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TITLE **FREQUENCY CHARACTERISTICS OF THE RECEIVER**
**( *TELEVISION PRINCIPLES — CHAPTER 5* )**

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Approved W. A. MacDonald

# FREQUENCY CHARACTERISTICS OF THE RECEIVER
## (TELEVISION PRINCIPLES - CHAPTER 5)

By C. E. Dean

TABLE OF CONTENTS

## SPECIFICATIONS SELECTED FROM THIS CHAPTER

| | |
|---|---|
| Number of Lines per Frame - - - - - | 441 |
| Number of Used Lines with 7 Percent Field Blanking - - - - - - | 410 |
| Same with 10 Percent Field Blanking - - - | 397 |
| Vertical Resolution Factor - - - - | 70% |
| Approximate Vertical Resolution Afforded by Above Standards - - - - - | 280 Lines |
| System Cutoff Frequency for 280-Line Horizontal Resolution - - - - | 2.8 Mc |
| Same for Any Horizontal Resolution - - | $N_h/100$ |
| Maximum Overshoot Resulting Solely from Sharp Cutoff - - - - - - | 9% |
| Theoretical Tolerance of Vector Sum of Amplitude Distortion in Napiers and Phase Distortion in Radians for Excellent Reproduction - | 0.1 |

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# FREQUENCY CHARACTERISTICS OF THE RECEIVER (TELEVISION PRINCIPLES - CHAPTER 5)

## INTRODUCTION

In the preceding chapter (Report 1837) there is given a statement of the general requirements on the receiver as established by the details of the transmitted video wave and also in regard to sensitivity and selectivity. In the present chapter the discussion of general receiver requirements is completed, taking up particularly the frequency characteristics of the scanning spots and of the electrical circuits which determine the picture detail.

A general treatment of this subject is given in the paper, "The Fine Structure of Television Images", by H. A. Wheeler and A. V. Loughren, Hazeltine Report 771b-W, which was published in the PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS for May 1938. The present chapter gives a brief discussion of the subject.

The electrical transmission of low-frequency video components, including the direct-current component, is necessary in order to reproduce the picture with the proper average brightness, and with correct general shading over the reproduced scene. The electrical results of insufficient low-frequency transmission are discussed in one of the sections below, beginning on page 111.

The high-frequency characteristics of the circuit are closely related to the horizontal resolution since, in the rapid motion of the spot as it scans successive lines of the transmitted image, high-frequency components are developed by fine horizontal detail in the scene. This subject and the related matter of scanning-spot characteristics are discussed in one of the sections below.

## THE MEASURE OF DETAIL

Detail in television practice is measured by the number of alternate black and white lines (the black lines having the same width as the white lines), which can be separately seen. In case the lines lie horizontally, the resulting observation obviously gives the resolution in the vertical direction; if the lines are vertical, the resulting observation gives the resolution in the horizontal direction.

Various charts have been designed on this principle for use as the subject for the television camera and so arranged that observations at the receiver can be conveniently made, giving the horizontal and vertical resolution of the system. In Figure 1 there is shown such a chart which we have used; the original has a height of approximately 30 inches. This chart includes two horizontal wedges of approaching lines for observing vertical resolution. The point along such a wedge at which the separate lines partially disappear determines the resolution. The receiving picture tube is viewed at a fairly close distance for this purpose.

Reading the resolution chart requires some discretion and experience. Our recommendation is to locate a region along the wedge pattern as follows, and to take the reading in the middle of this region. This is the region of diminishing contrast between black and white lines. At one edge of this region, the lines just begin to lose their normal contrast; that is, the black lines begin to assume a grayish shade. At the other edge, the lines are just barely perceptible on the gray background. At the middle reading which is taken as the observed resolution, the lines are visible at reduced contrast.

If Figure 1 is held at a distance of about fifteen feet, such a reading for the eye alone may be made, and will illustrate the use of the chart.

The extremes of each wedge are designated 100 and 300; these figures indicate the total number of black and white lines resolvable in the entire height of the picture. Intermediate markers are provided at 150, 200, and 250 lines. The reasons why a maximum value of 300 lines is sufficient, and it is not necessary to go to 441 or beyond, are made clear in the later section entitled "Vertical Resolution". This method may be checked on a standard 441-line system operating under favorable conditions, where the vertical resolution should be about 280 lines.

Figure 1 also includes three vertical wedges for observing the horizontal resolution. These are identical to the horizontal wedges just described. They therefore give the number of lines resolvable horizontally in a length equal to the height of the picture. The number of lines resolvable in the entire width of the picture is obtainable by multiplying by the aspect ratio, which is 4/3. However it is not desirable to use this quantity and in practice it is not done, because the important advantage of comparable figures for horizontal and

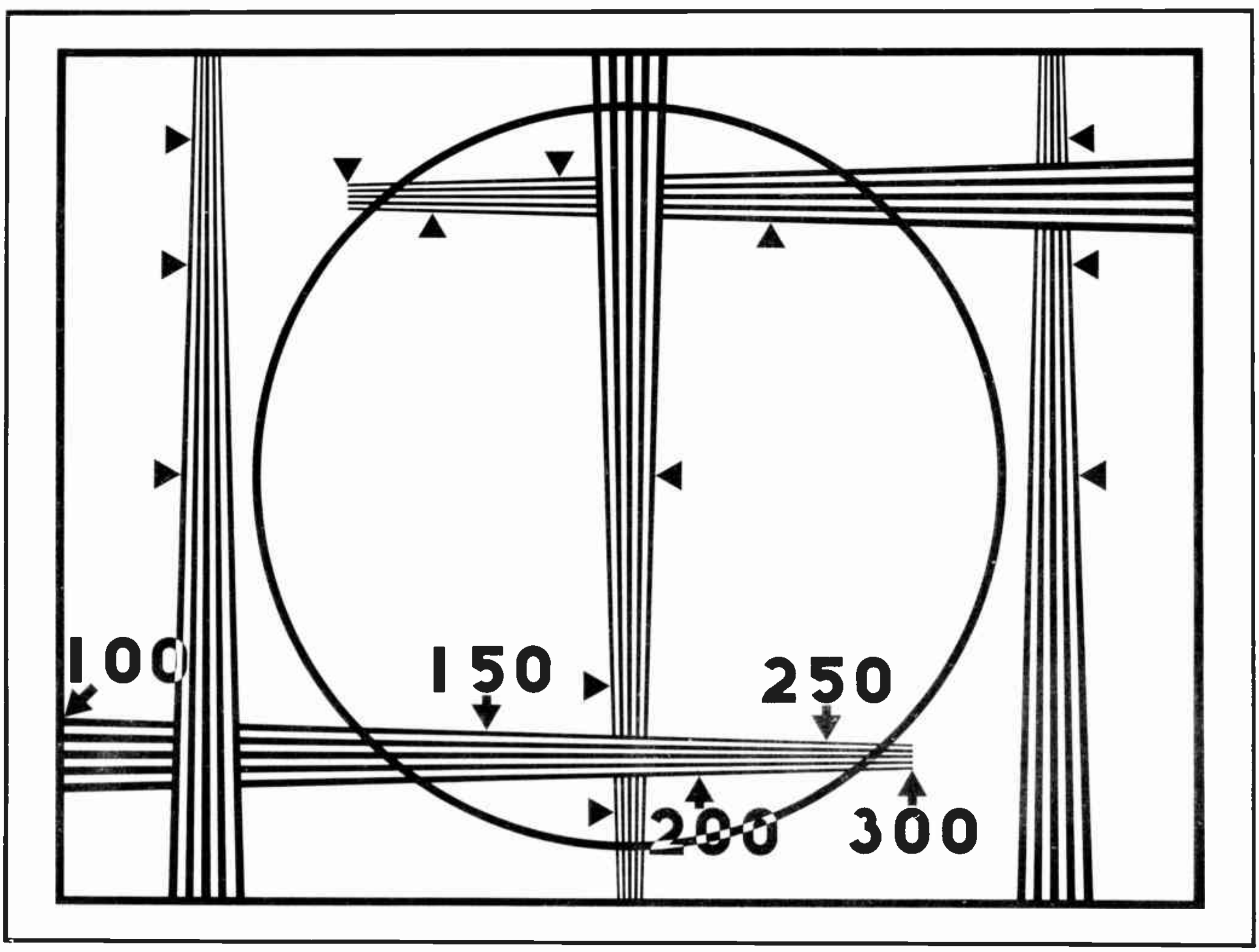


Fig. 1. Resolution Chart Used in Hazeltine Laboratories.

vertical resolution would be lost. The horizontal resolution is therefore generally stated as the number of resolvable lines in a horizontal distance equal to the height of the picture.

Another resolution chart, which includes provision for separate observations of horizontal and vertical resolution in twelve portions of the area of the scene, is described by A. V. Bedford of the RCA Manufacturing Company in his paper, "A Figure of Merit for Television Performance", which is listed below in the section "References". The paper includes a procedure for obtaining an overall figure of merit for the resolution from the data observed for the individual portions of the field.

