The Ring Armature Telephone Receiver

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A new type of telephone receiver is described, in which the permanent magnet, the pole piece and the armature, which drives a light weight dome, are all ring-shaped parts. This structure exhibits a substantially higher grade of performance than present receivers of the bipolar type, with regard to efficiency, frequency range, leakage noise level, and response when held off the ear. In addition to showing the characteristics of this new receiver, an analysis of the various losses is given, and ideal performance limits are established. The advantage of providing an auxiliary path for the air gap flux is indicated, and other applications of the device as a transducer are described.

Introduction

THE ring armature receiver is a new type of telephone receiver developed for use in the subscriber's telephone set. It differs from other types in that the diaphragm consists of a thin, lightweight, dome-shaped central portion made of low density, non-magnetic material whose function is to radiate sound energy, surrounded by a narrow ring-shaped armature to which it is attached. The ring armature is not clamped at the outer periphery, but is held in place solely by magnetic attraction. It is driven at its inner periphery by the magnetic force. A ring-shaped pole and magnet structure serves as the motor element to drive the diaphragm. The new receiver is shown in sectional view in Fig. 1.

The advantage of the composite diaphragm construction in the new receiver is that the central portion moves almost wholly like a piston and is therefore nearly 100% effective and that its contribution to the total moving mass is small, being of the order of $\frac{1}{5}$. For these reasons it has been found possible to reduce the mass per unit area to approximately $\frac{1}{3}$ of that of the diaphragm of the bipolar receiver. Because of the large effective diaphragm area and the low mass, the acoustic impedance of the new receiver is low, being about $\frac{1}{7}$ of that of the earlier receiver. Although the motor efficiency is approximately equal to that of the bipolar receiver, the improved diaphragm construction yields a receiver of higher available power response,[1] wider frequency range, improved characteristic when the receiver is held off the ear, and having greater discrimination against room noise.

The ring armature construction is also applicable to devices other than earphones, such as microphones and loudspeakers.

[1]A.S.A. Standard Z24.9-1949 "Coupler Calibration of Earphones."

Early Steps in the Development

It has long been evident that the effective mass of the magnetic disc type diaphragm used in the bipolar receiver is high, and is therefore a serious limitation to obtaining an extended frequency range without sacrificing efficiency. Attempts were made to reduce this mass by using lightweight cone type radiators driven by relatively small magnetic discs at the center as in Fig. 2(a). The difficulties, however, of controlling the vibrational stability

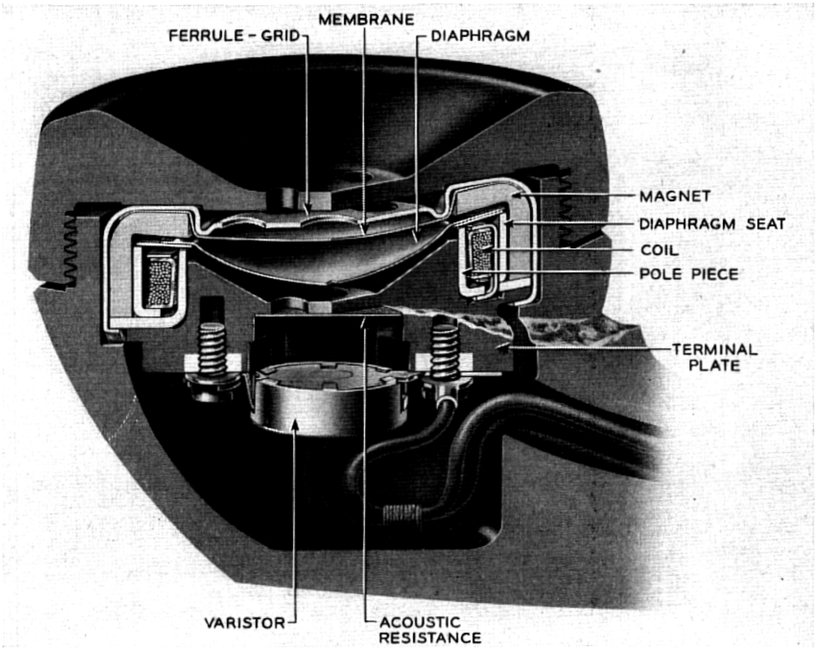

Fig. 1—Sectional view of the ring armature receiver in a handset.

of such structures made them impractical. Moreover, the mass of the armature was 100% additive to the moving system.

By reversing the positions of the armature and the light-weight portion of the diaphragm, putting the latter in the middle and using a ring of magnetic material around the outside edge as shown in Fig. 2(b), much better results were obtained.[2,3] The armature, having one edge resting on a seating surface, added only 30% of its mass to the moving system. Also, since the large central portion of the diaphragm carries no flux, it could now be replaced by a lightweight non-magnetic material instead of the relatively

[2] U. S. Patent No. 2,170,571, E. E. Mott, Filed August 12, 1936.
[3] U. S. Patent No. 2,171,733, A. L. Thuras, Filed October 6, 1937.

heavy magnetic material needed for armatures. These two factors permitted a very substantial reduction in the effective mass to be made in the moving system. In addition it has been observed that the peripherally driven diaphragm moves as a piston over a wide frequency range, while a centrally driven cone type diaphragm, as in Fig. 2(a), is more likely to have parasitic modes of vibration in the frequency range of interest. However, the receivers of the type shown in Fig. 2(b) needed small air gaps in order to get the force factor necessary to attain a high efficiency. Moreover, the thin

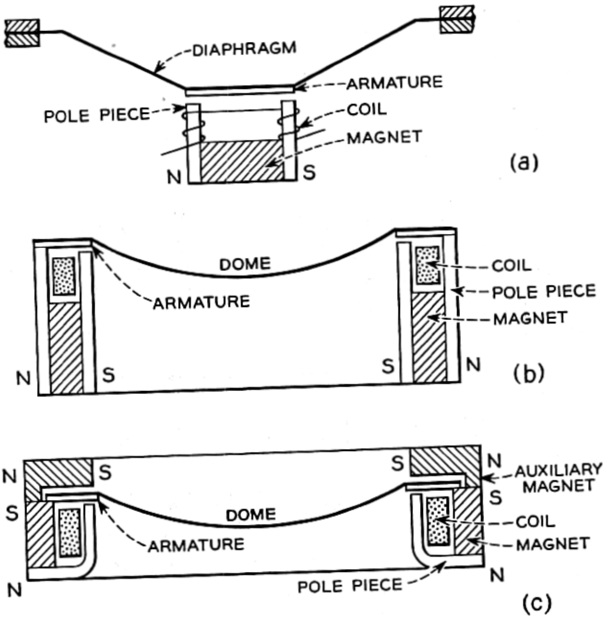

Fig. 2—(a) Early composite diaphragm receiver.
(b) Simple ring armature receiver.
(c) Ring armature receiver with auxiliary magnet.

magnet mounted between the inner and outer pole pieces presented manufacturing problems because of curved surfaces that had to be ground to close tolerances. The magnet in this case had to be of low reluctance and large section area, and this resulted in a rather tall structure.

By adding an auxiliary ring magnet overlying the front of the diaphragm, as in Fig. 2(c), radially magnetized in aiding relation to the lower magnet, a large increase in force factor was attained with larger air gaps than in Fig. 2(b).[4, 5] In addition an upright main magnet, as shown, could then be

[4]U. S. Patent No. 2,249,160, E. E. Mott, Filed May 19, 1939.
[5]U. S. Patent No. 2,249,158, L. A. Morrison, Filed July 15, 1941.

used to advantage, even though it had a relatively higher reluctance. With this design, magnetic fields were produced in the two air gaps above and below the diaphragm. In addition, the auxiliary ring magnet acted to shunt a portion of the d-c. flux around the armature, which resulted in reduced saturation in the middle portion of the armature, which permitted increased flux density in the air gap below the diaphragm. This partially separated the paths of the a-c. and d-c. flux in the magnetic structure, and adjusted the magnetic forces exerted on the diaphragm, so that lower stiffness armatures

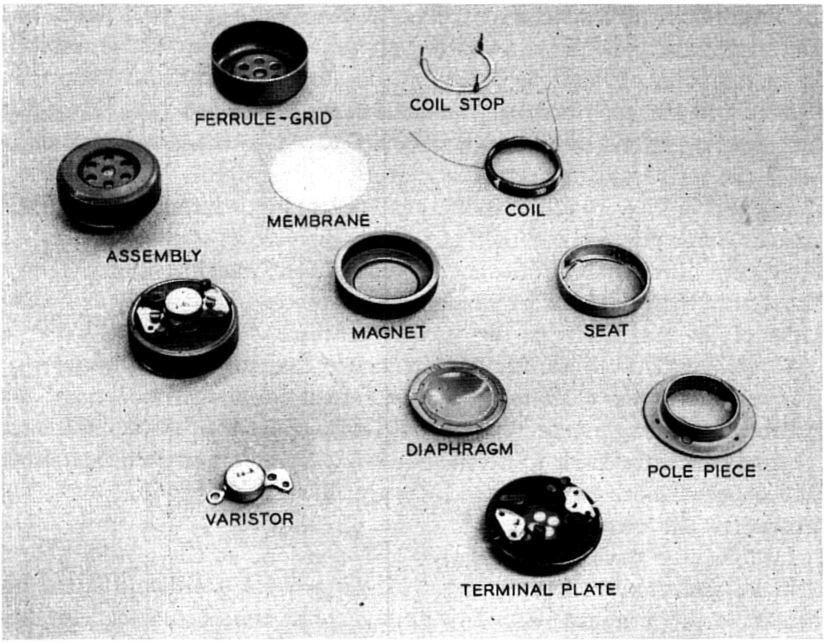

Fig. 3—Photograph of the ring armature receiver and its parts.

could be used than in the structure of Fig. 2(b). Application of the auxiliary ring magnet in front of the diaphragm contributed very substantially toward the development of a suitable motor element. The coil and magnet relationship shown in Fig. 2(c) also resulted in a lower axial height and a more compact structure.

