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A STUDY OF THE OPERATING CHARACTERISTICS OF THE RATIO DETECTOR AND ITS PLACE IN RADIO HISTORY

By

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THE RADIO CLUB OF AMERICA

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Many years ago, beyond the memory of most of those who will read this paper, there occurred a remarkable incident in the technical history of radio. It occurred during the year 1914, shortly after the invention of the regenerative circuit.

That part of this assembly whose experience in radio dates back to those early days will recall the revolution that the regenerative circuit brought about in the communication art, as that art was then practiced with spark transmitters and crystal detectors. They will also recognize the incident which I am going to identify presently.

For that part of this assembly whose experience in radio does not go back to those early days, some historical background will help in the understanding of that incident.

To put yourself in the atmosphere of those days you must perform a difficult feat of mental gymnastics; that of jumping backward into the radio world of over thirty-five years ago, a world where telephony[1] and loudspeakers were unknown, where communication was confined to the American and Continental Morse codes as manifested in headphone whispers, and where the strength of the signal heard was completely dependent upon the amount of energy that could be captured from the passing electromagnetic wave by the receiving antenna. That energy, and that alone, was all that was available to move the diaphragm of the receiving telephones. In order to hear weak signals it was necessary to use painfully tight headphones, frequently with the equally uncomfortable necessity of holding one's breath for prolonged intervals.

The continuous wave now in universal use had barely entered the picture, and its merit as compared to the almost universally used spark system was the subject of a lively and then unresolved controversy. In 1912, it is safe to say, 99.9% of radio communication was carried on with spark transmitters and rectifying (crystal and Fleming valve[2]) or magnetic detectors. Not a tenth of one percent of the stations made use of the deForest audion (triode), and those that did use the audion were mostly stations of the amateurs.

Static interference was combatted by arranging that the number of sparks per second at the transmitter were regularly spaced and lay within the musical range, so that the note heard in the phones had a distinguishing musical characteristic. Controversy existed over whether the high pitched whistle of the one thousand spark per second transmitter was superior to the deeper chord-like tone of one sparking at the rate of only three to four hundred times a second.

About a dozen continuous wave stations (arc and alternator) were operating with limited success in the United States and Europe, for the "undamped" wave system was severely handicapped by lack of a satisfactory means of reception. The receiver most generally used was a curious device known as the "tikker" which, while comparable to or perhaps slightly better in sensitivity than the crystal, suffered from the overwhelming handicap that it produced an unclear, non-musical signal impossible to read through heavy static.[3] Although the important virtues of the rectifying detector-heterodyne had been discovered by Lee and Hogan, the difficulty of providing a heterodyning source, quiet and stable enough for reception of what were then considered weak signals, had held up the introduction of the heterodyne into commercial radio.

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1 Fessenden had demonstrated radio telephone transmission in the Fall of 1906, but as the modulation problem had not been solved, radio telephony as a practical entity was non-existent.

2 Diode.

3 In 1912 two commercial transoceanic circuits were in operation - the Clifden, Ireland - Glace Bay, Nova Scotia circuit (spark system) operated by the Marconi Company, and the San Francisco-Honolulu circuit (Poulsen arc system) operated by the Federal Telegraph Company. The reported power for the spark circuit was 125 kilowatts, and for the arc 30-60 kilowatts. Antennas hundreds of feet in height were used for reception on both systems. The receiving antennas on the Clifden - Glace Bay circuit were several thousand feet long to insure additional and directive pick-up properties.

For those who never had the experience of living in the strange world I have just described - where amplifiers of audio frequencies were unknown, where the amplification of radio frequencies was undreamed of, and where the generation of even moderate amounts of continuous wave power at frequencies in excess of 100 kilocycles was impossible - it will be difficult indeed to imagine the conditions under which the men in the art worked in those days.

And it will be still more difficult for them to grasp the incredible fact that the three element vacuum tube (audion), now in use in every transmitter and receiver in the world, had been invented six years before the period I have just described and yet lay idle and neglected and almost forgotten.

If you will examine the pages of seven leading text books published prior to 1914 you will find that out of a total of three thousand pages for the seven volumes <u>less than one page</u> of material for the lot is devoted to the audion detector.[4] Some of the authors make no reference to it at all and, where reference is made, the audion is described solely as a <u>detector</u>, slightly more sensitive than the Fleming valve.

The reason for this almost unbelievable situation lay in the following set of facts. The inventor of the audion had never understood the operation of his device. Nor did anyone else in radio understand it, for the idea that there might be such a thing as an electron discharge had not penetrated into the art. As a result, some weird theories of the operation of the audion were advanced. In the inventor's version, gaseous ions were supposed to carry the current across the gap from filament to plate. The action of the audion was casually disposed of with the statement that the gaseous carriers were repelled upon the imposition of a negative charge on the grid, while the imposition of a positive charge enabled the grid to hold the ions in its vicinity, so that in either event a diminution of the plate current resulted.[5] This learned pronouncement had the effect of obscuring the potentialities of the audion as anything other than a detector of damped wave trains. Too long was the theory blindly accepted, without anyone taking the trouble to make a serious investigation to verify or disprove it.[6]

With the art in the state that I have described, there came in the Fall of 1912 the invention of the regenerative circuit. That circuit not only amplified the incoming radio frequency currents and increased the sensitivity hundreds or thousands of times, but also by reason of its ability to generate continuous oscillations with a stability and uniformity theretofore unknown, brought heterodyne reception to commercial perfection and ushered in a new era in long distance communication. In 1913 it had become possible in New York City, with an antenna of amateur dimensions, to receive spark and CW signals from European stations, as well as continuous wave signals from the West Coast of the United States and the Hawaiian Islands, and to demonstrate regularly such reception.[7]

So firmly entrenched was the "knowledge" in the art, however, that such things could not be, that most of those who listened to the signals were

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4 (Armstrong, letter to the New York Herald-Tribune, Dec. 21, 1930):
See: Kennelly's "Wireless Telegraphy and Telephony" 1909; Pierce's "Principles of Wireless Telegraphy" 1910; Fleming's "Principles of Electric Wave Telegraphy and Telephony" 1910; Zenneck's "Lehrbuck der Drahtlosen Telegraphie" 1912; Reins' "Radiotelegraphisches Praktikum" 1912; Erskine-Murray's "Handbook of Wireless Telegraphy" 1913; Edelman's "Experimental Wireless Stations" 1914.

5 Proceedings I.R.E., March 1914, page 20, there appears the following statement by Lee DeForest:
"If the charge thus impressed upon the grid be negative a repulsion or scattering of the negatively charged carriers emanating from the filament occurs. If the impressed charge be positive, then these carriers may be attracted to the grid and discharged there, or delayed in the neighborhood. In either case, therefore, a diminution in the number of ions reaching the plate results, and we observe a diminution in the deflection of a sensitive milliammeter or galvanometer in the "B" circuit when a prolonged series of impulses is delivered to the grid. ....
"An insight into what forces are at work in the audion is afforded by experiments with a special circuit .... This experiment seems to show that in the normal operation of the Audion the imposition of a charge, negative or positive, upon the grid acts either to repel from its neighborhood the ionic carriers or to hold them idle there, thus in either case increasing the effective resistance in the filament-to-plate path."
Even after the operation of the audion had been fully explained by me in the Electrical World, December 12, 1914 in an article entitled "Operating Features of the Audion", and in a paper presented before the Institute of Radio Engineers, March 1915, the theory given in these articles was challenged by the inventor of the audion in the following language:
"I have frequently proven that a positive as well as a negative charge will reduce the plate current." (Proceedings I.R.E., Sept. 1915, page 239).

6 The single exception prior to the Summer of 1912 was Fritz Lowenstein, who made use of the audion in the Spring of that year as an amplifier of telephone currents. U.S. Patent 1,231,764.

7 Ability to read the signals depended upon the level of the static at the time. Complete messages could usually be copied.

incredulous of their origin and those to whom the reports of such reception came by word of mouth greeted them with the same disbelief[8] that was to be accorded the announcement over twenty years later that an operative noise eliminator had at last been devised. Checks of copied messages with the stations originating them were required for what we might term today in our modern jargon "proof of performance", before the "reports" of transoceanic reception passed from the stage of disbelief openly expressed on the part of the leaders in the communication field to the stage where such reception became a commonplace in the art.

It was then that the incident I am about to discuss took place. After the regenerative circuit had been demonstrated to the leading communication companies and had passed its "proof of performance" test, there was announced the discovery of a device called the "ultraudion"[9]. It was claimed to perform the same functions as those of the regenerative circuit. However, it was held to perform them in a new way, not involving the regenerative principle. As a matter of fact, superficially, the circuits did look different.

The ultraudion circuit configuration was given as follows:

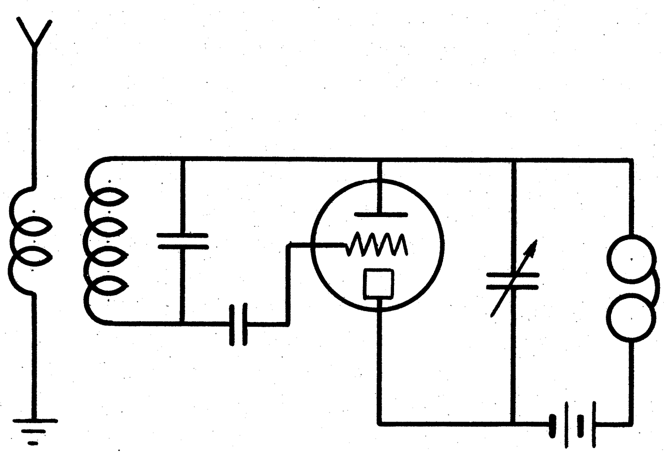

Fig. 1

In the words of its inventor, its manner of operation was described as follows:

"The ultraudion circuit is not and cannot be a regenerative circuit. There is only one oscillating circuit. This circuit is such that a sudden change of potential impressed on the plate produces in turn a change in the potential impressed on the grid of such a character as to produce in its turn an opposite change of value of potential on the plate, etc. Thus the to-and-fro action is reciprocal and self-sustaining."[10]

With our present knowledge of vacuum tube circuits it is difficult to believe that even a part of the radio art could be long misled by this fantastic explanation. Yet so it was, and not until the circuit was analyzed in the light of factual understanding and was redrawn so that the coupling between the plate and grid circuits, as well as the part played by the grid-filament capacitances became manifest, was the operation of the ultraaudion set forth in its true light.[11] The operation of the circuit as redrawn below is now, of course, accepted and understood by everyone.

