III. U-H-F Reception and Receivers

By **BEVERLY DUDLEY** *Acting Managing Editor, Electronics*

I. Problem of Ultrahigh Frequency Reception

ULTRAHIGH frequency communication involves point to point transmission with little or no broadcast service. There is only one receiver (or at most, only a few receivers) for each transmitter but there may be an appreciable number of transmitters in operation at a given time. In order that the frequency spectrum may be most effectively utilized with interference reduced to a minimum, it is desirable to reduce the transmitter power and increase the receiver sensitivity to the greatest extent. The factors which limit the sensitivity of receivers thus become of paramount importance. Because a relatively few receivers are in operation, mass production methods are not applicable to their construction. Cost of manufacture is secondary to results obtained so that the engineer designing ultrahigh frequency receivers faces totally different economic and design problems than the designer of broadcast receivers.

The condition of propagation of radio waves in the ultrahigh frequency spectrum places emphasis on certain receiver problems which are different from those encountered in the broadcast band. At frequencies below 10 to 30 Mc, receiver noise is usually not the factor limiting its effectiveness. From 50 to 80 Mc there is appreciable man-made noise from spark, ignition and similar sources but there is little natural static. At frequencies above approximately 80 Mc, man-made noise and static decrease to such an extent that above approximately 100 Mc, noise originating within the receiver limits its effectiveness. As a result, noise becomes the factor limiting receiver sensitivity, although other factors are also of importance.

The chief problems in the reception of signals at ultrahigh frequencies are concerned with: (a) the signal-to-noise ratio, (b) the bandwidth to which the receiver is responsive, and (c) the selectivity of the receiving equipment. These three factors are interrelated. Optimum design for each one of the quantities may not always be achieved in a single receiver design.

Beyond a certain point an increase in receiver sensitivity is not useful because the noise in the receiver masks the signal. Accordingly, sensitivity is intimately associated with the signal-to-noise ratio.

In the u-h-f spectrum the wavelengths of received signals are comparable to the physical dimensions of circuit elements. Accordingly, the concept of lumped circuit constants is no longer valid. At those frequencies for which distributed circuit constants must be given consideration, the physical dimensions and mechanical construction of the receiver become of primary concern. Tuning is usually accomplished by application of transmission line principles. The operation of the receiver is appreciably affected by the presence of stray or distributed capacitance and inductances. Requirements of frequency stability necessitate the most rigid mechanical construction and frequently require voltage regulating devices.

Since the superheterodyne is used almost exclusively and only the first tube usually operates at the carrier frequency, u-h-f receiver problems are largely confined to design of the input stage. The design and construction of the i-f and audio portions of the system follow usual practice, and consequently will not be treated here.

II. Characteristics of Tubes at Ultrahigh Frequencies

The limitation of ordinary vacuum tubes at ultrahigh frequencies has been rather thoroughly investigated.[1] Thompson[2] has shown that by reducing all physical dimensions of a tube by the same scale factor, the interelectrode capacitances are considerably reduced without affecting the transconductance or amplification factor. Transit time is likewise reduced as is also the power input of a tube of small dimensions. The introduction of acorn, and other tubes of physically small dimensions, is a valuable contribution to u-h-f.

At ultrahigh frequencies, the input impedance of a tube can no longer be considered as infinite or even very large. Exact expressions for the u-h-f input admittance of a tube are extremely cumbersome, but Strutt[3] has shown that it may be expressed by a conductance term proportional to the square of the frequency, and a susceptance term proportional to the frequency.

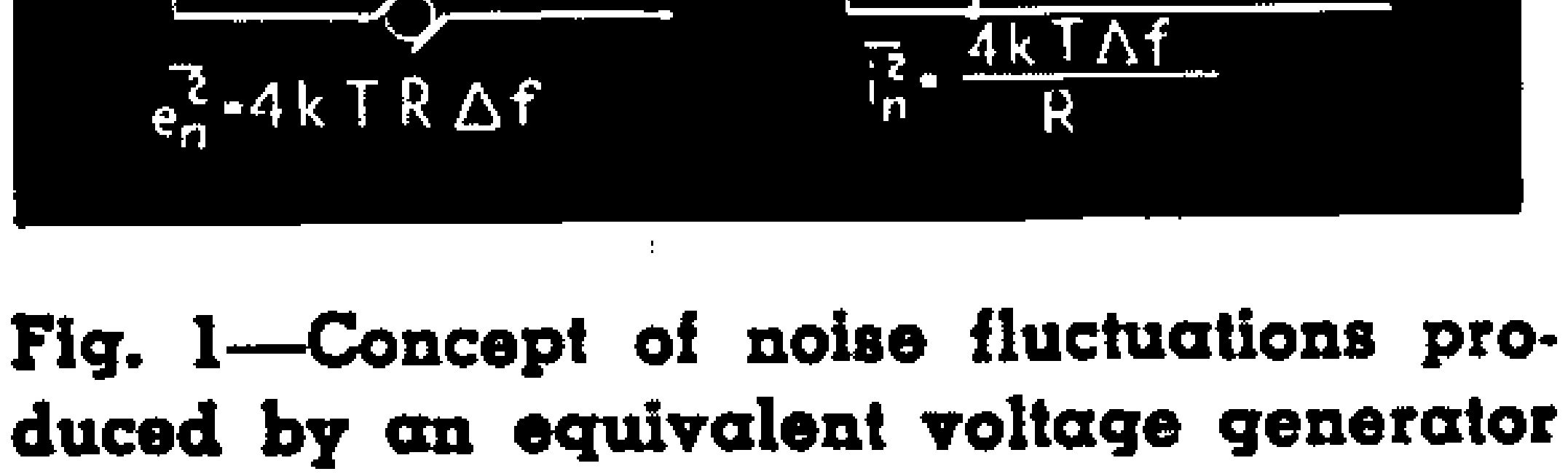

Fig. 1—Concept of noise fluctuations produced by an equivalent voltage generator (left), or as a current generator, (right)

North and Ferris[4] have derived an expression for the input conductance which shows that this is proportional to g_m at low frequencies, and is proportional to f^2 as well as to the square of the time required for an electron to travel from cathode to grid.

At ultrahigh frequencies the grid-cathode capacitance becomes of extreme importance. Published values usually refer to this capacitance as measured when the heater is cold, but this capacitance increases above published figures when the tube is heated.

At ultrahigh frequencies the plate current is not in phase with the grid voltage. Consequently, g_m becomes a transadmittance rather than a transconductance. However, although the magnitude of the conductance and susceptance current individually vary appreciably with the frequency, the magnitude of the total transadmittance is reasonably constant with frequency. This variation with frequency may be neglected for a consideration of amplifier operation but not for oscillator operation.

