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Short-wave transoceanic telephone receiving equipment[†]

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THE commercial importance of a single radio channel used for transoceanic telephone communication is such as to permit considerable effort being placed upon obtaining the most efficient and satisfactory operation from each unit of equipment. In this paper, it is proposed to discuss, in a general manner, the receiving equipment used on the short-wave transatlantic telephone channels to England and some of the methods of analysis used in attacking problems encountered in the design of the receiving equipment.

Fields Obtained

A highly important factor in radio reception is the signal-to-noise ratio obtainable. This is, in most cases, a function of the field strength received. The field strengths obtained at the high frequencies are highly variable, ranging from a value well below that necessary to give the faintest audible signal to perhaps 60 db. above a microvolt per meter (1 millivolt per meter), depending upon the time of day, the season of the year, and magnetic conditions. They are also a function of the particular path, the fields obtained over the North Atlantic path between New York and England being affected by magnetic storms to a greater extent than over any other important path. Mr. Burrows has shown[1] in a very graphical manner the field which may be expected at various times of the day over the transatlantic channel to England. One of his graphs is shown in Fig. 1. The lines on the graph are lines of equal field strength and the values are in decibels above one microvolt per meter. It must be remembered that the values shown are for a particular season and are averages only. Even though the figure may show that a field of 20 db. above a microvolt per meter (10 microvolts) is to be expected, the presence of a magnetic storm on a particular day may reduce the field over the North Atlantic to a value so far below that required for commercial operation that it is probable that an increase of the transmitted power to several hundred kilowatts (the ordinary carrier energy radiated by the transmitter is about 15 kw.) would not give an audible signal. During such times, transatlantic service must be given over the long-wave channel which radiates about 50 kw. in the vicinity of 60 kc., and which is likely to be somewhat better than usual during a magnetic storm.

As can be seen from Fig. 1, the time at which the field strengths at the various frequencies are highest is not the same for all frequencies, and consequently, it has been found necessary to have available three or four frequencies of roughly 7,000 kc., 9,000 kc., 13,000 kc. and 19,000 kc., in order to insure that service can be given under all normal conditions. In practice, it is the custom to use a particular frequency so long as it is satisfactory, and then shift to the next frequency.

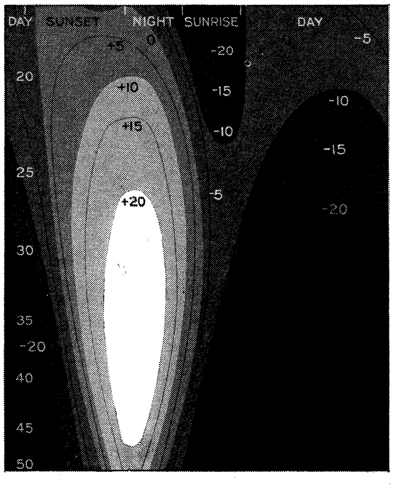

Fig. 1. Average field strength surface for June, 1926, db. above 1 microvolt per meter for 1 kw. radiated.

In the operation of the receiving station at Netcong, New Jersey, considerable effort is made to use the frequencies available to the best advantages. A monitoring group known as a "channel efficiency bureau" is maintained to advise the operators of the best frequency at a given time and of the best time to shift to another frequency. The monitoring group also makes periodic measurements of the field strength and frequency on all channels which may be in operation and of such other short-wave stations as may be of interest. On each day, when operation is commenced on a particular frequency, the operator advises the channel efficiency bureau of the amount of attenuation it is necessary to place in his receiver to obtain a standard output, and this information is compared with the normal value for the field being obtained. This gives a check on the condition of the receivers, transmission lines and antennas.

Use of Directive Antennas

Knowing the field strength which he can expect, the problem that confronts the station designer is how to make the best use of it. Since the minimum commercial field may be only a fraction of a microvolt per meter, the receiver must have considerable gain. In receivers having high gains, noise will be generated in the first circuits and tubes by the thermal agitation of the

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†Presented before the Radio Club of America.

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[1] *C. R. Burrows' "The Propagation of Short Radio Waves Over the North Atlantic." Proc. I. R. E., Vol. 19, pp. 1634-59, Sept., 1931.*

electrons which are moving about in every conducting substance. This noise is ordinarily called "Johnson noise," after its discoverer, or merely "thermal noise." The maximum Johnson noise energy which can be drawn from a circuit is independent of its resistance but the noise voltage varies as the square root of the resistance. If the signal is to override this noise satisfactorily when weak signals are being received and static is very low, it is essential that a maximum of voltage be applied to the input of the receiver for any given field. Antennas having a high signal pickup are, therefore, used at the receiving station. Fortunately at high frequencies it is comparatively easy, by means of what is usually called a directive antenna, to obtain a high signal collecting power as well as directivity. A directive antenna is essentially a number of elementary antennas so arranged that the output of all the elements is combined to good advantage when waves arrive from a certain direction and is combined less advantageously for waves arriving from other directions. The increase in voltage which may be obtained with a directive antenna is ordinarily from 10 to 16 decibels (3 to 6 times) over what would be obtained with a single half-wave vertical antenna.

