.013mm).

2.2 The position of the vacuum guide shall be set so that the eccentricity of its center of curvature with respect to the axis of rotation of the video heads is as indicated in the table. The eccentricity shall be such that the extension of a line joining the center of curvature of the vacuum guide and the axis of rotation of the heads intersects the tape at the midpoint of its width. The center of curvature of the vacuum guide shall lie between the axis of rotation of the heads and the vacuum guide.

Vacuum Guide Radius		Eccentricity	
Inches	Millimeters	Inches	Millimeters
1.0334	26.248	0.0000	0.000
1.0333	26.246	0.0001	0.003
1.0332	26.243	0.0002	0.005
1.0331	26.241	0.0003	0.008
1.0330	26.238	0.0004	0.010
1.0329	26.236	0.0005	0.013

Note: These dimensions are based on a nominal tape thickness of 0.0014 inch (0.0356mm) and a radius of rotation of the magnetic head pole tips of 1.0329 inch min. to 1.0356 inch max.

APPENDIX

The achievement of tape playback interchangeability requires, among other things, that means be provided to accommodate variations of (a) the radius of rotation of the magnetic head pole tips, (b) the radius of the vacuum guide and (c) tape thickness. These effects are compensated by the stretching of the tape into a slot cavity in the vacuum guide by virtue of the radius of rotation of the magnetic head pole tips projecting beyond the unstretched oxide surface of the tape as held in the vacuum guide. Over the limits normally encountered, the stretching provides automatic compensation if the vacuum guide is positioned to give the minimum geometric distortion in the reproduced picture.

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* A copy of this Recommended Practice may be obtained without charge upon request to Society Headquarters.

SMPTE RECOMMENDED PRACTICE RP 16–1964

Specifications of Tracking Control Record for 2-In. Video Magnetic Tape Recordings

Approved by the Video Tape Recording and Standards Committees, this proposal was published for trial and comment in the October 1963 Journal. The recommendation received final approval by the Society's Board of Governors in April 1964.

1. *Scope*

This recommended practice specifies the recorded dimensional relationships among (a) tracking-control signal, (b) frame-pulse signal, and (c) vertical synchronizing signal for 2-in. video magnetic tape recordings.

2. *Dimensions*

2.1 The dimensional relationships among the tracking control record, frame pulse record, and video record, not specified elsewhere in this practice, shall be as specified in Figs. 1a and 1b and in the table.

2.2 Dimensions pertaining to the video, audio, and control records on 2-in. magnetic tape shall be as specified in the appropriate American Standards.

3. *Magnetic Coating*

With the direction of tape motion shown, the magnetic coating is on the surface facing the observer.

4. *Frame Pulses*

4.1 A pulse to identify the position of the vertical synchronizing pulse shall be superimposed on the tracking control signal.

4.2 One pulse shall be recorded per television frame to identify the vertical blanking interval that is preceded by a full horizontal line when the tape is recorded at 15 in./sec and to identify the vertical blanking interval that is preceded by a half horizontal line when the tape is recorded at 7.5 in./sec.

4.3 The pulse shall be positioned so that the centerline of the recorded pulse and the extended centerline of the area between the second and third video tracks after the track containing the vertical synchronizing pulse shall intersect within ±0.002 in. at the reference edge of the tape when the recording is made at 15 in./sec tape speed (Fig. 1a). The pulse shall be positioned so that the centerline of the fifth video track after the track containing the vertical synchronizing pulse shall intersect within ±0.002 in. at the reference edge of the tape when the recording is made at 7.5 in./sec tape speed (Fig. 1b).

4.4 The amplitude of the frame pulse current shall be greater than 150 percent of the peak-to-peak value of the tracking control signal current in the record head.