The output admittance of a tube is always of much less importance than the input admittance, and consequently is usually neglected, even at the highest frequencies encountered.

III. Noise Due to Statistical Fluctuation

Because it limits the sensitivity of the receiver by masking the weakest signals, noise in the receiver is of extreme importance. Noise due to statistical fluctuation may be attributable to: (1) thermal agitation noise arising from the random motion of electrons in the conductor, (2) electron emission noise, (3) noise due to current division in the electrodes of the tube (4) noise due to emission of secondary electrons and (5) noise due to formation of gas within the tube.

Nyquist[5] has shown that noise voltages appear in many circuits because of the random motion of the electron within the conductor and that these noise voltages may be represented in terms of an equivalent noise resistance R which may be determined from the relation

$$e^2 = 4kTR\Delta f$$

where k is Boltzmann's constant
T is the temperature of the resistance in degrees absolute

R is the value of the equivalent noise resistance across which the voltage is produced and

Δf is the bandwidth of the receiving or measuring instrument

The concept of an equivalent noise resistance which is responsible for producing the noise voltage is a great convenience in the construction of equivalent circuits and the analysis of receiver operation. As shown in Fig. 1, the thermal noise may be represented by means of a voltage or current generator whose output is e_n or i_n as indicated in the diagram. It should be noted that in dealing with noise, the square of the current or voltage is referred to since it is more convenient to deal with powers than with voltages or currents.

In these equivalent noise diagrams, the resistance R is assumed to be noise-free, the equivalent noise being generated by the voltage or current generators as shown. Likewise any physical tube may be replaced by an ideal noise-free tube operated in conjunction with the equivalent noise resistance.

Another type of noise existing only at ultrahigh frequencies is the noise induced on the electrode within the tube. North and Ferris[12] have shown that the noise in the grid circuit is equal to

$$i_{gn}^2 = 5 \times 4\,k\,T\,g_e\,\Delta f$$

where g_e is the effective input conductance for the tube and the other symbols have the meaning already given them.

The noise in the plate circuit measured by i_{pn}^2 may be referred to the grid or input circuit by making use of the relationship $i_p = e_g g_m$, consequently the plate circuit noise is equivalent to that produced by a grid voltage noise

$$e_n^2 = 4k\,T\,R_{eg}\,\Delta f$$

where R_{eg} is the equivalent noise resistance in the grid circuit. An equivalent circuit of a tube with thermal and induced noise generators in the grid circuit is given in Fig. 2. The thermal noise is shown as being produced in the plate circuit (left) whereas at the right it is produced in the grid circuit.

In those cases where a tube is represented with suitable noise generators, it is assumed that the tube is noise free and that any noise resulting occurs because of the presence of the noise generators.

