REPORT CRPL-4-4 ISSUED MAY 3, 1948



U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
CENTRAL RADIO PROPAGATION LABORATORY
WASHINGTON, D. C.

# THE EFFECTS OF ANTENNA CIRCUIT LOSS, RECEIVER NOISE AND EXTERNAL NOISE ON RADIO RECEPTION IN THE FREQUENCY BAND FROM 50 TO 5,000 KILOCYCLES

By William Q. Crichlow

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## Contents

| | | Page |
|---|---|---|
| I. | Summary | 2 |
| II. | Introduction | 2 |
| III. | Receiver and Resistance Noise | 4 |
| IV. | Antenna and Input Circuit Loss | 8 |
| V. | External Noise | 11 |
| VI. | The Distribution of Noise Voltage and Its Influence on Measurements | 14 |
| VII. | The Required Signal-To-Noise Ratio for Telephony | 18 |
| VIII. | The Required Signal-To-Noise Ratio for the Reception of L. F. Loran Pulses | 21 |
| IX. | Required Field Intensity | 22 |

## I. SUMMARY

Receiver noise is evaluated in terms of a "noise figure" which relates the effective input circuit noise to kTB, the noise power available from a passive resistance at room temperature. The magnitude of input circuit loss to be expected with various types of antennas is discussed and this loss is combined with the "noise figure" to show the available signal power that is required from the antenna to overcome receiver noise.

Noise received external to the antenna is also referred to kTB and evaluated in terms of an "external noise factor". Curves have been plotted which show the expected values of this factor during the daytime hours, both at mid-latitudes and in arctic regions.

Signal-to-noise ratios that are required for satisfactory reception of voice communication and of Loran signals are given. It is pointed out that methods of measuring noise differ and that proper interpretation of the measurements is necessary in order to determine the signal required in the presence of different types of noise.

Curves are presented which give the field intensity that is required under various conditions of reception. These curves show that, when short antennas are used in arctic regions, reception is limited for a large percentage of the time by input circuit losses and receiver noise. The curves also show the possible improvement in reception obtainable by appropriate equipment modifications.

## II. INTRODUCTION

The minimum field intensity that is useful for radio reception in the absence of interference from other stations is determined usually by one or more of the following factors: (1) Noise external to the receiving system including atmospheric, man-made, and cosmic noise; (2) Antenna and input circuit loss; (3) Receiver noise originating in the resistance components of impedance elements and the random noise due to the fluctuation of electrons in vacuum tubes; and (4) Receiver gain. Generally, at low and medium latitudes between $\pm 45^{\circ}$ and within the frequency range under consideration between 50 kc and 5,000 kc, the atmospheric noise level is relatively high. With average receiving equipment operating under these conditions, the required field intensity is determined almost entirely by the atmospheric noise level.

Recently, however, there has been an increased interest in radio propagation in arctic regions, in connection with applications to both communication and navigation systems. At these latitudes the atmospheric noise is very low and the other factors mentioned above have a considerable influence on reception, particularly in aircraft where short antennas necessarily must be used. In most cases the receiver gain can be made sufficiently high so that it imposes no limitation on sensitivity, but receiver noise combined with the loss in the antenna and input circuits then become important considerations. For services operating in these areas of low atmospheric noise it thus becomes desirable to reduce the receiver noise and input circuit losses as much as possible.

A determination has been made of the quantitative effect of the above parameters on radio reception both in the arctic and middle latitudes and calculations have been made of the field intensities required for service under various conditions.

## III. RECEIVER AND RESISTANCE NOISE

The noise characteristics of a receiver may be expressed in terms of its "noise figure", $\overline{NF}$, which shows numerically how much noisier it is than an ideal receiver which introduces no noise other than that inherently associated with the internal resistance of the standard rf source. "Noise figure" may be defined by the following expression:

$$\overline{NF} \equiv \frac{\text{Available signal power at input} \,/\, kTB}{\text{Available signal power at output} \,/\, \text{Available noise power at output}} \qquad (1)$$

where:

$k = 1.37 \times 10^{-23}$ = Boltzmann's constant

$T$ = Absolute temperature in degrees Kelvin (taken as 300°)

$B$ = Effective noise band width of the receiver in cycles/second

$kTB = 4.11 \times 10^{-21}$ watts for a dummy antenna at room temperature ($T = 300°$) and with a receiver noise band $B = 1$ cycle/sec. and represents the available noise power from the passive resistance of the dummy antenna. 1/

Available power may be defined as the power which would be delivered into a matched load by a generator with open circuit voltage, E, and internal resistance, R, and is thus $E^2/(4R)$. It should be noted that the available power from a generator is independent of the actual load impedance since the generator itself is not changed by changes in the load.