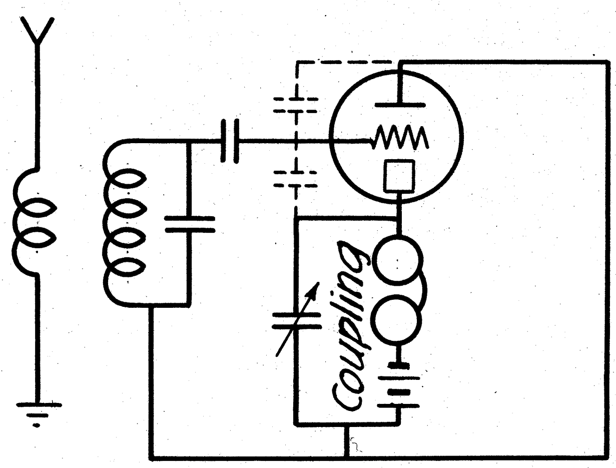

Fig. 2

I have related to you three instances of "Ripleyian" episodes in the past history of radio that a great many of you never heard about. Those of you who did not live through those early days may find it difficult to believe that the audion could have kicked around the art for six years without anyone, including the inventor, unlocking its secrets. You may likewise find it hard to visualize how only one page, out of three thousand

8 See Appendix Two for an account of the response of the chief engineer of the world's greatest communication company - the American Telephone & Telegraph Company - when informed of the reception of signals from Honolulu at the Marcellus Hartley Research Laboratory at Columbia University by Professor Michael I. Pupin, then head of the Department of Electrical Engineering at the University.

9 Electrical World, Feb. 20, 1914.

10 Proceedings I.R.E., June 1916, page 266; Lee DeForest.

11 Proceedings I.R.E., June 1916, Armstrong, pages 264, 265 and 266.
Proceedings I.R.E., April 1918, Hazeltine, page 87.
The idea of tube capacitance did not exist at the time. This may seem strange today, where interelectrode capacitances of vacuum tubes are taken into account as a matter of everyday design and where every college student studying communications knows all about them. However, in 1914 the idea that two little pieces of metal inside of a glass bulb could have capacitative properties in an amount that would have any effect on the operation of a radio circuit never occurred to anyone.

in the leading radio textbooks, was devoted to the audion, or that anyone could have failed to perceive the quite obvious coupling between the input and output circuits of the ultraudion. But these things actually happened, and you can read about them in the literature. They were determinative of significant events which followed in the course of radio history. They are, in fact, basic radio history itself, and the course of events which they brought in their wake are worthy of most careful study.

Now with these reminiscences of the ancient days of radio as a background for perspective, I want to introduce the subject of my talk this evening, with the statement that we have a modern counterpart of the ultraudion episode in the debut of what has been christened the "ratio detector".

As you all know, thirteen years ago I showed the art how to do something which was then considered impossible - how to eliminate noise. Values of noise reduction of 1000 to 1 in energy, as compared with the standard system of communication, were obtained, and I do not need to tell you that these figures were received with the same incredulity that greeted the reports of the results obtained with the regenerative circuit twenty years before.

Now, as with the regenerative circuit, the proof of performance tests have been passed and the facts of "FM" have become accepted as a part of our daily life. As with most "impossible" problems, the solution was achieved by a new approach. The discovery was described and the principles involved were presented in a paper delivered before the Institute of Radio Engineers in November 1935, and the following month before the Radio Club of America, and, of course, they are now well understood throughout the whole world.

For good reason the history of the application of FM to public use was quite unlike the history of the regenerative circuit. The regenerative circuit could be put into operation at once at the receiving end of all long distance communication circuits, with immediate improvement to the service and with relatively little expense. No change was required at the transmitter. Thus, as soon as its principle became known, it was widely installed in all transoceanic and naval communication circuits.

In the case of FM, on the other hand, new transmitters as well as new receivers were needed. A substantial financial outlay had to be undertaken. As in any new and significant departure from convention, forces of the kind attributable to men rather than to Nature had to be overcome. The value of the system was at first appreciated by only a relatively small number of individuals.[12]

General realization of the commercial value of FM was delayed for many years. But when its commercial value became apparent to everyone, history repeated itself and the modern counterpart of the ultraudion appeared on the scene in the form of the ratio detector. Let us now examine this seemingly technical innovation.

The "ratio detector" has been described in a paper presented before the Institute of Radio Engineers, and also in a bulletin issued by the RCA License Laboratory, wherein the statement was made that limiting was unnecessary and that amplitude modulations need not be removed in the receiver because of the "insensitiveness" of the device to such changes in amplitude. In that manner the representation was made to the industry that the ratio detector was something quite different in principle from the system that I had originated, in which amplitude variations are removed in order to suppress noise. As the paper before the Institute appears to have been withdrawn from publication, there has not been the usual opportunity for open, critical discussion of the mode of operation with all the serviceable clarification that such debate ordinarily engenders.

The ratio detector circuit as it was first published[13] was drawn as follows:

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[12] The basic noise suppression patent, issued December 26, 1933, explained how improvements in noise ratio of 100 to 1 or greater were to be obtained. Possibly because of the complexity of the subject, and also because a claim of 100 to 1 noise reduction was then considered too preposterous to be credited, no one - with the exception of those to whom the apparatus was demonstrated - paid the slightest attention to the patent.
At the June 1936 hearing of the Federal Communications Commission, six months after the presentation of my paper before the Institute of Radio Engineers, only two persons urged provision of space in the spectrum for FM broadcasting - Paul deMars, Technical Advisor of the Yankee Network, and the writer.
Leading text books published during the next several years repeated the statements that had been current for a decade or more, that Frequency Modulation was not a satisfactory method of modulation. See, for instance, Radio Engineering by Terman (1937) and Communications Engineering by Everett (1937).

[13] Fig. 2 of Bulletin No. 645 issued by the RCA License Laboratory entitled "Ratio Detector for F.M. Receivers."

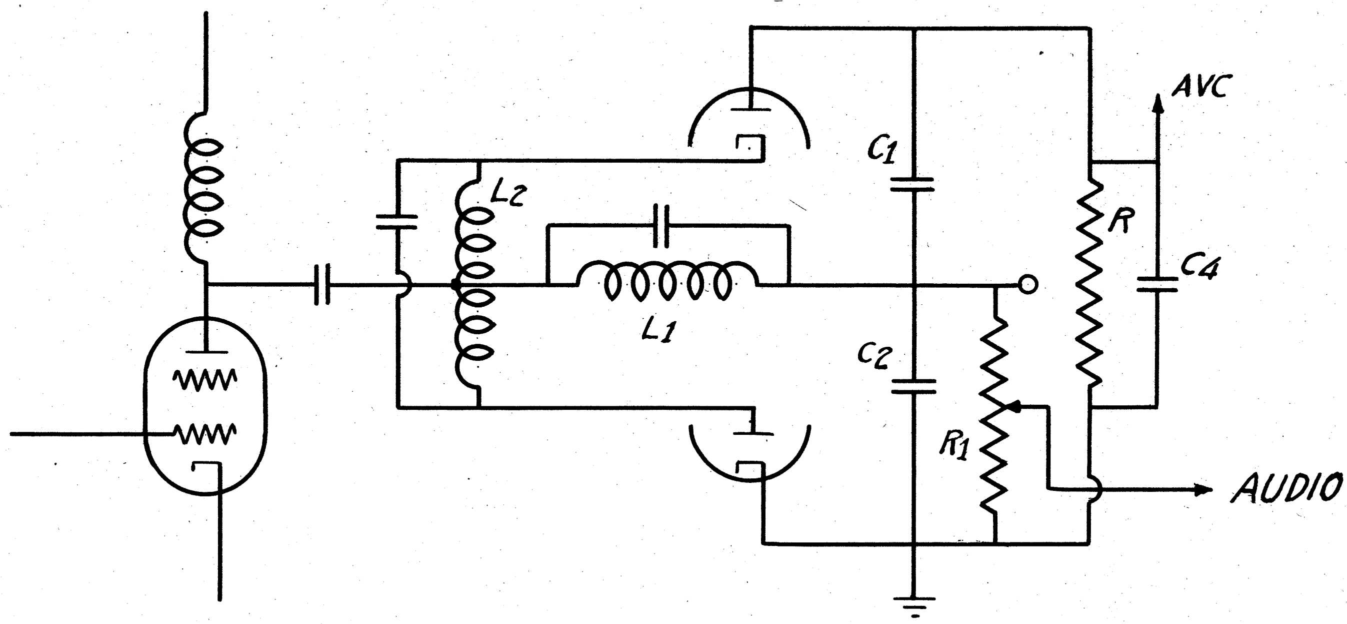


Fig. 3

In the particular form in which this circuit was drawn, any semblance to previous well known circuits was not apparent. The method of drawing the circuit, coupled with the fact that the explanation of the circuit's operation was, to say the least, obscure and unconventional, left one with the impression that an aura of mystery hung over this seemingly unfamiliar device.

Let us now redraw this curcuit, rearranging the elements in a more familiar manner, but preserving exactly the same electrical connections. This technique, as you have already seen, when it was applied to the ultraudion, removed the obscurity theretofore surrounding the behavior of the device. In the same way, rearrangement of the elements of the ratio detector will clarify the electrical operations of this circuit. Figure 4, which illustrates a rearrangement of the elements of Figure 3, is the same circuit as that shown in that figure, but as now drawn it begins to show a considerable resemblance to an ordinary two-path balanced discriminator circuit.