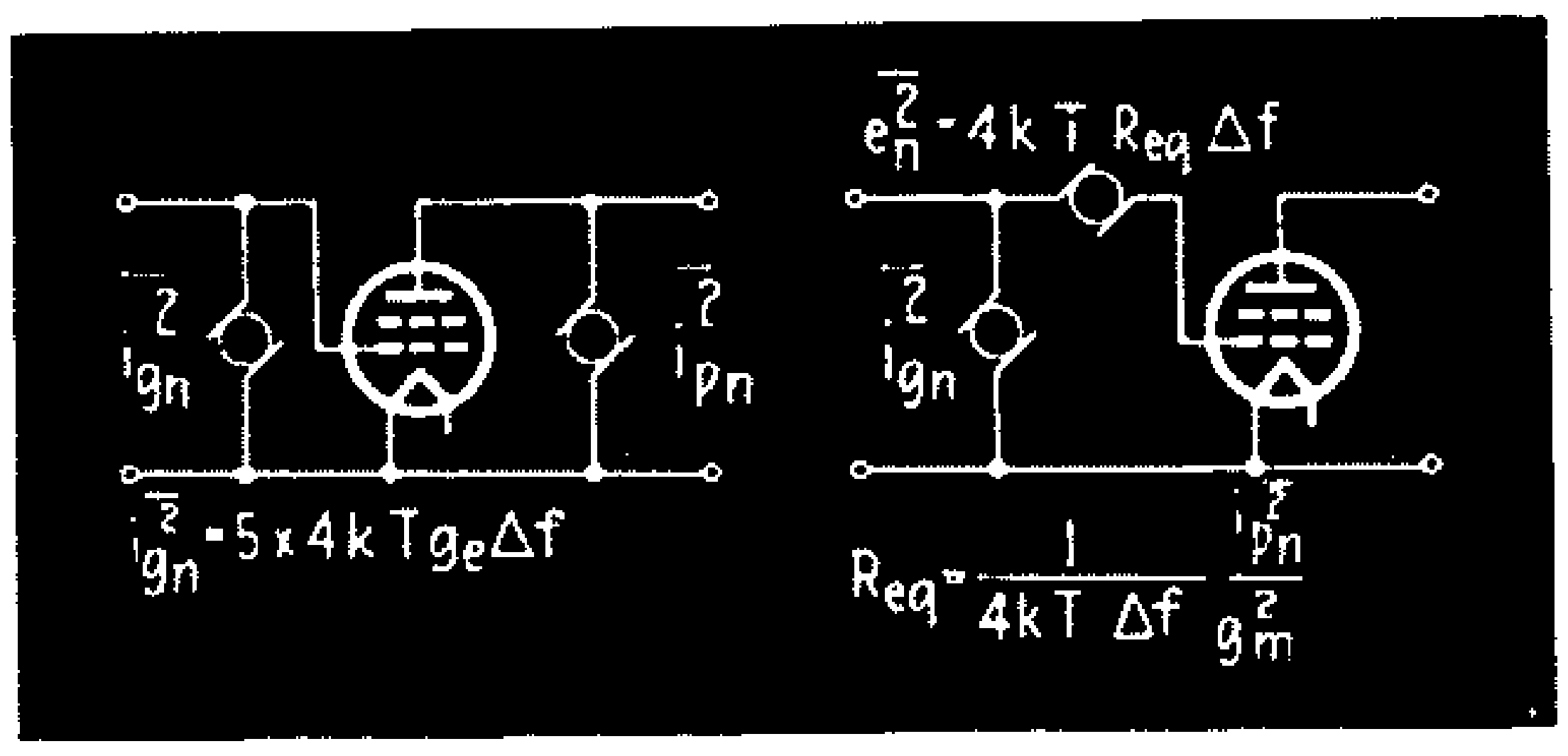

Fig. 2—Equivalent circuit of a tube with thermal and induced noise generators

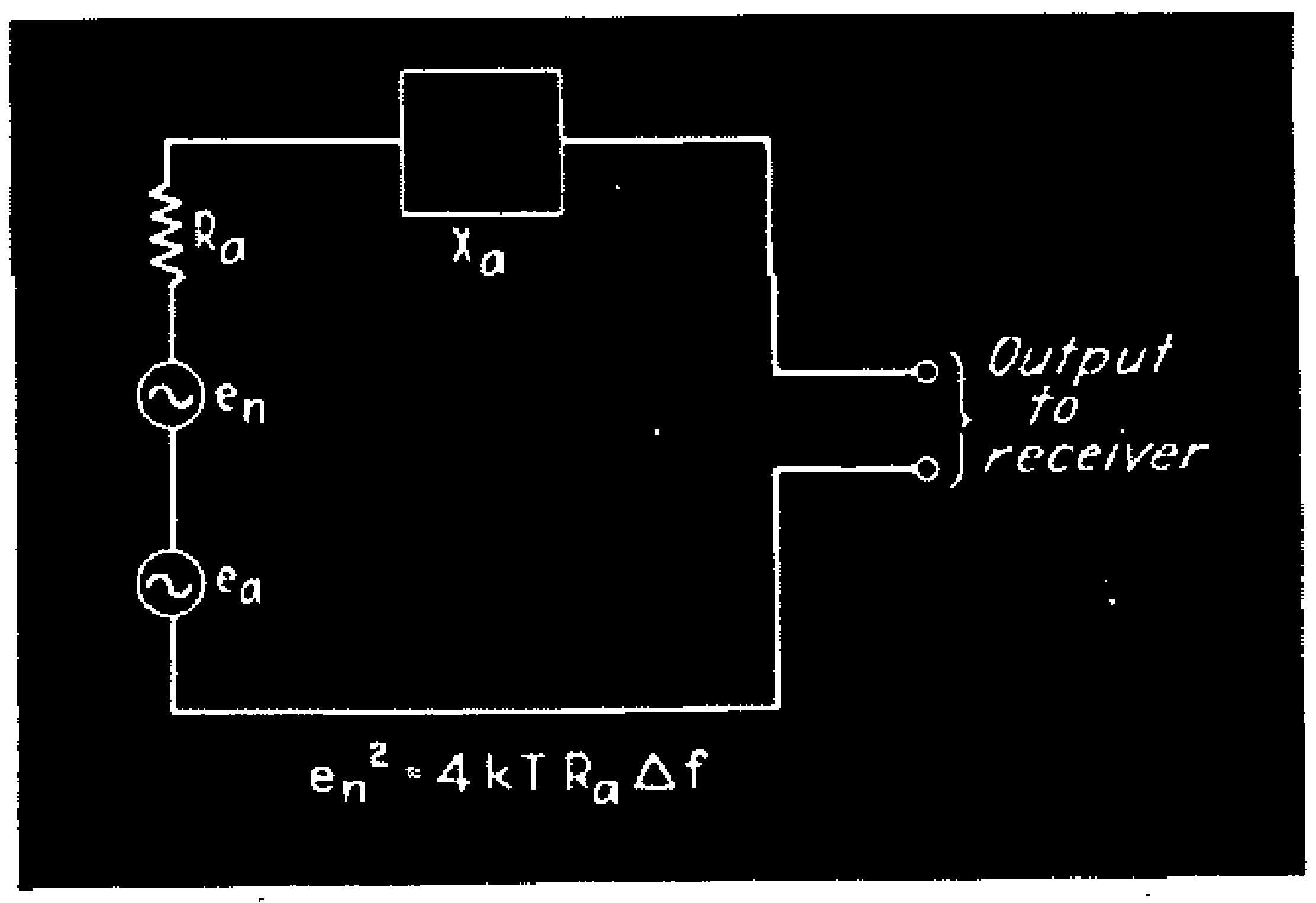

Fig. 3—Equivalent circuit of u-h-f receiving antenna with sources of signal voltage, e_a, and noise voltage, e_n

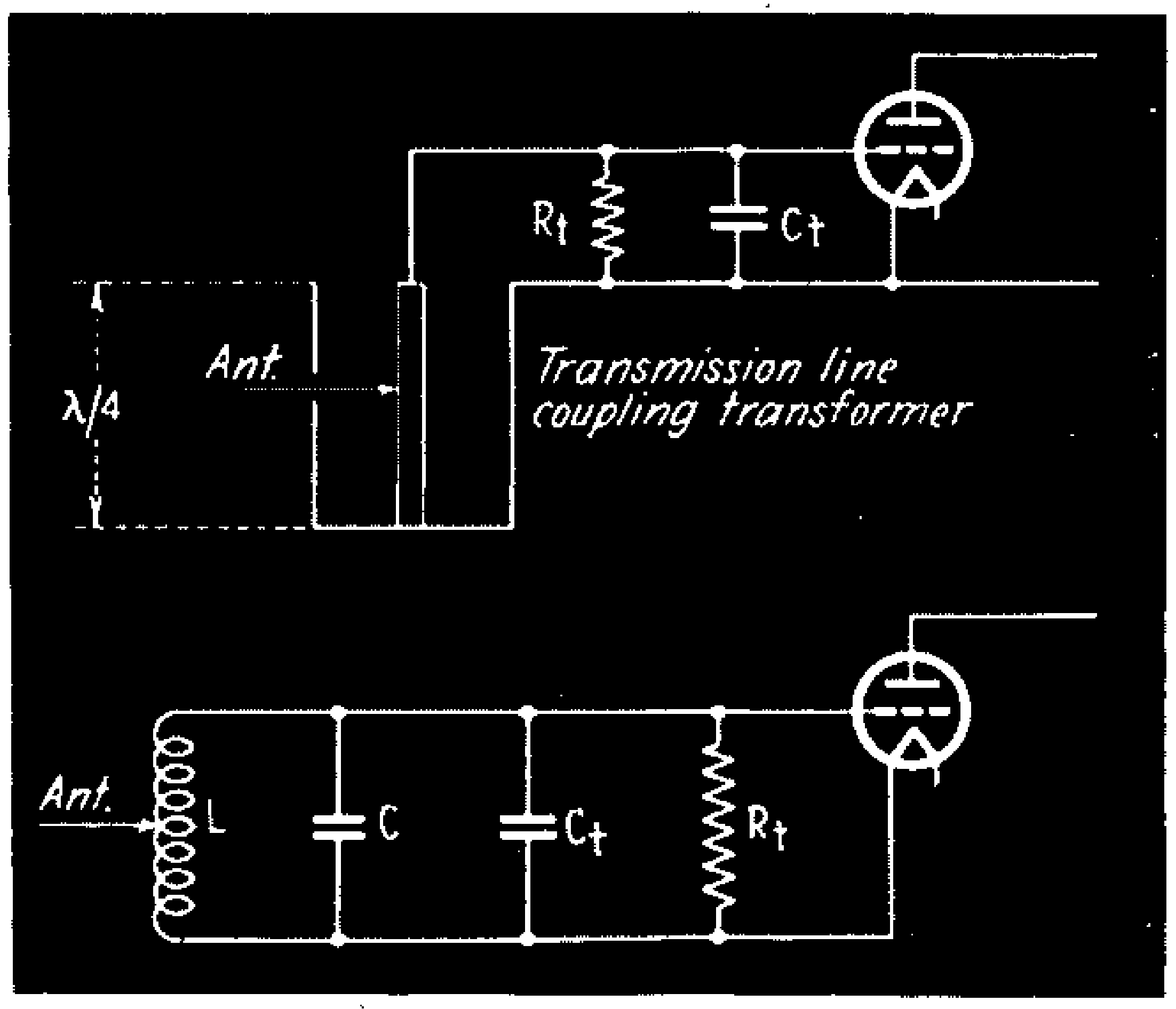

Fig. 4—Transmission line u-h-f input coupling transformer and its equivalent circuit