4.5 The polarity of the pulse with respect to the tracking control signal shall be as shown in Figure 1a.

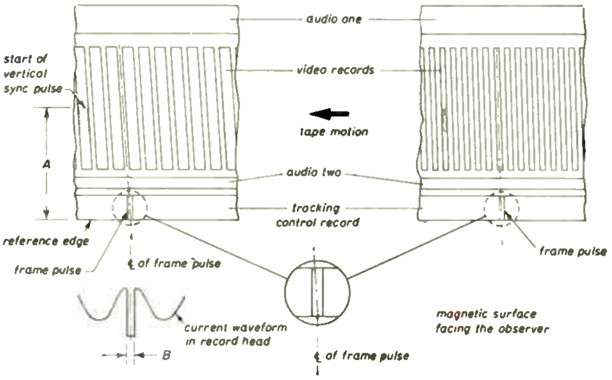


Fig. 1a. 15 in./sec **Fig. 1b.** 7.5 in./sec

Dimensions	Inches Minimum	Inches Maximum	Millimeters Minimum	Millimeters Maximum	Seconds
A	1.10	1.20	27.9	30.5	
B					60 μsec* ±10 μsec

* Measured at 50 percent amplitude points. Widths observable and measurable on developed tape will vary with recording level and properties of developing solution.

5. *Tracking Control Signal*

5.1 The frequency of the tracking-control signal shall be four times the field frequency of the television video signal.

5.2 The amplitude of the tracking-control signal current in the recording head shall be such that the tape is driven to the verge of saturation. This amplitude can be established by the method described in the Appendix.

5.3 The tracking-control signal shall be positioned so that a point of maximum record current and the extended centerline of the area between the second and third video tracks after the track containing the vertical synchronizing pulse shall coincide within ±0.001 in. at the reference edge of the tape when the recording is made at 15 in./sec tape speed.

The tracking-control signal shall be positioned so that a point of maximum record current and the extended centerline of the fifth video track after the track containing the vertical synchronizing pulse shall coincide within ±0.001 in. at the reference edge of the tape when the recording is made at 7.5 in./sec tape speed.

5.4 The point of maximum record current coinciding with the frame pulse shall be one that immediately follows an area on the control record to which a south-seeking pole of a compass will be attracted.

5.5 The wave shape of the tracking-control signal current in the record head should be sinusoidal.

APPENDIX

(This Appendix is not a part of SMPTE Recommended Practice RP 16–1964, Specifications of Tracking Control Record for 2-In. Video Magnetic Tape Recordings, but is included to facilitate its use.)

1. The transfer characteristic of magnetic tape is nonlinear. The B_r, I_r curve of the tape as recorded has a shape indicated in Fig. 2a. When a sinusoidal record current (Fig. 2c) is applied to the record head, the resulting recorded flux density is as shown

in Fig. 2b. The playback voltage waveform (Fig. 2d) is the first derivative of the recorded flux. Thus, the zero axis crossing region of the playback signal corresponds to the maximum recorded flux region. The verge of saturation is considered to be the condition where the recorded flux waveform is just noticeably flattened on its peaks. This flattening of the flux peaks results in an inflection in the playback signal waveform in the zero axis crossing region. The verge of saturation can thus be determined by increasing the record current until a just perceptible inflection occurs in the zero axis crossing region of the playback signal.

2. Areas to which a compass is attracted (see Section 5.4) do not coincide with point of maximum record current. The compass will be attracted to two areas (X, as shown in Fig. 2) adjacent to the point where the record current crosses the zero axis. The two areas will appear as bars when the track is developed with carbonyl iron or an equivalent material.

3. The location of vertical sync and the frame pulse, as specified herein, will apply only if the recorder video head and capstan servos are referenced to the incoming video signal or its sync generator.