## THE SCANNING SPOT

In a mechanical television system, the shape of the scanning spot is determined by the shape of the aperture. In such a system the scanning operation is performed by the motion of this aperture. The intensity over the area of the aperture is constant. The characteristics of such an aperture may therefore be represented three-dimensionally by a plateau of illumination, having a flat top and vertical sides determined by the shape of the aperture.

In distinction to the mechanical aperture, a cathode-ray spot under practical conditions is circular in shape and non-uniform in intensity over this area. Such a spot may be visualized as a small mound with the highest point at the center. At the receiver the scanning spot is generally made as small as possible to give sharper detail, with the result that the line structure may be seen on inspection at close range. However, at the usual viewing distance the line structure is nearly imperceptible, and therefore the apparent width of the scanning lines is equal to the line pitch.

A picture tube, under the conditions just described, may be said to have a "flat field", a term which indicates that the line structure cannot be seen. At the receiver this effect is ordinarily obtained by virtue of the viewing distance or, in other words, by virtue of the characteristics of the eye. However, in the mosaic tube at the transmitter it is desirable that a physically flat field be obtained, at least as viewed with the aberration of the camera lens. In Figure 2, the production of such a field by the motion of a cathode-ray spot is shown. The outside width of the spot, and therefore the outside width of each line, is approximately twice the line pitch. In this way the center of each

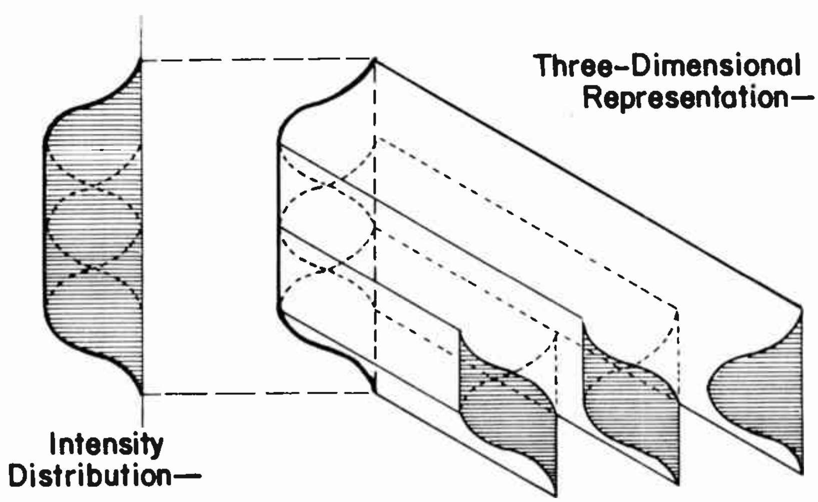


Fig. 2. Flat Field Obtained By Scanning With Cathode-Ray Spot.

line is produced only by the motion of the spot for this particular line, but all other points are produced with equal intensity by the addition of suitable contributions from the two adjacent lines. If the distribution across any one scanning line has a cosine-squared characteristic, as described in the Wheeler-Loughren paper, and the outside width is just twice the line pitch, a flat field will be obtained.

In order to obtain a cosine-squared distribution across the lines, the spot itself must have a slightly different distribution, and the effect of camera lens or eye lens must be considered. This is a necessary consequence of the fact that the line is produced by the motion of the spot, and its effective width depends also on the lens. The theoretically necessary spot distribution can be approximately obtained in practice.

In Figure 3 there is shown the manner in which a slightly sloping line might, under certain conditions in the transmitter, be reproduced with gaps or overlaps so as to have the objectionable appearance of "beads". The drawing is made for a rectangular aperture in the interest of simplicity. The stepped effect in normal reproduction is unavoidable and disappears at a distance. The overlap type of beads is the less serious because the two-to-one intensity relation is not conspicuous. Also it is unlikely to occur because the spot is never intentionally made larger than required. The gap type of beads would be serious because of the much larger contrast; it is caused only by too small a spot in the camera tube, and this is not usual at present.

Another aspect of this effect, associated with the nature of the scanning process, is shown in Figure 4, which is taken from the volume "Fernsehen: Die neuere Entwicklung insbesondere der deutschen Fernsehtechnik", ("Television: Recent Developments, Especially in German Television Practice"), edited by F. Schröter and published in 1937. Figure 4 shows the possibility of an ambiguity in that either of the fine-structure patterns at the top, scanned by a square spot of the indicated size, produces the same electrical signal, which is reproduced as the

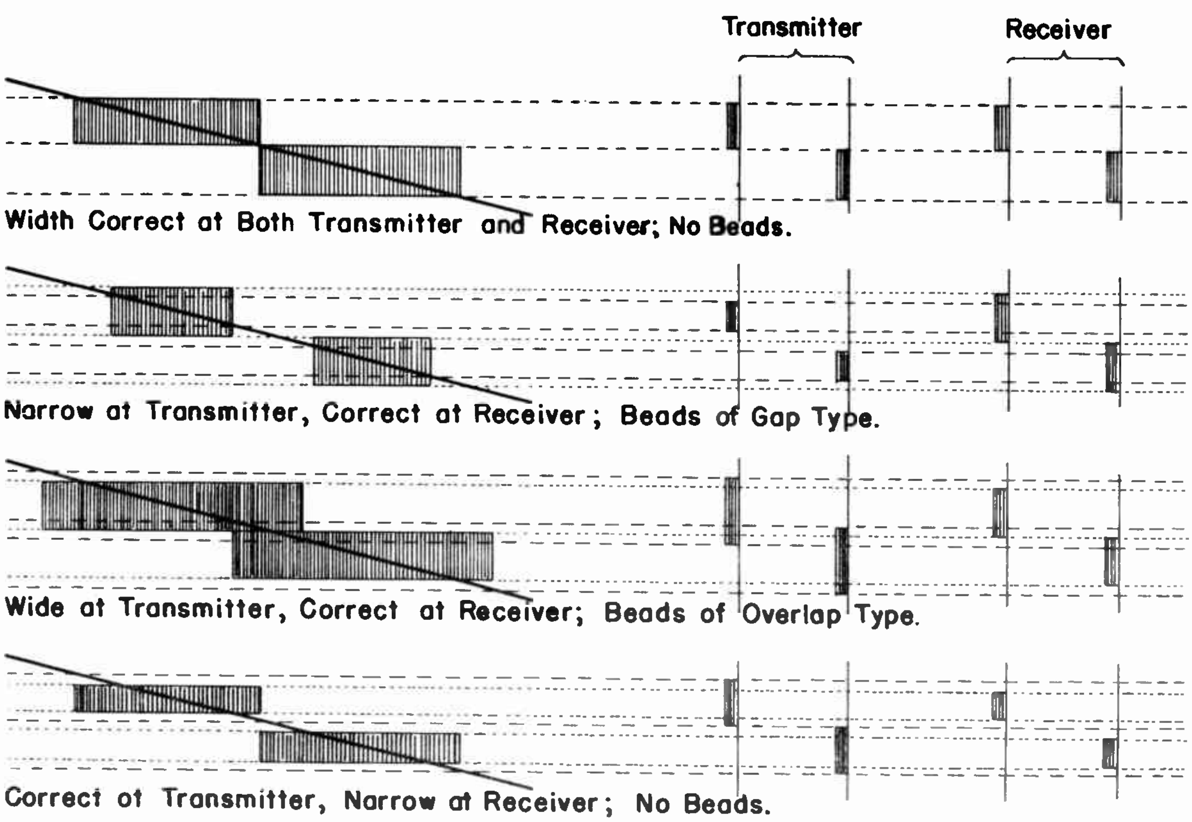


Fig. 3. The Production of Beads by Improper Width of Scanning Line in the Transmitter.

image shown at the bottom. The receiver cannot distinguish between the two patterns.

## VERTICAL RESOLUTION

As mentioned above, at the usual viewing distances a flat field is seen and therefore the apparent width of each scanning line is equal to the line pitch. The proper viewing distance is that which is barely sufficient to secure this effect. A horizontal narrow line in the scene will be reproduced by either one or two scanning lines depending on its position with respect to the scanning lines in the camera. If it is reproduced by one scanning line we may say that the relative resolution is unity, but if the reproduction requires two scanning lines we may say that the relative resolution is one-half.