Description of the Production Design

The main and auxiliary magnets of the early designs were Alnico castings, and were expensive to produce. In the production design, they have been combined into a single L-sectioned remalloy ring magnet, and the diaphragm seat has been transferred from the main magnet to a non-magnetic nickel-chromium alloy ring.

The details of this construction are shown in Figs. 1 and 3. The diaphragm consists of a flat ring-shaped vanadium permendur[6] armature, to the inner periphery of which is cemented a lightweight, plastic-impregnated and molded cloth dome. The dome is placed in a concave downward position with respect to the receiver cap, which greatly enhances its strength with respect to suddenly applied air pressures. At the outer periphery, the armature rests on the non-magnetic seat, and is driven at the inner margin by the magnetic field produced at the tip of the ring-shaped pole piece. The 45% permalloy[6] pole piece, at its end opposite the air-gap, has an integral flange extending outward, to which the armature seat is welded. The magnet also rests on the pole piece flange, outside of the armature seat. This magnet is made of a material similar to remalloy,[6] but of a modified composition in which the molybdenum content is increased, which results in a higher coercive force but lower residual induction. It is hot formed from sheet material into the shape of a cup and then punched to provide an opening in the base of the cup, the diameter of the opening being slightly smaller than the inner diameter of the cylindrical portion of the pole piece. The inwardly extending flange of the magnet forms the auxiliary portion.

Acoustic controls of the response-frequency characteristic of the receiver are provided in the same manner as in former telephone receivers of the controlled-diaphragm type,[7] except that lower values of acoustic impedance are used which are easier to control. Coupling chambers on each side of the diaphragm connect to constricted passageways having acoustic mass and resistance. The coupling chamber under the diaphragm exhausts into the handset handle cavity through four holes, molded in the phenol plastic terminal plate, which are covered with an acoustic resistance fabric cemented to the terminal plate. This acoustic mesh serves to extend the frequency range of the receiver because of its negative reactance characteristics, and the acoustic resistance damps out the diaphragm resonance. The coupling chamber above the diaphragm exhausts into the listener's ear cavity through the acoustic mass and resistance of the holes in the receiver cap. Proper selection of the acoustic impedances of the elements of this mesh serves still further to extend the frequency range of the receiver. The relationships of all the acoustic and mechanical elements is such as to produce the desired response frequency characteristic (See section entitled "Network Representation").

There are several parts of the ring armature telephone receiver whose

[6] "Survey of Magnetic Materials and Applications in the Telephone System," V. E. Legg, *The Bell System Technical Journal*, Vol. XVIII, July 1939.

[7] Instruments for the New Telephone Sets, W. C. Jones, *The Bell System Technical Journal*, Vol. XVII, July 1938.

functions are almost completely mechanical, as compared with the magnetic, electrical, or acoustical functions of other parts. The armature seat, which already has been mentioned, is one of these. An interesting design feature of this part is the necessity for high electrical resistivity since most of the a-c. flux links the seat and it is therefore subject to eddy current losses. A nickel-chromium alloy has been found suitable for this part. Another part having a purely mechanical purpose is the coil stop. This part consists of a flat strip of metal punched in a curved shape so as to fit on top of the coil, and having three prongs bent at right angles to the strip. The tips of the prongs pass through slits in the pole-piece flange and are bent over in assembly to hold the coil in place. A membrane is mounted between the protective grid and the magnet flange to keep dust and other foreign substances out of the instrument. In this receiver the protective grid and the clamping ferrule, which is crimped over in the final assembly, are combined into one part.

Low manufacturing costs are realized by the use of multiple-purpose parts. Some examples have been noted already. The single magnet serving as both main magnet and auxiliary magnet is an example. The combined ferrule-grid, which eliminates the fabrication, finishing, and handling of one part as compared with previous designs, is another. The terminal plate also falls into this class of parts. It not only serves as an electrical termination for the receiver, but also is molded in such a way as to provide the correct coupling air volume in back of the diaphragm; it contains the acoustic passageways leading out of the back of the instrument and provides a mounting surface for the acoustic resistance fabric cemented over these passageways; it mounts and protects a click-reduction varistor which is made a part of the receiver; it is molded with projections which prevent the spade tip terminals of the handset cord from shorting against the varistor case or turning in such a manner as to cause the cord conductors to be pinched between the receiver and its handset seating surface; it has other projections which key into the coil lead holes of the pole-piece and provide insulation between the wires and the pole-piece and at the same time orient and prevent rotation of the terminal plate with respect to the pole-piece; and it is provided with two slots into which the crimped edge of the ferrule is staked to prevent rotation of the ferrule.

Perhaps the most interesting example of a multiple-purpose part is the diaphragm dome. Its primary purpose is, of course, to radiate sound energy in its capacity as a lightweight, rigid closure for the central opening of the armature. In addition, it has six small projections molded to its top surface just outside of the dome portion, which will touch the inner edge of the magnet flange if the diaphragm is lifted upward off of its seat by mechanical shock. Thus the projections prevent the armature from coming close enough to the auxiliary magnet to be held there by magnetic attraction and insure that the armature will always return to its seat in case it is dislodged by mechanical shock. Another function which is built into the dome serves to prevent the outside edge of the armature from coming into contact with the inside surface of the cylindrical main portion of the magnet. Contact of this nature has been found to produce irregularities in the response-frequency characteristic of the receiver and a variability of the output level of a few decibels. These undesirable variations are controlled by six spokes of the dome material which extend outward beyond the edge of the armature a few thousandths of an inch and thus tend to prevent contact between the armature and magnet. Finally, the dome contains a small hole which introduces a low frequency cut-off in the response-frequency characteristic of the re-

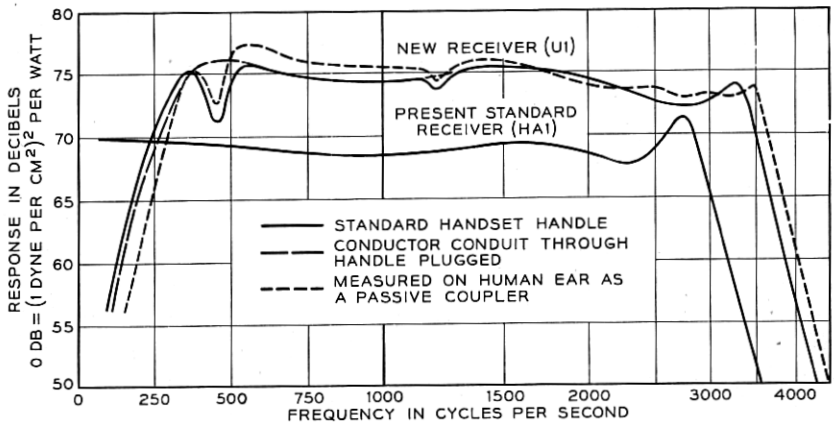

Fig. 4—Available power response-frequency characteristics measured with a source impedance of 128 ohms on a 6 cc. coupler, except as noted.

ceiver, which has been found to be desirable to reduce interference picked up in telephone circuits from electrical power circuits.

Performance Characteristics

A partial evaluation of the performance improvements of the ring armature receiver as compared with its predecessor is illustrated in Fig. 4, which shows available power response-frequency characteristics[8] for the two receivers. The two solid curves in this figure show the relative sound pressure output of the new U1 receiver and the present standard HA1 receiver over

[8]Response-frequency characteristics in this article are shown on a new frequency scale which gives a well balanced visual emphasis to the various frequency bands. The scale is linear from 0 to 1000 cycles per second, and logarithmic from 1000 to 10,000 cycles per second, the two sections having a dimensional ratio of 4 to 9. See "A New Frequency Scale for Acoustic Measurements", W. Koenig, *Bell Laboratories Record*, August 1949.

their frequency ranges. These solid curves were measured with the receiver on a standard closed coupler[9] of six cubic centimeters volume, using a source impedance of 128 ohms, and the ordinate scale is given in terms of the square of the pressure generated in the coupler per unit of electrical power available to a pure resistance of 128 ohms substituted in the electrical circuit in place of the receiver. The new receiver shows 5 decibels improvement in output level and about 500 cycles per second extension in the frequency range. This represents a very substantial increase in transducer efficiency, and the increase in range results in a quite noticeable improvement in the quality of speech sounds. The low frequency cut-off obtained by a hole in the diaphragm of the U1 receiver, mentioned in the preceding section, appears in the response-frequency characteristic below 350 cycles per second. The irregularities in the characteristic of the U1 receiver at 450 and 1200 cycles per second are not inherent in the receiver, but are acoustical effects of the passageway molded in the handset handle, which serves as a conduit for the wires connected to the receiver unit. This is indicated by the dashed line curve, which shows the response-frequency characteristic of the receiver when the passageway is plugged at the receiver bowl of the handset. No adverse effect of these irregularities has been discerned.