1/ H. Nyquist, "Thermal Agitation of Electric Charge in Conductors", Physical Review, vol. 32, p. 110, July 1928.

The available signal input power, $S_i$, required at the receiver input to produce a given output signal-to-noise ratio, $(S_o/N_o)$,[2/] may be written from (1):

$$S_i = \overline{NF}\ kTB\ \frac{S_o}{N_o} \qquad (2)$$

In order to evaluate (2), it is necessary first to determine $\overline{NF}$ for the receiver used.

The simplified input circuit of a typical receiver is shown in Fig. 1-a with a signal voltage being applied from a generator having an open circuit voltage, E, and internal resistance, $R_1$, which is made equal to the resistance presented to the receiver by the antenna (in this case the antenna is assumed to be resonant). The voltage step up ratio of the receiver input tuned circuit, LC, is designated as m. Fig. 1-b shows the equivalent circuit for Fig. 1-a in which $R_2/m^2$ represents the combined tuned circuit and first tube input losses referred to the input of the tuned circuit. $R_e$ is an equivalent noise resistance representing the noise generated throughout the receiver and $R_e/m^2$ is its value when referred to the input of the tuned circuit. An approach may be made to an ideal receiver when $R_e$ and m are simultaneously made very small.

Since all the noise introduced by the receiver is represented by the passive network of Fig. 1-b, the signal-to-noise ratio at the network output will be equal to the signal-to-noise ratio at the receiver output and the "noise figure" of the receiver may be obtained by computing the "noise figure" of the network from (1). The available signal power at the input, $S_i$, is:

$$S_i = \frac{E^2}{4R_1} \qquad (3)$$

2/ $S_o/N_o$ should be measured at the RF or IF output to eliminate the effect of different types of detectors.

and the available signal power at the network output, $S_o$, is given by:

$$S_o = \frac{E^2 \left[R_2/(m^2R_1 + R_2)\right]^2}{4R_1\left[R_2/(m^2R_1 + R_2)\right] + 4R_e/m^2} \qquad (4)$$

The available noise output power from a passive network is equal to kTB and (1) becomes:

$$\overline{NF} = \frac{S_i}{S_o} = \frac{m^2R_1 + R_2}{R_2} + \frac{R_e}{m^2R_1}\left(\frac{m^2R_1 + R_2}{R_2}\right)^2 \qquad (5)$$

By differentiating (5) with respect to m and equating to zero, the optimum voltage step up ratio, $m_o$, is found to be:

$$m_o = \sqrt[4]{\frac{{R_2}^2}{{R_1}^2}\left(\frac{R_e}{R_2 + R_e}\right)} \qquad (6)$$

When the coupling between the signal generator (or antenna) and the grid of the first tube is such that $m = m_o$, the best possible "noise figure" for the receiver will be obtained and its value may be determined by substituting (6) in (5).

The "noise figure" may be expressed in a more convenient form by introducing a mismatch factor, n[3/], which is defined as:

$$n \equiv \frac{1}{m}\sqrt{\frac{R_2}{R_1}} \qquad (7)$$

Combining (5) and (7), the expression for "noise figure" becomes:

$$\overline{NF} = 1 + \frac{1}{n^2} + \frac{R_e}{n^2R_2} + \frac{n^2R_e}{R_2} \qquad (8)$$

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3/ It may be noted that with resonant coupled circuits n is equal to the ratio of the coefficient of coupling used to the coefficient of coupling with critical coupling.

The optimum mismatch factor, $n_o$, may be obtained from (6) and (7) and is:

$$n_o = \sqrt[4]{\frac{R_2 + R_e}{R_e}} \tag{9}$$

When $n = n_o$, the minimum possible "noise figure", $\overline{NF}_o$, is given by:

$$\overline{NF}_o = 1 + \frac{2n_o^2}{n_o^4 - 1} \tag{10}$$

Equation (10) is a useful expression because, as has been pointed out by Cottony[4], $n_o$ frequently can be determined to a good approximation by measuring the ratio between two radio frequency voltages and is given by:

$$n_o^2 = \sqrt{\frac{R_2 + R_e}{R_e}} = \frac{V_1}{V_2} \tag{11}$$

where:

$V_1$ = RF (or IF) output voltage with antenna input disconnected.