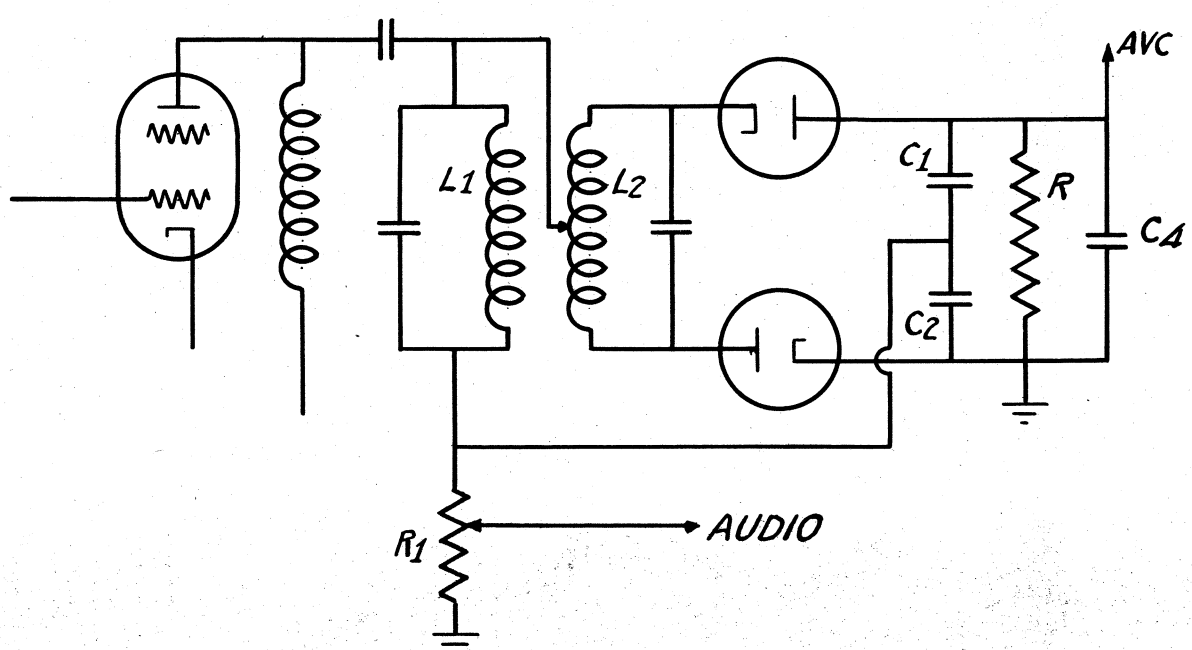


Fig. 4

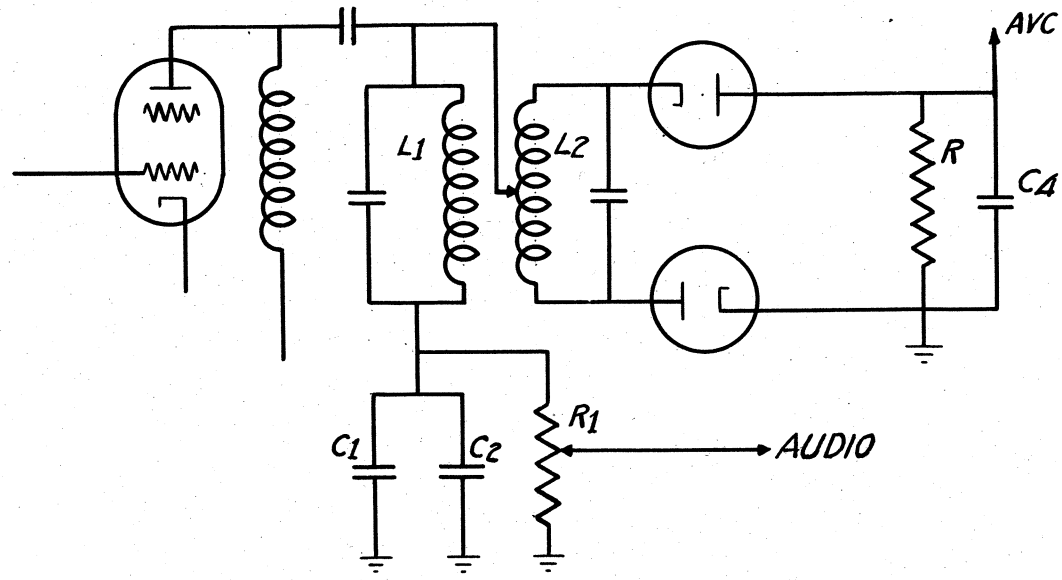


Fig. 5

Let us now take another step in the redrawing of the arrangement shown in Figure 4 without in any way changing the circuit, but merely rearranging the elements on the paper in a manner better adapted to portray the electrical characteristics of the circuit.[14] (See Figure 5)

Finally, let us redraw it as shown in Figure 6, merging the condensers C_1 and C_2 into a single unit, since it is now obvious these condensers are in parallel, and replacing the biasing elements RC_4 with biasing batteries B_1 and B_2, which, as the RCA Bulletin states, is the equivalent of the biasing combination RC_4.

Having clarified the original ratio detector circuit of Figure 3 by redrawing it in step by step fashion, it is now easy to look backward

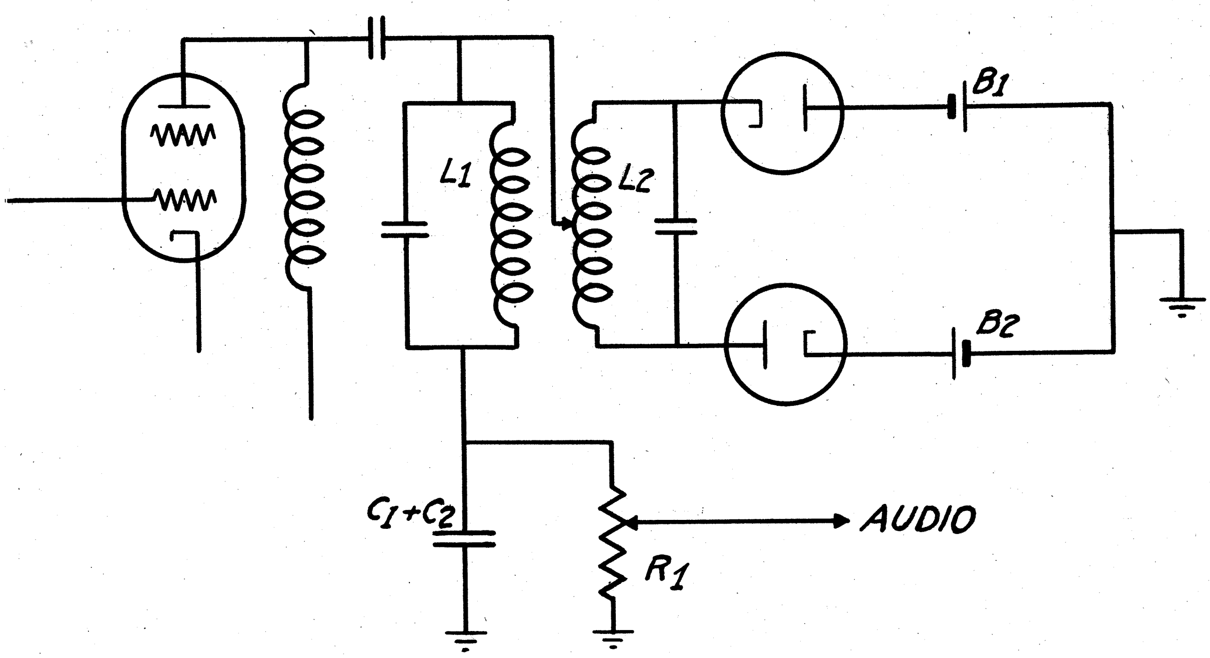


Fig. 6

14 (Neglecting, of course, the niceties of RF bypassing close to the diode elements.)

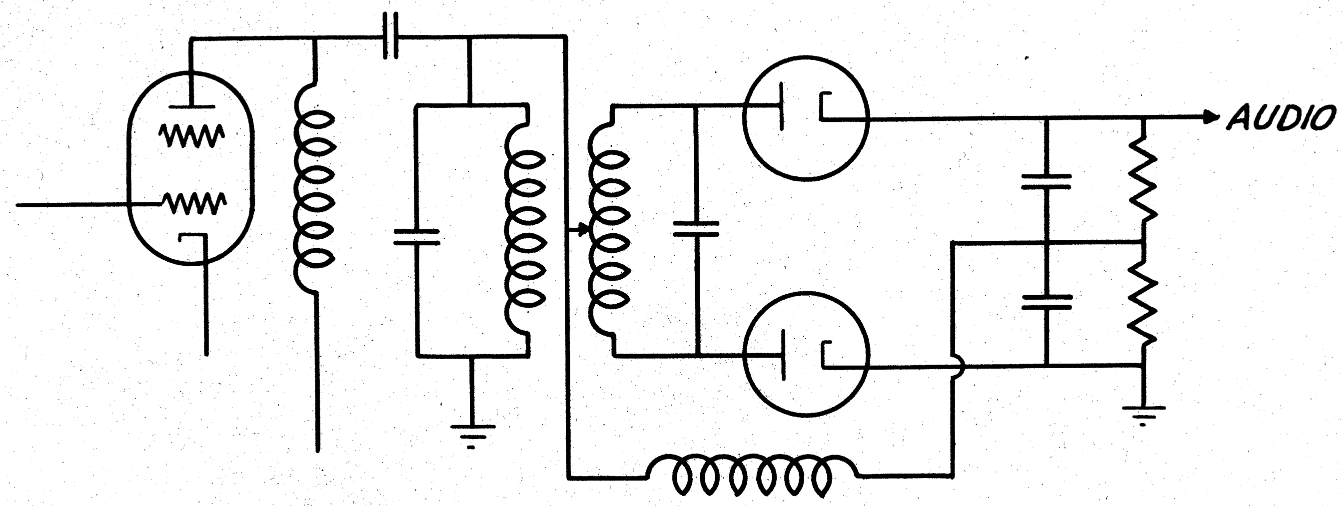


Fig. 7

and observe not only that the arrangement of Figure 6 is identical with Figure 3 but that its elements are arranged in such a way that the electrical functions of the device, instead of being obscured, are now well on their way to becoming evident.

Let us now, for the purposes of comparison, examine a conventional discriminator circuit of Figure 7 shown herewith.

Disregarding for the moment the biasing voltages of the circuit of Figure 6, it is now evident that what has been done circuitwise in the "ratio detector" is merely the substitution of a current balanced type of rectification for the ordinary