When receiving near New York on frequencies above 10,000 kc., the receiver noise is likely to be higher than static for the larger part of the time, while for frequencies of less than 10,000 kc., static is more prominent and is likely to be the limiting noise.

The ratio of signal-to-static can also be improved by the use of directive antennas in most cases. The directive antenna increases the desired signal. If the static arrives from the same direction as the signal, it is also increased and no improvement in signal-to-noise ratio over a non-directional antenna will result, while if the static all comes from a direction from which the antenna gives no output, an infinite improvement over a non-directional antenna is obtained. The customary improvement obtained is somewhere between these two extreme cases and on the average may approximate the condition where the static comes equally from all directions so that the improvement in signal-to-noise ratio over a non-directive antenna is equal to the improvement in signal pickup of the antenna[2] over a non-directive antenna.

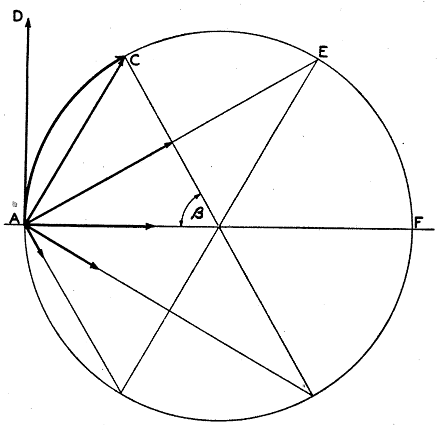

Fig. 4. Diagram for obtaining amplitude of radiation in a given direction.

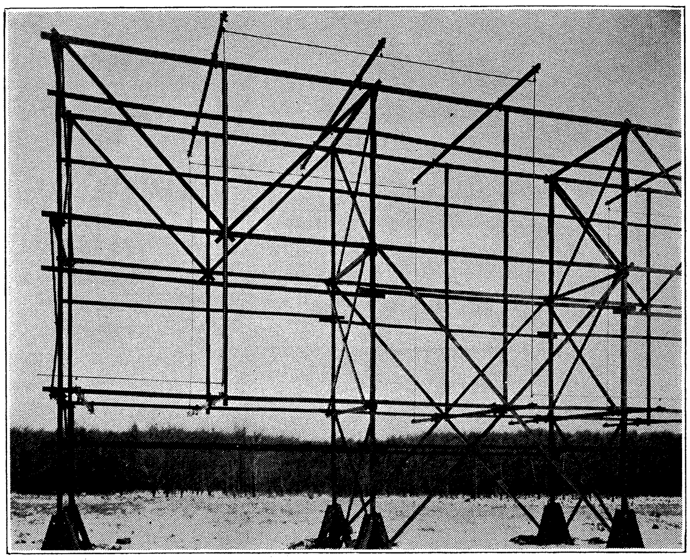

Fig. 2. End view of Bruce array.

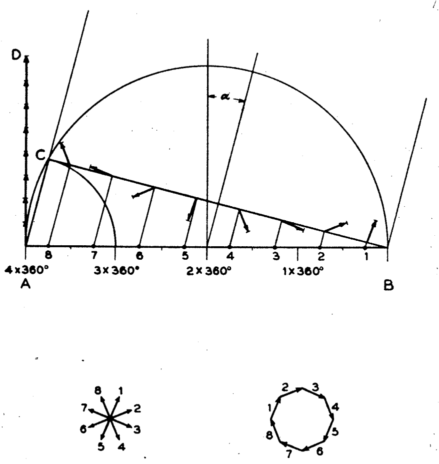

Fig. 3. Graphical computation of radiation from a plane array.

The directive antennas used for reception in the Bell System have been of two types. The first was called a "Bruce Array" and consisted of a number of quarter wavelength vertical elements spaced a quarter wavelength apart and connected to each other alternately at the top and bottom. Fig. 2 shows an end of one of these antennas. The direction of maximum reception is at right angles to the length of the antenna.