For comparison with the closed coupler characteristic, the dotted curve in Fig. 4 shows the pressure generated by the U1 receiver at the entrance to the human ear. This curve is an average of 90 observations on 30 subjects measured by a small diameter search tube inserted into the outer ear cavity through the receiver cap and connected to a microphone external to the handset, so that the ear is used as a passive coupler. Figure 5 shows the manner of using the apparatus, which includes a 640AA condenser transmitter mounted on the handset and coupled to the search tube through a very small chamber. It will be noted that the curve of Fig. 4 taken on a human ear shows increased low frequency cutoff because of leakage between the receiver cap and the ear, but that otherwise the 6 cc. closed coupler response is a good representation of the data taken on the ear. Considerable deviations from the average curve were observed from person to person, as illustrated in Fig. 6 which shows the maximum and minimum values of all measurements at various frequencies and the standard deviation of the measurements at three frequencies.

An interesting comparison of the performance of the U1 and HA1 receivers is made by holding the receivers slightly away from the ear. It is observed that the degradation in response caused by this condition, which represents a very large amount of acoustical leakage between the ear and the receiver cap, is much greater in the HA1 receiver. The effect is illus-

[9]Type 1 coupler per A.S.A. Standard Z24.9-1949.

trated by Fig. 7, which shows available power response-frequency characteristics for the two receivers when they are raised one-eighth of an inch from the normal sealed position on a standard coupler. The U1 receiver shows better response than the HA1 receiver at both high and low frequencies. The low frequency end is cut off less in the U1 receiver, because it has 2.5

Fig. 5—Method of measuring receiver response on a human ear, using a search tube microphone.

times larger effective area and therefore is a better radiator of sound at low frequencies. The high frequency end is better because of the inherent extension of frequency range in the U1 receiver.

Another interesting characteristic of the new receiver is its performance under conditions of high ambient noise levels. Noise leakage between the receiver cap and the external ear generates an acoustic noise pressure in the ear cavity which may mask the sound signal from the receiver. This leakage

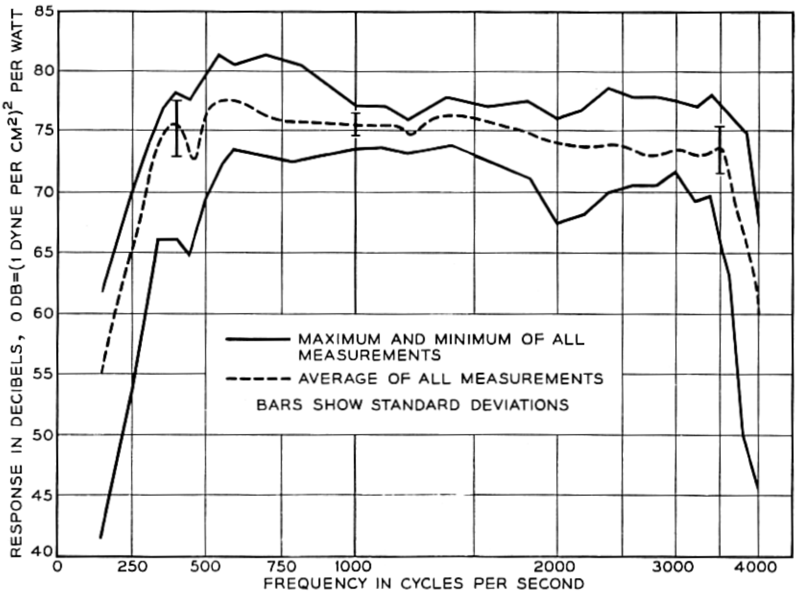

Fig. 6—Available power response-frequency characteristics of U1 receiver, measured with a source impedance of 128 ohms, on human ears as passive couplers.

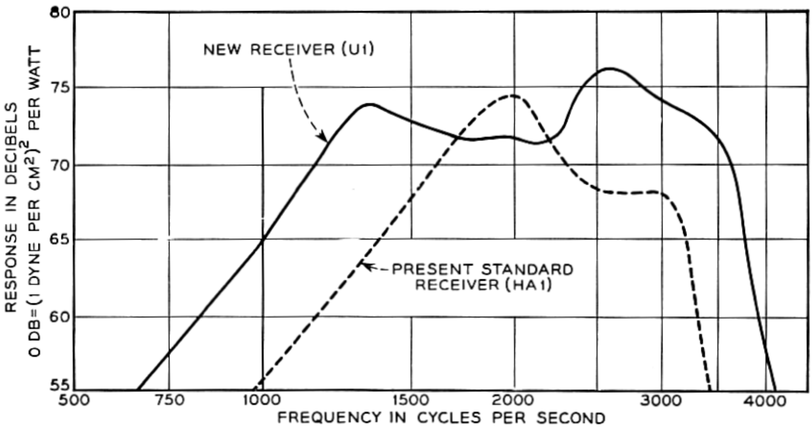

Fig. 7—Available power response-frequency characteristics, with receivers raised $\frac{1}{8}$ inch from normal position on coupler.

noise is predominantly low frequency noise not only because typical room noise characteristically decreases with increase in frequency,[10] but also because the leakage path has an acoustic impedance which rises with fre-

[10] "Room Noise Spectra at Subscribers' Telephone Locations," D. F. Hoth, *Journal of Acoustical Society of America*, Vol. 12, April 1941.

quency. The U1 receiver has considerably lower acoustic impedance than the HA1 receiver and, since the acoustic impedance of the receiver shunts the ear coupling chamber impedance, the same degree of noise leakage under the U1 receiver generates a lower noise pressure in the ear cavity with a resultant decrease in the masking effect on a given signal. Figure 8 shows data on this characteristic. Tests were made by measuring the pressure in a 6 cc. coupling chamber closed by the receiver except for a leakage path having acoustic resistance and mass values approximating those of the worst leakage condition shown by the data presented in Fig. 6. The measurements were made in a highly absorbent room, with a loud-speaker as the sound source. The curves show that below 1500 cycles per second the noise leakage sound pressure generated in the coupler when the U1 receiver is used is less than that of the HA1 receiver by as much as 5 db over a considerable portion

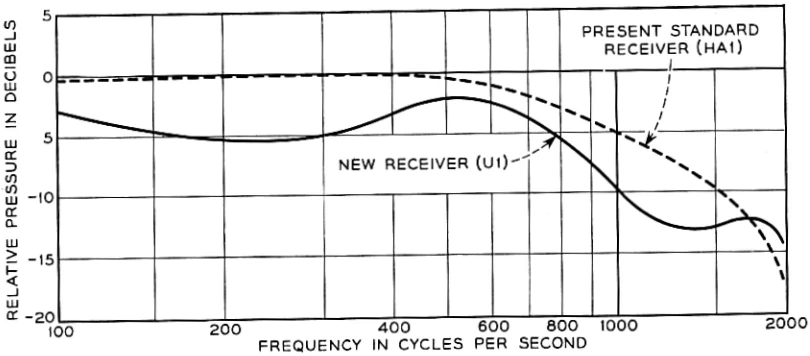

Fig. 8—Relative noise leakage sound pressure in a 6 cc. coupler having a simulated ear leak. Reference level is the pressure at the coupler with the receiver removed.

of the frequency range. The effect of this difference has been observed in listening tests using real voices* and in subjective tests† while measuring the shift in the threshold of intelligibility between the two receivers under quiet and noisy conditions. Since under certain conditions a reduction in the noise may be equivalent to a corresponding gain in signal strength, this feature of the ring armature receiver represents a distinct improvement.

A characteristic of considerable importance in the development and design of a telephone receiver is the manner in which the receiver output level varies with direct current superimposed on the alternating current flowing in the receiver coils. The direct current may be applied in such a way that it develops flux in the magnetic circuit which either aids or opposes the polar-

*Unpublished work by W. D. Goodale, Bell Telephone Laboratories.
†Unpublished work by R. H. Nichols, Bell Telephone Laboratories.

izing flux of the permanent magnet. Superimposed direct-current characteristics are shown for both the U1 and the HA1 receivers in Fig. 9. The vertical line in the plot labeled zero represents the normal operating condition of the receiver with no direct current in the coils. Increasing values of opposing current are plotted to the left and increasing values of aiding current are plotted to the right of this axis. In order that such curves may be compared fairly, they have been plotted on the basis of equal impedances for the two instruments, and each receiver has been referred to an impedance of 100

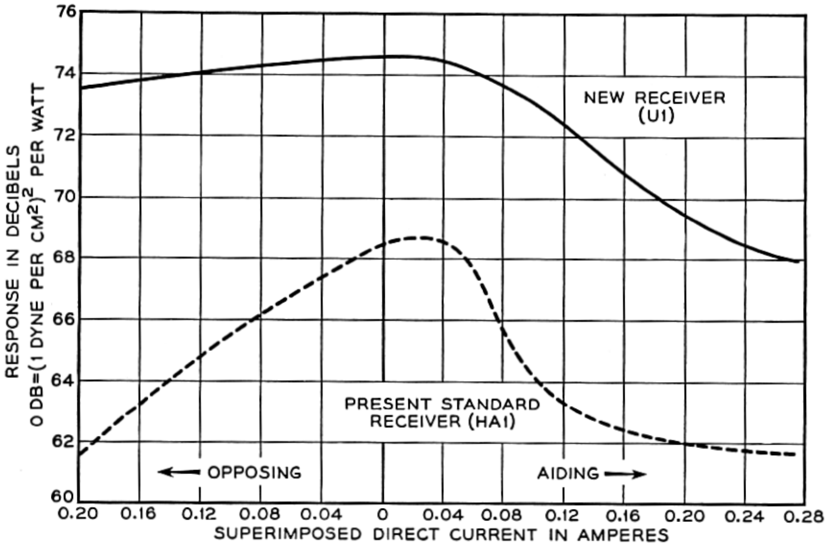

Fig. 9—Available power response versus superimposed direct current characteristics measured from a source impedance of 128 ohms on a 6 cc. coupler at 1000 cps. Each receiver has been referred to 100 ohms impedance by multiplying its current values by $\sqrt{\frac{Z_{1000}}{100}}$.

ohms. Thus, if both receivers were of 100 ohms impedance at a frequency of 1000 cycles per second the curves would be compared directly. If an instrument has an impedance differing from 100 ohms, its direct current values along the scale are multiplied by a suitable scale factor as follows:

$$\text{Current scale factor} = \sqrt{\frac{Z_{1000}}{100}}$$

where Z_{1000} is the magnitude of the receiver impedance at 1000 cycles per second.