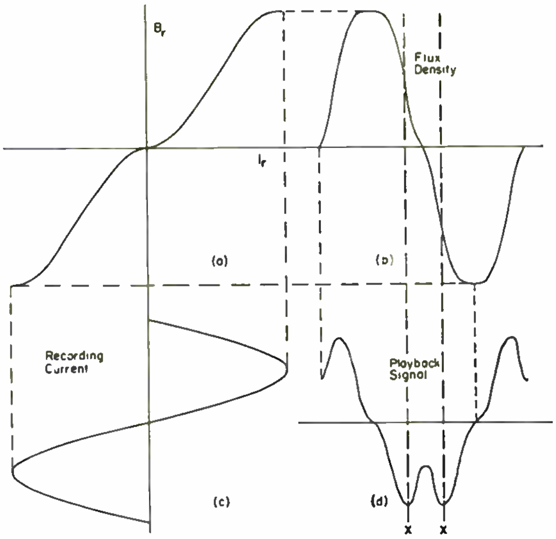


Figure 2

SMPTE RECOMMENDED PRACTICE

RP 26–1968

Label Specifications for 2-In. Quadruplex Video Magnetic Tape Recordings

1. *Scope*

This recommended practice specifies the minimum information required on labels attached to reels and reel containers of 2-in. quadruplex video magnetic tape recordings.

2. *Specifications*

The following represents the minimum information required on a video tape label. The label shall be affixed to both the reel and container:

(1) Name of company or studio
(2) Name of program or commercial
(3) Number of program or commercial
(4) Modulation practice—high band or low band
(5) Color or black and white
(6) Original or copy

SOCIETY OF MOTION PICTURE AND TELEVISION ENGINEERS
9 East 41st Street, New York, N.Y. 10017

Approved January 1968

American Standard Specifications of

Monochrome Video Magnetic Tape Leader

ASA
Reg. U.S. Pat. Off.

C98.2-1963

*UDC 681.85:621.397.5

1. Scope

This standard specifies the audio and video information that precedes and follows the recorded program material (for purposes of insuring uniformity of reproduction), and provides the necessary identification "cue up" and "run out" information. The standard also specifies the minimum lengths of tape required to ensure proper "threading" and "wrap around" for monochrome video-tape recordings.

2. Alignment Signal

2.1 At the head end of the tape, at least 35 seconds of test pattern shall be recorded at the same level and under the same conditions of equipment adjustment used for recording the video program material. (It is desirable that test pattern or test signal include reference black and reference white information. The signal should be of such a nature as to facilitate vacuum guide adjustment, e.g., stairstep signal.)

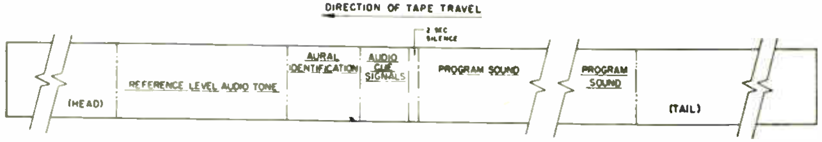
2.2 Simultaneously, a reference level audio tone of 400 cps (cycles per second) ± 5 per cent shall be recorded at the same level and under the same conditions of equipment adjustment used for recording the audio portion of the program material.

2.3 The alignment signal shall be preceded by at least 10 seconds of blank tape for "threading" purposes.

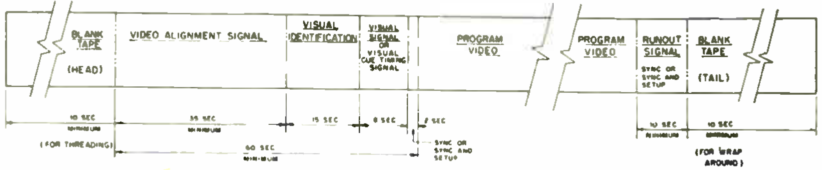
3. Identification Information

3.1 Visual identification information shall be recorded for at least 15 seconds following the video alignment signal specified in Section 2. In a typical case, the identification might contain:

(1) title
(2) subject
(3) production number
(4) "take" number
(5) recording studio name
(6) date of recording



A = Sound portion of video tape leader



B = Video portion of video tape leader

Note: The figures of picture and sound sequences are shown related on a time basis. There is separation of the picture and sound records on the recorded tape as defined in American Standard Specifications of the Audio Records for 2-In. Video Magnetic Tape Recordings, C98.3-1963.