In practice, two curtains having the same construction are used, the second curtain being placed a quarter wavelength behind the first. The output trasformer is placed next to the front curtain and connected between the front and rear curtains. A wave arriving from the front induces a voltage in the front curtain and, passing on, induces a voltage in the reflector curtain a quarter cycle interval later. The voltage induced in the reflector must then be transmitted back to the antenna, requiring an additional quarter cycle interval. The transformer, therefore, has voltages 180° out of phase impressed on its terminals and a maximum of output is obtained. Waves arriving from the rear of the antenna induce a voltage first in the reflector curtain. This voltage is transmitted along the lead to the output circuit, arriving in phase with the voltage induced in the antenna curtain and thus giving no difference in voltage across the output transformer.

The directional pattern of an antenna is best expressed by a three-dimensioned figure and is customarily found by mathematical calculation. It is possible, however, to make approximate computations of the horizontal or vertical characteristics graphically in some cases.[3] Assume, for instance, that a transmitting antenna AB Fig. 3 consisted of a large number of elements in broadside relation and having currents of equal magnitude and phase. In a direction in front of the antenna the radiation from all elements will add up and may be represented as the sum of the small vectors (Fig. 3). At an angle α, such that the distance from one end of the antenna to a distant point is one wavelength less than from the other end, the sum of the radiation from the various elements will be zero, i.e., the vectors will form a closed circle; and when the angle is such, that the differ-

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[2] *For details of improvement caused by directive antennas at Netcong, N. J., see article, "High Frequency Atmospheric Noise," by R. K. Potter, Proc. I. R. E. Oct.,* 1931.

[3] *See article, "Beam Wireless Telegraph," by N. Wells, in The Electrical Review (London), May* 25, 1928.

ence in distance is one and one-half wavelengths, the vectors will again add up to give a lobe in the directive diagram. The amplitude of the lobe will not, however, be as great as the major lobe, as all of the vectors will not be adding up in exact phase but rather will be adding up in the form of a circle and a half in which the diameter of the circle is the length of the lobe in the diagram.

The amplitude of the radiation in various directions can be found from the diagram, Fig. 4. The angle β is 1/6 of that from the front to the first null. The vector AD is the sum of the unit radiations from the various elements in the front direction. At the angle 1/6 α the vectors form the arc of a circle subtending the angle β. The cord of the arc represents the radiation in the direction β. The radiation in the direction 2β from the front can be found in a corresponding manner, and is equal to one-half the vector AE. At 3β the vector would be 1/3 AF and so on. If the antenna has a reflector the diagram thus found must be multiplied by a cardioid, which is the diagram obtained with one of the antennas and one reflector element considered alone.

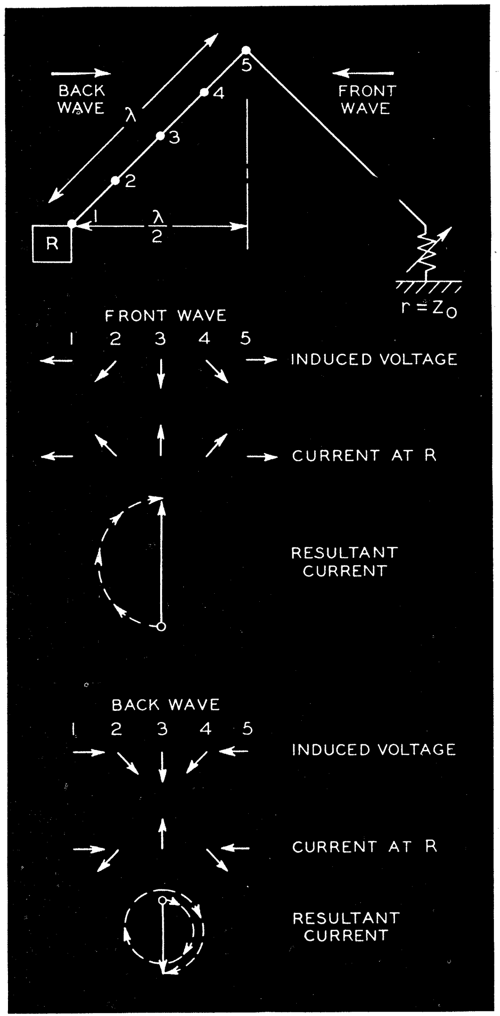

Fig. 5. Addition of voltages in an inverted "V" antenna, equivalent to half of a horizontal rhombic antenna.

This explanation has been made in terms of a transmitting antenna for simplicity but applies equally well to a receiving antenna.

The second type of antenna which has been used for receiving purposes in the Bell System is called a horizontal rhombic antenna and consists of wires forming a rhomboid or diamond-shaped figure, supported above the ground on poles. At one corner of the rhomboid, a transmission line is connected and at the diagonal corner a resistance. Horizontally polarized waves arriving at an angle above the horizontal from a direction opposite to the end connected to the transmission line induce a voltage into the various units of the antenna which add up across the transmission line terminals. A wave arriving from the opposite direction induces a similar voltage which is dissipated in the resistance at the front end of the antenna. The directive properties of this antenna are a complex function of the angles between the sides of the antenna, the length of the sides and the height above ground[4] and are not quite as simply shown by vector diagrams as in the previous case. The manner in which the voltages add up in one-half of the antenna can be seen in Fig. 5, which was originally drawn for an inverted V-antenna working to ground.