The superimposed direct-current characteristics are an indication of the stability of the receivers. Slight changes in the air-gap of a receiver may occur during its life due to external mechanical stresses, extreme temperature variations, or magnetic influences. The application of direct current to the receiver winding produces such changes in the air-gap artificially in a controllable and reproducible manner, and shows that within a certain range there is no serious effect on the response level to be expected from slight alterations in the air-gap. The curve also shows that there is an optimum magnetization for the instrument at which the response is a maximum, and the sharpness or bluntness of the response peak is a measure of the stability.

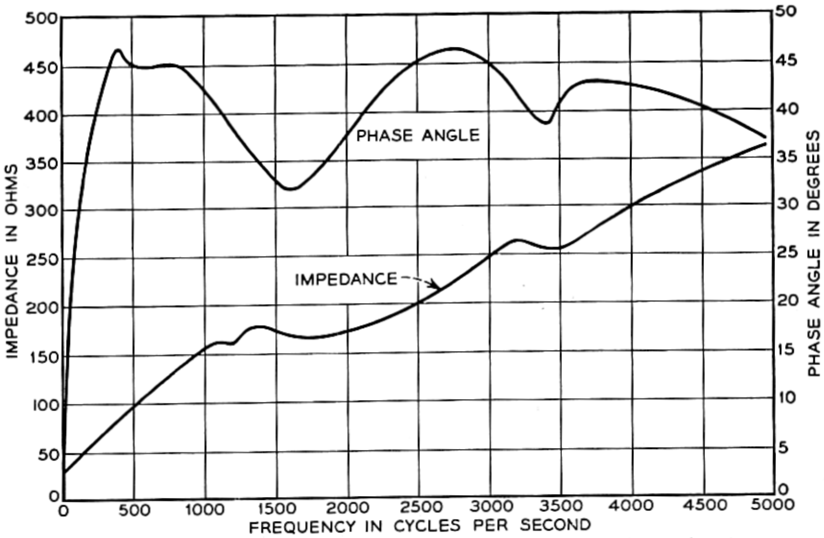

Fig. 10—Impedance of ring armature receiver, measured on a closed chamber of 6 cc volume.

The comparison between the two receivers shows that the U1 receiver is less sensitive to changes in superimposed direct current than the HA1 receiver.

The impedance-frequency characteristic of a typical U1 ring armature receiver, measured on a closed chamber of 6 cc. volume, is shown in Fig. 10. The magnitude of the impedance rises with frequency because of the inductance of the instrument. The departures of the impedance curve from a smooth upward sweep with frequency represent the contributions of the mechanical and acoustical elements of the receiver to the electrical impedance, that is, the motional impedance. The phase angle of the ring armature receiver averages 40°, which is somewhat lower than that of bipolar receivers such as the HA1 because of the larger part played by eddy currents in the impedance of the former.

Network Representation

The representation of electro-acoustical transducers as electrical networks has long been a useful tool.[11, 12] Extensive use of this analogy has been made in the development and design of the ring armature receiver. The saving of time and increase in accuracy and completeness of analysis possible with this technique is apparent when it is realized that a complete family of response-frequency characteristics, showing the effects of variation of one or more of the mechanical or acoustical constants of the instrument, can be obtained by electrical measurements of voltage on an electrical network for various settings of variable inductances, capacitances, or resistances which simulate the mechanical or acoustical constants of interest. The amount of work required to obtain the same information by building and testing mechanical and acoustical models is such that in many cases it would be impractical or impossible within a reasonable time interval.

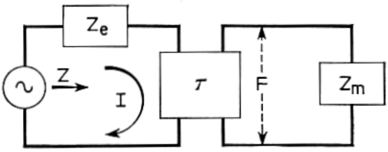

Fig. 11—Block diagram network representation for receivers.

A complete generalized representation of the ring armature receiver is shown in Fig. 11 in block diagram form. Z_e is the electrical impedance of the instrument with all motion of the armature blocked mechanically. Z_e includes a mesh which simulates the effects of eddy currents in the metallic structure of the instrument. τ is the force factor, defined as the force applied to the armature per unit of current flowing in the receiver winding. Z_m is the mechanical impedance of the mechanical and acoustical portion of the receiver at the point of application of the force, F. The relationships in this diagram are

$$\tau = \frac{F}{I} \quad \text{and}$$

$$Z = Z_e + \frac{\tau^2}{Z_m}.$$

The term $\frac{\tau^2}{Z_m}$ is the motional impedance of the instrument.

[11] "High Quality Recording and Reproducing of Music and Speech," J. P. Maxfield and H. C. Harrison, *Bell System Technical Journal*, July 1926.
[12] "Theory of Magneto-Mechanical Systems as applied to Telephone Receivers and Similar Structures," R. L. Wegel, *Am. Inst. of Elec. Eng.*, October 1921.

In studying the performance of an instrument the three elements in the above block diagram, Z_e, τ, and Z_m are considered separately, and a differ-

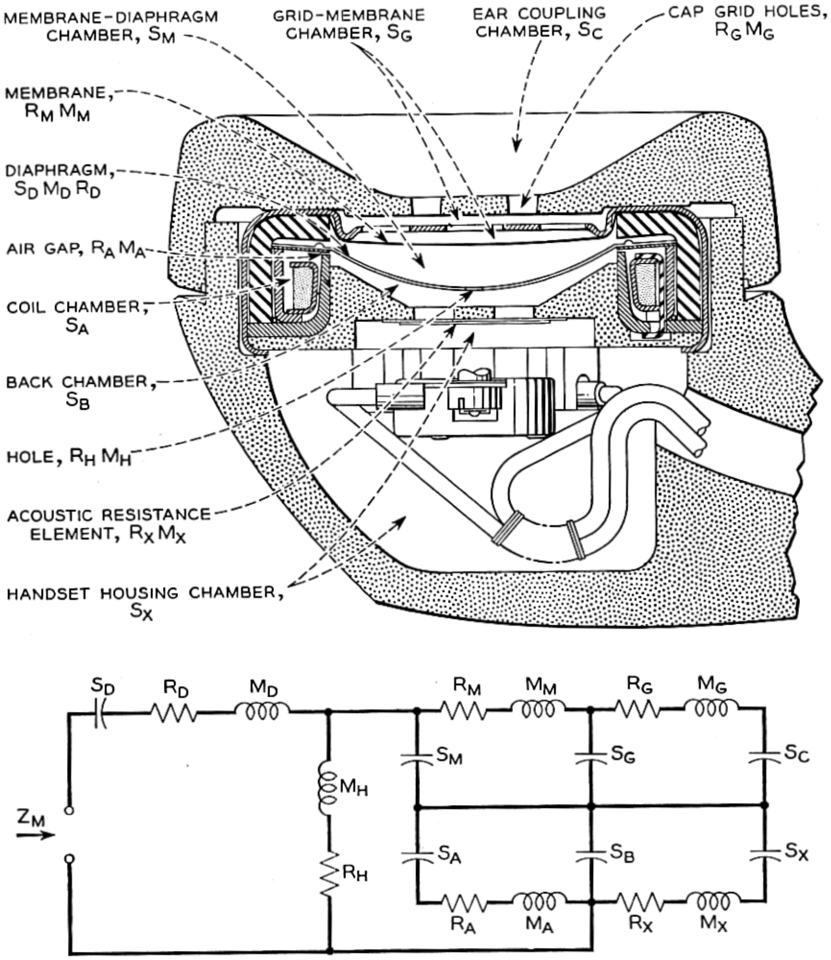

Fig. 12.—Z_m. Equivalent network of mechanical and acoustical elements of ring armature receiver.

ent type of analysis applied to each. These three elements and their analyses and uses will be discussed separately below:

(a) *Mechanical and Acoustical Elements*

The element of the block diagram represented by Z_m is the portion of the network representation of most use in the development and design of receivers. Figure 12 shows an expansion of Z_m into an equivalent electrical network which has been used extensively in the study of the ring armature receiver. The cross-sectional drawing of the receiver and associated handset handle and cap is labeled to indicate the various acoustical and mechanical elements which are represented by the electrical circuit in the lower portion of the figure. Thus S_D, M_D and R_D represent the stiffness, mass, and mechanical resistance of the diaphragm; M_H and R_H represent the mass and resistance of the hole in the diaphragm which provides the low-frequency cut-off in the receiver, etc. One item of interest in this circuit representation, which differs from that of previous receivers, is the division of the chamber in back of the diaphragm into two parts, S_B and S_A, connected by the air passageway R_AM_A of the magnetic air-gap between the armature and the pole-piece tip. Under certain conditions, particularly those representing the receiver with some of the acoustical controls removed, the acoustical constants of the air-gap have been found to be of sufficient magnitude to warrant this division of the total back chamber into two connected parts. An approximation is involved in this representation of the back chamber in that the force applied to the coil chamber, S_A, by the motion of the armature is ignored, but this approximation is justifiable through a consideration of the relative magnitudes of the effective areas and volumes involved, and the representation has been found to be in good agreement with measurements on the actual physical structures.