A careful study has been made of the average width with which such a line is reproduced, considering all possible relations between it and the scanning lines. This was done by taking a slightly sloping line, almost horizontal in position, such as used above for the explanation of beads. It was then necessary only to obtain the average width of reproduction along this line. The result arrived at in such an analysis is that a horizontal line is on the average reproduced with a width which is greater than

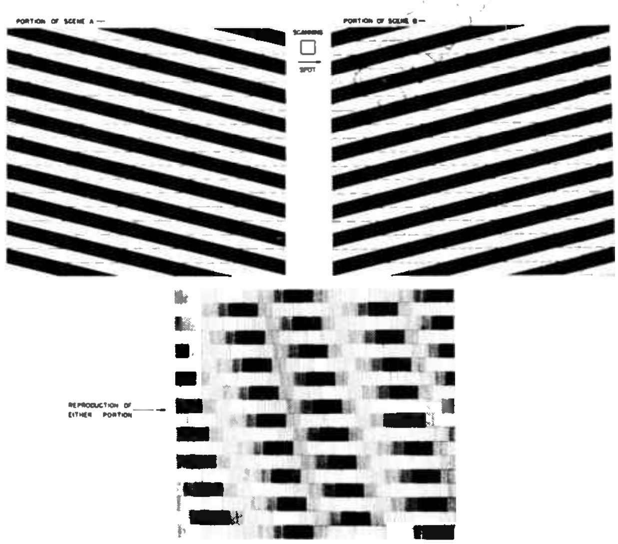


Fig. 4. Failure to Distinguish Patterns Having Lines of Same Width as the Scanning Lines.

the line pitch by the factor $\sqrt{2}$. Remembering that this is for average conditions in regard to the fortuitous relation between the narrow line and the scanning lines, it may be seen that a given number of scanning lines afford a vertical resolution which is only $1/\sqrt{2}$ times as great. The quantity $1/\sqrt{2}$ (or 70 percent) may be called the "vertical resolution factor". This is the chief factor explaining the need for only 300 lines as the maximum on the resolution chart of Figure 1.

In the case of the American television standards, 441 lines per frame are provided. Of this number only 410 or 397 are used, the figure depending on whether 7 percent or 10 percent field blanking is employed. Upon multiplying either of these numbers of useful lines by the vertical resolution factor, we obtain approximately 280 lines as representing the vertical resolution afforded by the American standards.

## HORIZONTAL RESOLUTION

The analysis of vertical resolution in the foregoing paragraphs is in terms of a line in a horizontal direction, or almost horizontal. For horizontal resolution, it is advantageous in an analogous manner to consider a very narrow vertical line, such as would be produced by a distant white flagpole against a dark background. The width with which such a narrow vertical line is reproduced at the receiver depends on (1) the size of the receiver spot, (2) the transmission characteristics of the electrical system, and (3) the size of the camera spot.

Considering only the size of the receiver spot, the narrowest vertical line in the picture is a vertical succession of spots as shown in Figure 5. Each spot producing this line is the result of a very short electrical impulse acting on the control grid of the picture tube. To produce such a pulse it is necessary that the camera spot be much smaller than the receiver spot and that the electrical system have perfect transmission characteristics. It is seen in Figure 5 that, under these circumstances, the vertical line has the same width as a horizontal line produced by the motion of the spot.

Therefore the effective width of the vertical line is likewise equal to the line pitch.

Adding the effect of a camera spot of substantial width to that of the receiver spot causes, as would be expected, a greater blurring or soft-focus effect in the reproduction. There is therefore a greater width of reproduction of a narrow vertical line in the scene. This is caused by the width of the camera spot giving substantial duration to the electrical pulse. If the camera spot has the same relative size as the receiver spot, it is found that it increases the effective width of the vertical line by a factor of 4/3. The effective width is then 4/3 times the line pitch.

In addition to the camera and receiver spots, the third factor which determines the width of the reproduced narrow vertical line is the electrical characteristics of the connecting circuits. Irregularities in the transmission over the video-frequency range, in the nature of amplitude and phase distortion, may seriously widen and otherwise distort the received electrical signal pulses, and thereby increase the width of reproduction. This is considered below in the section, "Requirements at the Higher Video Frequencies".

A scanning spot of a given size will handle the larger details of the field effectively. However, it will fail to handle very fine details, smaller than the spot size. Figure 6 shows an enlarged view of closely spaced vertical bars constituting very fine horizontal detail, too fine for the spot to handle. It may be seen that, with the spot shown, the action with successively finer detail is steadily poorer. This applies to either the camera spot or the receiver spot. The signal frequency associated with such detail rises as the detail becomes finer; in fact, it is equal to the frequency with which the spot passes alternate lines in the fine detail. On this account the spot may be said to attenuate the higher-frequency picture components to an increasing degree, and therefore to have low-pass-filter characteristics. In Figure 7 curves are given showing these characteristics for one and two spots of equal size relative to the picture height. The curve for one spot represents the effect at one end of a television system, and the curve for two spots represents the total effect of the camera and receiver spots. However, in practice the receiver spot often has a smaller relative size than the camera spot.

The curve of frequency transmission for a spot, such as the upper curve in Figure 7, if plotted for numerical values of frequency, applies to a spot of a particular size and velocity of scanning. A smaller spot would give a curve holding up better for the high frequencies, and vice versa, a larger spot would give a curve falling off more rapidly. Likewise, a faster-moving spot is better at the higher frequencies.

The lower curve in Figure 7, which gives the characteristics of two spots of equal relative size, is obtained by squaring the ordinates of the upper curve. The two spots produce factors

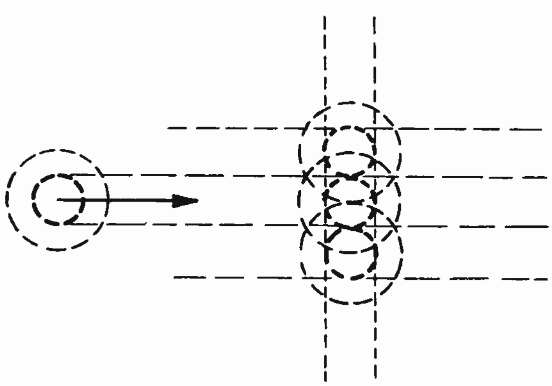

Fig. 5. Demonstration That the Minimum Width of Reproduction of a Vertical Line is Equal to the Pitch of the Scanning Lines.

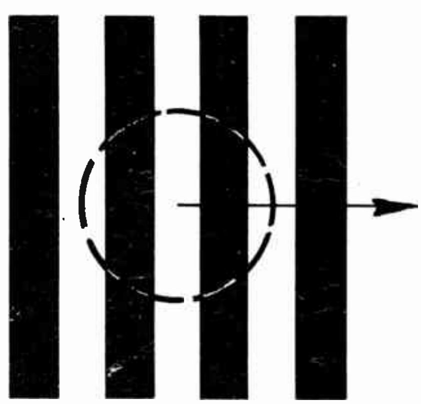

Fig. 6. The Failure of the Scanning Spot to Handle

which multiply together in the same way as those of filters in succession.

For curves falling off as gradually as these, it is evident that there is no critical cutoff frequency. However, it is desirable to have a numerical value for the cutoff frequency in these cases, and such a figure may be obtained by suitable definition. This may be done by defining the cutoff frequency as the width of a rectangle having the same height as the spot curve at low frequencies and having an area equal to that under the transmission curve, both sets of coordinates being plotted linearly. Such a cutoff frequency for the one-spot curve in Figure 7 is shown as $f_c'$, and for the two-spot curve as $f_c''$.

The attenuation manifested by the spots for the higher frequencies is due essentially to the comparable size of the spot and the horizontal details. With a given size of detail, a particular spot will manifest the same blurring for various scanning velocities. It is convenient, however, to take the standard scanning velocity, in which case the attenuation for a particular spot may be expressed as a function of the frequency of the signal rather than of the size of the detail. This is the basis of the curves of Figure 7.

The reproduction of a very narrow vertical line, which has already been used in the analysis of horizontal resolution, occupies an appreciable length of time, if its width is considered with the scanning velocity. Let us take $\Delta t$ as the time required for the center of either scanning spot to traverse the effective width (not the outside width) of the

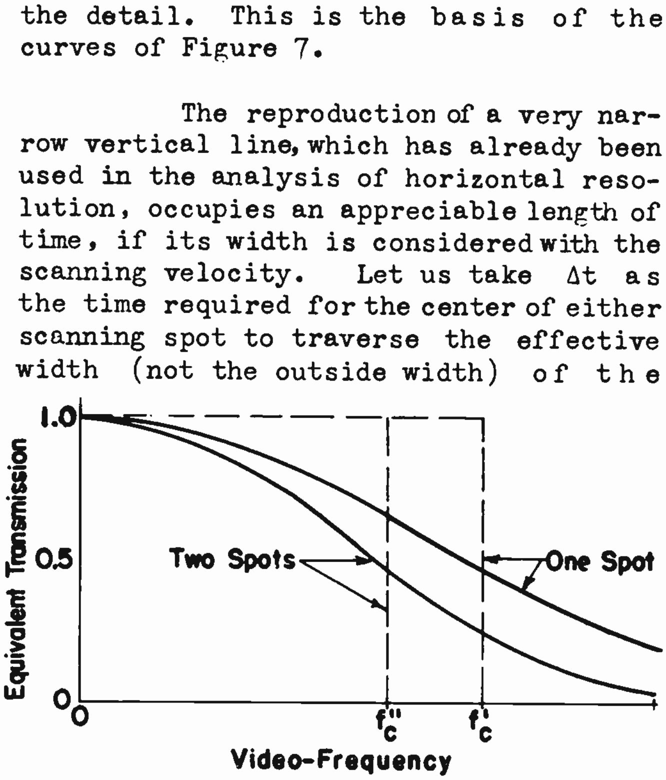


Fig. 7. Frequency Characteristics of the Transmitter Scanning Spot Alone, and of Both Transmitter and Receiver Spots Together

vertical line made by the two scanning spots. It has been shown that this time-width is equal to half the period at the cutoff frequency; that is, $\Delta t = 1/(2f_c'')$. If the value of $f_c''$ is taken as 2.8 megacycles, which will appear later as of special interest, the value of $\Delta t$ is slightly under 0.2 microsecond. For greater resolution it is necessary that the width of reproduction be less, and therefore that $\Delta t$ be less and the cutoff frequency be greater.