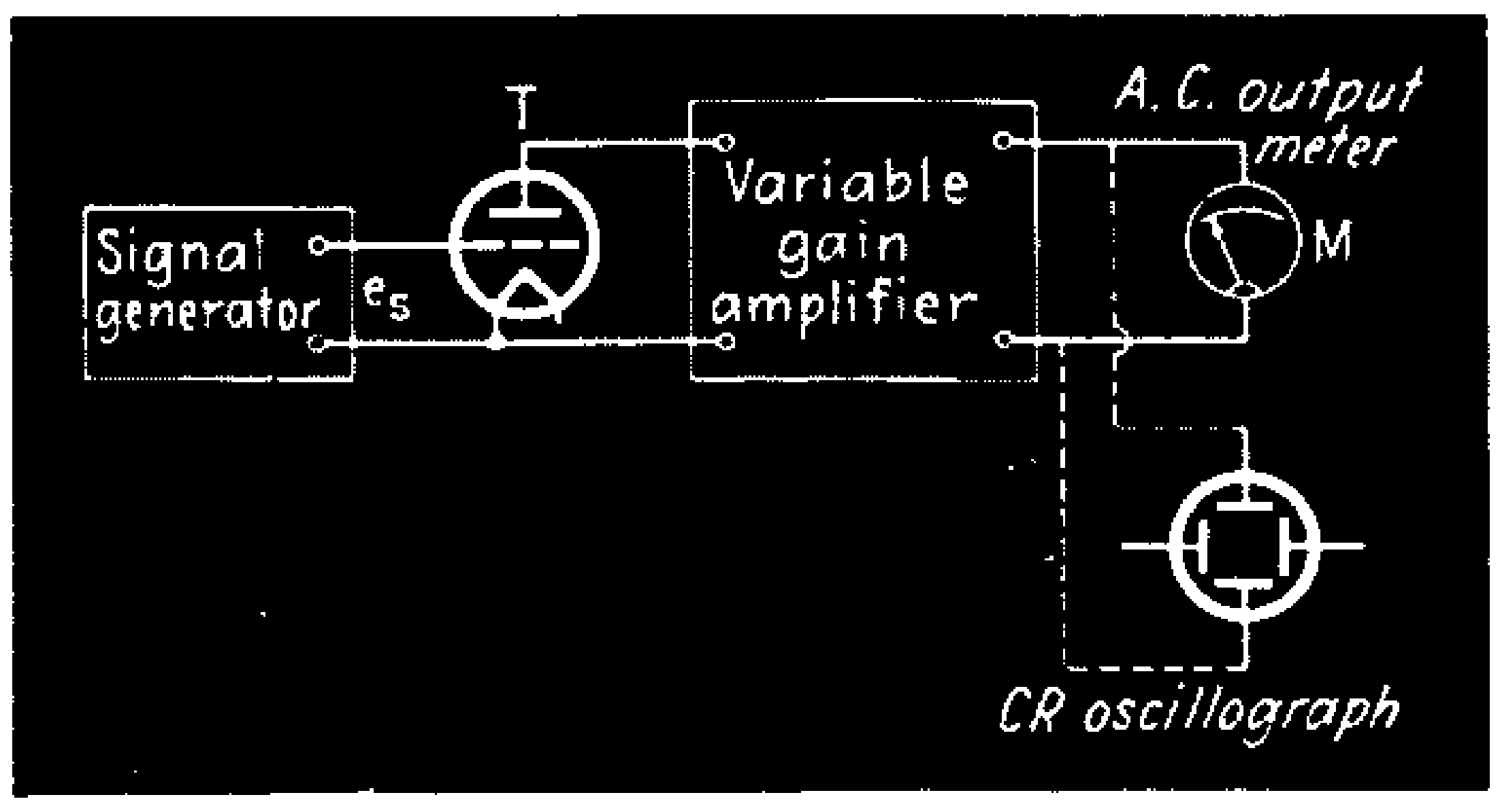

Fig. 5—Diagram illustrating concept of measurement of noise voltage in terms of signal voltage

IV. The Receiving Antenna

The receiving antenna may be looked upon as a device for coupling the receiver to the medium through which electromagnetic waves are propagated. It may also be looked upon as an impedance matching device to transfer power from free space to the receiving equipment.

Two factors are important in u-h-f antennas: (1) the power picked up by the antenna and which is transferred to the receiver, and (2) the noise occurring within the antenna circuit. The factor of merit of an antenna is the ratio of the desired signal voltage to the noise voltage.

Power picked up by the receiving antenna is given by

$$P_R = e_a^2/R_a = \lambda^2 D_a^2 S/2\pi$$

where e_a is the voltage at the terminals of the antenna

R_a is the radiation resistance

λ is the wavelength of received signal

D_a is the directivity of the receiving antenna, and

S is a factor, measured in watts per unit area, specifying the signal intensity at the location of the receiving antenna and is determined by directivity and power in the transmitting antenna, and distance between the transmitting and receiving antennas.

At any receiving location, the value of S, from a specified transmitter, will be fixed. From this equation it is evident that the power of the received signal can be increased by increasing the wavelength. However, if the frequency of the communication circuit is definitely established, the only means by which the power in the receiving antenna may be increased is by increasing the directivity of the receiving antenna, D_a. Fortunately, it is relatively easy to increase the directivity of receiving systems at shorter wavelengths. Consequently, the loss in power which occurs as the wavelength is reduced can be compensated by increasing the directivity of the system. This procedure has the further advantage of decreasing the interference due to transmission from other stations.

The noise in the antenna due to the thermal agitation is given by

$$e_n^2 = 4\,kTR_a\Delta f$$

where R_a is the radiation resistance of the receiving antenna and the other symbols have the meaning already assigned. Combining this equation with that given above for the power in the receiving antenna, we may express the signal-to-noise ratio as

$$(e_a/e_n^2) = \lambda^2 D_a^2 S/8\pi kT\Delta f$$

As is true in so many instances, the signal-to-noise ratio depends upon the bandwidth of the system.