The constants of the equivalent circuit are determined by various physical measurements and computations. For example, the effective mass of the diaphragm, M_D, is estimated from the weights and the integrated vibratory kinetic energy of its various parts. The diaphragm stiffness, S_D, is then computed from its resonant frequency. The diaphragm resistance, R_D, is determined from a circle diagram analysis. The various chamber stiffnesses are computed from their air volumes, knowing the integrated effective area of the diaphragm. The acoustical resistances and masses are obtained from a combination of theoretical computations and special tests on the network, using circuit conditions in which these constants play the predominant role.

In setting up this equivalent circuit for analysis and study, mechanical resistances are replaced by electrical resistances; masses are replaced by inductances; and compliances, the reciprocal of the stiffnesses, are replaced by capacitances. Response-frequency characteristics may then be determined by applying a constant voltage to the input terminals and noting the voltage across S_C, which is proportional to the pressure generated in the ear coupling chamber for constant force applied to the armature. The effects of changes in any of the elements can be determined by simply changing the electrical value of the equivalent network element and repeating the measurement. In this manner, optimum values or combinations of values may be determined to provide the desired response-frequency characteristic, the effect of proposed design changes may be predicted, and other characteristics determined without building large numbers of physical models.

(b) *Damped Electrical Impedance*

The damped electrical impedance of the receiver, that is, the electrical impedance when the armature is blocked so that it cannot move, is represented by Z_e in the block diagram of Fig. 11. The damped impedance of the ring armature receiver plotted against frequency is shown in Fig. 13. The

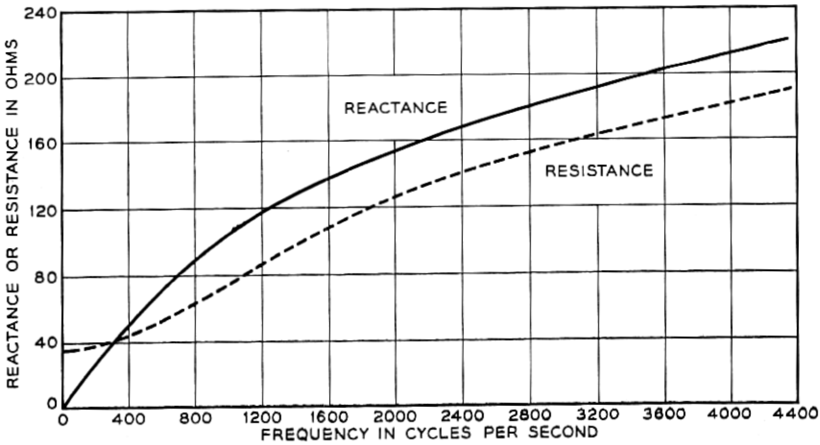

Fig. 13—Damped impedance of ring armature receiver without varistor.

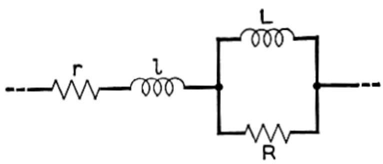

Fig. 14—Z_e. Network representation for the damped impedance.

rise in resistance and the departure from linearity of the reactance are due to the effects of eddy currents in the metallic parts of the instrument.

A circuit representation for Z_e is shown in Fig. 14. This circuit is derived on the assumption of a single eddy current path coupled to the receiver winding. The electrical resistance and inductance of the winding are represented by r and ℓ, and the eddy current circuit by R and L. Analysis of this circuit is useful in determining the extent to which eddy currents have a detrimental effect on the efficiency of the receiver. In general, the effect of eddy currents is greater in the ring armature receiver than in the bipolar types, largely because of the toroidal form of the motor element. Slotting of the ring-shaped parts has been found to be ineffective in reducing the eddy currents. However, with the low effective mass and large effective area of the diaphragm, the constants of the acoustical elements shown in Fig. 12 can be adjusted to compensate almost completely for the effects of eddy currents, even up to quite high frequencies.

(c) *Force Factor*

The third element in the block diagram of Fig. 11 is τ, the force factor, defined as the force on the armature per unit current flowing in the receiver

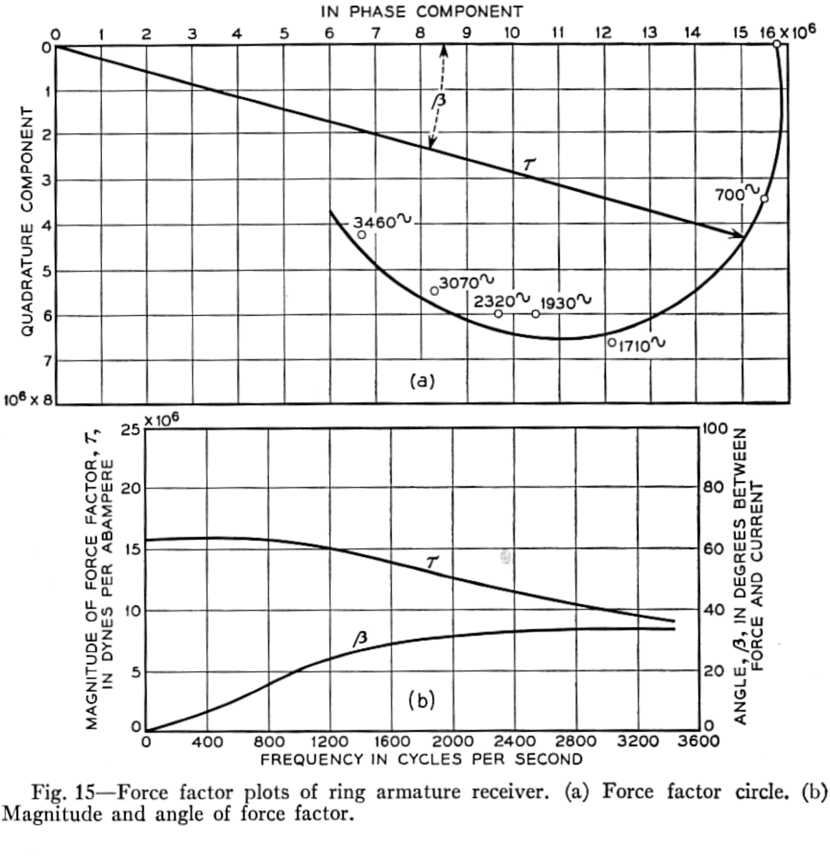

Fig. 15—Force factor plots of ring armature receiver. (a) Force factor circle. (b) Magnitude and angle of force factor.

winding. This is a complex quantity whose angle between force and current is designated by the symbol β. In magnetic receivers like the ring armature receiver, the force factor varies with frequency, both in magnitude and in phase. Fig. 15(a) shows a vector plot of this quantity, and indicates how the terminus of the vector follows an approximately circular path with change in frequency. Figure 15(b) is a chart showing the magnitude of τ and the angle β as functions of frequency.

The force factor diminishes with increasing frequency, and is largely dependent upon the alternating component of flux in the field of the air-gap. The presence of eddy currents produces a component of flux there also, which is usually in opposition to that produced by the current in the coil winding. The net amount of flux is thus diminished with increasing frequency as the effect of eddy currents becomes greater. It has been shown[12] that, for a single eddy current path, the locus of the vector plot such as that of Fig. 15(a) would be a semicircle with its center on the horizontal axis. The fact that the center of the circular locus shown here is somewhat below the horizontal axis indicates a departure from the simple theory. It seems likely, however, that if two or more eddy current paths exist having substantially different time constants, the departure shown here might be explained.

The values of force factor are obtained from a circle diagram analysis with the diaphragm resonated at different frequencies in the middle and upper frequency range. For very low frequencies, the mechanical impedance of the receiver is determined by the stiffnesses of the system, provided the hole in the diaphragm is closed, and a simple expression for the force factor at low frequencies can be derived in terms of the pressure generated by the receiver in a closed coupler for a given current in the receiver. This expression is

$$\tau_0 = \frac{(p_0)}{(I)} \cdot \frac{S_r + S_f}{S_f} \cdot A \text{ dynes per abampere.}$$

where τ_o is the low frequency force factor, p_o is the low frequency pressure generated in a closed coupler for current I in the winding, S_r is the total mechanical stiffness of the diaphragm and acoustic chambers back of the diaphragm referred to the effective diaphragm area A, and S_f is the mechanical stiffness of the closed coupling chamber in which p_o is measured.

Since the force per unit current will depend on the number of turns in the coil, force factor is not independent of receiver impedance. Thus, when comparing the force factors of receivers, it is necessary to refer the measured values of force factor to a common value of impedance by introducing a factor based on the ratio of the square roots of the impedances of the receivers being compared. Such comparisons between the ring armature receiver and its bipolar predecessor show approximately equal values of force factor at low frequencies, with the ring armature receiver force factor falling off more rapidly at higher frequencies.