The electrical portion of a television system has to pass only the components handled by the spots, and especially the major components. The more intense components appear to be at the harmonics of 30 and 60 cycles up to one or two kilocycles and at the harmonics of the line frequency of 13,230 cycles up to about one-half megacycle. Higher-frequency components are essential for horizontal picture detail but the amplitude of each is usually small.

The declining filter-like shape of the curve giving the equivalent transmission of a spot suggests the possibility of electrical compensation by the provision of circuit characteristics favoring the upper video frequencies to give a complementary effect. In the transmitter such provision may well be made in the amplifier chain between the camera and the point where the modulation is performed. Such compensation gives the effect of a smaller camera spot.

The provision of spot compensation in the receiver is complicated because the compensation must be inserted before the distortion occurs. Also, the spot size is variable with modulation of its brightness. There is doubtful need for receiver compensation. This subject is discussed below on page 104.

## EQUAL VERTICAL AND HORIZONTAL RESOLUTION

An optical system, such as a telescope or microscope, usually has a circle of confusion giving non-directional resolution characteristics; that is, the vertical resolution is equal to the horizontal. The presence of unequal resolution in the two directions gives an effect analogous to astigmatism in the eye, making small symmetrical objects appear unsymmetrical. In setting up the standards of a television system, it is natural to provide for equal vertical and horizontal resolution. It may be noted that this provision is consistent with the future possibility that, after standards are established and the vertical resolution is fixed, it may be beneficial in the receiver to have the horizontal resolution as great as possible, even if this is greater than the vertical. This subject is considered further in the section below entitled "Requirements at the Higher Video Frequencies".

The criterion of equal vertical and horizontal resolutions means that the widths of reproduction of the very narrow vertical and horizontal lines, which are considered above, are equal.

An important use of this criterion is to determine what upper video-frequency range is necessary to make the horizontal resolution equal to the vertical. Or the criterion may be used in the choice of standards to determine the optimum number of scanning lines for a given frequency range.

It is now appropriate to derive the expression for the required width of frequency band on the basis of equal resolution in the two directions. If the aspect ratio is R, and if the horizontal resolution, as read on a resolution chart, is $N_h$, then the number of alternate black and white points which may be resolved along a horizontal line is $RN_h$. Neglecting the loss of time during horizontal blanking, this number of points is equal also to $T/\Delta t$, where T is the line period, and $\Delta t$ is the time width of one point. The value of T is $1/f_pN_s$, where $f_p$ is the frame frequency in cycles per second and $N_s$ is the number of lines per frame. The value of $\Delta t$ is given above on page 101 as $1/(2f_c)$, where $f_c$ is the system cutoff frequency as defined. Dividing the new expression for T by that just obtained for $\Delta t$ gives an alternative approximate expression for the number of points in a horizontal line, namely $2f_c/f_pN_s$.

The number of points obtainable in practice is reduced by the fact that the horizontal blanking makes the system unavailable for picture transmission during this portion of the time. If $B_h$ represents the horizontal blanking fraction (for example the standard value of 0.15), the useful portion of the line cycle has a relative duration of $(1-B_h)$. Placing this in the formula, we obtain the following expression for the number of resolvable points in a horizontal line:

$$RN_h = 2f_c(1-B_h)/f_pN_s$$

This relation may be seen to involve the horizontal resolution $N_h$ and the cutoff frequency $f_c$ as variables, together with other quantities which have been fixed in standardization. Upon solving for $f_c$ there is obtained the formula,

$$f_c = \frac{f_pN_s}{2(1-B_h)} RN_h$$

which gives the required bandwidth in cycles for any desired horizontal resolution.

On substituting the value of 4/3 for the aspect ratio R, the value of 30 frames per second for $f_p$, the value of 441 lines per frame for $N_s$, and the value of 0.15 for $B_h$, and expressing $f_c$ in megacycles, we obtain the simple formula,

$$(f_c)_{Mc} = \frac{N_h}{100}$$

It is seen therefore that with the American standards a complete television system requires a cutoff frequency in megacycles which is one-hundredth of the desired value of the horizontal resolution. Since this applies to an entire system, this cutoff frequency includes the effect of the spot attenuation.

It has been shown above that the vertical resolution afforded by the American standards is 280 lines. For equal resolutions in the two directions, the horizontal resolution must also have this value. Substituting 280 for $N_h$ in the equation shows the required cutoff to be 2.8 megacycles. In other words, horizontal resolution equal to the vertical resolution requires for the system a frequency range extending to a cutoff frequency of 2.8 megacycles, the definition of the cutoff frequency placing it about half way down the gradually declining transmission curve. For less horizontal resolution, a lower cutoff frequency is sufficient; for example, a resolution of 150 lines, requires only 1.5 megacycles. Solving the last equation for $N_h$ gives the formula

$$N_h = 100\ (f_c)_{Mc},$$

which expresses the horizontal resolution afforded by various values of cutoff frequency.

The fact that the constants in these two formulas are even decimal values makes them convenient relations to remember. It should be borne in mind, however, that they apply to an entire television system including spot attenuation. They are approximately true for the electrical cutoff frequency if the horizontal resolution is less than the vertical, but otherwise the spot attenuation may have more effect than the electrical cutoff.

The value of the vertical blanking factor does not enter these relations explicitly, though it is implicit in the figure of 280 for the vertical resolution. It does not appear because the equations are essentially descriptions of operations during the scanning of one line; that is, a cutoff frequency is derived which is high enough to transmit the desired degree of horizontal detail during the useful portion of the line period. On the other hand the vertical blanking must be considered to determine how many lines are used in reproducing the picture, and how many are lost in the field retrace.

The formula for the vertical resolution, as computed above on page 99. is

$$N_v = (1-B_v)N_s/\sqrt{2}$$

in which $B_v$ is the vertical blanking factor (0.07 or 0.10 in the standards).

On the basis of equal resolution, we substitute this expression for $N_v$ in place of $N_h$, and obtain the following consolidated formula for the cutoff frequency of the system:

$$f_c = \frac{Rf_p N_s^2(1-B_v)}{2\sqrt{2}\,(1-B_h)}$$

These relate 441 lines with a cutoff frequency of 2.8 megacycles according to present standards.

It should be noted that the cutoff frequency $f_c$, as defined, is not in general associated with a sharp change in transmission over a narrow frequency range. Too sharp a cutoff is not easy to obtain, nor is it desirable from the standpoint of performance. Selective circuits of moderate cost have gradual cutoff, and may be designed to give satisfactory characteristics. A sharp cutoff would introduce transient oscillations due to the amplitude and phase changes associated with the sharp cutoff. Recalling that the cutoff frequency $f_c$ is a characteristic of an entire television system, it may be said that all the major frequency components occur below this value, but minor components of higher frequencies can contribute appreciable detail and are therefore useful. The bandwidth represented by the cutoff frequency $f_c$ is therefore an indication of the frequency range employed most intensively.

The American television standards, as well as the standards adopted in other countries for high-definition transmission, give a good picture in the sense that non-technical persons viewing the received programs consider them to have adequate entertainment value. Certain technical data which account for this fact may be mentioned. In comparison with motion picture practice the aspect ratio of 4/3 is the same. As another point, the receiving-tube screen gives satisfactory results when viewed at the optimum distance of 5 or 6 times the picture height. At this distance, the width of reproduction of the narrow line is about two minutes of arc, which is not much greater than the limit of resolution of the eye for light conditions on a picture tube.

## REQUIREMENTS AT THE HIGHER VIDEO FREQUENCIES

The characteristics of a television system at the higher video frequencies, including both carrier-frequency and video-frequency operations, affect the sharpness of fine horizontal detail. If these higher-frequency characteristics are not satisfactory, spurious details may appear in the picture in the form of fine shadows and multiple images at vertical lines or edges. In this section the transmission requirements at the higher video frequencies are considered, after which the tolerance for irregularities in the amplitude and phase characteristics is stated.