The directivity factor, D_a, represents the voltage gain in the receiving antenna over that of a perfectly non-directional antenna. For a half wavelength dipole D_a is approximately equal to 3. The directivity of the antenna system may be increased through the use of additional elements properly arranged in an antenna array. The power obtainable from a properly constructed antenna array is proportional to the number of elements but the difficulty of construction also increases with the number of elements so that frequently a four or eight element array is the maximum which is feasible.

It is sometimes convenient to represent an actual antenna by its equivalent circuit, (Fig. 3) where X_a represents the antenna reactance, R_a represents the antenna radiation resistance, e_n represents the equivalent noise voltage on the antenna, and e_a represents the voltage of the desired signal, or the antenna voltage.

Because it is not desired to change the size of the antenna every time it is desired to receive signals of a new frequency, the effective bandwidth or frequency range of an antenna is important. Antennas for u-h-f reception are always tuned and are usually half wave dipoles.

The input circuit of the receiver usually contains a coupling transformer in the form of a section of a transmission line whose purpose is (1) to match the impedance between the antenna and the receiver, and (2) to obtain the required selectivity or bandwidth. A section of the transmission line used as a coupling transformer and its equivalent input circuit are shown in Fig. 4.

In practice the length of the transmission line forming the input transformer is usually slightly less than one-quarter of a wavelength. The Q of the transmission line coupling unit increases as the input resistance R_t and input capacitance, C_t of the tube to which it is connected are increased. When the antenna is connected to the input circuit of the receiver the added antenna resistance, R_a, produces increased loading which broadens the band to which the transformer is responsive.

To increase the selectivity, it may be desirable to connect the grid of the input tube farther down toward the grounded end of the transmission line rather than connecting it, as shown in Fig. 4 at the quarter wavelength position. When this is done, it will be found that it is also usually desirable to tap the antenna farther down the line from the position which is optimum when the grid is tapped at the quarter wave section of the coupling transformer.

V. The First Tube and Its Noise

The plate current of any vacuum tube, such as T of Fig. 5, possesses instantaneous fluctuation of plate current of a random nature, which, appearing as noise, establishes a limit to the useful operation of the tube. The mean or average value of the minute fluctuations cannot be detected directly by placing a current measuring instrument in the plate circuit of the tube since the fluctuations are usually masked by other currents and also because they occur at too rapid a rate for them to be registered by the meter. However, they may be detected when the gain of the amplifier is sufficiently high if the output meter is replaced by a cathode-ray oscillograph. The presence of fluctuations is then indicated by an irregular trace on the screen. The presence of noise, in terms of equivalent input signal voltage, may be measured by means of the circuit of Fig. 5. A signal generator producing an input or grid signal e_s, is fed to the grid of the tube whose plate circuit is connected to an amplifier of variable gain. The output of this amplifier is connected to an indicating or output meter M. For large or moderate values of e_s, indications of the meter M are proportional to the magnitude of the voltage applied to the grid of the tube.

For a signal voltage, e_s, impressed upon the grid, the plate current due to the signal is given by the expression

$$i_{ps} = g_m e_s$$

where g_m is the transconductance of the tube. Likewise, the current in the plate circuit due to random noise may be represented in terms of the equivalent noise voltage on the grid by the equation

$$i_{pn} = g_m e_n = g_m (4\,kTR\Delta f^{1/2})$$

The signal-to-noise ratio may be expressed as

$$(e_s/e_n)^2 = e_s^2/4\,kTR\Delta f$$

The signal-to-noise ratio will increase with an increase in signal strength, and with a decrease in the equivalent noise resistance and decrease in the bandwidth to which the receiver is responsive. For receivers operating above approximately 300 Mc, practically all of the noise is due to that originating within the plate circuit of the first tube. For this reason it is important to pay more than usual attention to the noise originating within the first tube.

VI. Signal Noise Ratio for Simple U-H-F Receiver

To illustrate the value of some of the noise concepts, let us investigate the signal-to-noise ratio for a simple receiver operating at frequencies of 300 Mc. The equivalent input circuit is shown in Fig. 6 in which for simplicity, only one source of noise (thermal noise) will be employed. This is introduced in the grid circuit by means of the generator labeled e_n^2. In Fig. 6, e_a is the voltage delivered by the antenna, and R_a is the antenna radiation resistance of the receiving antenna. The transformation ratio of the coupling transformer is designated as m, while C_t is the input capacitance of the first tube, and R_t represents the input loading of the first tube. For the coupling transformer to match the antenna to the tube input resistance, the equivalent ratio of transformation must be $m^2 = R_t/R_a$. For this adjustment, maximum grid voltage and maximum gain are obtained. The voltage across terminals AB is one-half of the antenna voltage so that the signal voltage applied to the grid is

$$e_s = me_a/2 = \tfrac{1}{2}\, e_a\, (R_t/R_a)^{1/2}$$

The signal-to-noise ratio may be determined from the square of this quantity and the square of the noise voltage as given in Fig. 6. The result is

$$(e_s/e_n)^2 = \left(\frac{e_a^2}{R_a}\right)\frac{1}{4\,k\,T\,\Delta f}\left(\frac{R_t}{4\,R_{eq}}\right)$$

The first term on the right-hand side of the equation is the signal-to-noise ratio of the antenna. For a given antenna this is fixed and cannot be modified to obtain an improved signal-to-noise ratio. Likewise, for given bandwidth, the second term is fixed. However, the third term involving R_t and R_{eq} depends entirely on the characteristics of the first tube in the receiver. Accordingly, by selecting the most suitable tube, it is possible to increase the signal-to-noise ratio appreciably. To increase this ratio we must have a tube with a high input resistance, R_t, and a low equivalent noise resistance, R_{eq}.

Although the above analysis was based on adjustment of the coupling transformer to provide maximum gain, the signal-to-noise ratio is also a function of m.

Herold[23] has shown that the coupling of the input transformer for maximum signal-to-noise ratio is less than that required for maximum gain. The relationship between signal voltage on the grid, the equivalent noise voltage, bandwidth, and signal-to-noise ratio is shown graphically in Fig. 7, for the case in which the input resistance of the first tube is 400 times the radiation resistance of the antenna. It is evident that optimum signal-to-noise ratio occurs for a smaller value of m than that required to give maximum signal voltage on the grid.