Transmission Lines

Since directive antennas are quite large and it is not desirable to place several antennas in too close proximity, transmission lines are used when several antennas are located on the same plot. A very convenient type of line is the concentric line described by Sterba and Feldman in the Proceedings, Institute Radio Engineers for July, 1932. An examination of the equations for the loss in a concentric line shows that, contrary to low frequency experience, for high frequencies there is an optimum ratio of the diameter of the inside and outside conductors of 3.6 corresponding to an impedance of approximately 72 ohms. The loss is only slightly higher, however, for ratios from 2½ to 5 times. Three sizes of concentric line have been found convenient; ⅜ inch, ¾ inch and 1⅜ inches, outside diameter. The ⅜ inch size, constructed with Isolantite insulators spaced every inch or two, has been found convenient for inside wiring as it can be bent by hand, and jacks and cords can be used for patching from one receiver to another. The sections of the 1⅜ inch line are joined by means of copper water pipe unions. This size serves admirably for long runs out of doors. Neglecting the effect of insulators the loss in the line in decibels varies inversely as the diameter, directly as the square-root of the frequency and amounts to 1 db. per 1,000 feet at 22,000 kc. for the 1⅜ inch copper line. The loss in the insulators of the large size of line is very small while with the ⅜ inch line it is an appreciable part of the total.

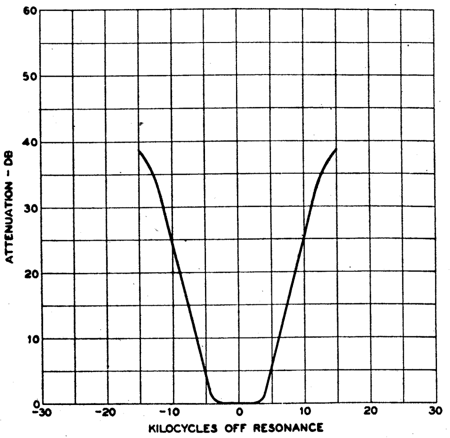

Fig. 7. Selectivity of transoceanic telephone receivers.

Some of the concentric transmission lines have been placed in a sinusoidal form, to allow for expansion, and about a foot above the surface of the earth. Other lines have been buried under the surface of the soil, and in this case no provision need be made for expansion.

Receivers

The receivers used on the transoceanic channels were designed in 1928

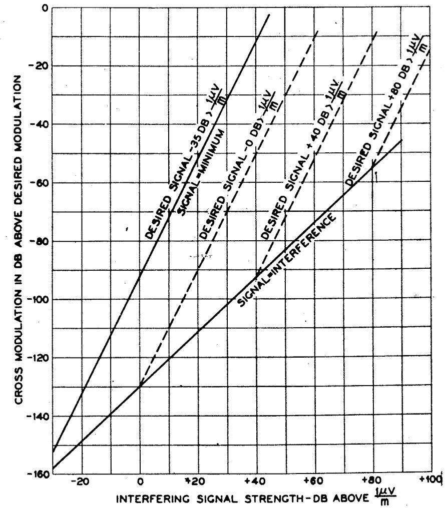

Fig. 9. Effect of volume control on cross modulation in a receiver.

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[4] *Proc. I. R. E. Vol.* 19, *pp.* 1406-1433, *for Aug.,* 1931.

and are of the double detection or superheterodyne type. They are mounted on three relay racks as shown in Fig. 6. The left bay contains two stages of high-frequency amplification, the first detector and one stage of intermediate-frequency amplification as well as two testing oscillators, one for high frequency and the other for intermediate frequency. The second bay contains a voice-frequency amplifier, a variable attenuator of 120 db., the intermediate amplifier of six stages of three-element tubes, the second detector and the volume control circuits. The third bay contains fuses; protective lamps for each plate circuit, plate, filament circuit and line jacks and meters which can be cut into the plate or filament circuits by inserting a plug into the proper jacks, a volume indicator and a shelf with telegraph key and sounder.