Spot Compensation

In regard to the cutoff of the higher video frequencies, the essential features are the frequency at which this occurs and the sharpness of the cutoff. Signal components in this region are attenuated in various parts of the television system, including the camera tube, the electrical circuits of the transmitter, the receiver circuits, and the receiver picture tube. The camera and the transmitting apparatus are beyond the control of the receiver engineer; it appears likely that these parts of the system will be designed as a unit and they may include compensation for the camera spot. Such compensation has the effect of reducing the apparent width of the camera spot, and gives the higher-frequency signal components the greater values which they would have with a smaller spot.

At the receiver there is doubtful need for compensation, since the spot is small. This is a fortunate fact because increase of signal components is caused by receiver compensation and overloading is very likely to be encountered. The general nature of compensation at the receiver is a predistortion to prepare the signal for such distortion as will be caused by the spot in the picture tube. For this it is necessary to accentuate the higher video frequencies. But the picture tube is already, under the influence of low-frequency components, being modulated over the entire range from black to white. The result of the necessary rising frequency characteristic is therefore to produce picture signals at the higher frequencies which exceed the black and white limits. Such excursions beyond the black level, where the beam current of the picture tube is already cut off, will not be effective in the picture tube. The benefit is therefore limited to the lighter shades. In addition to this overloading, there are other practical difficulties which would be encountered in an effort to provide receiver compensation.

The transmission characteristic of the receiver should extend to the value of $f_c$, which is 2.8 megacycles, and preferably somewhat above, in a gradual cutoff. If the receiver has a higher cutoff than this, the horizontal resolution will slightly exceed the vertical, in case the station transmits these components. Such improvement in picture detail must be weighed against the increased cost of the extended receiver transmission characteristic. If the receiver cutoff is below 2.8 megacycles, there will be a proportional reduction of the horizontal resolution.

Sesqui-Sideband Requirement

The sesqui-sideband method of operation introduces a transmission requirement which is superimposed on the other requirements described, and which can be considered as relating to the higher video frequencies. This is the requirement described in the preceding chapter (Report 1837, pages 69 and 70) that the system have an attenuation of 6 decibels for the carrier relative to the transmission for the upper video frequencies of modulation of the full sideband. In other words, these upper video components must be accentuated by 6 decibels in comparison with the carrier. The division of this 6 decibels between the transmitter and receiver has not as yet been standardized.

In Figure 8, the upper diagram shows three transmission characteristics for the receiver, on the basis respectively of zero, 3 decibels, and 6 decibels as the receiver's share of the attenuation of the carrier. The ordinates and abscissas in Figure 8 are plotted on linear scales. At the left of the upper diagram an additional guard band of 0.25 megacycle is shown as an added protection against interference from the sound carrier of the next lower channel. In the case of more than one television station in a given city, there will probably be receiving locations where such an undesired adjacent-channel sound carrier is considerably stronger than the picture carrier of the desired station. At the right of this diagram, the curve is shown sloping down to a very small value of transmission for the sound carrier of the desired station. In the lower diagram of Figure 8, a representative transmission characteristic for only the video portion of the receiver is given.

Effects of Amplitude and Phase Distortion

Certain variations from the general criteria which have been set up are unavoidable. Before proceeding to the specification of tolerances of such variations, it is instructive to examine in a few examples the effects of amplitude and phase distortion. In Figure 9A, the solid curve (1) gives the equivalent transmission of the camera and receiver spots, including associated apparatus affecting the apparent size of the scanning spots, such as the camera lens, the eye, the grain size of screens, etc. If the electrical circuits of the system had perfect transmission characteristics, this curve would give the transmission characteristics of the complete system. Under these circumstances the narrow vertical line, which is used in preceding sections for the analysis of horizontal resolution would be reproduced with the width shown magnified in Figure 9D.

Figure 9B shows by the solid-line curve a sample phase characteristic for a network such as the electrical portion of a television system. The dashed straight line designated $b_0$ is drawn thru the origin with a suitable slope to be a close approximation to the solid curve. Such a straight line as $b_0$ represents a phase angle proportional to the frequency. Since, at higher frequencies, a given time

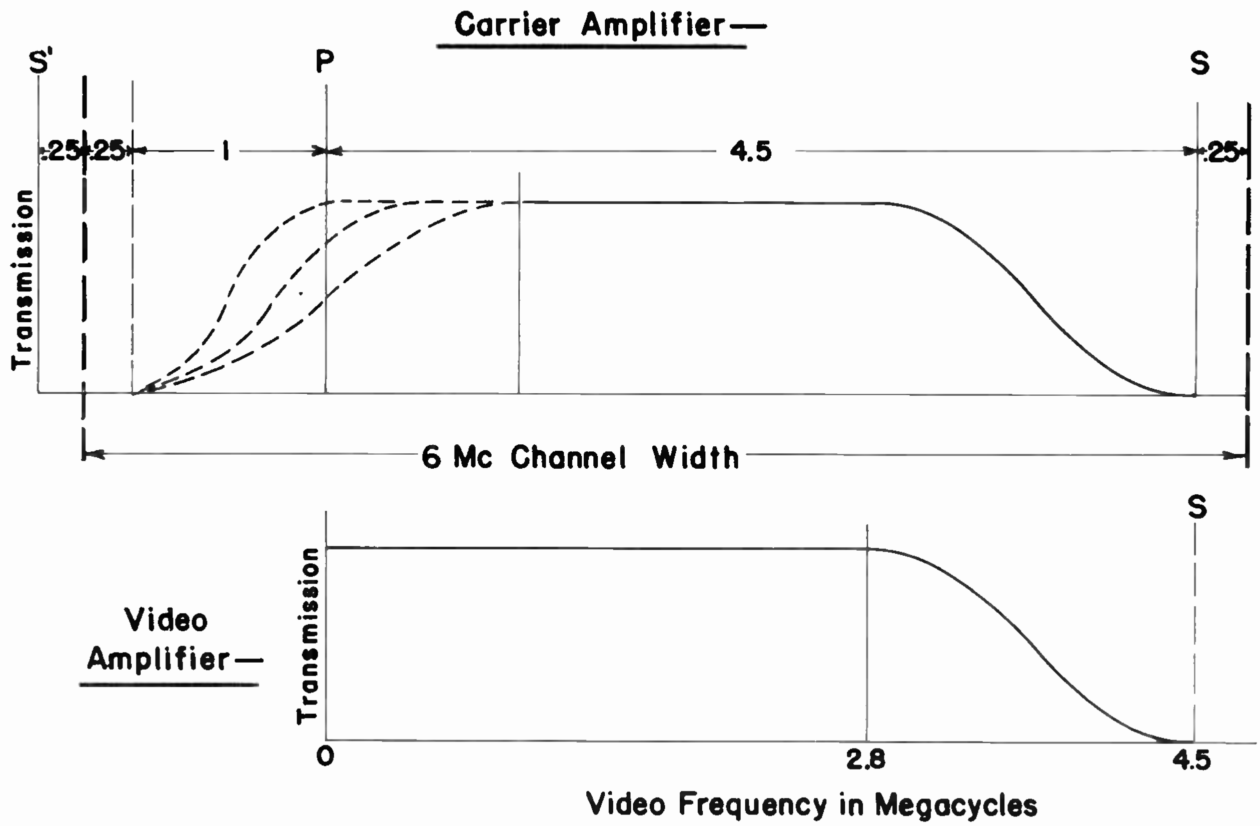


Fig. 8. Amplitude Characteristics of the Carrier-Frequency and Video-Frequency Amplifiers of the Receiver.