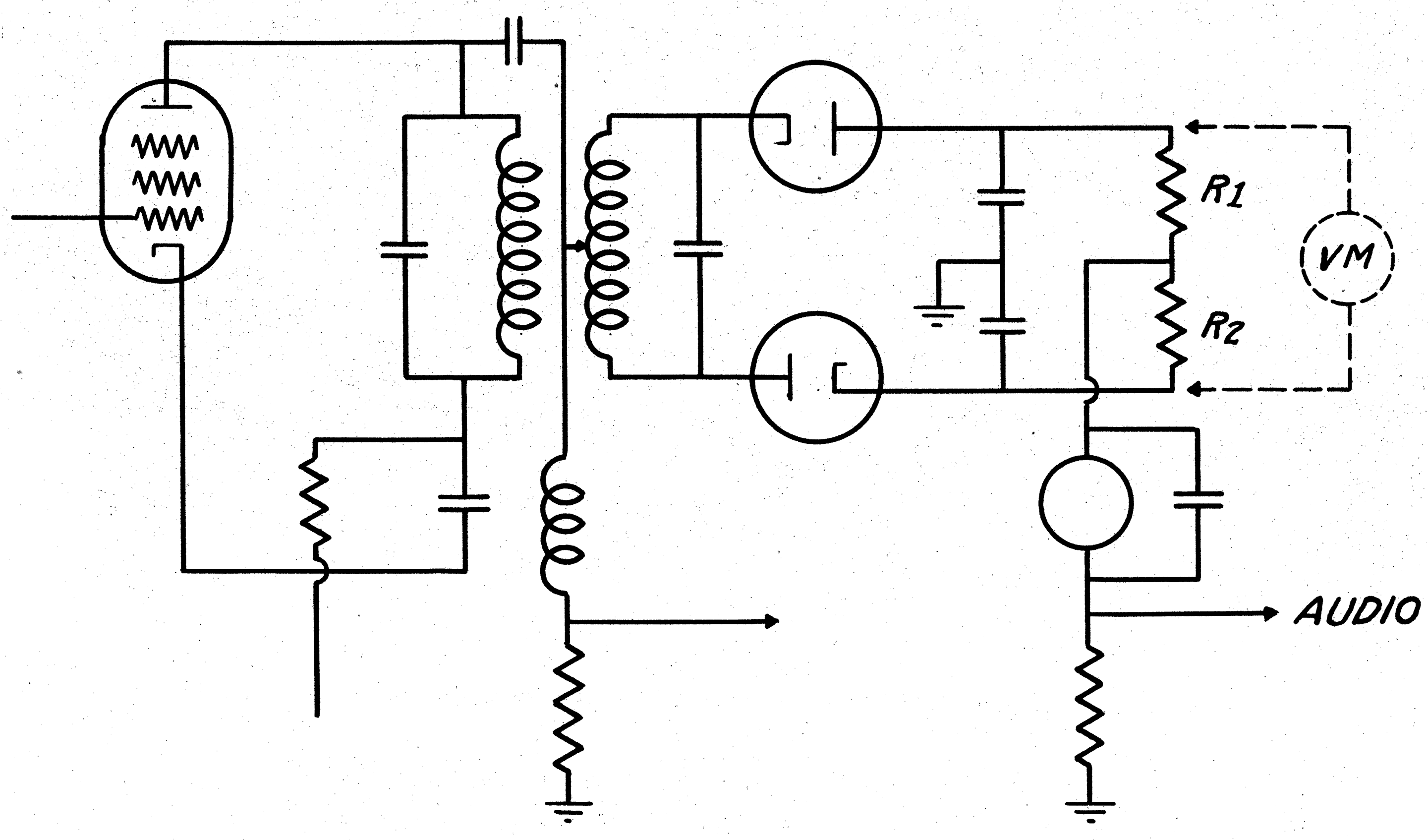


Fig. 8

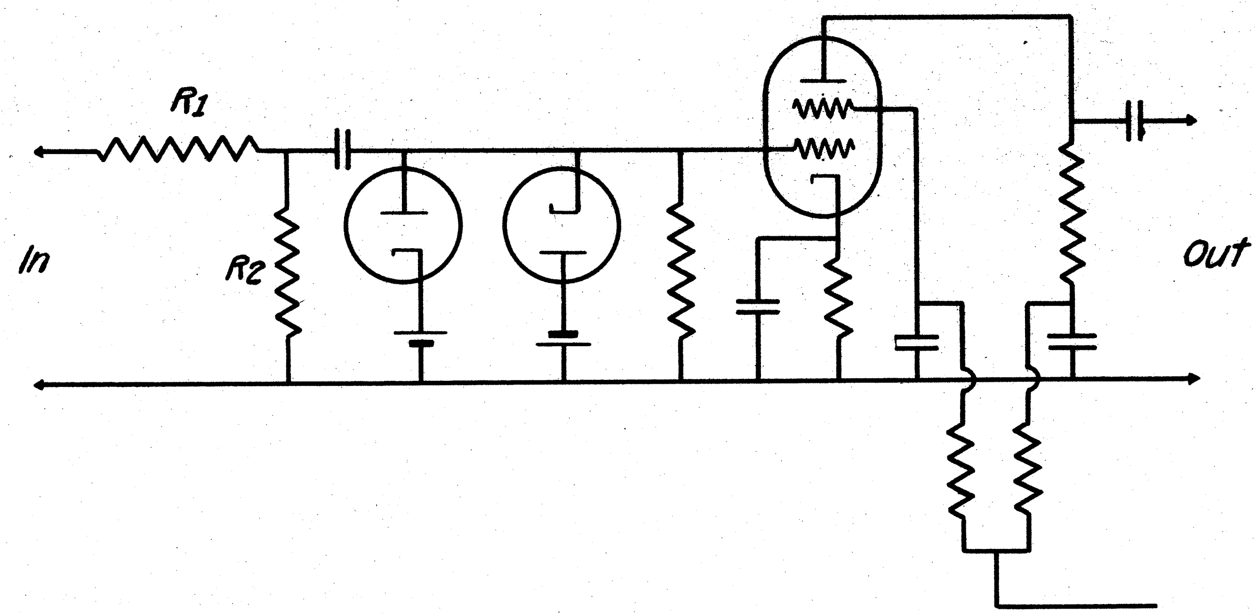


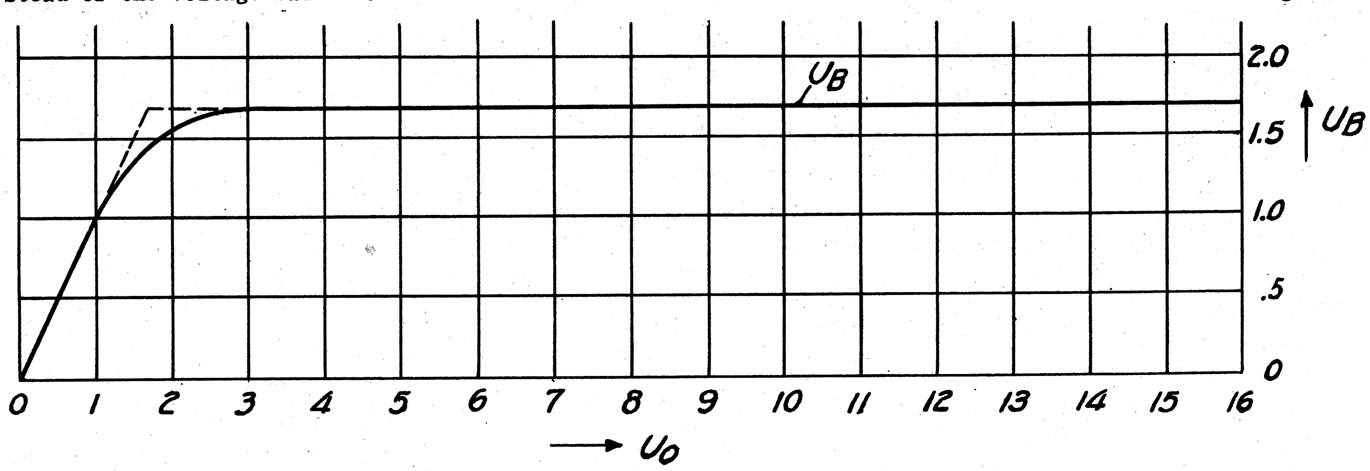
Fig. 9

voltage balanced type[15], something which is not at all novel in the art.[16]

The current balance type of discriminator has been used for a number of years in the General Electric FM Station Monitor. In the Summerhayes paper the author gives a straight-forward explanation of the action of the device which he labels "Current Sensitive Frequency Discriminator Circuit", and the reasons for using the current instead of the voltage balance. The circuit from the Summerhayes paper is reproduced in Fig. 8.

Wherein, then, does the operation of the "ratio detector" differ from the Summerhayes arrangement, since, with the exception of the biasing voltage obtained by the condenser-resistance combination RC_4 of Figure 4, they are diagrammatically the same?

To understand what really happens in the "ratio" detector circuit it is in order to go back



Author's Note. Two stages of limiting were used to obtain the above characteristic.

Fig. 10

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15 As a matter of definition it is convenient to call the condition existing when separate currents flowing through separate impedance elements bring about a condition of zero voltage across the two elements a "voltage balance", and to call the condition a "current balance" when currents flowing in opposite direction through a single element cancel each other out to produce zero current through the common impedance. Of course the illustration is figurative only, as the physical picture in the case of a balance is simply that no current flows, and in the case of an unbalance that a residual or difference current passes through the common impedance.

16 Proceedings I.R.E. June 1943, Summerhayes. Paper presented June 23, 1941.

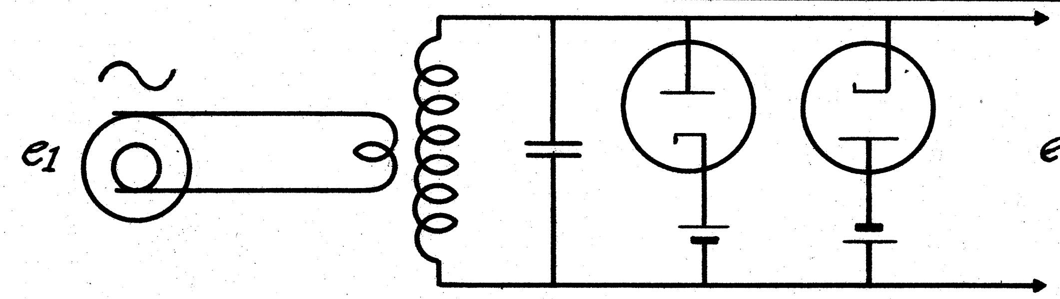


Fig. 11

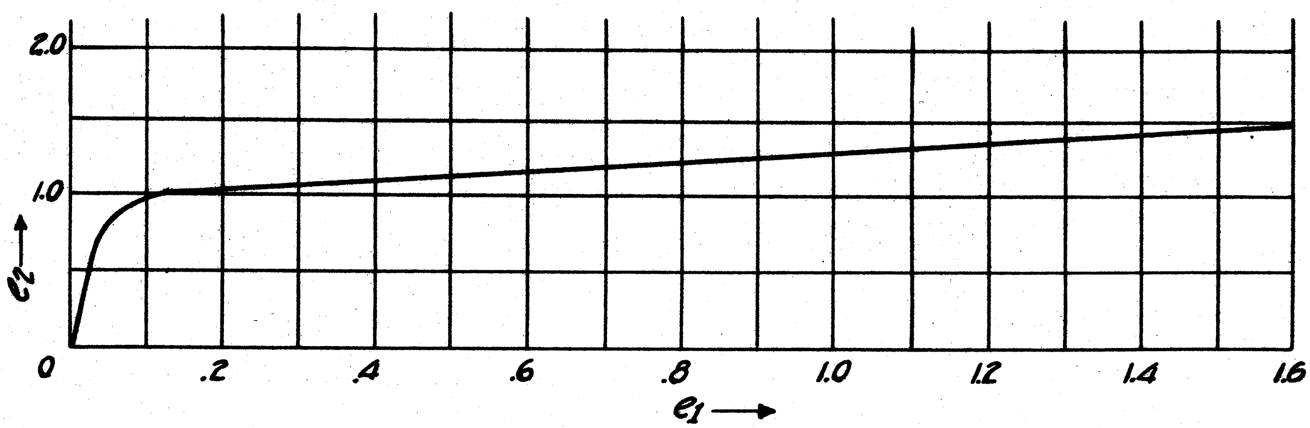
to a paper by Zuhrt[17] which reports an investigation of the F.M. phenomena presented to the Institute of Radio Engineers in my November 1935 paper. In this article Zuhrt describes a method of using diodes as limiters, the particular arrangement shown being reproduced herewith as Figure 9 (Zuhrt Fig. 19).

In this arrangement the biased-off diodes conduct after the level across resistance R_2 rises beyond a critical value, and by properly relating the various resistances to diode impedances a typical characteristic of the type shown in Figure 10 is obtained. (Zuhrt Fig. 20).

Although Zuhrt made use of resistors[18] in limiting the rise of voltage beyond the desired level, the principle is equally applicable to tuned circuits of the type indicated in Fig. 11 herewith, where a similar type characteristic as shown in Figure 12 is obtained.

It should now be apparent how the "ratio detector" operates. It is a device in which the limiting functions of the diode as disclosed by Zuhrt is made use of in the series diode connection of Summerhayes to give combined limiting and detection by means of a single tube. If there is any novelty in the device, it would seem to reside in the proportioning of the diode impedances to the characteristics of the discriminator circuit so that the function of removing amplitude variations - that is, limiting - becomes superimposed upon the function of detection.

The foregoing explanation of the operation of the ratio detector has been verified by an oscillographic study made of a typical set of this type.[19] An input signal of suitable level unmodulated in frequency but modulated in amplitude 50% was introduced, and the condition of this amplitude modulated wave as it progressed through the various tubes and circuits of the receiver explored at the mid-frequency of the band to which the receiver was tuned and at various other points within the band up to plus and minus 75 kilocycles.



Single stage diode limiter characteristic of circuit of Fig. 11.