$V_2$ = RF (or IF) output voltage with grid of first tube shorted to ground.

This method should be used with caution, however, because considerable error may be encountered under certain conditions, such as when there is feedback from the output to the input of the first stage.

$\overline{NF}_o$ has been plotted as a function of $n_o^2$ in Fig. 2 and it can be seen that the best possible "noise figure" approaches a value of unity as $n_o^2$ becomes large. This condition exists, of course, when the tube noise is small compared to the resistance noise. When $n_o^2$ approaches unity, $\overline{NF}_o$ rapidly approaches infinity and within this region $\overline{NF}_o$ is difficult to determine accurately from the above voltage measurements. For example, when

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4/ H. V. Cottony, Lab. Notes, Division 14, Section 5, National Bureau of Standards, Washington, D. C.

$n_o^2$ has a value of 1.1, a 5% decrease in $n_o^2$ causes more than a 100% increase in $\overline{NF}_o$.

When the receiver input impedance is matched to the generator impedance, n equals unity and the "noise figure", $\overline{NF}_m$, can be obtained from (8) and expressed:

$$\overline{NF}_m = 2 + \frac{2R_e}{R_2} = 2 + \frac{2}{n_o^4 - 1} \tag{12}$$

This equation also has been plotted on Fig. 2 and it can be seen that for large values of $n_o$, $\overline{NF}_m$ approaches a value of 2. When $n_o$ approaches unity, $\overline{NF}_m$ becomes very large and is approximately equal to $\overline{NF}_o$. From Fig. 2 it is clear that the use of the optimum coupling always results in the lowest "noise figure" but for noisy receivers the optimum and matched couplings are nearly identical and under those circumstances it is often more convenient to match the receiver to the generator.

The value of $R_e$ is determined by the particular tube in the first circuit and the design of the receiver following the input circuit. Once this value has been determined, it is evident from Fig. 2 that for the best "noise figure", $R_2$ should be large with respect to $R_e$. Within the frequency band considered here (50 kc to 5000 kc) the grid input resistance will be very high and $R_2$ will be determined almost entirely by the tuned circuit. For values of Q greater than about 10, $R_2 = QX$, where X is the reactance of the grid inductor, L. Then for the minimum "noise figure" the inductor should be constructed so that QX is as large as possible at the operating frequency.

## IV. ANTENNA AND INPUT CIRCUIT LOSS

When the receiving antenna is a small fraction of a wavelength long, its impedance consists of a small radiation resistance, a grounding loss resistance, and a large series capacitive reactance. The reactance should be tuned out and this is usually accomplished with a series loading inductor. The loading-inductor resistance and ground-loss resistance then appear in series with the antenna and their combined resistance is represented by $R_3$ in Fig. 1-c. In this figure, $R_1$ represents the resistance of the signal source and is equal to the radiation resistance of the antenna to be used. A loss factor, L, may be introduced to represent the loss in available signal power between the signal source and the receiver. L may be defined by:

$$L \equiv \frac{S_g}{S_i} \qquad (13)$$

where:

$S_g$ = Available signal power from the antenna or signal source.

$S_i$ = Available signal power at the receiver input terminals.

and for the circuit of Fig. 1-c:

$$L = \frac{R_1 + R_3}{R_1} \qquad (14)$$

where:

$R_1$ = Internal resistance of the signal source.

$R_3$ = Resistance due to the loading inductor and ground loss.

Equation (2) may be written:

$$S_g = LS_i = L\overline{NF}\, kTB \frac{S_o}{N_o} \qquad (15)$$

It can be seen by (15) that the available signal power from an antenna that is required to override the receiver noise is proportional to L $\overline{NF}$. Thus L $\overline{NF}$ is equal to the "noise figure" that would be measured at the antenna terminals. In order to keep $S_g$ at a minimum the circuit parameters should be chosen so that L is as small as possible. For the circuit shown in Fig. 1-c, $R_3/R_1$ should be minimized. This may be accomplished by reducing ground loss and making the Q of the loading inductor high. L $\overline{NF}$ has been plotted as a function of frequency for several types of antennas on Fig. 3. In plotting these curves it was assumed that a "noise figure" of 2.5 (4 db) could be attained easily. A ground loss of 5 ohms was assumed and the loading inductor loss was determined by assuming a Q of 100, the inductive reactance being sufficient to resonate the capacitive reactance presented by the antenna circuit. $R_1$ was taken to be equal to the radiation resistance of the antenna, $R_a$, which for a short cylindrical antenna perpendicular to a perfectly conducting plane is given by:5/

$$R_a = 40\pi^2 \left(\frac{h}{\lambda}\right)^2 \text{ ohms}, \qquad (h < \lambda/8) \qquad (16)$$

where:

$R_a$ = Radiation resistance in ohms

h = The length of the antenna in meters

$\lambda$ = The vacuum wavelength in meters

and the series capacitance, $C_a$, is given by:6/

$$C_a = \frac{24.15h}{\log_{10}\frac{2h}{d} - a} \ \mu\mu f \qquad (17)$$

5/ S. A. Shelkunoff, Electromagnetic Waves, D. Van Nostrand Co., Inc., New York, New York.