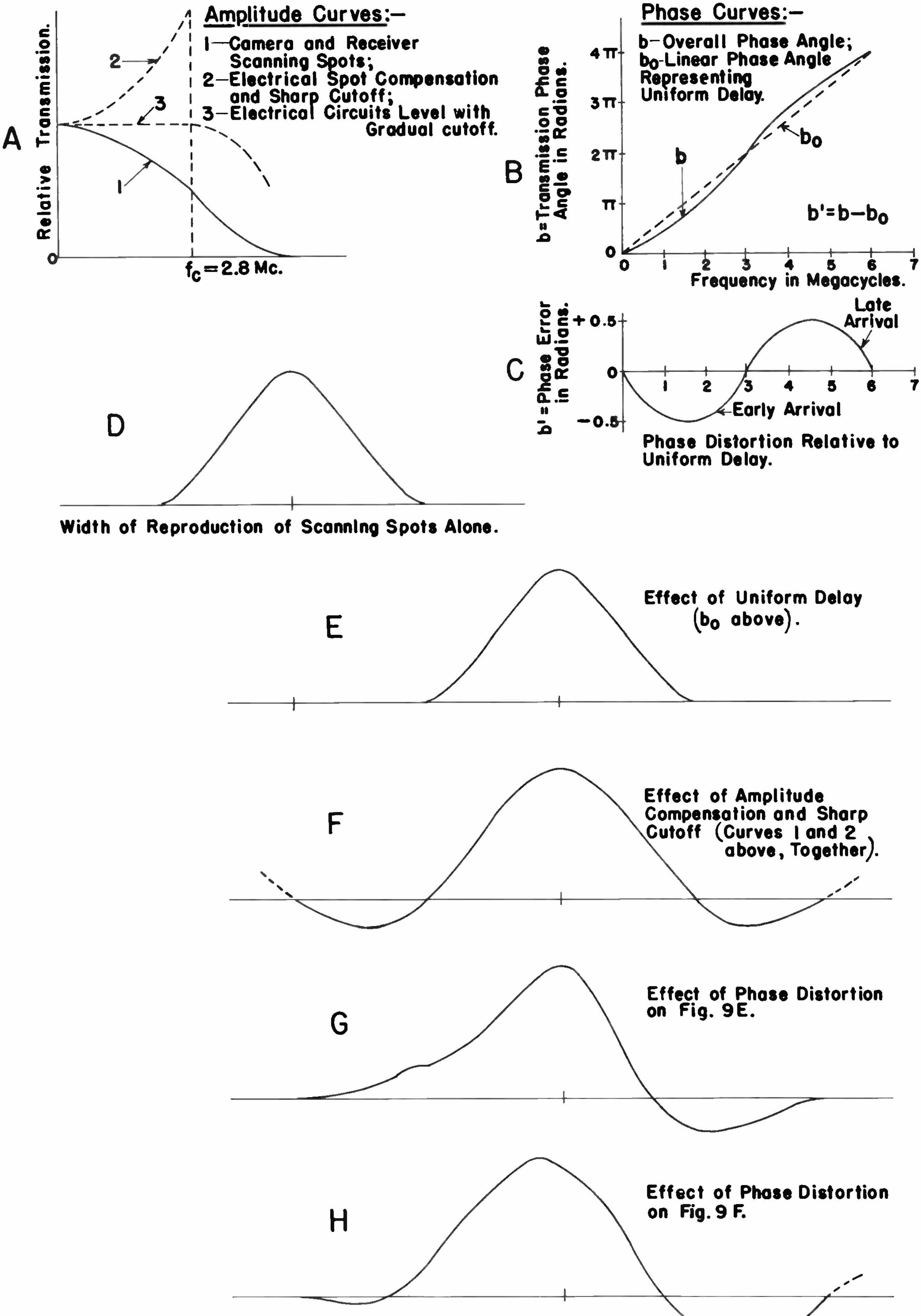


Fig. 9. Amplitude and Phase Effects in Reproduction of a Narrow Vertical Line.

of delay represents a proportionately increasing phase angle, such a straight line as $b_o$ indicates a constant time delay in the transmission of the components of various frequencies, and therefore represents a distortionless phase condition. It amounts to a very small displacement of the entire picture. Any other straight line thru the origin would also represent freedom from phase distortion, the time delay being greater for greater slope of the straight line. In Figure 9C, the phase variation, $b' = b - b_o$, is plotted for the various frequencies. This curve shows the angle in radians by which the components of various frequencies lead or lag the phase which they should have if they were transmitted with uniform delay corresponding to the straight line $b_o$.

If the electrical circuits passed all the frequency components with no distortion, with only the uniform delay of curve $b_o$ in Figure 9B, the signal pulse would be shifted in time as shown magnified in Figure 9E. This is not distortion, because it merely represents a slight displacement of the entire picture in the scanning process. Amplitude and phase correction can be used to secure nearly distortionless uniform delay.

Let us consider now that the electrical circuits of the television system have amplitude compensation for both spots up to the cutoff frequency $f_c$ and have a sharp cutoff at this frequency; the required electrical characteristic is shown as curve (2) of Figure 9A. This is more compensation than a system would be expected to have, and represents a condition of a sharp electrical peak. Such a peak introduces amplitude distortion, usually accompanied by phase distortion. It is instructive, however, to consider only the amplitude distortion, since phase distortion may be compensated to any desired degree by the use of appropriate networks. In Figure 9F, the width of reproduction of the narrow vertical line is shown for these conditions. The compensation for both spots makes the overall amplitude curve of the system flat to $f_c$, and the complete cutoff of the electrical channel beyond this point removes all higher frequencies. The negative excursions in Figure 9F, called overshoots, are caused by the sharp cutoff of the higher frequencies; the presence of the higher frequencies is required to avoid the overshoots.

The presence in the electrical system of the phase characteristic of curve b in Figure 9B, but with no amplitude distortion or compensation in the electrical system (curve (3) of Figure 9A giving its amplitude characteristic), causes the narrow vertical line to be reproduced with the transverse distortion shown in Figure 9G. The gradual leading edge of the reproduced width is caused by the earlier arrival of the low frequencies. The sharper trailing edge is caused by the later arrival of the higher frequencies. In the system of Figures 9B and 9C, the low frequencies arrive earlier than the high frequencies.

The presence of the amplitude correction characteristic of curve (2) of Figure 9A together with the phase characteristic of curve b of Figure 9B causes the narrow vertical line to be reproduced with the transverse distortion shown in Figure 9H. The smooth shape of the leading edge of the pulse is due to the opposing effects of phase and amplitude distortion. This is a point of practical interest, because transmission faults usually produce both kinds of distortion with the resultant small effect on the leading side of a reproduced line. The effects of both kinds of distortion are then additive on the trailing side.

The best characteristics, to obtain the width of reproduction shown in Figure 9E, are the combination of uniform amplitude in electrical circuits, such as curve (3) of Figure 9A, and uniform delay obtained by phase correction.

Example of Large Objects with Sharp Edges

In Figure 10 are shown pulses representing vertical objects in the picture, these objects having widths greater than the narrow line heretofore considered. In order to have a concrete case, the groups of pulses shown in Figures 10A and 10B may be considered to represent a signal for 6 and 2 vertical objects respectively in the picture. In this case, the fundamental frequency of the closely spaced narrow pulses is about 100 kilocycles. The widely spaced broad pulses are drawn with a period three times as great, and therefore have a fundamental frequency of about 33 kilocycles. In each case the pulses have a duration equal to 1/10 of the period.

Such pulses as shown in Figure 10, having a rectangular shape with sharp corners, give an infinite number of components of generally decreasing amplitude at higher frequencies, when analyzed by the Fourier series method. It is instructive to introduce a sharp cutoff at a definite frequency, and to observe the effect of the absence of the higher frequencies. In Figure 9F, such a condition is shown to cause overshoots in the reproduction of a narrow vertical line. In the present instance distortionless uniform transmission is assumed for frequencies up to 3 megacycles, with a sharp cutoff at that point. This provides for the 30th harmonic of the narrow pulses and for the 90th harmonic of the broad pulses. On adding together these components, there are obtained the curves of Figures 11A and 11B. These also show the overshoots and oscillations caused by the absence of higher frequencies.

The curves in Figure 11 show that the steepness of the wave front is the same for the two sets of pulses. This leads to the interesting conclusion that the sharpness of reproduction of such a transition edge depends on the cutoff frequency and is independent of the width of the pulse.

The oscillations in Figure 11 have a maximum overshoot which is 9 percent of the pulse height. This is a constant of fundamental significance for any sharp cutoff. For a gradual cutoff, the amplitude of the oscillations is less. In practical cases, the cutoff is necessarily more or less gradual, so that the amplitude of the overshoots is less than 9 percent. The presence of such overshoots in a television picture can sometimes be seen in the dark background beside a light object.

In practical cases, transmission irregularities generally produce both amplitude and phase distortion. The transverse reproduction of a narrow vertical line under these circumstances is shown above in Figure 9H. In Figure 12 the reproduction of an object of appreciable width is shown under somewhat similar conditions.

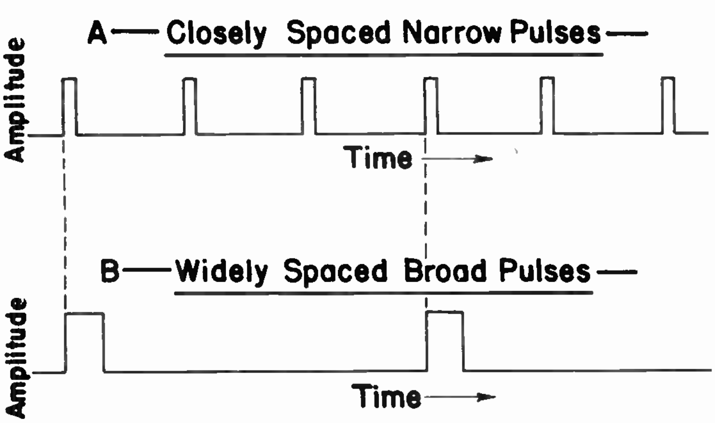


Fig. 10. Recurrent Pulses Representing Vertical Objects in the Picture.