Fig. 12

17 Jahrbuch der Drahtlosen Telegraphie und Telephonie, Bd. 54 (1939), Heft 2.

18 The investigation was carried out at low frequency.

19 R.C.A. Crestwood Type 612V1.

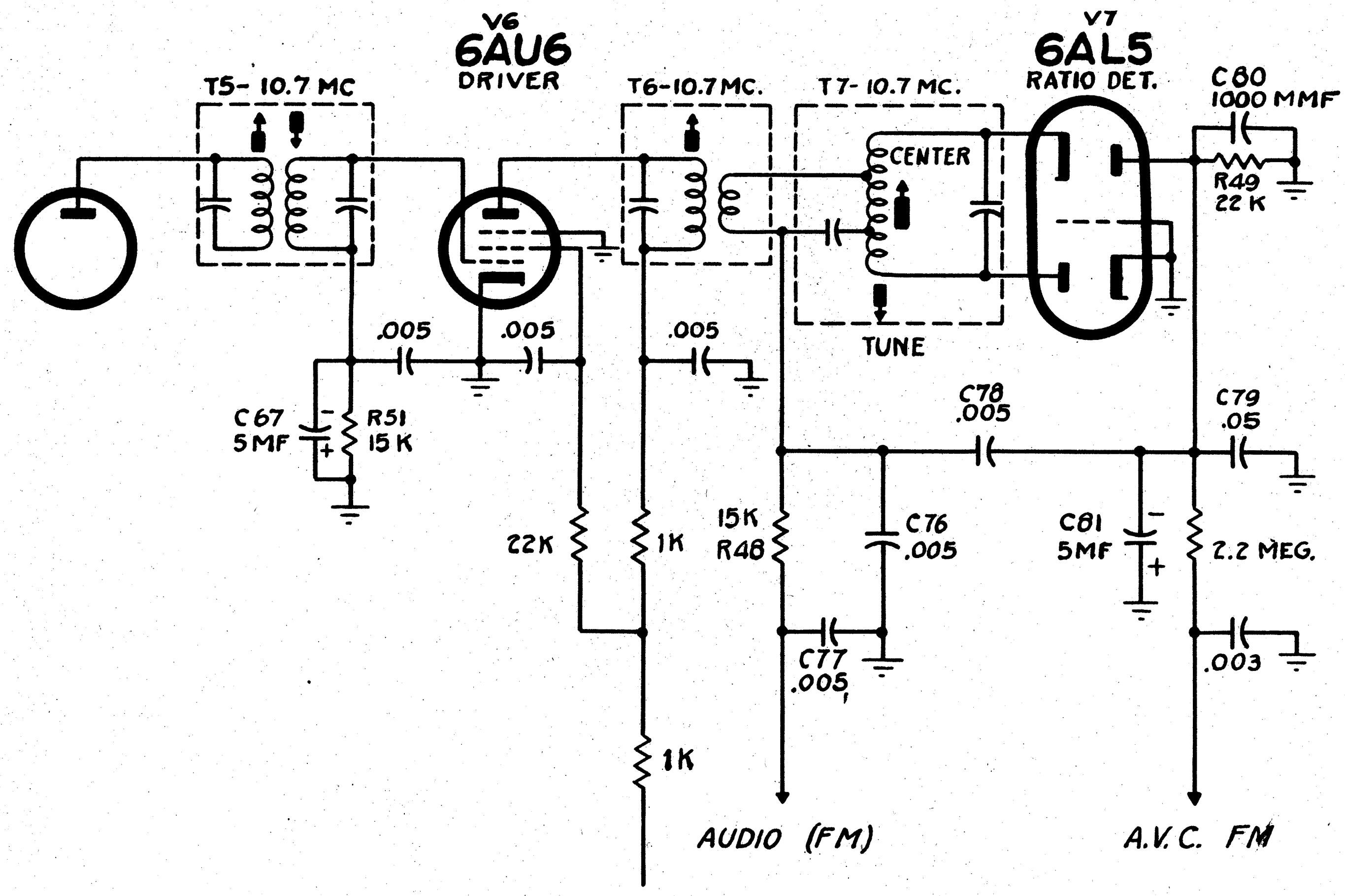


Fig. 13

Two methods of observation of the conditions existing within the circuits were employed. In one, the 10-megacycle IF currents and voltages were observed directly by means of a 10 megacycle oscilloscope. In the other, the exploration was made by means of a superheterodyne receiver arranged to beat the 10 megacycle intermediate frequencies down to values where they could be conveniently examined with the ordinary low frequency scope. In each instance the amount of energy abstracted from the circuit examined was held to a value sufficiently small so that the circuit characteristics remained unaltered by the sampling operation. Figure 13 illustrates the schematic arrangement of the circuits examined.

The arrangement of the "ratio detector" circuit of this receiver differed in some details from the arrangement described in RCA Laboratories Bulletin No. 645, but electrically the differences are not significant. The so-called "driver" tube circuits, however, contain a change which is significant. Instead of the usual biased amplifier connection, an unbiased grid circuit containing a large condenser and shunted resistance having a long time constant is employed. This arrangement serves to reduce the amplification to about one-third that obtainable with a biased amplifier. The purpose of sacrificing amplification in this way will appear from the following reproductions of oscillograms of the currents in the "driver" tube circuits. The essential elements of the ratio detector circuit of Figure 13 are redrawn in Figure 14 to clarify the diagrammatic portrayal of the circuit.

The method of investigation of what happens in the "driver" and detector circuits of the receiver of Figure 13 was carried out in the following way. The driver tube V6 had the large condenser C67 and resistance R51 replaced by a biasing battery of the proper value to give the same output. The cathode heater currents of the ratio detector tube V7 were cut off so that the resistance across the secondary circuit of the discriminator transformer became virtually infinite.

Under these conditions, with a 50% AM modulated signal applied to the grid of the driver tube the currents in the grid circuit and the plate cir-

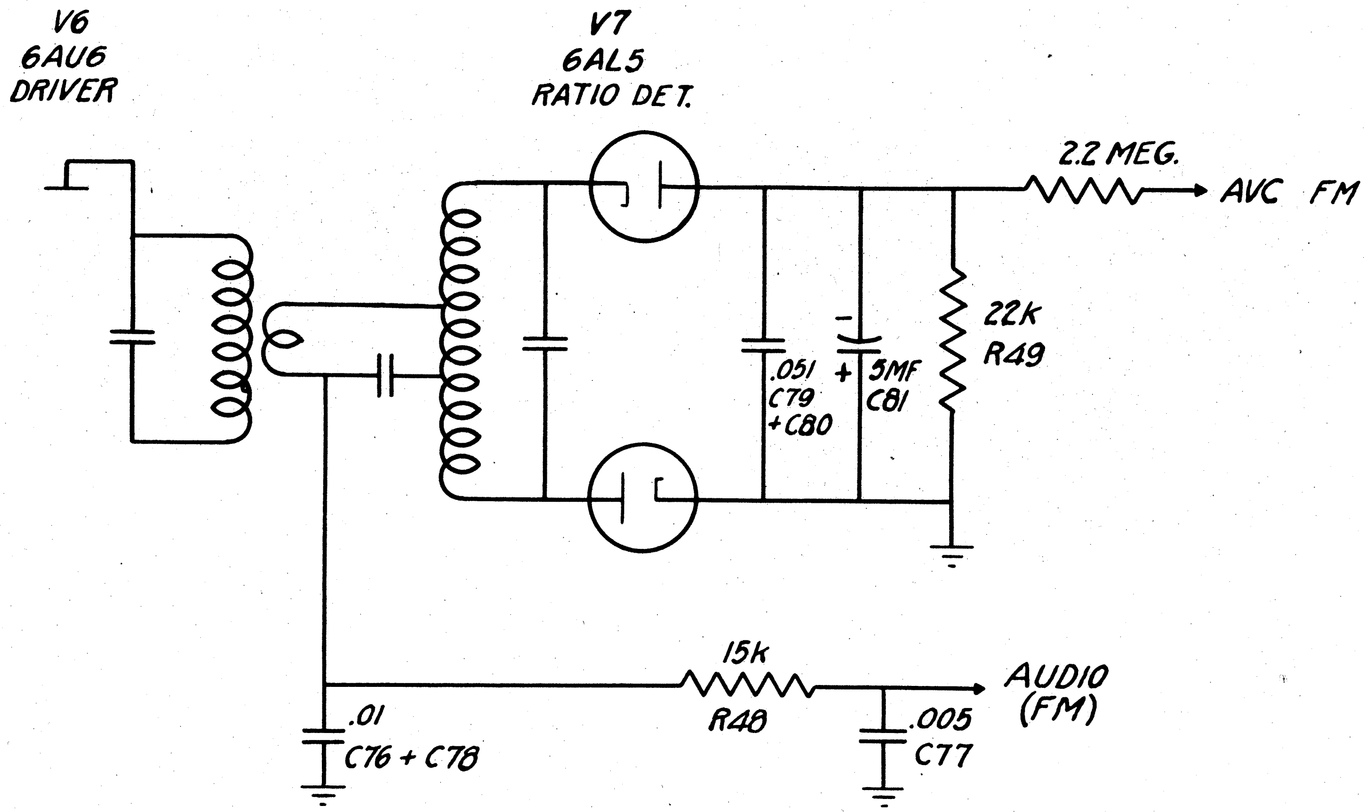


Fig. 14

cuit of V6 were investigated with a probe. The level was appropriate to give linear amplification in the driver tube, so it follows that a 50% amplitude modulated signal of the character shown, respectively, in Figures 14a, 14b and 14c was observed in the grid circuit, the plate circuit, and the secondary of the discriminator transformer.

Next, the biasing battery on the driver tube was removed and the normal grid circuit of the large condenser C67 and the resistance R51 was restored. The grid circuit of the driver tube now loads the tuned circuit to which it is connected, so that a reduction in amplification of about 3 to 1 takes place, which is accompanied with a reduc-

Wave form at grid of V6-6AU6 - "DRIVER" tube.
Signal generator - 50% modulation.
Grid return of this tube (V6) battery biased to produce approximately linear operation as an amplifier.

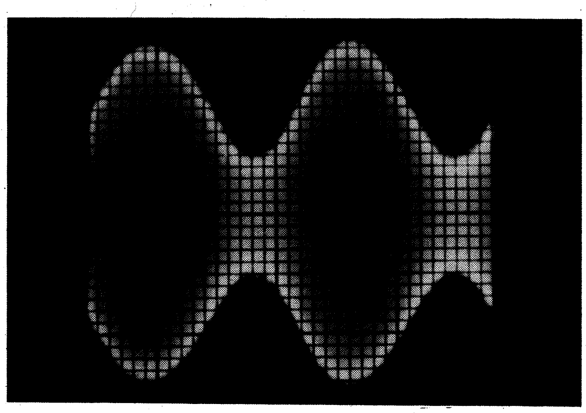


Fig. 14a

Wave form at plate of V6.
Signal generator - 50% modulation.
Grid return of V6 battery biased.