6/ F. E. Terman, Radio Engineers Handbook, p. 116, McGraw-Hill Book Co., New York, New York.

where:

$h$ = length of antenna in meters

$d$ = diameter of antenna in meters

$a$ = constant depending on $h'/h$ = .403 when ($h'/h = 0.02$)

$h'$ = height of lower end of antenna above the ground in meters

The diameters were taken as 1 inch and 1/4 inch respectively for the 30 foot and 5 foot antennas. A radiation resistance of 36.5 ohms was assumed for the quarter wave antenna.

In computing curves 1, 2, and 4 of Fig. 3, it was assumed that the effect of the base insulator was negligible, but in computing curves 3 and 5, it was assumed that the insulator had a capacitance of 50 $\mu\mu$f and a shunt resistance of 1 megohm as represented by $C_1$ and $R_1$ in the equivalent circuit of Fig. 4. In this figure, the radiation resistance ($R_a$), antenna capacitance ($C_a$), ground loss resistance ($R_L$), loading inductance, ($L_c$) loading coil resistance ($R_c$), and receiver input resistance ($R_2/m^2$) are also shown. In this case L includes the additional loss caused by the base insulator and from Fig. 3 it can be seen that these losses are appreciable; particularly in the case of the 5 foot antenna.

## V. EXTERNAL NOISE

External noise may consist of atmospheric, man-made, or cosmic noise and its magnitude can conveniently be expressed by a dimensionless external noise factor, $\overline{EN}$, which was defined by Norton and Omberg[7/] to be the ratio of the available antenna noise power, $N_a$, to kTB with T taken as

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7/ K. A. Norton and A. C. Omberg, "The Maximum Range of a Radar Set", Proc. I.R.E., vol. 35, January 1947.

300°K and may thus be written:

$$\overline{EN} = \frac{N_a}{kTB} \qquad (T = 300°K) \qquad (18)$$

where:

$N_a$ = The available noise power from the antenna in watts.

B = Effective noise bandwidth in cycles/second[8]

Thus, when a receiver is connected to an antenna, the overall system noise is changed and an "effective noise figure," $\overline{NF}'$, must be used instead of $\overline{NF}$ in (2) in order to determine the receiver input power required to over-ride both the external and internal noise; this effective noise figure depends upon $\overline{NF}$, L, and $\overline{EN}$,[7] thus:

$$\overline{NF}' \equiv L\,\overline{NF} + \overline{EN} - 1 \qquad (19)$$

The available antenna signal power, $S_a$, that is required to produce a given output signal-to-noise ratio, $(S_o/N_o)$ may be obtained from (2) by substituting $\overline{NF}'$ and $S_a$ for $\overline{NF}$ and $S_i$ respectively. The resulting equation is:

$$S_a = \left[L\,\overline{NF} + \overline{EN} - 1\right] kTB \frac{S_o}{N_o} \quad \text{watts} \qquad (20)$$

Within the frequency band of 50 to 5000 kc, cosmic noise is usually considered to be negligible and with suitable filtering and proper choice of antenna site, man-made noise may usually be practically eliminated. The predominant influence on $\overline{EN}$ then is the unavoidable atmospheric noise.

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8/ In this report the effective noise bandwidth has been taken as 1 cycle per second and all noise values have been adjusted on the assumption that the noise power is proportional to bandwidth.

The available antenna noise power, $N_a$, produced by a root-mean-square atmospheric noise field intensity, $F_n$, may be obtained from:

$$N_a = \frac{F_n^2 \, H_e^2}{4R_a} \text{ watts} \tag{21}$$

where:

$F_n$ = rms atmospheric noise field intensity in volts per meter for the bandwidth, B.

$H_e$ = Effective height of antenna in meters.

$R_a$ = Radiation resistance of antenna in ohms.