Approved November 19, 1963, by the American Standards Association, Incorporated
Sponsor: Society of Motion Picture and Television Engineers

* Universal Decimal Classification

10 East 40th Street, New York 16, N.Y.

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ASA1M1263/50

3.2 Simultaneously, an aural identification of the information specified in Section 3.1 should be recorded under the same conditions as defined in Section 2.2.

4. Cue Timing Signals

4.1 Audio cue signals, as described below, shall be recorded on the audio program track following the aural identification signals specified in Section 3.

4.1.1 The audio cue tone signals shall consist of a series of 400 cps ± 5 percent bursts, each of $^1/_2$-second duration, occurring at one-second intervals over the range from ten or more seconds ahead of the program material to two seconds ahead. The recording level shall be as defined in Section 2.2.

4.1.2 In addition, a steady component of the audio cue tone shall be recorded approximately 20 db (decibels) below the level used in Section 4.1.1 above, starting with the first tone burst and ending with the last one, to leave a two-second silent interval before the start of program material.

4.2 A visual signal shall be recorded during the entire period of the steady component of the above-described audio tone signals. Sync (or sync and setup) only shall be recorded during the two-second interval from the end of the tone bursts to the start of program. The recording level shall be as described in Section 2.1.

If a visual cue timing signal is used, it shall be coincident with and identify the tone burst in Section 4.1.1.

5. Continuity of Recorded Signals

Continuity of recorded signals, beginning with the video alignment signal, shall not be interrupted. This continuity shall be achieved by continuous recording or by equivalent splicing, provided that the requirements of Section 2.1 are fulfilled.

6. Run-Out Signal

6.1 There shall be at least 10 seconds of sync (or sync and setup) recorded immediately following the conclusion of program material.

6.2 The run-out signal shall be followed by at least 10 seconds of blank tape for "wrap around" purposes.

American Standard Specifications of the

Audio Records for 2-In. Video Magnetic Tape Recordings

ASA
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C98.3-1963

*UDC 681.85:621.397.5

1. Scope

This standard pertains to the audio records as defined in Proposed American Standard Dimensions of Video, Audio and Tracking Control Records on 2-In. Video Magnetic Tape, C98.6.

2. Mechanical Characteristics

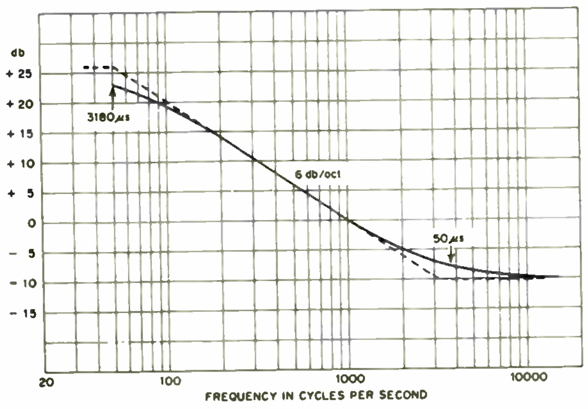
The audio-video separation shall be 9.250 in. ±0.100 in. with the audio record on the tape preceding the corresponding picture record. This tape path distance between the video and audio recording heads shall be taken as that between the point of intersection of transverse and longitudinal center lines of each magnetic gap, with the video head positioned at the angle of rotation which places it at the center of the audio track.