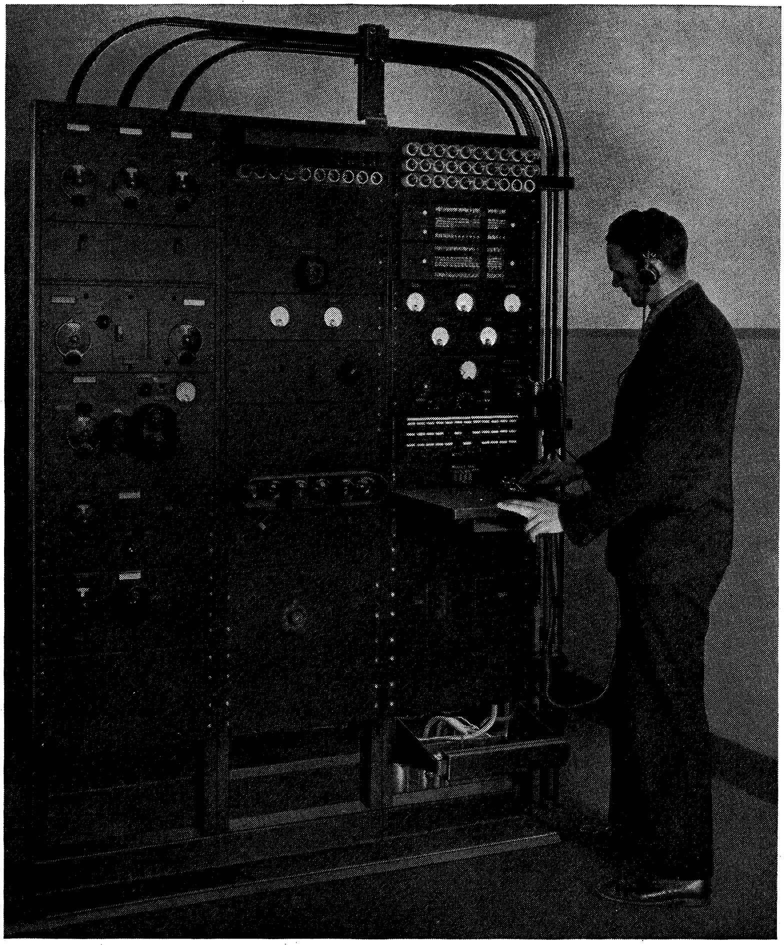

Fig. 6. Receiver used on transoceanic telephone channels.

In the design of these receivers every effort was made to obtain the highest quality and signal-to-noise ratio. The fidelity and selectivity of the receiver is shown in Fig. 7. This curve represents the intermediate-frequency selectivity corrected for audio-frequency equalization.

At frequencies of 12,000 to 20,000 kc. the static is likely to be low enough so that receiver noise is a limiting factor. In a well designed receiver, an effort is made to have substantially all the receiver noise originate as Johnson or thermal noise in the first circuit. The thermal noise voltage is proportional to the square-root of the circuit impedance.

If the first circuit noise is to override the first tube and second circuit noises, the impedance of the first circuit must be high. An analysis of the equation for the ratio of first tube grid voltage to transmission line voltage, when impedances are matched, and the equation for the impedance of the circuit, shows that the noise and signal increase in direct proportion as the impedance of the circuit is raised. By connecting the transmission line across the whole coil instead of tapping the coil to match the transmission line impedance, an improvement in the signal-to-noise ratio on the first grid of 3 db. is possible. However, this condition is not generally a practical one as the signal voltage on the transmission line is not stepped-up before reaching the first grid and is, therefore, not likely to be of sufficient magnitude to override satisfactorily the first tube noise. Where a transmission line from antenna to receiver is used the signal-to-first-circuit-noise ratio will be less than if no transmission line were used by the amount of the loss in the transmission line. To overcome this the first circuit, together with the first tube and its output circuit may be placed at the antenna. This arrangement forms a repeater which may be supplied with power over the high-frequency transmission line by the use of suitable filters.

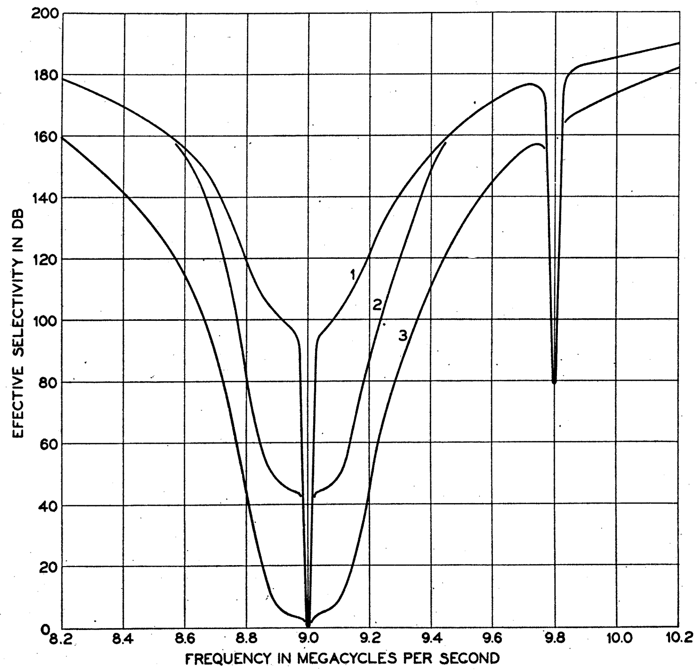

Fig. 8. Variation of effective selectivity caused by cross modulation.