The signal-to-noise ratio for maximum gain depends only upon the input resistance of the first tube and its equivalent noise resistance. If the coupling transformer at the input of the receiver is adjusted for maximum signal-to-noise ratio rather than for maximum gain, the signal-to-noise ratio is given by

$$\left(\frac{e_s}{e_n}\right)^2 = \left(\frac{e_a^2}{R_a}\right)\frac{1}{8\,\pi\,k\,T}\left(\frac{1}{(\Delta f)^2\, C_t\, R_a^2}\right)$$

where R_a is the radiation resistance of the antenna and C_t is the effective capacitance of the input circuit.

Since both the bandwidth and the signal voltage vary with the coupling ratio of the input transformer, maximum signal-to-noise ratio will be obtained (if bandwidth is not a consideration) for that value of m corresponding to the condition of maximum efficiency. However, if a specified bandwidth is desired, some lower value of m may be required to produce a maximum signal-to-noise ratio for the specified bandwidth.

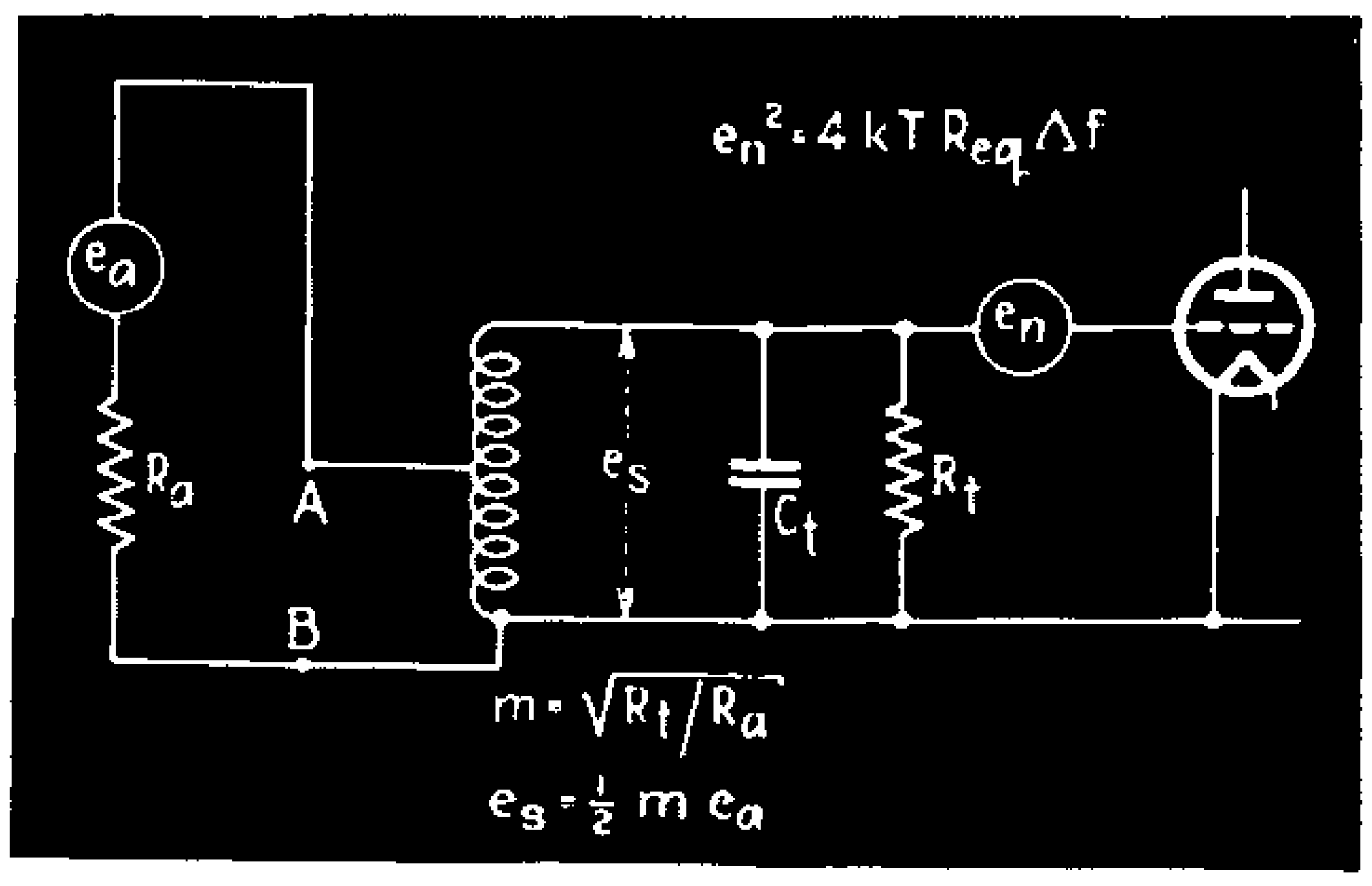

Fig. 6—Antenna and input coupling circuit

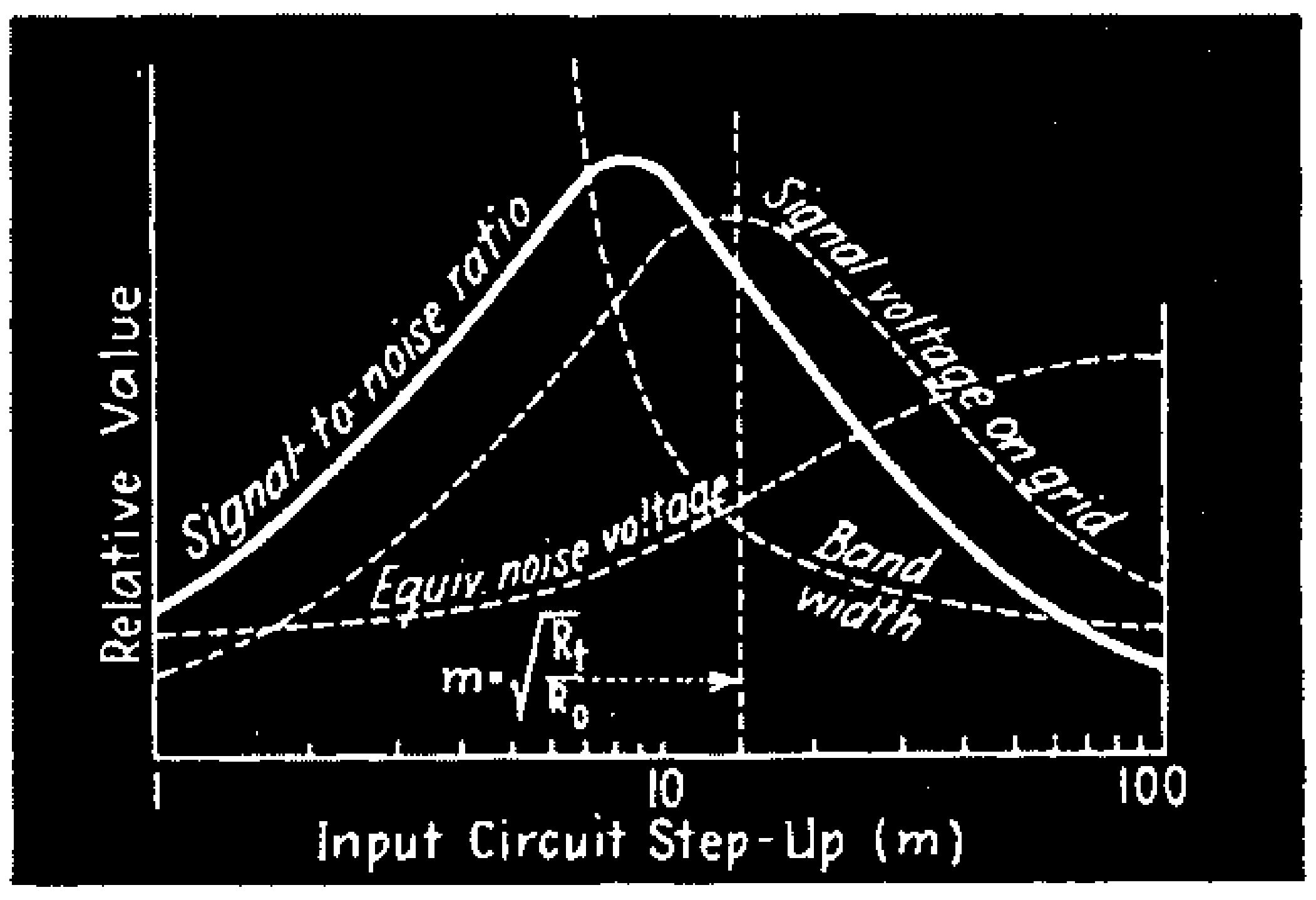

Fig. 7—Dependance of signal and signal-to-noise voltages upon input transformer coupling ratio

TABLE I—Optimum Input Circuits

	STRONG SIGNALS	WEAK SIGNALS
MODERATELY HIGH FREQUENCY	The circuit impedance for moderately high frequencies is given by the term $Z = 1/(2\pi C\Delta f)$ In this case, the gain of a radio-frequency amplifier is approximately four times that which may be obtained from a converter. Consequently, so far as gain is concerned, it is advisable to make the first tube a radio-frequency amplifier. This has the further advantage of tending to reduce the undersired image signal.	The signal-to-noise ratio is much more important than the gain. The gain consideration remains the same as for strong signals at moderately high frequency. However, the equivalent noise resistance of a converter is much greater than that of an amplifier and accordingly, the use of at least one stage of radio-frequency amplification in the input circuit is desirable.
U-H-F	The impedances at the frequency of the imput signal are much less than those which can be built up for the intermediate frequency, and for such a case, the radio-frequency gain is much less than that obtainable in an intermediate-frequency stage For still higher frequencies this condition is even more greatly exaggerated. Accordingly, above a certain transition frequency f_1 it is advisable to use a converter stage immediately at the input of the receiver.	The signal-to-noise ratio is of primary consideration. The considerations of gain are the same as for those of strong signals in the ultrahigh-frequency band. The necessity for a high signal-to-noise ratio makes it desirable to change from a tuned amplifier to a converter input stage at a lower frequency than that transition frequency designated for the case of strong signals at ultrahigh frequency.