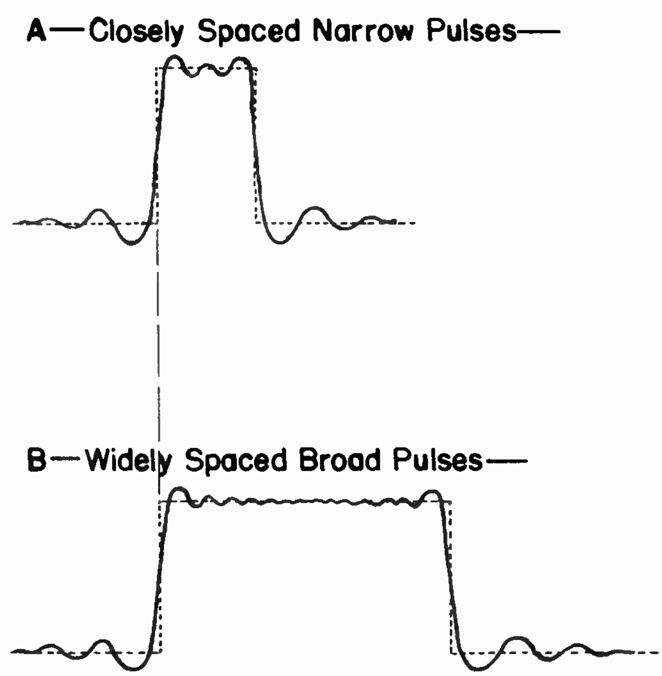


Fig. 11. The Effect of Cutting Off the Higher-Frequency Components of the Pulses of Fig. 10.

Figure 12 is computed for a pulse repeating with a period of ten times its width. Components above the twentieth harmonic were cut off. That is, the highest-frequency component included has a period one-half the width of the pulse. It is computed for slight uniform delay and a superimposed phase distortion of maximum about one radian, leading at the lower frequencies and lagging at the higher frequencies. Such a sharp cutoff is an extreme condition not found in practice, but this amount of phase distortion may occur in a receiver. The combined effect of sharp cutoff and this phase distortion gives little distortion of the leading edge but a severe transient oscillation (multiple images) on the trailing edge.

Tolerances of Amplitude and Phase Distortion

A careful theoretical study of small distortions resulting from amplitude and phase irregularities has disclosed that the relative intensity of spurious lines at the edge of an object, caused by amplitude distortion alone, is the same as that caused by phase distortion alone, if the amplitude distortion stated in napiers equals the phase distortion stated in radians. (One napier = 8.7 decibels.) In the present instance, the usefulness of the napier and the radian lies in the quantitative similarity of the effects of the two types of distortion if the irregularities are expressed in these units.

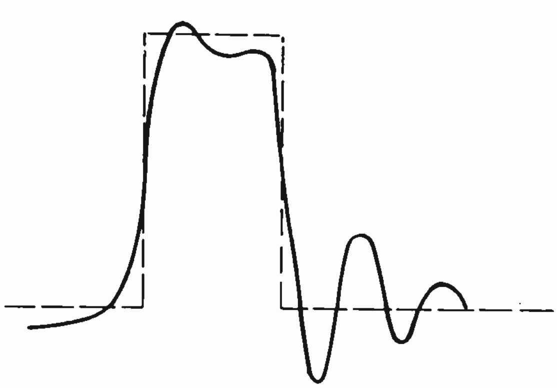

Fig. 12. The Effect of Both Sharp Cutoff and Phase Distortion on a Fairly Narrow Pulse.

According to this rule, the distortion component due to any video frequency being a fraction of one napier greater or less than it should be, is objectionable to the same degree as the distortion at this frequency which would be caused by the phase leading or lagging from its proper position by the same fraction of one radian. In case both amplitude and phase distortion are present at a given frequency, their combined effect can be evaluated by taking the quadratic sum (the vector sum at right angles). In Figure 13, the vector OV represents the proper amplitude and phase of a component at any frequency for distortionless reproduction. The effect of amplitude distortion is to lengthen or to shorten this vector, so that it will be represented by $OA_1$ or $OA_2$. The incremental vector $VA_1$ or $VA_2$ represents the amplitude distortion component. The effect of phase distortion is also to add an incremental vector, but in this case it is (if small) at right angles to the desired vector. This distortion component is shown by vectors $OP_1$ and $OP_2$ in the figure. Should distortion of both types be present, the incremental vectors add vectorially.

The study from which these relations are taken led also to a theoretical conclusion as to tolerances. For high-grade reproduction, the vector sum of napiers and radians, expressing the amplitude and phase distortions, should not exceed about 0.1 at any frequency of the video range, except at the higher frequencies near cutoff. In Figure 13, the dotted-line circle represents this tolerance. Generally the peaks of amplitude distortion occur at different frequencies from the peaks of phase distortion; for this reason the probable

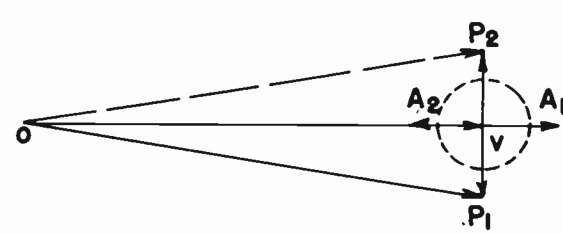


Fig. 13. Amplitude and Phase Distortion Components Superimposed on a Signal Component.

tolerance is a maximum of about 0.1 for either type of distortion, increasing to about 0.2 at cutoff. In round numbers, this may be stated at ± 1 decibel in amplitude and ± 6 degrees in phase. Each of these quantities is measured relative to a reference line giving the desired characteristics (proper cutoff of amplitude or linear phase), this line being superimposed to best approximate the actual curve. In the case of phase distortion, the reference line is the best straight line thru the origin, such as the line $b_o$ in Figure 9B.

Much greater distortion than the amount permitted by this criterion is often encountered, especially if no phase correcting networks are used. It is merely a statement of what theoretically appears permissible for excellent reproduction thru the entire television system. Its verification waits on further experience, especially with phase correction.

## Application of These Principles to the Sections of the Receiver

The foregoing discussion of high-frequency transmission characteristics and tolerances is in terms of the video frequency, including the effect of carrier-frequency circuits on the video modulation. From a practical standpoint, the various portions of the receiver must be considered and this is done briefly in the following paragraphs.

The antenna and its transmission line, taken with the wave pattern in the transmission medium, may introduce serious amplitude and phase distortion. Such effects are produced by nearby reflections of the waves and by reflections due to mismatching or departure from critical damping in the antenna system. From a design standpoint, the solution lies in the matching of impedances at the various points, or in the provision of critical damping. Attenuation in the transmission line reduces some of these effects.

As for the antenna design, it should be free from frequency selectivity over its operating range. This property is obtained in highly damped small antennas, but only in certain types of large antennas (large as compared with the operating wavelengths). Also this requirement must be considered in the use of reflectors or other devices for securing directive characteristics.

In the installation of a television receiver a certain amount of experimentation may be essential even with a well designed antenna kit. It is necessary to locate the antenna at a point where sufficient signal from one or more stations is received without objectionable echoes and without objectionable noise. There is a possibility of serious interference from automobile ignition systems.

The radio-frequency amplification of the receiver should not be too selective, although it may be called on for the reduction of image response and the prevention of cross-modulation. Its selectivity in the desired channel is considered as modifying the band-pass characteristics of the intermediate-frequency amplifier.

The intermediate-frequency amplifier of the receiver is the main source of selectivity. It is desirable that it have level amplification and linear phase characteristics within the tolerances given above. However, if some of the carrier attenuation necessary in the sesqui-sideband method of operation is to be furnished in the receiver, some or all of the receiver's share may be located in the intermediate-frequency amplifier. In this case it will probably be sufficient for the phase to be linear over only the fully used sideband. There should be enough selectivity in the intermediate-frequency amplifier against the sound carrier of the same station to avoid sound detection in the picture detector, which would produce interference in the picture by the audio frequencies appearing as low video-frequency components. It is considered that 15 to 25 decibels attenuation relative to the picture carrier is sufficient.

In connection with the video amplifier, the above discussion of transmission characteristics is directly applicable. If some carrier attenuation in connection with the sesqui-sideband method is to be provided in the receiver, some of this may be located in the video amplifier in the form of reinforcement of the higher video frequencies. Should the provision of phase-correcting networks be made, it is better to locate them in the video amplifier, where such correction is obtained more easily than in the carrier amplifiers. Some selectivity against the sound carrier of the same station should be provided in the video amplifier to prevent the formation of a very fine line by the sound carrier acting as a high-frequency picture component. For such a high video frequency, namely 4.5 megacycles corresponding to the beat note with the sound carrier, there is appreciable attenuation in the receiver spot; adding this to the electrical attenuation should give a total overall figure of the order of 40 decibels. About 15 to 20 decibels at 4.5 megacycles is desirable in the video-frequency amplifier.