Cross-modulation may be particularly troublesome in double detection receivers having high-frequency amplification for the reason that the first detector of a double detection receiver is inherently a non-linear device.

The matter of cross-modulation has been treated by writers in a mathemati-

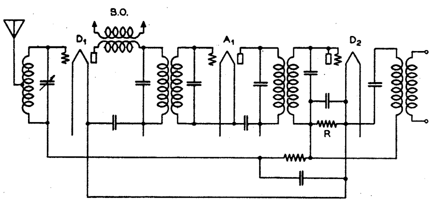

Fig. 10. Schematic diagram of double detection radio receiver with automatic volume control.

cal way. To obtain a physical picture of cross-modulation consider that two signals are impressed upon an amplifier, one wanted and one unwanted. It can be seen that the unwanted signal will sweep the operating point for the wanted signal back and forth. If the amplification is not the same at all points, the amplitude of the wanted signal will be changed periodically in accordance with the modulation of the unwanted signal.

Cross-modulation can be explained rather simply in terms of algebraic equations. By the ordinary trigonometric transformations it can be shown that if two voltages

$$P \cos pt + Q \cos qt$$

are applied to an amplifier, the output current of which is represented by the usual power series

$$i = a_0 + a_1 e + a_2 e^2 \ . \ . \ .$$

the important component of the resulting current is

$$i = \cos pt\,[a_1 P + \tfrac{3}{4} a_3 (P^3 + 2 PQ^2)].$$

If the voltage Q cos qt, which we will call the unwanted signal, is modulated to the degree M by a frequency $g/2\pi$, the previous equation, after dropping negligible terms, can be written

$$i = a_1 P \cos pt\,[1 \times (\frac{3a_3}{a_1}) Q^2M) \cos gt].$$

It will be noted that this equation is that of a modulated wave in which

$\frac{3a_3}{a_1} Q^2M$ is the degree of modulation.

This equation indicates that the cross-modulation is proportional to the ratio of the third power coefficient to the first power coefficient, and to the square of the amplitude of the unwanted signal.

Where the cross-modulation occurs in a heterodyne detector the degree to which the desired signal is modulated by the undesired signal is proportional to $6\frac{a_4}{a_2} Q^2M$. Both of the equations which have been given have neglected the effect of higher order terms. These terms may not be negligible and have to be considered in some cases.

The effect of cross-modulation upon the effective selectivity of one of the transoceanic radio receivers, as originally installed, is shown on Fig. 8. Here the upper curve shows the total selectivity as the sum of the high-frequency selectivity and the intermediate-frequency selectivity. If the unwanted signal is very weak this will be the effective selectivity of the receiver. However, for stronger unwanted signals the effective selectivity is reduced and is given by the other curves. In this particular receiver the cross-modulation occurred almost entirely in the first detector. By applying automatic volume control to the high-frequency amplifier tubes the amplitude of the unwanted signal on the first detector can be reduced when the wanted signal is high and the amount of cross-modulation cut down.

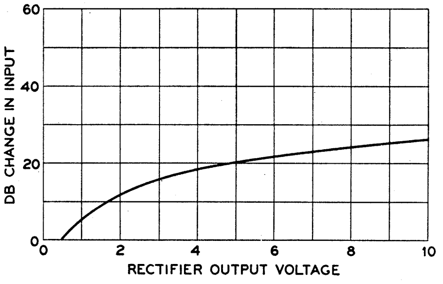

Fig. 11. Volume control rectifier output voltage.

Fig. 9 shows how the amount of cross-modulation can be conveniently plotted when it occurs all at one place. The upper left curve gives the amount of the cross-modulation in the receiver when the wanted signal is so low as not to operate the automatic volume control. The lower curve gives the modulation when the wanted and unwanted signals are kept equal. Since the amount of cross-modulation varies as the square of the interfering signal other lines representing various values of unwanted signal can be drawn in with a slope of 2:1 through the intersection of the bottom line and a given value of abscissae.