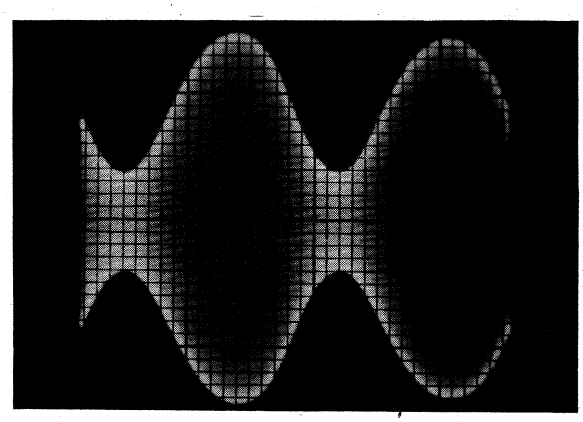


Fig. 14b

Wave form in discriminator secondary.
Signal generator - 50% modulation.
Grid return of V6 battery biased.
Heaters of V7 - off.

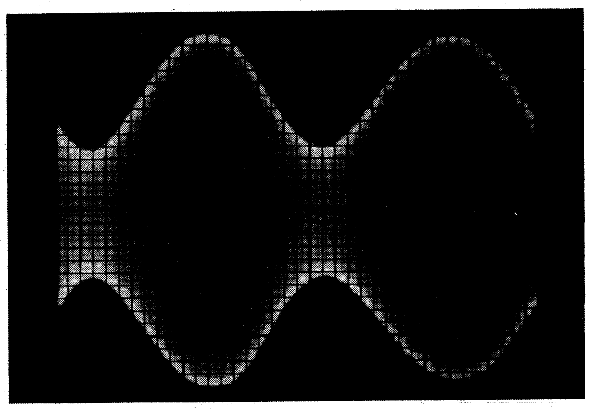


Fig. 14c

tion in the percentage of amplitude modulation because of the potential limiting of amplitude changes in the grid circuit by the RC combination in the grid.

Figure 15 now shows the wave form in the plate of tube V6 where an elimination of approximately half the amplitude modulation has taken place. A similar wave form is found in all the discriminator circuits, for the heater current has not yet been turned on. Next, the heater current was turned on and the diodes put into normal operation. Under these conditions the current in the secondary now becomes as illustrated in Figure 16, wherein the

Wave form in plate circuit of V6.
Signal generator - 50% modulation.
Grid return of V6 - normal.
Heaters of V7-6AL5 - "Ratio DET." off.

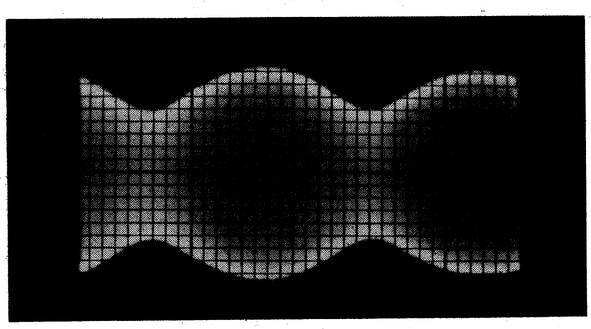


Fig. 15.

Wave form in discriminator secondary.
Signal generator - 50% modulation.
5 MF condenser (C81 and C79) in circuit, driver grid circuit normal.

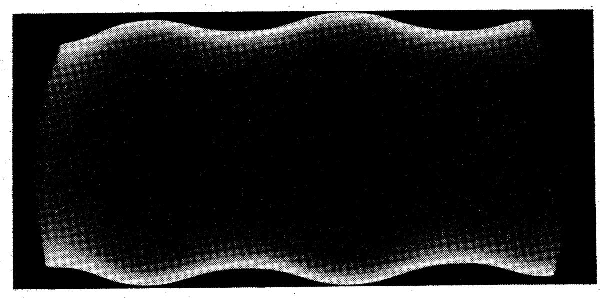


Fig. 16

amplitude modulation is almost completely removed. This result, of course, is caused by the limiting action of the diodes on the secondary in the manner shown by Zuhrt.

The manner of operation of the ratio detector is now perfectly clear. When examined for the properties of a limiter it is found to have them. In other words, it has the inherent property of suppressing amplitude modulations. Similarly, when viewed as a discriminator-detector, it is found to function as such.

The fact that these two properties are combined into a single circuit configuration and are therefore inherent in its operation does not alter these facts. However, as in all devices which perform double functions, the choice between conflicting requirements of design must be a compromise, and depending upon the choice made by the designer, various degrees of effectiveness of the limiting function may be expected.

The experimental part of this investigation, reported in the paper and in Appendix One attached hereto, has been carried out by Messrs. John Bose and Glenn Musselman, to whom the full credit is due. The work, extending over a period of many months, has produced a large amount of additional information not appropriate to the immediate paper. Further measurements will be made public in due course.

APPENDIX ONE

There are, of course, all degrees of effectiveness of the removal of amplitude modulation in the various arrangements of these self-limiting circuits. A method of examination which may be conveniently used for comparing the steady state operation of the different arrangements is described herewith.

As a standard of reference a Zenith Model 7H822 was employed, with its limiter tube modified to act as a straight amplifier. With this arrangement the audio output voltage was measured for a 50% amplitude modulation on a fixed frequency carrier at the balance point and at various points throughout the band. With the amplitude modulation removed and a frequency deviation of 75 KC the FM audio output was obtained as a standard of reference. This enabled a ratio of E_{fm} to E_{am} voltage to be obtained for various points within the band. A similar set of readings was obtained for a type RCA 68R3 ratio detector set with the electrolytic condenser removed from the circuit so that the self-limiting action did not take place.

Figure 17 illustrates the readings obtained at voltages corresponding to an input level of 100 microvolts. It will be observed that the ratios obtained with the voltage balance type of discriminator as used in the Zenith set, and those obtained with the current balance type employed in the RCA set, were substantially the same.

RATIO OF E_{FM} / E_{AM} (NO LIMITING)
RCA MODEL No. 68R3 and ZENITH MODEL No. 7H822

f	E_{fm} / E_{am} R.C.A.	E_{fm} / E_{am} Zenith
+ 75	1.78	1.9
60	2.27	2.2
37	3.33	3.2
20	6.25	5.4
0	83.33	72.2
20	6.25	6.0
37	3.12	2.7
60	2.08	1.6
- 75	1.56	1.2

Fig. 17

In order to make the ratio detector measurements it was necessary to remove the ground from one end of the load resistor and center-tap that resistor to ground. This, however, produces no change in the operation of the device.

RATIO OF IMPROVEMENT DUE TO LIMITING,
RCA MODEL No. 68R3

f	E_{fm} / E_{am} Without Limiting	E_{fm} / E_{am} With Limiting	Improvement Ratio Due To Limiting
+ 75	1.78	27.7	15.5
60	2.27	27.7	12.2
37	3.33	27.7	8.3
20	6.25	31.2	5.0
0	83.33	41.6	.5
20	6.25	31.2	5.0
37	3.12	20.8	6.6
60	2.08	16.6	8.0
- 75	1.56	17.8	11.6

Fig. 18

After these ratios had been obtained, the function of limiting was restored to the two sets and a similar set of ratios determined for each. Figure 18 illustrates the improvement in the ratio of E_{fm} / E_{am} which takes place when the large condenser is connected across the load to produce self-limiting. The effect is most pronounced at the extremes of the band, where the greatest unbalance for the non-limiting condition occurs. Hence, the ratio of E_{fm} / E_{am} at + 75 KC of 1.78 without limiting improves to 27.7 with limiting, or a matter of fifteen and a half times; and at - 75 KC the ratio of 1.56 becomes 17.8, or an improvement of eleven and six-tenths times in the reduction of amplitude variations. As these are voltage ratios, the reduction in the noise level on an energy basis at these points is over one hundred-fold at one end of the band, and over two hundred-fold at the other end. The improvement decreases as the center of the band is approached. At the exact center the ratio reverses and is somewhat less for the case with the limiter, as a more accurate amplitude balance appears to be obtainable without it.

There are a variety of types of connections for self-limiting circuits, and no attempt will be made to analyze them all. Figure 19, however, illustrates a series of E_{fm} / E_{am} ratios for a number of receivers now on the commercial market. These figures are not intended to be illustrative of the individual performance of the different sets, as such comparison would require examination of a number of samples of each make and a determination of the figure of merit for various input levels. The figures are, however, designed to

RATIO OF IMPROVEMENT DUE TO LIMITING, OF SOME COMMERCIAL TYPES OF F.M. RECEIVERS

f	Zenith 7H822	R.C.A. 68R3	R.C.A. 8R71	Philco 48-475
+ 75	14.6	15	2.8	22
60	14.8	12	2.8	23
37	13.5	8	2.6	20
20	14.0	5	2.4	13
0	.8	0.5	0.5	0.5
20	16.6	6	4.0	10
37	16.6	7	4.0	17
60	15.2	8	4.5	27
- 75	15.0	12	5.0	29

Fig. 19

give a rough idea of the performance of the various sets under the conditions of the test.

It should be noted that the ratios measured are steady-state ratios and are not representative of what happens under conditions of ignition interference or of improper I.F. band characteristics, as the performance of the ratio detector deteriorates rapidly under such conditions.

In these measurements the operational characteristics of the detection systems were isolated from the effects of faulty line-up of IF transformers by determining the voltage produced on the grid of the limiter or of the driver tube for an input signal of 100 microvolts (300 ohms in series with the signal generator) at the mid-frequency. Corresponding IF voltages were then applied to the grids of the limiter and driver tubes at the proper intermediate frequency.

APPENDIX TWO

(Author's Note: The substance of the following account of the disclosure of the regenerative circuit to the leading engineers of the American Telephone and Telegraph Company in February and April of 1914 was related during the presentation of the paper.)

Shortly after my graduation from Columbia University as an electrical engineer in 1913 the University decided to set up a course of instruction in radio. I was given the job of assistant in the Department of Electrical Engineering by Professor Walter I. Slichter, who evidently thought I had absorbed enough of his course on Alternating Current Theory to qualify me, and went to work in the laboratory of Professor Michael I. Pupin, then a world renowned figure in the field of communications. A small antenna was set up on the campus between two of the buildings and we went to work on the course. In the latter part of 1913 I found the time to bring the regenerative circuit apparatus down from my home in Yonkers to the Marcellus Hartley Research Laboratory and to give a series of demonstrations for the leading communication companies.

Professor Pupin happened to be around late one evening when darkness covered the path to Hawaii, so that the signals from the Poulsen arc station at Honolulu were coming in very well. Professor Pupin, who had been a close friend of Marconi since his first lecture in this country, and who had warmly sponsored Marconi's objectives for many years, became highly enthused about the demonstration. Shortly thereafter he chanced to meet a group of acquaintances at the University Club in New York City, among whom was J.J. Carty, then chief engineer of the American Telephone and Telegraph Company. He related the story of the demonstration, and I do not doubt that it was a most animated account.

Mr. Carty at the time said nothing. But on the next get-together of the same group Mr. Carty remarked that Pupin had quite successfully "pulled his leg" at the time but he had since been able to consult his radio staff about the matter, and he now was in a position to say that the story Pupin had told was impossible.

This pronouncement was met with the prompt rejoinder by Professor Pupin to come to the laboratory and see the "impossible". On the evening of February 6, 1914, Mr. J.J. Carty, Mr. Bancroft Gherardi and Dr. F.B. Jewett, then the leading engineers of the A.T.& T., visited the Marcellus Hartley Research Laboratory for a demonstration. They brought along a young fellow by the name of Lloyd Espenschied to read the signals and check up on the identification of the stations which were heard. The demonstration was successfully carried out, and as usual without disclosing the circuit connections or how the apparatus functioned.