Limits of Receiver Efficiency and Distribution of Losses at Low Frequencies

In the design of this receiver, an object has been to make the efficiency as high as practicable over the frequency range from 350 to 3500 cps. Since there are theoretical limits to the level of efficiency which cannot be surpassed even in the ideal case where there are no losses, it becomes of interest to determine the magnitude of these upper limits. It is also of interest to determine the amount and origin of the various types of losses that occur, and to what extent they can be minimized.

In the case of a telephone receiver, the character of the ear load is predominantly a reactance, corresponding to the stiffness reactance of an ear cavity of about 6 cc. volume. The power transfer to such a load is not ordinarily used to denote the efficiency, as may be done for a resistance terminated device such as a loudspeaker for example. Instead, the available power response is taken as a measure of relative efficiency of receivers, and it is defined as follows:

$$\text{Response} = 10 \log \eta = 10 \log \frac{|p|^2}{E^2/4R_0} \tag{1}$$

Where

$10 \log \eta$ = available power response in *db* referred to $(1 \text{ dyne/cm}^2)^2$ per watt.

p = pressure developed in the ear cavity in dynes/cm^2.

E = voltage of source in volts.

R_o = source resistance in ohms; chosen in this discussion to be equal to the receiver impedance at the midband frequency f_o, 1000 cps.

In this expression, the numerator $|p|^2$ is proportional to the acoustic power output, while the denominator $E^2/4R_o$ is the available power input.

Low Frequency Loss Analysis

It will now be shown that the available power response approaches a theoretical limit which is about 17 *db* higher than the response level of this receiver at low frequencies, and that this expression may be arranged to give five loss factors, each of which has an important physical significance.

For this purpose we need to consider only the stiffness, force factor, and inductance of the receiver working into a closed chamber representing the ear load. It is well known that in this instance for frequencies below 500 cps, with the receiver working out of a source of constant voltage E, and resistance R_o, the equations of motion are:

$$\begin{aligned} (R_o + R + j\omega L)\, I + j\omega\tau\, .10^{-7}\, x &= E \\ -\tau I + (S_r + S_f)\, x &= 0 \end{aligned} \tag{2}$$

where L = low frequency inductance of receiver winding in henries

R = low frequency resistance of receiver winding in ohms

τ = transduction coefficient or force factor in dynes per ampere

S_r = stiffness of receiver diaphragm, including the rear chamber, negative field stiffness, etc. in dynes per cm.

S_f = stiffness load of coupler and front volume in dynes per cm.
I = current in amperes
x = displacement of diaphragm in cms.

The solution of these equations for the displacement is

$$x = \frac{\tau E}{(R_0 + R + j\omega L)(S_r + S_f) + j\omega\tau^2 \cdot 10^{-7}} \tag{3}$$

For an adiabatic change, the pressure p in the chambers in front of the diaphragm due to a small displacement x is

$$p = \frac{\gamma P_0 A}{V_g + V_c} x = \frac{S_f}{A} x, \tag{4}$$

where γ = ratio of specific heats of air = 1.405
P_o = atmospheric pressure = 1.013 x 10^6 dynes/cm²
A = effective area of diaphragm in cm²
V_g = receiver front volume beneath the grid holes, in cm³
V_c = coupler volume = 6 cm³

Combining equations (3) and (4) we have

$$p = \frac{\gamma P_0 A}{V_g + V_c} \cdot \frac{\tau E}{(R_0 + R)(S_r + S_f) + j\omega[\tau^2 10^{-7} + L(S_r + S_f)]}. \tag{5}$$

Substituting equation (5) in equation (1) and expressing η as a power ratio we obtain

$$\eta = \frac{\gamma P_0}{V_g + V_c} \cdot S_f \cdot \frac{4R_0\tau^2}{(R_0 + R)^2(S_r + S_f)^2 + \omega^2[\tau^2 10^{-7} + L(S_r + S_f)]^2}. \tag{6}$$

Let $$K = \frac{\tau^2 10^{-7}}{L(S_r + S_f)} \quad \text{or} \quad \tau^2 = KL(S_r + S_f)10^7$$

Then

$$\eta = \frac{4\gamma P_0 .10^7}{V_c} \cdot \frac{V_c}{V_g + V_c} \cdot S_f \cdot \frac{R_0 KL(S_r + S_f)}{(R_0 + R)^2(S_r + S_f)^2 + \omega^2[KL(S_r + S_f) + L(S_r + S_f)]^2} \tag{7}$$

and factoring

$$\eta = \frac{4\gamma P_0 .10^7}{\omega V_c} \cdot \frac{V_c}{V_g + V_c} \cdot \frac{S_f}{S_r + S_f} \cdot \frac{K}{1 + K} \cdot \frac{R_0\omega L(1 + K)}{(R_0 + R)^2 + \omega^2 L^2(1 + K)^2} \tag{8}$$

At low frequencies, the reactance of the receiver as seen from the electrical side is $X = \omega L(1+K)$. Hence the last factor of the above equation becomes $\frac{R_0 X}{(R_0 + R)^2 + X^2}$. Taking the case of a pure reactance receiver first, we may place $R = O$, and if we further match R_0 to X at the midband frequency f_0, and then denote the value of X at f_0 as X_0, we have

$$\frac{R_0 X}{(R_0 + R)^2 + X^2} = \frac{X_0 X}{X_0^2 + X^2} = \frac{f/f_0}{1 + (f/f_0)^2}$$

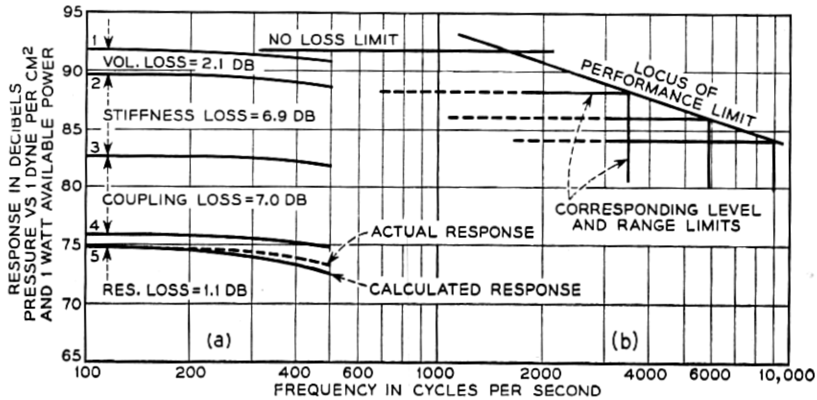

Fig. 16—(A) Low frequency loss distribution of ring armature receiver. (B) Theoretica limits of response level and frequency range, for receivers with uniform response down to zero frequency.

The latter step assumes that the low frequency reactance X is a linear function of frequency. For the pure reactance receiver, the response then becomes

$$10 \log \eta = 10 \log \frac{2\gamma P_0 .10^7}{V_c \pi f_0\left(1 + \frac{f^2}{f_0^2}\right)} \cdot \frac{V_c}{V_g + V_c} \cdot \frac{S_f}{S_r + S_f} \cdot \frac{K}{1 + K} \qquad (9)$$

Thus it is seen that the expression for the efficiency may be factored into four terms, each of which has a significant physical interpretation.

A plot of these factors versus frequency is shown in Fig. 16(a). Curve (1) represents the first term only, the others are assumed to be equal to unity. This may be called the ideal response, where no loss occurs and it has a level of 91.7 *db* vs. (1 dyne/cm²)² per watt for a 6 cc. front volume and a matching frequency of 1000 cps. Curve (2) represents the product of the first two terms; added is the volume loss $V_c/V_g + V_c$, which is the effect of introducing additional front volume between the diaphragm and cap, thus increasing the total front chamber volume of the load. Curve (3) includes the effect of the third term of the equation, which may be called the stiffness loss, because it adds a diaphragm stiffness S_r, in series with the load stiffness, S_f. Curve (4) includes the coupling factor, $K/1 + K$, which depends on the force factor that can be developed in relation to the inductance and stiffness of the system. This factor contains the term $K = \dfrac{\tau^2 10^{-7}}{L(S_r + S_f)}$ which is a sort of coefficient of coupling, analogous to the electrical coupling coefficient of a transformer, except that it may exceed unity. The whole factor, however, $K/1+K$, can never exceed unity, and we may call it k^2, defining k as the "coupling factor." Thus each term of this equation may be associated with some physical part of the receiver, which contributes to the losses.

A fifth term will now be developed, which may be called the resistance loss, due to the electrical resistance of the receiver. If the receiver has a resistance R, the last term of equation (8) may be written as $\dfrac{R_0 X}{(R_0 + R)^2 + X^2}$ where R and X are taken as the measured low-frequency resistance and reactance of the receiver.

In equation (9) however, the term $\dfrac{f/f_0}{1 + (f/f_0)^2}$ was factored out of this expression and included as part of the first term. To take account of this, the remaining term for the resistance loss becomes

$$\text{Resistance Loss} = \frac{R_0 X}{(R_0 + R)^2 + X^2} \cdot \frac{1 + (f/f_0)^2}{f/f_0}$$

If this remaining factor is included, the expression for the response of the receiver with resistance becomes

$$10 \log \eta = 10 \log \left(\frac{2\gamma P_0 10^7}{V_c \pi f_0 \left(1 + \frac{f^2}{f_0^2}\right)} \right) \cdot \left(\frac{V_c}{V_g + V_c} \right) \cdot \left(\frac{S_f}{S_r + S_f} \right) \cdot \left(\frac{K}{1 + K} \right) \cdot \left(\frac{R_0 X}{(R_0 + R)^2 + X^2} \cdot \frac{1 + f^2/f_0^2}{f/f_0} \right) \tag{10}$$

This is the equation of the curve (5) shown in Fig. 16a. This curve checks quite closely with the measured response of the actual receiver, shown by the dashed curve (5). The close coincidence of the solid and dashed curves constitutes a check on the accuracy of both the theoretical and measured response of the receiver. The slight divergence of these curves in the range from 300 to 500 cps is due to the effect of the mass of the diaphragm, which was neglected in the calculations.