Another matter of interest in the design of a radio receiver is to be able to predict the operation of the automatic volume control. A simple radio receiver with automatic volume control is shown on Fig. 10. The system is the conventional one where the rectified output of the second detector is used to decrease the efficiency of the first detector. In Fig. 11 the variation of the rectified output of the second detector

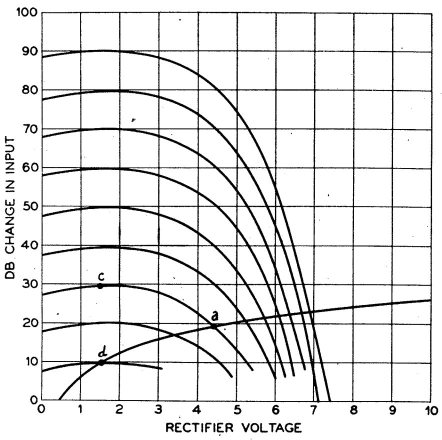

Fig. 14. Diagram for graphically obtaining automatic volume control characteristics of receiver.

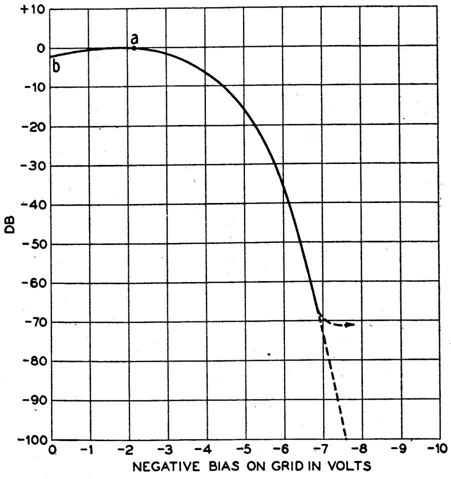

Fig. 12. Variation of efficiency of the first detector of the transoceanic receivers with change in grid bias.

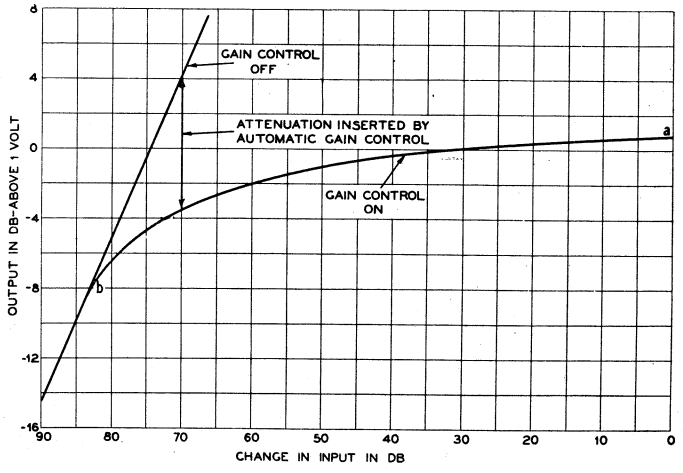

Fig. 13. Input vs. output curves of a receiver with and without automatic volume control.

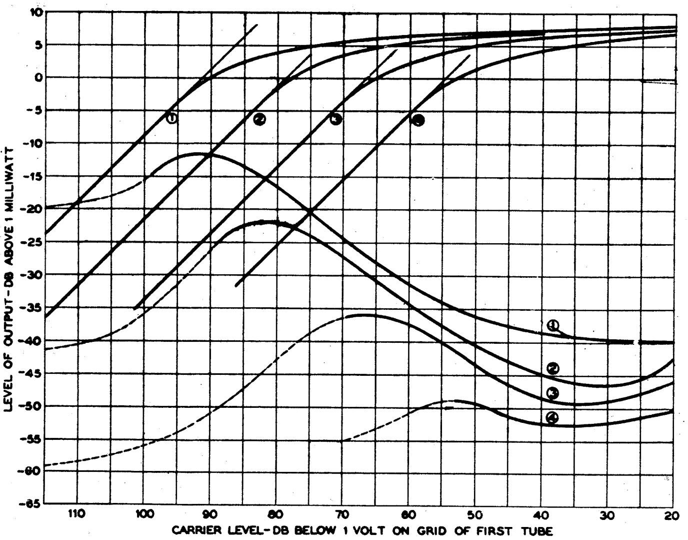

Fig. 16. Signal and set noise output of radio receivers.

(volume control rectifier) with input is shown. This curve would be a straight line if both ordinate and abscissae were in the same units. The variation of the efficiency of the first detector with variation of the negative bias is shown on Fig. 12. If the variation of receiver output with input were plotted the curve of Fig. 13 would be obtained. This curve can be synthesized from the previous figures in the manner shown in Fig. 14. In this figure, the detector efficiency curve has been retraced at intervals of 10 db., representing changes of that amount in signal intensity. Consider the signal to be such as to give a rectifier output of 1½ volts and the output of the rectifier to be the +10 db. indicated by the intersection of the rectifier output curve and the lower detector efficiency curve (point d). If the detector bias were held constant and the input raised 20 db. the output would also go up 20 db. to the point "c." If the rectifier is allowed to change the detector bias in the usual manner, however, the rectifier output will increase to "a" and the detector efficiency decrease from "c" to "a." The net increase in output when the automatic volume control is connected is seen to be 9 db. for the 20 db. increase in input. An increase of 10 db. more in input will increase the output only 2 db. Further increases in input give smaller and smaller increments in output.