The spark signals were, of course, heard with their natural tone and so excited no particular comment. The arc signals, however, had the assembled company much puzzled. Signalling on the Poulsen arc at that time was carried out by varying the frequency of the arc a few percent, and at the low frequencies then employed for transmission (approximately 50,000 cycles) the "back wave" was generally audible for the best adjustment of the receiver. I well remember Mr. Carty's asking about it and his humorous comment that "It sounds like an 'inebriated' flute player".

On April 25, 1914, at a further demonstration of the equipment, a full disclosure of the principles of operation was made to Mr. Gherardi, Dr. Jewett and Mr. E.H. Colpitts. These demonstrations and disclosures brought about the entry of the American Telephone and Telegraph Company into the field of communication by radio. From that date its radio staff, which then consisted of Lloyd Espenschied and the late Austin Curtis, began the never-ending expansion that has resulted in the amazing organization of today.

APPENDIX THREE

During the presentation of the paper a visual and aural demonstration of the removal of amplitude variations by the ratio detector circuit was conducted, using the arrangement of Figure 20. The receiver employed in the demonstration was the R.C.A. "Crestwood", Type 612-V1, to which reference has heretofore been made.

Conditions existing in the secondary circuit of the arrangement of Fig. 20 were examined by obtaining a sample of the current flowing in it with a single turn coil around the discriminator secondary. This coil could be switched to a 10-megacycle scope or to a crystal rectifier - amplifier - speaker system for indicating aurally the noise levels.

Two sets of demonstrations were made. The first showed the effect of the 15,000 ohm resistance and 5-microfarad condenser combination in reducing amplitude variations in the driver tube circuit. This was illustrated by the picture seen in the scope under the following conditions______;

The heater current of the ratio detector tube V7 was cut off so as to remove all limiting action from the circuit by that tube. A 50% amplitude modulated signal at mid I.F. frequency was fed into the I.F. system and so applied to the driver tube, and the voltage obtained from the biasing source indicated at B was adjusted to give the same amplification with S1 to the left with the fixed bias, as when S1 was thrown to the right and a self bias furnished by the resistance-capacity combination.

Observation of the current in the secondary of the discriminator by means of the scope showed that the 50% modulation which appeared in the secondary circuit when the separate bias was used dropped to less than half of that when the resistance-capacity combination was cut into the grid

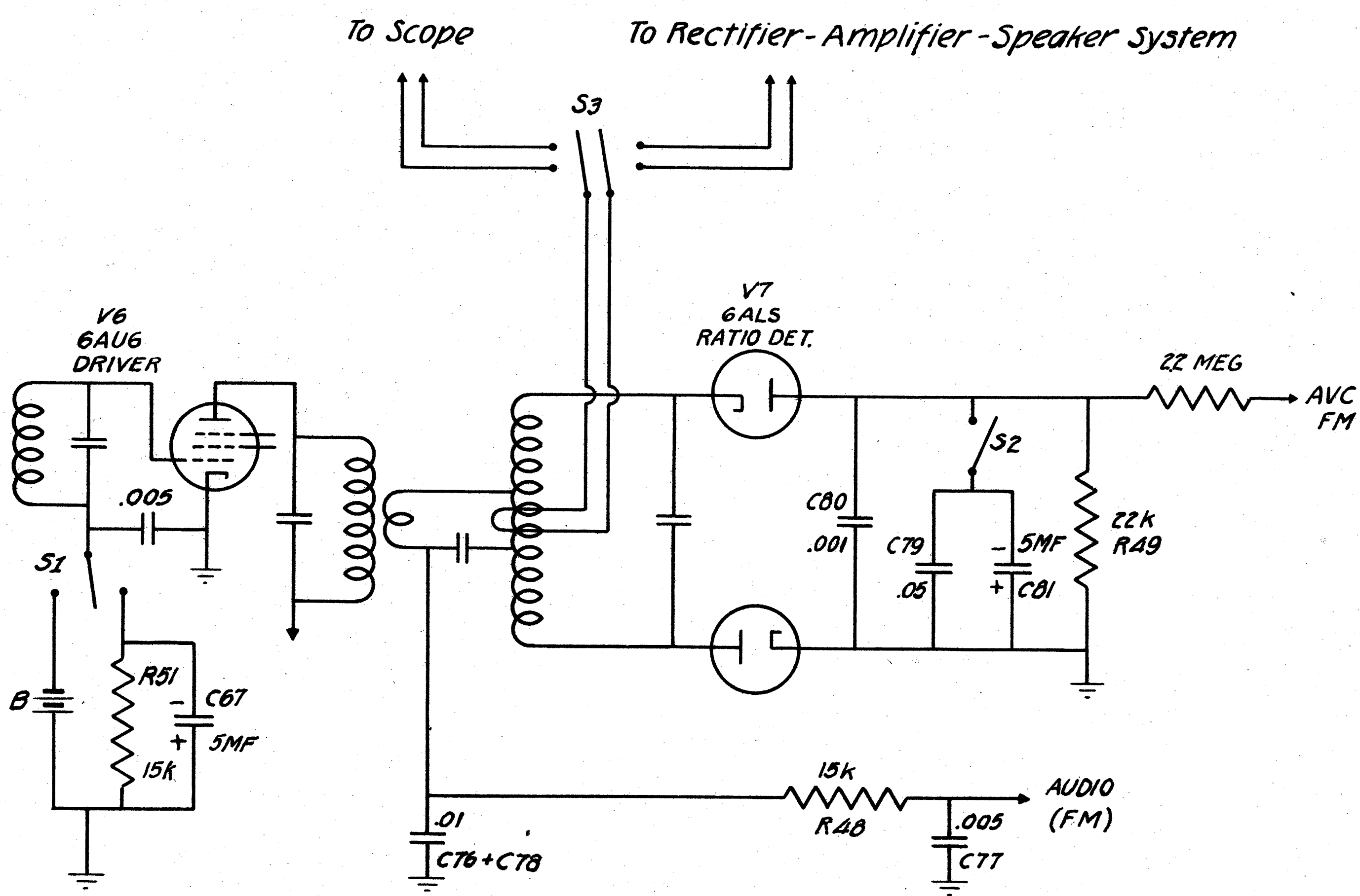


Fig. 20

circuit of the driver tube.

The second step in this demonstration was carried out with the heater currents in the ratio detector tube switched on and with the switch S2 closed to restore the normal ratio detector circuit. Under these conditions the amplitude modulation as indicated by the scope was reduced to a very small fraction of carrier level.

In this test the automatic volume control was cut out so that constant level at the input of the driver tube was maintained.

The second demonstration was arranged to show, aurally, the limiting action of the ratio detector tubes on thermal or tube noise in the secondary circuit of the discriminator. With the full receiver in operation and switch S1 on the separate bias the sampling loop was connected to the crystal rectifier - audio amplifier - speaker system, so that an audible response to the currents in the secondary circuit resulting from thermal and tube noise was produced.

An R.F. carrier was introduced at the input terminals of the receiver and adjusted in level so that with switch S2 open the noise level could be clearly heard throughout the room. The closing of the switch S2 put into operation the limiting action of the diodes, and the noise dropped to a small fraction of that obtained when S2 was open. The reading of a direct current meter in series with the crystal rectifier stayed constant, regardless of whether switch S2 was opened or closed, indicating that the level of the R.F. current in the secondary circuit had not changed and that the decrease in the noise from the speaker was due entirely to the elimination of amplitude variations in the secondary current. In this test, likewise, the A.V.C. circuit was cut out, although the D.C. voltage measured across R49 indicated no change when the 5 mfd condenser was cut in and out.

The elimination of the noise modulation on the secondary current with the closing of switch S2 could also be observed visually on the scope.

APPENDIX FOUR

During the presentation of the paper, reference was made by the writer to two documents which may have an effect in radio history similar to that which the lost order of General Robert E. Lee, Commander of the Army of Northern Virginia, had on the fortunes of the Confederacy during the invasion of the North in the Summer of 1862.[1]

The first document was a "Report on the RCA Ratio Detector" written by the head of the Patent Department of the Philco Corporation and embodied in an exhibit in a securities registration statement filed with the Securities and Exchange Commission (at Philadelphia, Pa.)[2] Excerpts from the report were read which confirm the analysis of the paper.

A second document, written by the head of the FM Section of the Patent Department of the Radio Corporation of America, was likewise referred to, and excerpts from that document defining the nature of the wide swing invention were likewise read.

The character of these documents and their relation to the public interest is such that the writer felt the situation justified some special comment. Recalling how some thirteen years ago, when he had last appeared before the Radio Club on the occasion of the presentation of the original FM paper, he had predicted the day was in sight in broadcasting when the noise of the thunder coming in the window would be more disturbing to the radio listener than the effect of the lightning on his radio set, and that that prophecy had now come to pass in the areas served by the 673 FM stations now on the air, he stated that the time had arrived to venture another prophecy.

That prophecy was that the day would surely arrive when the direction of engineering by the members of the legal profession would come to an end, because the unholy mess that they had made of radio would soon be apparent to everyone. The writer predicted that engineering would again be directed by engineers, and he even ventured to think that the day might arrive when some highly successful executives would come to believe that there was something after all to the text of the Eighth and Ninth Commandments,[3] stating that in case the audience could not immediately place them by number that they were "Thou shalt not bear false witness against thy neighbor" and "Thou shalt not steal".

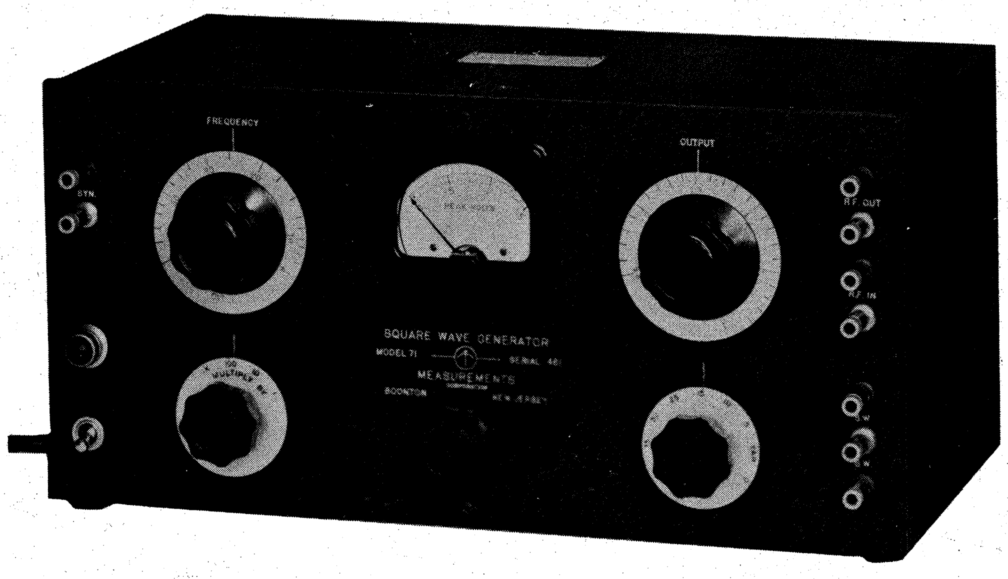
---

1 The lost order of General Lee to Major General D.H. Hill which fell into the hands of General McClellan, Commander of the Army of the Potomac, disclosed the disposition of General Lee's forces and enabled the Union Commander to fight the Battle of Antietem (Sharpsburg) under circumstances so unfavorable to the Army of Northern Virginia as to compel its retirement across the Potomac River into Southern territory. For the best accounts of the story of the lost order and its subsequent effect, see: "Lee's Lieutenants", Volume 2, by Douglas Freeman, and "Robert E. Lee", Volume 2, by the same author. Also "Battles and Leaders of the Civil War", a compilation of articles written by leading participants on the Union and Confederate sides.