While the above analysis is limited to low frequencies, it gives one an indication of the magnitudes of the various types of losses. It shows that, of these, the stiffness loss and coupling loss are the greatest. Considerable progress has been made in the design of this receiver in reducing the stiffness loss from 11.3 *db* for the HA1 receiver to 6.9 *db*. This is due largely to the increased effective area and low acoustic impedance of the diaphragm.

Receiver Efficiency Limits

In the analysis above, it is shown that for an ideal receiver having no losses, operating into a 6 cc. chamber, and matched at 1000 cps, the response approaches an upper limit of 91.7 *db* vs. (1 dyne per $cm^2)^2$ per watt. In other words, this is the limit which the low-frequency response of an idealized receiver approaches when the diaphragm stiffness S_r, the front chamber V_g, and the coil resistance R all approach zero, and the coupling factor k approaches unity. However, in addition to the level limit there exists a frequency range limit which lowers the level of the former limit. The curve labelled "Locus of Performance Limit" of Figure 16(b) determines both these boundaries. Thus, if any point is selected on this curve, a horizontal and a vertical line through it determine simultaneously the maximum response level and the highest frequency range obtainable. The calculation of both

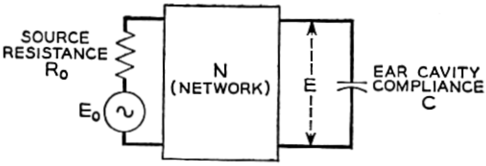

Fig. 17—Network of an ideal receiver having a uniform response over a given band of frequency.

limits may be based on H. W. Bode's resistance integral theorem.[13] In accordance with this theorem, when an ideal coupling network N, shown in Fig. 17, is used to give the maximum performance between a resistance source R_o and a capacitative load C, we have the general formula

$$\int_0^\infty e^{2a}\, d\omega = \frac{\pi}{2CR_0} \tag{11}$$

where $e^{2a} = \left(\frac{E}{E_0}\right)^2$

E_0 = the source voltage

and E = the voltage developed across the load C.

[13] "Network Analysis and Feedback Amplifier Design," H. W. Bode—D. Van Nostrand Co.—p. 362.

If a flat transmission is required over a given band of frequencies we may replace the limits of integration by ω_1 and ω_2, these quantities representing the edges of the useful band, which yields

$$\left(\frac{E}{E_0}\right)^2 \cdot \int_{\omega_1}^{\omega_2} d\omega = \frac{\pi}{2CR_0}$$

or

$$\frac{E^2}{E_0^2/4R_0} = \frac{2\pi}{C(\omega_2 - \omega_1)} = \frac{1}{C(f_2 - f_1)} \tag{12}$$

Translating this expression into the equivalent acoustical system, where C represents the compliance of the human ear cavity, it may be shown* that, by substituting $C = \dfrac{V_c}{\gamma P_o}$, replacing the voltage E by the pressure p developed in the cavity, and by using the factor of 10^7 to convert from practical to c.g.s. power units the following equation results

$$\eta = \frac{p^2}{E_0^2/4R_0} = \frac{\gamma P_0 .10^7}{V_c(f_2 - f_1)}. \tag{13}$$

This is the expression for the available power response of an ideal receiver which is assumed to have a flat response over the band of frequencies extending from f_1 to f_2.

The plot of this equation expressed in decibels, and marked "Locus of Performance Limit" is shown in Fig. 16(b) taking V_o as 6 cc and f_1 as zero. From this curve, an ideal receiver having a bandwidth of 3500 cps would have a response level of 88.3 *db*. It is also evident that the low frequency analysis given in the preceding section corresponds to a receiver with a range of approximately 1600 cps, while for wider ranges the response level would be lower, corresponding to the three other bands shown in the figure.

From the analysis given above, it is clear that the 88.3 *db* level limit supersedes the 91.7 *db* value based on the low frequency losses alone, because the former value takes account of the frequency range over which a receiver is designed to operate. A complete loss theory would undoubtedly arrive at the lower limit. However, because of the reactive load, it has not been possible to derive a suitable formula which includes the dependence on frequency range, and at the same time shows the character of the losses. The utility of the low frequency analysis lies in the fact that it shows the relative importance of the various losses, and where the most opportunity for improvements lies, and their likely magnitudes. It must be realized that although ring armature receivers may be built in the laboratory, which have smaller losses than the receiver discussed, the present design is a compromise chosen to be most suitable for use in the subscriber's telephone set.

*Unpublished work by T. J. Pope, Bell Telephone Laboratories, Inc.

Magnetic Circuit

The essentials of the magnetic structure of the ring armature receiver, including an equivalent circuit, are shown in Figs. 18(a) and 18(b). As explained earlier, the magnetic structure includes an L-sectioned ring pole-piece of 45% permalloy having an outwardly extending flange which carries a non-magnetic ring, the latter acting as a support for the permendur diaphragm. The remalloy magnet, which is also an L-sectioned ring, is assembled over the pole-piece assembly so that its inwardly extending flange overlies the diaphragm. This overlying portion of the magnet plays an important part in that it enhances the force factor of the device by securing some of the advantages of a balanced armature type of receiver in a simpler

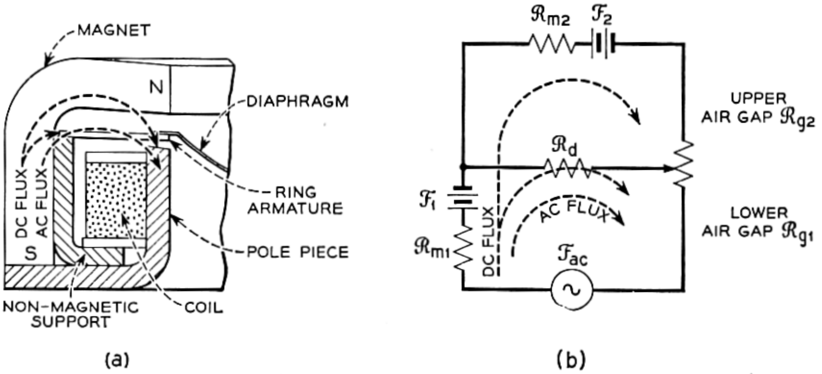

Fig. 18—Magnetic circuit analogy. (a) Physical arrangement of magnetic structure. (b) Equivalent magnetic circuit.

type of structure. The auxiliary magnet principle shown here was first used on the simple bipolar receiver,[5] and later was applied to the ring armature type structure.[4] In both cases, gains in force factor of 3 to 6 *db* were realized

The equivalent magnetic circuit of Fig. 18(b) shows to a first approximation the relations of the physical elements of Fig. 18(a), neglecting the leakage paths. As shown, the overlying portion of the magnet provides a shunt path so that a part of the d-c. flux flows around the armature and only through its inner marginal portion, while the lower portion of the magnet carries additional flux to the armature and through the main air gap. The magnetic circuit is a type of partially balanced circuit which, if fully balanced, will have no d-c. flux flowing through the armature provided the following relations are satisfied:

$$\frac{\mathcal{F}_1}{\mathcal{F}_2} = \frac{\mathcal{R}_{m1} + \mathcal{R}_{g1}}{\mathcal{R}_{m2} + \mathcal{R}_{g2}}$$

Where $\mathcal{F}_1$ = M.m.f. of lower cylindrical part of magnet
$\mathcal{F}_2$ = M.m.f. of flanged portion of magnet
$\mathcal{R}_{m1}$ = Reluctance of lower cylindrical part of magnet
$\mathcal{R}_{m2}$ = Reluctance of flanged portion of magnet
$\mathcal{R}_{g1}$ = Reluctance of main air gap (a variable modulating reluctance)
$\mathcal{R}_{g2}$ = Reluctance of auxiliary air gap
$\mathcal{R}_d$ = Diaphragm reluctance

The above relationship can be derived by placing the flux through the diaphragm reluctance $\mathcal{R}_d$ equal to zero in the circuit shown. Under these conditions, the armature carries no d-c. flux over its middle portion and will be operating at maximum permeability to a-c. flux. Moreover, the d-c. air gap flux density in the lower air gap where most of the field of force resides can be made higher before saturation begins to degrade the permeability of the inner marginal portion of the armature, than if all of the armature had to carry d-c. flux. The above factors tend to increase the a-c. and d-c. flux, and, since the force factor is a function of the product of these two quantities, a higher force factor will result from the addition of the overlying portion of the magnet.

In order to maintain the position of the freely supported diaphragm on its seat at the outer periphery, it has been found desirable to have only a partial balance of the circuit. This is accomplished by making the upper air gap approximately five times larger than the lower one. Thus the field in the upper air gap is weaker, so that a 25 to 50% unbalance in flux exists. Under these conditions, the flux component in the diaphragm due to the upper portion of the magnet only partially cancels that due to the lower portion. However, the resulting flux density in the diaphragm is such that the permeability will be only slightly below the maximum permeability which obtains for the perfectly balanced condition. The reluctance of the upper mesh to a-c. flux is so high, that the a-c. flux flowing in this branch can be neglected, hence the lower mesh carries substantially all of the a-c. flux, as shown in the figures. Thus, a partial separation of the a-c. and d-c. flux paths is accomplished.