3. Electrical Characteristics

The reproducing characteristics as herein specified for the audio records on 2-in. video magnetic tape recordings apply to both 15 in. per second and 7.5 in. per second linear tape speeds. The recordings shall be made such that the proper reproducing characteristic shall correspond to Section 2.80, Standard Reproducing Characteristic, of the National Association of Broadcasters Recording and Reproducing Standards for Mechanical, Magnetic, and Optical Recording and Reproducing—1953. This section is reproduced below:

"It shall be standard that a Standard Reproducing System is one having an "ideal" reproducing head,[1] the EMF of which is amplified in an amplifier with a response curve having the following characteristic:

At a tape speed of 15"/second: The response curve shall be that which results from the superposition of three curves; one that falls with increase of frequency at the rate of 6 db per octave; this curve to be modified at low audio frequencies by a curve that falls with decrease of frequency in conformity with the admittance of a series combination of a capacity and a resistance having a time constant of 3180 microseconds; and this same curve to be modified at high audio frequencies by a curve that rises with increase of frequency in conformity with the admittance of a parallel combination of a capacitance and a resistance having a time constant of 50 microseconds. The combined curve is shown in Figure 6."



[Fig. 6.] NAB Magnetic Tape Standard Reproducing Characteristic at 15 in./sec, June, 1953.

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[1] "An 'ideal' reproducing head is defined as a reproducing head the losses of which are negligible. With a normal ferromagnetic head this means that the gap is short and the arc of contact with the tape is long compared to the relevant wavelengths, and the losses in the material of the head are small. With the reproducing heads used in practice, an equalization to compensate for the head losses must be added to the replay amplifier."

American Standard Dimensions of
2-In. Video Magnetic Tape Reels

ASA
Reg. U.S. Pat. Off.
C98.5–1965
*UDC 681.85:621.397.5

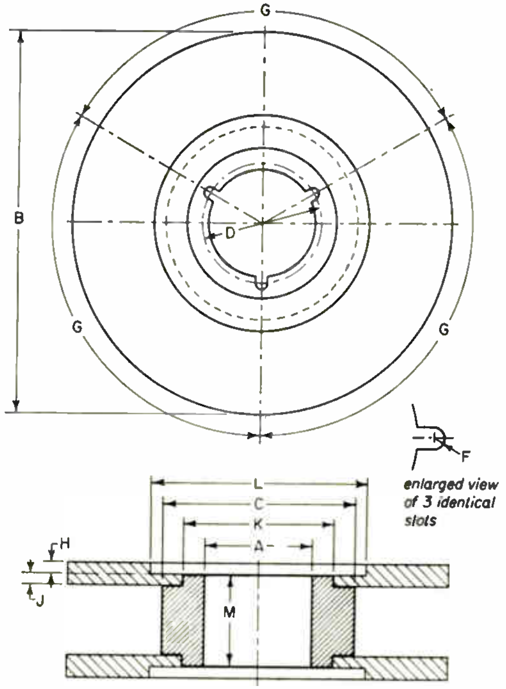
1. Scope

This standard specifies the dimensions of reels in maximum capacities of 750, 1650, 3600, 5540, and 7230 ft designed to accommodate the maximum thickness of 2-in. wide magnetic tape for television recording, as specified in American Standard Dimensions of 2-In. Video Magnetic Tape, C98.1-1963.

2. Reel Dimensions

2.1 The dimensions of the reels shall be as specified in the figure and tables.

2.2 Flange-fastening members shall be flush with or below the outer surface of the flanges.



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2.3 The outside cylindrical surface of the hub (C diameter) shall be concentric with the center bore (A diameter) within 0.002 in. (0.05mm) and shall have a maximum taper of 0.0004 in. (0.010mm).

2.4 The outside diameter of the flanges (B diameter) shall be concentric to the center bore of the hub (A diameter) within 0.02 in. (0.5mm).

Table 1

Reel Dimensions

Dimensions	Inches	Millimeters	Degrees
A	$3.000 \begin{smallmatrix}+0.004 \\ -0.000\end{smallmatrix}$	$76.20 \begin{smallmatrix}+0.10 \\ -0.00\end{smallmatrix}$	
B	See Table 2	See Table 2	
C	4.500 ± 0.100	114.30 ± 2.54	
D	3.250 ± 0.002	82.55 ± 0.05	
F	$0.109 \begin{smallmatrix}+0.003 \\ -0.000\end{smallmatrix}$	$2.77 \begin{smallmatrix}+0.08 \\ -0.00\end{smallmatrix}$	
G			120 ± 0.1
H	0.025 max†	0.64 max†	
J	0.099 max†	2.51 max†	
K	3.600 min‡	91.44 min‡	
L	6.000 min‡	152.40 min‡	
M*	2.212 ± 0.003	56.18 ± 0.08	

* The hub surfaces defined by M shall be parallel within 0.0002 in. (0.005mm) per inch and square with the hub outside diameter C within 0.001 in. (0.03mm) at maximum diameter.