The transition frequency, f_1, depends upon bandwidth. For a very broad bandwidth, the transition frequency will be very high, while for a narrow bandwidth, the transition frequency f_1 occurs at lower frequency. Transition frequency increases as the bandwidth increases.

TABLE II—Calculation of R_{in} and R_{cq} for Acorn Tube Mixer

Mixer	Oscillator Frequency	g_c μ mhos	R_{eq} (ohms)	R_{in} (ohms)	R_{in}/R_{eq}
954	Fundamental........	730	30,000	1,350	0.045
954	Second harmonic.....	520	72,000	2,700	0.036
955	Fundamental........	785	4,600	1,350	0.293
955	Second harmonic.....	560	11,000	2,700	0.245

VII. Converter and Mixer at UHF

The non-linear device producing oscillations of intermediate frequency as a result of the combination of incoming signal and locally generated oscillations impressed upon it, may be any tube having a non-linear characteristic between two or more electrodes. The important figure of merit for the tube operated as a mixer or converter, is the conversion transconductance. If we have a circuit (Fig. 8) in which the incoming and locally generated oscillations are combined on the grid of the mixing tube and oscillations of the lower (intermediate) frequency are taken from the plate circuit then it will be possible to measure the plate current at a lower or intermediate frequency if the plate circuit is tuned to that frequency. The ratio of the plate current change at the intermediate frequency, to the corresponding change in grid voltage producing it, is defined as the conversion transconductance. Mathematically the conversion transconductance is defined by

$$g_c = \frac{di_{p_{if}}}{de_{g_{rf}}}$$

where $di_{p_{if}}$ is the change in the plate current of intermediate frequency and

$de_{g_{rf}}$ is the r-f voltage impressed upon the grid and arising from the combination of the locally generated and received oscillations. It should be observed that while the mathematical expression for the transconductance is similar to that for the more familiar grid-to-plate transconductance (g_m) the conversion transconductance involves a change in frequency, which is not the case for the ordinary transconductance. Likewise, it should be noted that in deriving the expression for converter transconductance, it is assumed that sinusoidal received and oscillator voltages are referred to. The transconductance as defined above applies, of course, to a specific set of operating voltage conditions. In general, different values of transconductance will be obtained for various values of grid and plate operating voltages.

When two sinusoidal voltages of oscillator frequency and incoming frequency are combined in a non-linear device, additional frequencies not present in the input voltages appear in the output of the device. Of the various distortion currents thus produced, only those which are equal to the sum or the difference of the two impressed frequencies are of importance in superheterodyne reception.