If all of the intersections are plotted, using the ordinates found on Fig. 14 and steps of abscissae of 10 db. the curve of Fig. 13 will be obtained. If abscissae in absolute values are desired it is necessary to determine one point such as the point "b" by observing the output for a particular given input.

Considerable information of interest can be obtained from Fig. 13. If it is assumed that the abscissae figures are inputs in db. below one volt the maximum gain of the receiver is approximately the value of abscissae for an output of 1 volt. It is seen to be 74 db. This is actually the approximate intermediate-frequency gain of the transoceanic receivers, exclusive of high frequency amplification and first circuit transformation ratio. A reduction in gain of the receiver would result in the whole diagram being moved to the right only. The attenuation inserted by the automatic volume control is, in the absence of overloading which is assumed in the curve, the difference in ordinate between the conditions of automatic volume control on and off.

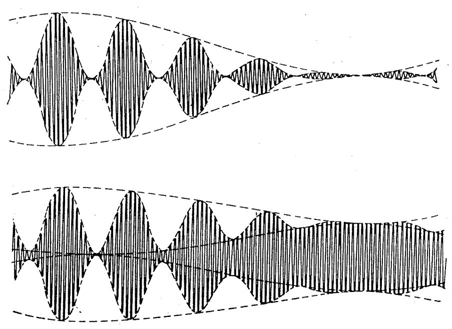

Fig. 15. a. Modulated signal with fading. b. Signal with varying modulation.

Where an attempt is made to obtain an automatic volume control of high speed (i.e., to follow fast fading) trouble may be experienced from distortion caused by the modulation on the received signal operating the volume control. The graph of a signal of constant mean amplitude but of varying modulation amplitude is shown in (b) Fig. 15. A fading signal having constant modulation is shown in (a). Since the mean amplitude of a wave of varying modulation is constant, it is evident from the curve (b) that no re-modulation at speech or syllabic frequencies will be obtained from the automatic volume control system if the volume control rectifier is linear but that a fading signal will vary the output of the volume control rectifier.

The point where attenuation is inserted by an automatic volume control must be carefully chosen if the maximum signal-to-noise ratio is to be obtained at all times in a receiving system in which the receiver noise is a limiting factor. If the gain approaches zero at any time, in say the first few stages of the receiver, the first circuit noise will no longer be controlling but much of the noise will come from the stage following the section of zero gain. For this reason it is, therefore, desirable to insert atteunation at as late a stage as possible in a receiver, but in practice a compromise must be reached with the requirement that the attenuation should be inserted at an early stage to prevent cross-modulation, as previously mentioned.

If the signal and set noise volumes at the output of a radio receiver of high gain are measured, a plot similar to Fig. 16 will be obtained. The upper curves show the variation in signal and the lower curves the variation in noise for maximum gain and for lesser gains obtained by inserting attenuation in the intermediate-frequency amplifier. The upper curves of signal and noise are for full gain in the receiver.

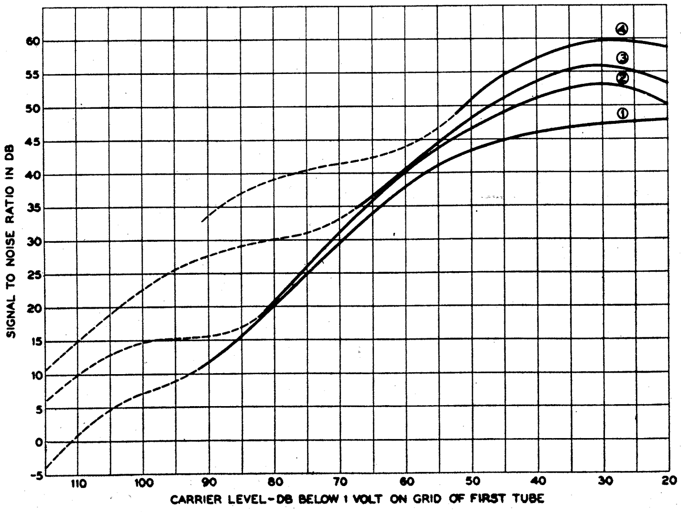

Fig. 17. Signal to set noise ratio of radio receiver.

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