† The surface of the flanges from B to L shall lie between the planes defined by H and J.

‡ Outside surfaces of reel flanges between diameters K and L shall not extend beyond the surfaces defined by Dimension M.

Table 2

Reel Capacities

Maximum Capacity,* Feet	Maximum Capacity,* Meters	Maximum Playing Time in Min at 7.5 In. (19.05 Cm) Per Second	Maximum Playing Time in Min at 15 In. (38.1 Cm) Per Second	Dimension B Inches	Dimension B Millimeters
750	228	20	10	6.50 ± 0.010	165.1 ± 0.25
1650	503	44	22	8.00 ± 0.010	203.2 ± 0.25
3600	1097	96	48	10.50 ± 0.010	266.7 ± 0.25
5540	1689	148	74	12.50 ± 0.010	317.5 ± 0.25
7230	2203	192	96	14.00 ± 0.010	355.6 ± 0.25

* Maximum capacity is based on a minimum distance of 0.2 in. (5mm) from the reel periphery to the tape stack, utilizing maximum thickness tape.

Appendix

(This Appendix is not a part of American Standard Dimensions of 2-In. Video Magnetic Tape Reels, C98.5-1965, but is included to facilitate its use.)

The outside diameters of the flanges, B, will give reels the capacities suggested in Table 2. These capacities should be regarded as maximum.

It is recommended that both flanges have air escape holes. If provided, these holes should extend to the hub periphery and be of such size at this point as to facilitate easy threading.

American Standard Dimensions of

Video, Audio and Tracking Control Records on 2-In. Video Magnetic Tape

ASA
Reg. U.S. Pat. Off.
C98.6–1965

*UDC 681.85:621.397.5

1. Scope

This standard specifies the locations and dimensions of the video, audio and tracking control records on 2-in. video magnetic tape.

2. Dimensions

The dimensions shall be as specified in the figures and tables.

3. Magnetic Coating

With the direction of tape motion as shown in Fig. 1, the magnetic coating is on the surface facing the observer.

4. Video Track Curvature

Each video track shall not deviate from a straight line by more than 0.001 in. (0.03mm).

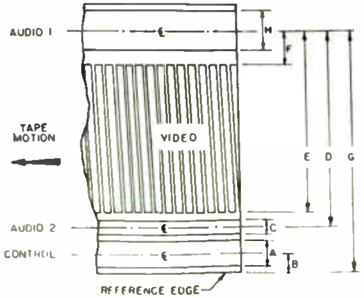

Fig. 1. Position of Records.

Table 1

Dimensions	Inches	Millimeters
A	0.045 ± 0.005	1.14 ± 0.13
8	0.022 ± 0.002	0.56 ± 0.05
C	0.022 ± 0.002	0.56 ± 0.05
D	1.894 ± 0.002	48.11 ± 0.05
E	$1.872 \begin{smallmatrix}+0.005\\-0.000\end{smallmatrix}$	$47.55 \begin{smallmatrix}+0.13\\-0.00\end{smallmatrix}$
F	$0.057 \begin{smallmatrix}+0.000\\-0.005\end{smallmatrix}$	$1.45 \begin{smallmatrix}+0.00\\-0.13\end{smallmatrix}$
G	1.962 ± 0.004	49.81 ± 0.10
H	0.070 ± 0.004	1.78 ± 0.10

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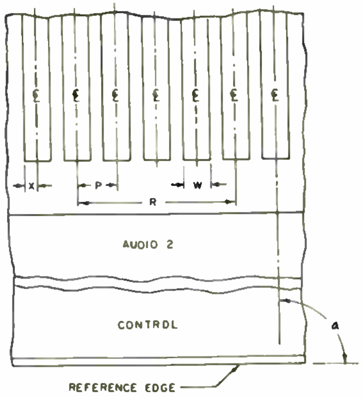

Fig. 2. Detail of Video Tracks.