For a short antenna over a perfectly conducting plane:

$$H_e \doteq h/2 \tag{22}$$

and $R_a$ is given by (16).

The value of $\overline{EN}$ can then be obtained from:

$$\overline{EN} \doteq \frac{F_n^2 \, \lambda^2}{640\pi^2 \, kTB}, \quad (h < \lambda/8) \tag{23}$$

Equation (23) has been plotted in Fig. 5 for frequencies between 50 and 5000 kc. The values of $F_n$ were calculated from a Signal Corps report[9/] for "noise grades" 1 and 3 and represent daytime noise intensities to be expected during the quietest seasons of the year in the arctic and midlatitudes, respectively. In the Signal Corps report, the minimum field intensities required for intelligible reception of radio telephony for 90% of the time in the presence of atmospheric noise were plotted as a function of frequency for various noise grades, seasons, and times of day.

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9/ "Minimum Required Field Intensities for Intelligible Reception of Radio Telephony in Presence of Atmospherics or Receiving Set Noise," Radio Propagation Unit Technical Report No. 5, Dec. 1945.

These curves were plotted initially on the assumption that a voltage ratio of telephone-signal-carrier-intensity-to- "average atmospheric noise"10/ of 380 (51.6 db) was required (B = 1 cycle/sec). As will be shown later the "average atmospheric noise" voltage must be increased by a factor of 1.51 (3.6 db) in order to obtain the rms value and therefore $F_n$ was calculated by decreasing the field intensities shown in the Signal Corps report by a factor of 251 (48 db). The values of $\overline{EN}$ thus obtained represent the actual noise power exceeded for 10% of the time. The 10% curves shown in Fig. 5 were plotted by taking the geometric mean of the 10% noise values during the daytime hours for each noise grade and the values of $\overline{EN}$ exceeded for other percentages of the time were estimated from daytime noise distributions measured on 180 kc in noise grade 3.11/ These distributions are strictly applicable to 180 kc only and thus the values of $\overline{EN}$ shown for percentages of time other than 10% are somewhat in error on other frequencies since they were obtained by extrapolation. In view of this uncertainty, values of $\overline{EN}$ below 1 (0 db) are not given; such values would correspond to antenna temperatures7/ less than 300 K and this is probably unreasonable at these frequencies.

## VI. THE DISTRIBUTION OF NOISE VOLTAGE AND ITS INFLUENCE ON MEASUREMENTS

The signal-to-noise ratio that is required for various types of service has been determined by a number of experimenters, both for atmospheric and for thermal noise. However, since these two types of noise do not have the same voltage distributions with time and since the measurement techniques

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10/ "Average Atmospheric Noise" is measured by connecting the output of a linear detector to a chart recorder through a dc amplifier having a charge and discharge time constant of about 1 minute. The recorder reading is thus proportional to the average value of the rf envelope voltage. The recorder is calibrated in terms of the rms values of a standard cw voltage.

11/ W. Q. Crichlow, J. W. Herbstreit, E. M. Johnson, K. A. Norton, C. E. Smith, "The Range Reliability and Accuracy of a Low Frequency Loran System," Report No. ORS-P-23, Operational Research Staff, Office of the Chief Signal Officer, The Pentagon, Washington, D. C.

were different, different characteristics of the noise were measured. In order to express these measurements in terms of noise power so that the two types of noise may be compared on the same basis, it is necessary to know the proper correction factor to apply in each case.

Landon[12/] has shown that the instantaneous voltage of thermal or fluctuation noise follows a normal distribution. Thus in the output of any linear network containing fluctuation noise, the probability that the noise voltage will lie between V and V + dV is given by:

$$d_p = \frac{1}{E\sqrt{2\pi}} \exp\left(\frac{-V^2}{2E^2}\right) dV \tag{24}$$

where:

E = the root-mean-square noise voltage

When the noise is fed to a linear detector which follows the envelope of the noise, the instantaneous output of the detector will follow a Rayleigh distribution.[13/] The probability that the instantaneous output voltage lies between A and A + dA is:

$$dp_A = \frac{A}{E^2} \exp\left(\frac{-A^2}{2E^2}\right) dA \tag{25}$$

The average detector output voltage, $\bar{A}$, that would be measured with a long time constant recorder is the integral from A = 0 to $\infty$ of A $dp_A$. Thus:

$$\bar{A} = \int_0^\infty \frac{A^2}{E^2} \exp\left(\frac{-A^2}{2E^2}\right) dA = E\sqrt{\frac{\pi}{2}} = 1.252E \tag{26}$$

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12/ Vernon D. Landon, "The Distribution of Amplitude With Time in Fluction Noise", Proc. I.R.E., vol. 29, Feb. 1941.