## REQUIREMENTS AT THE LOWER VIDEO FREQUENCIES

The lower video frequencies correspond in carrier amplifiers to side frequencies located so close to the carrier frequency that there is little likelihood of impairment of the transmission. The problem of securing satisfactory transmission characteristics at the lower video frequencies therefore exists chiefly in video-frequency couplings.

Low-frequency video components, including the direct-current component, may be transmitted thru a video amplifier by the use of direct coupling, or may be lost and recovered by the use of the principle of reinsertion as described in the third chapter (Report 1822, pages 53-55) and in the fourth chapter (Report 1837, pages 70-73). The preservation of the low video frequencies in addition to the direct-current component by means of reinsertion is possible because the reinserted direct-current component can vary with time in the manner necessary to reinsert these low frequencies. The grid condenser and leak constituting the alternating-current coupling associated with the reinserter must have a sufficient time constant to hold over the line period (76 microseconds) since the reinsertion is actuated by the line synchronizing pulses occurring at this periodicity. It is preferable to employ a time constant not greater than required from this standpoint.

In connection with the reinsertion problem, it is of interest to consider the action of an alternating-current coupling without reference to its association with a reinserter. The effect of inadequate low-frequency transmission in such a case is to cause a sustained applied pulse to decay steadily in amplitude with the lapse of time. In Figure 14, the alternating-current coupling consisting of condenser C and resistance R is shown, having the transmission characteristic indicated at the upper right. In the lower portion of this figure, it is shown how a rectangular pulse of duration D fails to maintain the height of its leading edge, even if the duration is much less than the time constant. During the pulse, the amplitude decays by the fraction A. At the termination of the pulse, the lagging edge overshoots by the same amount, as shown. Knowing the time constant of the circuit, the amount of the overshoot may be determined graphically or by means of a simple computation. For approximate graphical determination, proceed as follows: (1) locate a point on the time axis beyond the leading edge of the pulse by the amount of the time constant $T = CR$; (2) draw a straight line from this point to the leading crest of the pulse; and (3) note where this line crosses the lagging edge of the pulse, thus determining the amount of discharge during the pulse, which is the amount of the overshoot. The same result may be obtained from the formula $A = D/T$, where A is the fraction of overshoot, T is the time constant, and D is the duration of the pulse. Stated in words, the relative overshoot is equal to the ratio of the pulse duration to the time constant.

If C and R are known, the time constant T is merely the product of these two quantities. In case these are not known but there is available a transmission curve for the stage at low frequencies, the value of the time constant may be obtained as $T = 1/(2\pi f_c)$, where $f_c$ is the frequency at which the transmission connection with the sesqui-sideband method is to be provided in the receiver, some of this may be located in the video amplifier in the form of reinforcement of the higher video frequencies. Should the provision of phase-correcting networks be made, it is better to locate them in the video amplifier, where such correction is obtained more easily than in the carrier amplifiers. Some selectivity against the sound carrier of the same station should be provided in the video amplifier to prevent the formation of a very fine line by the sound carrier acting as a high-frequency picture component. For such a high video frequency, namely 4.5 megacycles corresponding to the beat note with the sound carrier, there is appreciable attenuation in the receiver spot; adding this to the electrical attenuation should give a total overall figure of the order of 40 decibels. About 15 to 20 decibels at 4.5 megacycles is desirable in the video-frequency amplifier.

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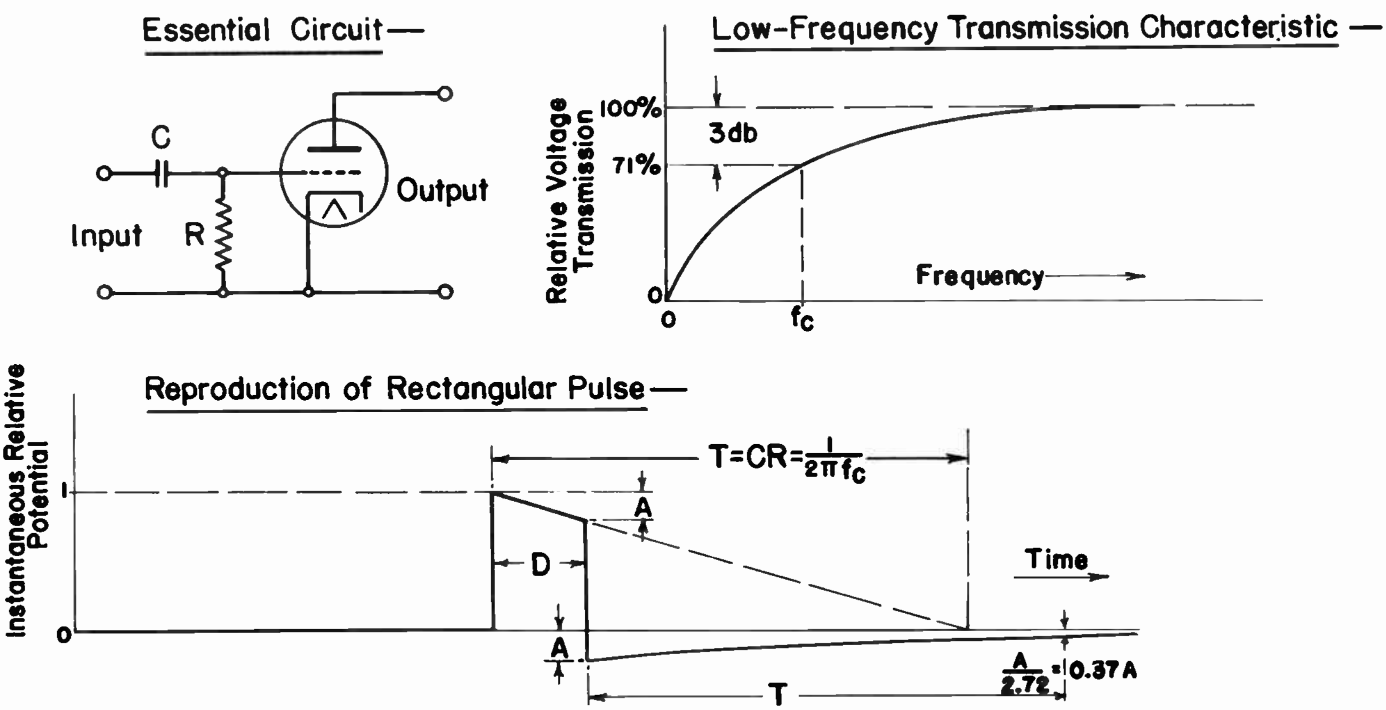


Fig. 14. Distortion of Pulse Caused Mainly by Phase Shift of Low-Freouency Components.

curve is three decibels down. This relation may be stated in words to the effect that the time constant of one stage is the time of one radian at the frequency $f_c$.

The discharge of the overshoot after the end of the pulse is a simple exponential, so it decays to 0.37 A after a lapse of time equal to the time constant.

For two or more stages, the time constants may be combined to obtain the resultant overall time constant by means of the relation $1/T = 1/T_1 + 1/T_2 +$ etc. This is the same as saying that the total rate of discharge is equal to the sum of the rates in the respective stages.

This distortion of the pulse is caused mainly by the phase shift of the lower-frequency components. Their amplitude reduction plays a secondary part.

In practice, the time constant of an alternating-current coupling at a reinserter, in case there is only one such circuit in the receiver, is usually given a value between 20 and 200 times the line period, that is, between 0.0015 and 0.015 second. If several grid-condenser couplings are used ahead of the final reinserter, their total discharging rate determines the effective time constant according to the above relation. It is immaterial how many of the preceding stages have reinsertion. The time constant at the final reinserter should not exceed the average among the stages, because it is desired to minimize the charging current of the condenser from the rectifier of the reinserter.

## CONCLUSION

The required video-frequency characteristics of the television system are closely related to the resolving power permitted by the system standards and to the scanning spots and their environment. A close compromise between selectivity and resolving power is required in the receiver, hence the careful attention to the factors determining the frequency band requirements.

The American standards are based on a video-frequency band within 4.5 megacycles, the separation between picture and sound carriers. They specify 441-line scanning, 30 frames per second, and other factors, which together correspond to a video cutoff frequency of 2.8 megacycles for the system. The remainder of the 4.5-megacycle band may be used to permit a gradual cutoff, which has advantages, or to secure horizontal resolution exceeding the vertical resolution. The vertical resolution is limited to 280 lines by the number of scanning lines and associated factors.

The electrical frequency characteristics are closely related with the attenuation at higher frequencies by the scanning spots. These two sources of attenuation are supplementary in the system as a whole.

Some general suggestions are given as to the required properties of the receiver components, related to the reproduction of all signal components which contribute to the light and shade in the picture.

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