The magnetic materials which comprise this structure include a remalloy magnet, a vanadium permendur diaphragm, and a 45% permalloy pole-piece. Some of the considerations which led to the choice of these materials are indicated below. The remalloy magnet can be formed from sheet material while at elevated temperatures, is machinable prior to the final heat treatment, and has good magnet properties. Although Alnico could be used as magnet material, it would not lend itself to forming, and the result would be a more expensive magnet. The vanadium permendur diaphragm has a higher permeability at the higher flux densities than other materials, and this results in a higher force factor. The high yield point and high modulus of elasticity of permendur give better elastic properties so that the diaphragm will restore over a wider range of deflections to which it may be subjected. The 45% permalloy pole-piece has a high resistivity, resists corrosion without the need of a finish to protect it, and is easily formed to the desired shape. Since it has a high permeability, and is not too sensitive to strains, it is well suited for pole-piece material.

Application of Ring Armature Receiver to Other Sound Devices

Several other applications of the ring armature transducer have been made on an experimental basis in addition to that of the handset receiver,

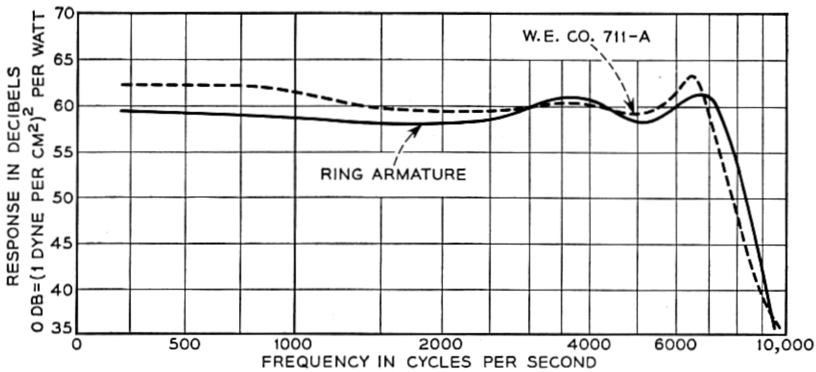

Fig. 19—Available power response-frequency characteristic of an experimental wide-range ring armature receiver, compared to a W.E.Co. 711-A moving coil receiver, measured on a 6 cc. closed coupler.

such as its use as a wide-range receiver, as a miniature horn-type loudspeaker, and as a microphone.

By narrowing the ring armature and suitably proportioning the acoustic networks, the receiver may be made to operate over a much wider frequency range at some sacrifice of efficiency, and may thus be used for high quality monitoring and audiometric work. A response characteristic of such a unit is shown in Fig. 19. The response compares favorably with the Western Electric 711-A moving coil type receiver used for the same purpose. Being comparable in efficiency, it has also a similar frequency range of about 7000 cps. More important, however, are the greater ruggedness and simplicity of the ring armature type receiver. Moreover, the impedance may be made to suit the application over a considerable range of impedance values, whereas the moving coil type is limited to a coil of about 25 ohms. While somewhat less pure in tone than the moving coil type the harmonics are 50 *db* below the fundamental at a sound pressure of 20 dynes per cm² in the coupler, and therefore are not noticeable under ordinary listening conditions. The attainment of wide frequency range in magnetic type units is unique, and is due in part to the use of a peripherally driven diaphragm. Centrally driven diaphragms used in magnetic type receivers usually have parasitic modes of vibration at these frequencies, which places a limit on the frequency range for which they can be designed.

As a loudspeaker, the ring armature structure has been found to have some experimental application when used with a horn, both for speech and as a sound source for measuring purposes. Response characteristics of such

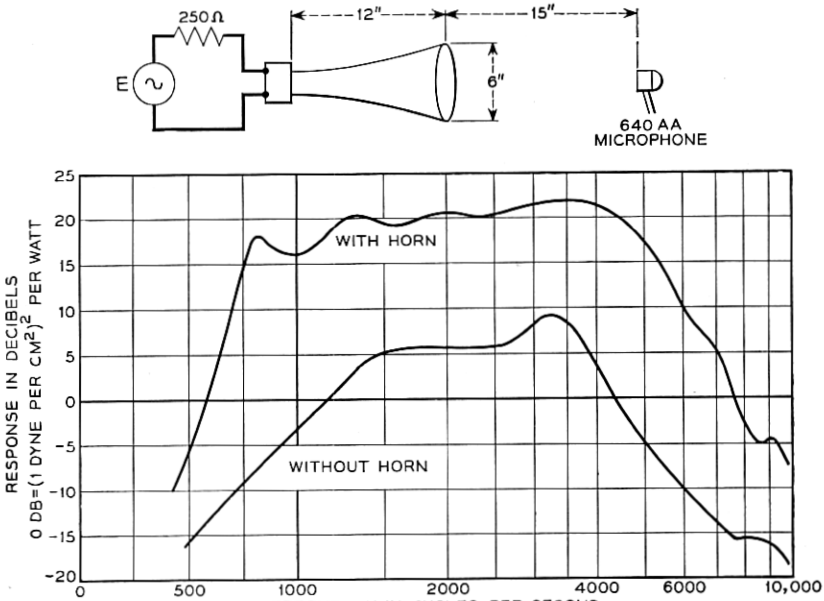

Fig. 20—Available power response-frequency characteristic of a ring armature receiver, measured as a loudspeaker with and without a horn.

a unit are shown in Fig. 20 for the instrument with and without a horn. In the case of the unit without a horn the unit had a receiver cap as used in the handset receiver, and the acoustic circuits were similar to those of the normal receiver. For the case of the horn attached to the unit a spherical plug was used to couple the horn closely with the diaphragm, and no acoustic damping circuits beneath the diaphragm were necessary. The horn pictured in the sketch was spaced 15 inches away from the measuring microphone, and the same distance was used for the curve without a horn. It is apparent that, with the horn, 15 db is added to the sound level on the axis, and the frequency is widened by a factor of 2 or more. The efficiency shown in Fig. 20

compares favorably with similar devices of the moving coil type. The maximum acoustic output, however, is lower, because the amplitude of the diaphragm is limited by the air-gap.

As a microphone, the ring armature structure may be modified to have characteristics which are quite favorable for certain types of applications. Figure 21 shows the field response of a ring armature unit modified for use as a microphone and measured on an open circuit voltage basis. A special housing of 30 cc. rear volume was used in this case, with a $\frac{1}{8}$ inch diameter orifice in the rear of the housing to act as a resonant circuit to produce the low frequency resonance shown with a desirable cut-off at 250 cps. By lowering the acoustic damping resistance of the unit, a second resonance was produced in the middle of the frequency range as shown. The peak at the upper end of the range is the normal characteristic of the instrument, but it may be enhanced somewhat by the use of a cavity in front of the diaphragm.

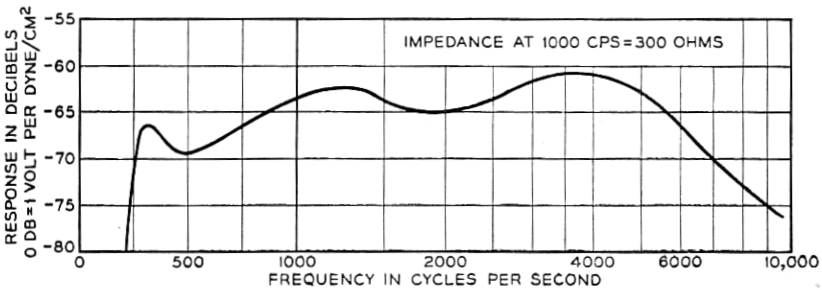

Fig. 21—Free field response-frequency characteristic of an experimental ring armature microphone, at normal sound incidence.

The output level of this microphone is about 9 *db* above the Western Electric 633A moving coil type at the same impedance level, but over a more limited frequency range.

Conclusions

It has been shown in the preceding sections that, by the use of the ring armature structure, it has been possible to realize a substantially higher grade of performance with regard to efficiency, frequency range, and leakage noise level, as compared to other types of telephone receivers in current use. To summarize, the ring armature receiver has been found to have the following advantages from a performance standpoint:

1. A gain in conversion efficiency of the order of 5 db as compared to the HA1 receiver and a corresponding increase in output capacity.
2. A wider frequency range, with an upper frequency of 3500 cps as compared to 3000 cps for the HA1 receiver.

3. A flexibility in frequency range, permitting the extension of the frequency range to approximately 7000 cps.
4. A broader superimposed direct current characteristic resulting in greater stability from a mechanical as well as an electrical standpoint.
5. A lower acoustic impedance, resulting in an improvement of the signal to ambient leakage noise ratio.
6. A substantial increase in the transmitted bandwidth when the receiver is held at small distances away from the ear.

Other advantages from a mechanical standpoint are:

1. A simple mechanical structure of ring-shaped or circular parts.
2. A low mechanical impedance, permitting the use of large air cavities and elements of low acoustic impedance for response control.
3. A concave, spherical dome-shaped diaphragm withstanding high transient pressures.

This work was carried on under the supervision of Messrs. W. C. Jones, F. F. Romanow, and W. L. Tuffnell, from whom many valuable suggestions were received. We also wish to acknowledge the valuable assistance of Messrs. P. Kuhn, L. A. Morrison, R. E. Polk, W. C. Buckland, R. R. Kreisel and R. E. Wirsching during the development of this receiver.