2 Exhibit 17-L, File No. 2-6525, filed June 20, 1946 with Securities and Exchange Commission, Philadelphia, Pa.

3 (Protestants numbering, generally)

SQUARE WAVE GENERATOR
Model 71



SPECIFICATIONS:

FREQUENCY RANGE:
Continuously variable from 5 to 100,000 cycles per second.

WAVE SHAPE:
Rise time less than 0.2 micro-seconds with negligible overshoot at 75 peak volts output. At 5 volts or less, rise time is 0.15 microseconds.

OUTPUT VOLTAGE:
Step attenuator giving 75, 50, 25, 15, 10, 5 peak volts fixed and 0 to 2.5 volts continuously variable.

OUTPUT IMPEDANCE:
20 ohms per volt.

SYNCHRONIZING OUTPUT VOLTAGE:
25 volts peak.

SYNCHRONIZING OUTPUT IMPEDANCE:
1500 ohms.

SYNCHRONIZING INPUT IMPEDANCE:
Over 20,000 ohms.

R.F. MODULATOR:
5 volts maximum carrier input. Transition gain is approximately unity. Output impedance is 600 ohms.

TUBES:
Two 6AG7's; three 6J5's; one 6SA7; one VR150/30; one 5Y3G.

POWER SUPPLY:
117 volts, 50-60 cycles. Self contained, no batteries. 100 watts.

DIMENSIONS:
7″ high, 15″ wide, 7½″ deep.

NET WEIGHT:
Approximately 15 lbs.

NOTE: This instrument is self contained and does not require an external driving source.

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MAKERS OF RADIO TUBES; CATHODE RAY TUBES; ELECTRONIC DEVICES; FLUORESCENT LAMPS, FIXTURES, WIRING DEVICES; ELECTRIC LIGHT BULBS

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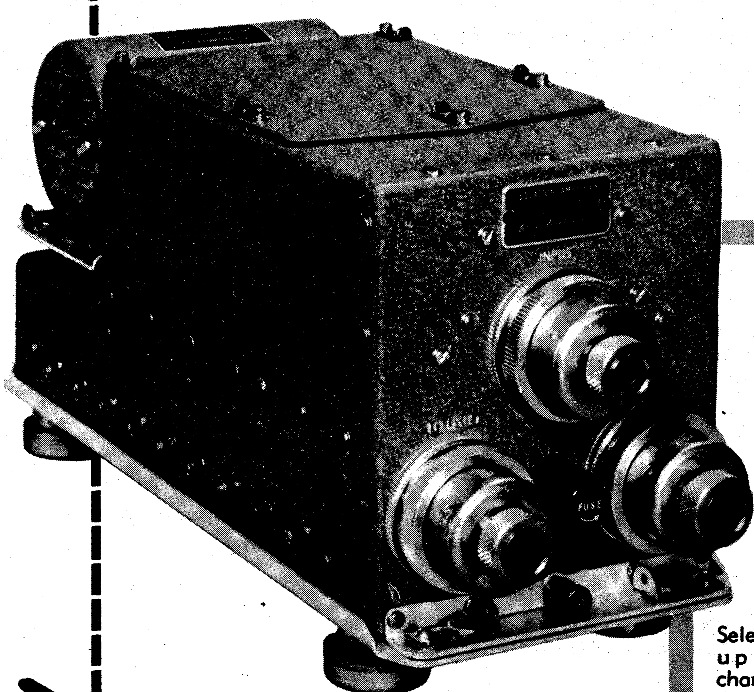

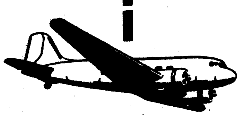

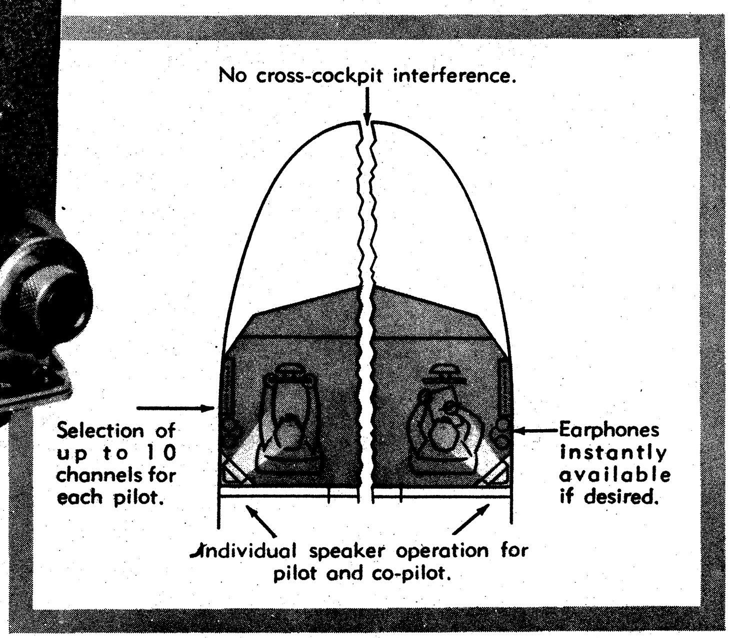

The new A.R.C. Isolation Amplifier performs two important radio-control functions that have long presented a vexing problem. With it, each pilot has independent selection of up to ten audio input channels in any combination—without cross-cockpit interference. And it operates individual cockpit speakers, with earphones instantly available if desired. Since CAA regulations no longer require wearing of headphones when cockpit speakers are installed, the Type F-11 Isolation Amplifier now relieves the pilots of considerable discomfort and fatigue—in addition to providing unprecedented freedom of control.

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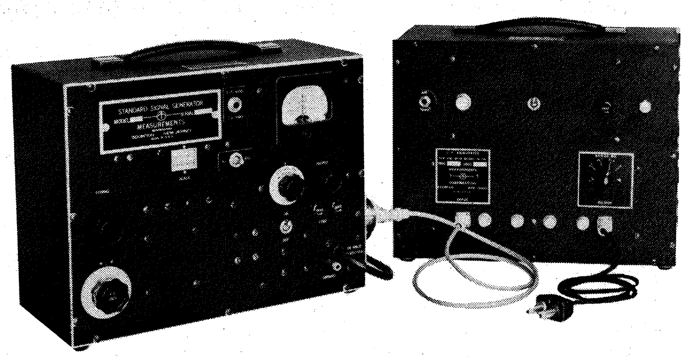
Laboratory Standards

MEASUREMENTS CORPORATION

MEASUREMENTS MODEL 78-FM

SPECIFICATIONS

FREQUENCY RANGE: 86 to 108 megacycles, individually calibrated dials. Accurate to ± .5%.
OUTPUT VOLTAGE: 1 to 100,000 microvolts.
LEAKAGE: Less than 1 microvolt.
MODULATION: Deviation continuously variable from 0 to 300 kc. Indicated on directly calibrated dial. 400 cycle internal audio oscillator can be modulated from an external source providing 6 volts across 5000 ohms.
FIDELITY: Flat within two db from DC to 15,000 cycles. Distortion is less than 1% at 75 kilocycles deviation. Transient response is excellent.
POWER SUPPLY: 117 volts, 50 to 60 cycles.
DIMENSIONS: 10" high x 13" wide x 7" deep, overall.
WEIGHT: Approximately 25 pounds.



MEASUREMENTS MODEL M-275 I.F. CONVERTER

This instrument is designed to be used with the Model 78-FM Standard Signal Generator to provide output frequencies in the I.F. range.

CARRIER FREQUENCIES: 4.5, 10.7, 21.7 Mc. plus provision for one extra frequency.

OUTPUT VOLTAGE: 10 microvolts to 1.0 v., variable with Model 78-FM attenuator.

BAND WIDTHS: 5% down, 250 Kc. from center frequency.

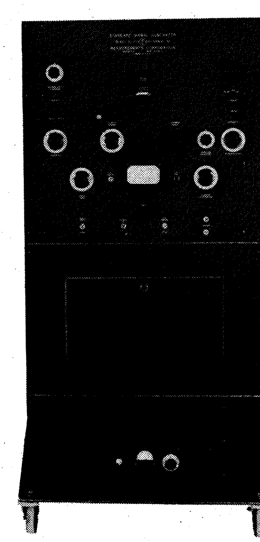
AMPLITUDE MODULATION: Provision for external AM up to approximately 80%, combined with, or exclusive of, FM. There is negligible spurious FM due to AM. The envelope distortion is less than 10% at 80% modulation.
DIMENSIONS: 10" x 13" x 7". 15 pounds.
POWER SUPPLY: 117 v., 50-60 cycles. 45 watts.

TELEVISION SIGNAL GENERATOR

MODEL 90

MANUFACTURERS OF
Standard Signal Generators
Pulse Generators
FM Signal Generators
Square Wave Generators
Vacuum Tube Voltmeters
UHF Radio Noise & Field Strength Meters
Capacity Bridges
Megohm Meters
Phase Sequence Indicators
Television and FM Test Equipment

This instrument is the first commercial wide-band, wide-range, standard signal generator ever to be developed. It is the master oscillator, buffer-amplifier, modulated power-amplifier type, and the output circuits are of the double-tuned, over-coupled, band-pass type, permitting modulation frequencies up to 5 megacycles. The excellent isolation between final amplifier and oscillator completely eliminates incidental frequency modulation.
The carrier range of 20 to 300 megacycles is covered in eight coil ranges. Video modulation is obtained from a built-in video modulator having a band width of 5 megacycles designed to operate from a standard R.M.A. television signal. Continuous monitoring is provided by a built-in oscilloscope. Audio modulation up to 100 percent may be obtained from a suitable external audio oscillator.
The Model 90 fills a long felt need for a real standard signal generator applicable to high definition television use.



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FM MODULATOR

THIS UNIT represents the most advanced stage in the development of the phase shift principle for generating frequency modulated signals, and is of the widest possible application. It combines in one design the finest performance commercially attained, with the utmost in simplicity, freedom from critical features, and permanent reliability.

AS APPLIED in an FM broadcast exciter unit, four receiving type tubes plus a crystal comprise the SERRASOID proper, and insure the following performance:

• NOISE - 80 DB below 100% modulation •

• Distortion - Less than 0.25% at 100% modulation •

• Carrier Stability - Direct crystal control •

THESE same four tubes, with design details altered to fit the application, are the modulating heart of a widening group of other FM signalling and multiplexing systems, yielding again the highest order of performance.

WHEREVER a modulating peak phase shift of ±90°, with almost nonexistent noise and distortion, is required, together with the ultimate in aperiodic simplicity and reliability, an application of the SERRASOID is the answer.