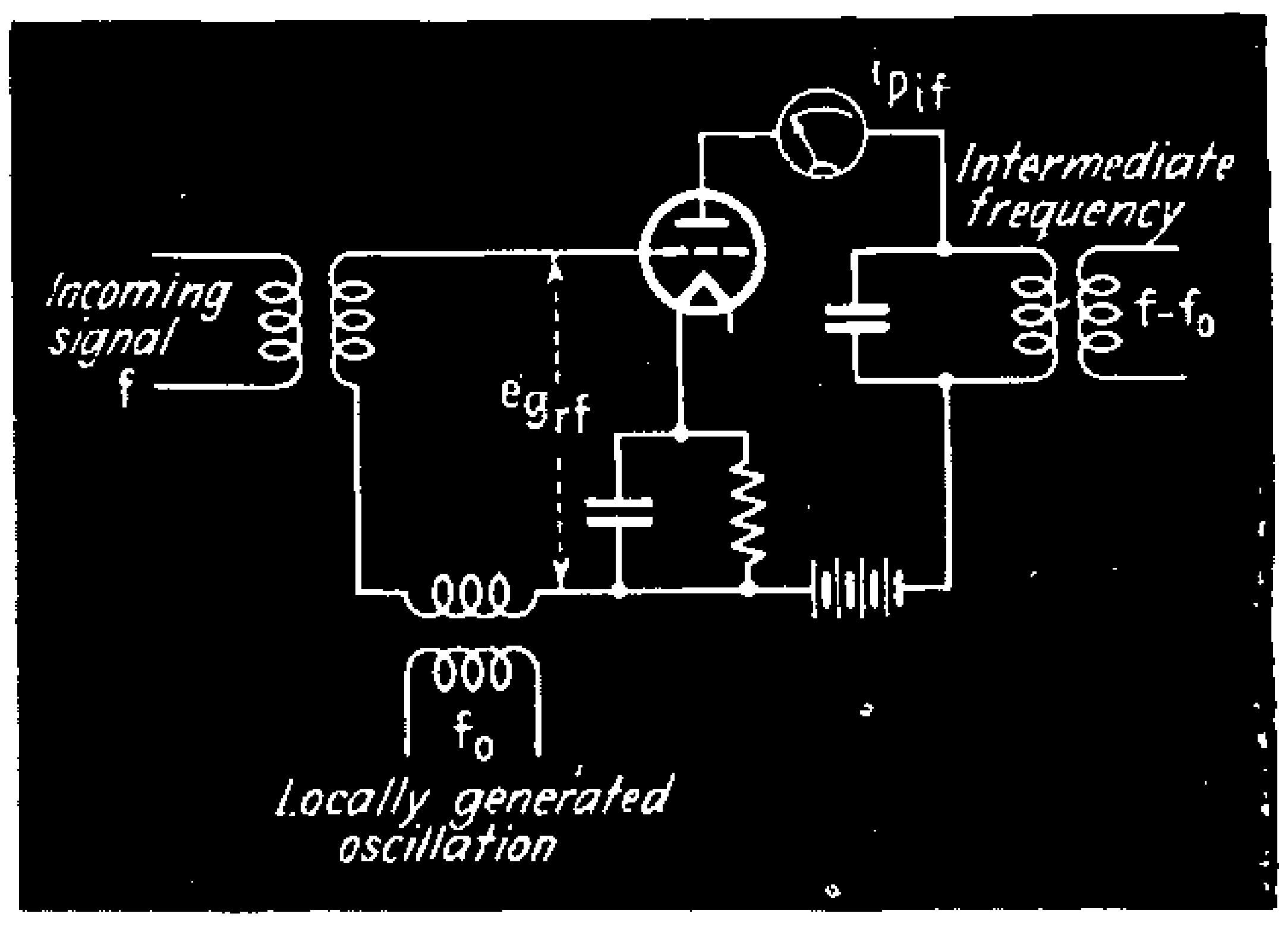

Fig. 8—Circuit for frequency converter

A useful empirical equation for determining the value of the intermediate frequency for u-h-f receivers in terms of the bandwidth and image ratio is

$$f = \tfrac{1}{4}\,\Delta f E_s/E_i$$

where Δf is the bandwidth of the receiver
E_s is the desired or signal frequency voltage and
E_i is the image frequency voltage

The ratio E_s/E_i is a measure of the ratio of the intensity of the desired signal to that of the undesired signal, and is expressed as a voltage ratio. The intermediate frequency should be raised as the bandwidth increases.

Instead of permitting the fundamental frequency of the local oscillator to beat with the incoming signal frequency, it may be more desirable, especially in u-h-f receivers, to utilize one of the harmonics of the oscillator to produce the beat frequency. With this arrangement it is usually possible to secure greater stability since the oscillator can operate at an integral sub-multiple of the carrier frequency.

VIII. Type of Input Tube

A problem of very practical importance in receiver operation assumes that a certain signal is to be received. The question then arises as to what type of circuit is to be used for the first tube. This tube may be used as a r-f amplifier or as a converter. Two considerations are of primary importance; (1) the signal-to-noise ratio must be as high as possible, and (2) consistent with its primary requisite, the gain must be as high as possible. It sometimes happens that the two requirements are not mutually consistent.

The choice of the most desirable type of input tube depends upon four principal factors: (1) the magnitude of the received signal frequency, (2) the bandwidth required of the receiver, (3) the field intensity or magnitude of the received signal, and (4) the nature of type of tube used in the first stage.

Table I gives an appraisal of the most suitable type of input tube under ordinary conditions for operations at moderately high frequencies and at ultrahigh frequencies, both for moderately strong and for weak signals.

IX. Classification of Converter Mixers

Frequency converters for superheterodyne receivers may be classified according to the position of the grid on which the signal is injected as: (1) converters with oscillator voltage applied to the same grid as the signal, (2) converters with oscillator voltage applied to an inner grid, (3) converters with oscillator voltage applied to an outer grid, and (4) diode converters.

Although diodes are sometimes used for mixers in u-h-f superheterodynes they are obviously incapable of providing any gain and for this reason are inferior to triodes or multi-grid tubes. They suffer from a further disadvantage in that the i-f oscillations are contained within the same circuit as oscillations of incoming and locally generated frequencies so that the intermediate frequency may beat with the local oscillator to produce additional spurious and undesired frequency components.

For converters in which the signal and local oscillator voltages are impressed on the same electrode, the signal-to-noise ratio is high, but bad interaction between signal and local oscillator circuit occurs.

When local oscillator voltage is impressed on an inner electrode with respect to that containing the signal frequency, interaction of signal and oscillator circuit is somewhat reduced but is still objectionable at the higher frequencies because of space charge coupling between the two grids. The disadvantages of these two methods may be somewhat reduced by the third method in which the local oscillator is applied to an outer electrode with respect to that containing the impressed frequency. By special tube design, this type of circuit may be still further improved.

An appraisal of the various merits of possible modes of operation of converters has been given by Herold[43] in tabular form. While this table may be used as a rough approximation for the design of converter stages, the relative merit of one type of operation as compared with another may depend somewhat upon the tube used. For this reason the table should be considered merely as a rough guide.

It has already been shown that the figure of merit for a tube, so far as concerns the signal-to-noise ratio, is given by the ratio of the input resistance to the equivalent noise resistance of the tube. Table II shows this figure of merit as well as other factors of importance for two types of acorn tubes employed as mixers and operating either at the oscillator fundamental frequency or at its second harmonic. From this table it is evident that a 955 mixer tube operating at the fundamental frequency of the oscillator is the most suitable of those listed so far as signal-to-noise ratio is concerned, with a 955 mixer operating at the same harmonic of the oscillator as second choice.

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