Table 2

Dimensions of Video Tracks (15 in./sec, 960 tracks/sec)

Dimensions	Inches		Millimeters
P = R/4	Calc		Calc
R	0.0625 ± 0.0010		1.588 ± 0.025
W	0.0100 ± 0.0005		0.254 ± 0.013
X	W/2 ± 0.0002		W/2 ± 0.005
α		90° 33′ ± 3′	

Table 3

Dimensions of Video Tracks (7.5 in./sec, 960 tracks/sec)

Dimensions	Inches		Millimeters
P = R/4	Calc		Calc
R	0.0312 ± 0.0010		0.794 ± 0.025
W	0.0050 ± 0.0005		0.127 ± 0.013
X	W/2 ± 0.0002		W/2 ± 0.005
α		90° 17′ ± 3′	

Appendix

(This Appendix is not a part of American Standard Dimensions of Video, Audio and Tracking Control Records on 2-In. Video Magnetic Tape, C98.6-1965, but is included to facilitate its use.)

A magnetic record or track is that area in which magnetization conveying the intended signal exists. A common technique for measurement of record locations and dimensions is the use of carbonyl iron to make them visible.

USA standard

Approved July 19, 1967

USAS
C98.9–1967

UDC 681.84.083:621.397.8

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Specifications for

Color Video Magnetic Tape Leader

1. Scope

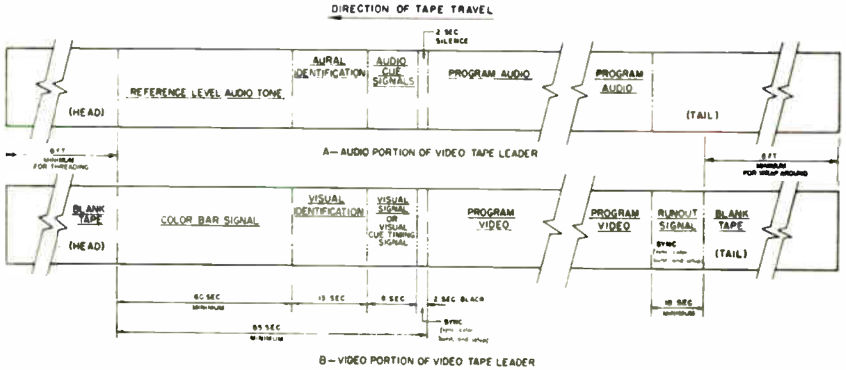
1.1 This standard specifies the minimum leader requirements for color video tape recording operation to permit adjustment of equipment for optimum performance during reproduction prior to the start of recorded program material.

1.2 The standard also specifies the audio and video information that precedes and follows the recorded program material (for purposes of ensuring uniformity of reproduction), and provides the necessary identification cue up and run out information, and the minimum lengths of tape required to ensure proper threading for color video tape recordings.

2. Color Bar Signal

2.1 At the head end of the tape, at least 60 seconds of color bar pattern, as defined by EIA Standard RS-189, Encoded Color Bar Signals, shall be recorded with maximum luminance at 77 IRE units corresponding to 75 percent chroma level, including a reference white bar and reference black bar.

The recording shall be made under the same conditions of equipment adjustment as used for recording the video program material. For original recording, the color bar signal shall originate in and be fed through the same studio and equipment used for the program.



NOTE: The figures of picture and sound sequences are shown related on a time basis. There is separation of the picture and sound records on the recorded tape, as defined in USA Standard Specifications of the Audio Records for 2-In. Video Magnetic Tape Recordings, C98.3-1963.

2.2 Simultaneously with the color bar signal, a reference level audio tone of 400 Hz ± 5 percent shall be recorded at the same level and under the same conditions of equipment adjustment used for recording the audio portion of the program material.

2.3 The color bar signal shall be preceded by 8 ft minimum of blank tape for threading purposes.

3. Identification Information

3.1 Visual identification information shall be recorded for at least 15 seconds following the color bar signal specified in Section 2. The identification shall contain the following information (if known):

(1) title
(2) subject
(3) production number
(4) take number
(5) name of recording studio
(6) date of recording
(7) broadcast date

3.2 Simultaneously, an aural identification of the information specified in Section 3.1 shall be recorded under the same conditions as defined in Section 2.2.

4. Cue Timing Signals

4.1 Audio cue signals, as described below, shall be recorded on the audio program track following the aural identification signals specified in Section 3.

4.1.1 The audio cue tone signals shall consist of a series of 400 Hz ± 5 percent bursts, each of $\frac{1}{3}$-second duration, occurring at one-second intervals over the range from ten or more seconds ahead of the program material to two seconds ahead. The recording level shall be as defined in Section 2.2.

4.1.2 In addition, a steady component of the audio cue tone shall be recorded approximately 20 dB below the level used in Section 4.1.1 above, starting with the first tone burst and ending with the last one, to leave a two-second silent interval before the start of program material.

4.2 A visual signal shall be recorded during the entire period of the steady component of the above-described audio tone signals. Sync (sync, color burst, and setup) only shall be recorded during the two-second interval from the end of the tone bursts to the start of program. The recording level shall be as described in Section 2.1.

If a visual cue timing signal is used, it shall be coincident with and identify the tone burst in Section 4.1.1.

5. Continuity of Recorded Signals

Continuity of recorded signals, beginning with the color bar signal, shall not be interrupted. This continuity of sync, color burst, and control track shall be achieved by continuous recording or by equivalent splicing, provided that the requirements of Section 2.1 are fulfilled.

6. Run-Out Signal

6.1 There shall be at least 10 seconds of sync (sync, color burst, and setup) recorded immediately following the conclusion of program material.

6.2 The run-out signal shall be followed by 8 ft minimum of blank tape for wrap around purposes.

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Drive-In Theaters	RP 12–1962*	July 1962
16mm Review Rooms	PH22.100–1967	Feb. 1968
Sensitometric Strips	RP 14–1964*	Apr. 1964 Aug. 1969[1]
Spindles		
16mm projector Withdrawn 1969	PH22.50–1960	Dec. 1952 Oct. 1960[3]
16mm projector	RP 34–1968	Dec. 1968
16mm camera	RP 24–1967	July 1967
35mm rewind	RP 21–1966	Aug. 1966
Splices		
16 & 8mm		
Laboratory type	PH22.77–1965*	Dec. 1965
Projection type	PH22.24–1965*	Dec. 1965
super 8		
Cemented	PH22.172.1	June 1968[1]
Tape	PH22.172.2	June 1968[1]
35mm	PH22.178	Nov. 1969[1]
70mm reinforcement	RP 23–1967	July 1967
Spools		
8mm, 25-ft capacity	PH22.107–1964*	June 1964
Double 8, 100-ft capacity	PH22.173–1969	Oct. 1969
16mm, daylight-loading, 50- to 400-ft capacity	PH22.174–1969	Oct. 1969
Sprockets		
16mm and 8mm	RP 1–1950* R1963	Feb. 1950
35mm	PH22.35–1962 R1969	May 1962
Synchronization, sound-picture	RP 25–1968	Mar. 1968
Unsteadiness, High-Speed Camera	RP 17–1964 R1969	May 1964

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* Under Committee review. R—Reaffirmed.

[1] Proposed standard or recommended practice. [2] To be withdrawn.

[3] Essential technical content is included in the early publication date. The later date lists editorial or nontechnical changes agreed to by SMPTE engineering committees and subsequently incorporated in a revision of the standard.

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