13/ K. A. Norton, Discussion of above paper, Proc. I.R.E., vol. 39, Sept. 1942, pp. 425-429 and Corrections November 1942, p. 526.

If the recorder is now calibrated by substituting a cw signal for the noise and adjusting its intensity to give the same recorder deflection, the recorder voltage will be:

$$A_s = \sqrt{2}\ E_s = 1.414\ E_s \tag{27}$$

where:

$A_s$ = detector output voltage with cw input

$E_s$ = rms voltage of cw input to detector

Since the cw input was adjusted so that $A_s = \bar{A}$ then the rms noise voltage is:

$$E = 1.129\ E_s \tag{28}$$

In a similar manner the appropriate correction factors can be calculated for thermal noise measured in other parts of the receiver using as a calibrating source, a rf signal, either modulated or unmodulated. These values have been tabulated in Table I and it may be seen that appreciable errors will be encountered in noise measurements unless the appropriate correction factor is used.

Atmospheric noise does not lend itself readily to mathematical analysis since it does not follow any specified distribution with time. Its characteristics vary over wide limits depending among other things on the distance to and number of sources, means of propagation, receiver bandwidths, and receiver center frequency. In spite of this variability, however, it has been found experimentally that when the "average atmospheric noise"[10] is measured with a long time constant recorder, good correlation is found between intelligibility and signal-to- "average

TABLE I

Correction factor for thermal noise measured with a calibrating rf signal of known rms carrier voltage, $E_s$, which is adjusted to give the same output meter reading as the noise with rms voltage, E.

| Metering Circuit | Type of Calibrating signal | Relative meter reading with noise | Relative meter reading with signal | rms noise voltage E |
|---|---|---|---|---|
| quare law detector r thermocouple in F or IF output | cw | 1.0 E | 1.0 $E_s$ | 1.0 $E_s$ |
| inear detector with eter reading average c output | cw | 1.252 E | 1.414 $E_s$ | 1.129 $E_s$ |
| inear detector with hermocouple meter n diode output | cw | 1.414 E | 1.414 $E_s$ | 1.0 $E_s$ |
| inear detector with hermocouple meter n diode output | 100% sine wave modulated carrier | 1.414 E | 1.73 $E_s$ | 1.225 $E_s$ |
| inear detector with ectifier type meter n audio output | 100% sine wave modulated carrier | 0.527 E | 0.9 $E_s$ | 1.71 $E_s$ |
| inear detector with hermocouple meter n audio output | 100% sine wave modulated carrier | 0.655 E | 1.0 $E_s$ | 1.528 $E_s$ |

atmospheric noise" ratio. This method has been found useful in evaluating the effects of atmospheric noise on a number of types of service, particularly those depending upon aural and visual observations of signals.

In order to translate "average atmospheric noise" measurements into the rms value of the noise, a correction factor must be applied. Jansky 14/ attempted to determine this factor experimentally for both thermal noise and atmospheric noise by measuring the ratio of average to effective voltage which he states as being 0.85 for thermal noise and 0.55 to 0.8 for atmospheric noise. From his circuit diagram it appears that he was measuring the average value of the noise envelope instead of the average value of the noise, the latter being defined by Jansky to be the average of the instantaneous noise values without regard to sign. It was shown theoretically in (28) that when thermal noise is measured with a linear detector calibrated with a cw signal, the ratio of the rms cw voltage to the rms noise voltage is 0.886. The theoretical calibration factor of 0.886 apparently corresponds to Jansky's experimental value of 0.85 for thermal noise and thus the ratio of rms cw voltage to rms atmospheric noise voltage has been assumed to fall between Jansky's measured values of 0.55 to 0.8. Using the geometric mean of these two limiting values, the rms atmospheric noise voltage will be 1.51 $E_s$, where $E_s$ is the rms cw carrier voltage used to calibrate an "average" recorder.

## VII. THE REQUIRED SIGNAL-TO-NOISE RATIO FOR TELEPHONY

Having determined appropriate correction factors, it is now possible to examine on a common basis the required signal-to-noise ratios that have

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14/ Karl G. Jansky, "An Experimental Investigation of the Characteristics of Certain Types of Noise," Proc. I.R.E., vol. 27, Dec. 1939.

been determined experimentally for various services. The FCC[15] has found for A.M. voice communication that a carrier-to-"average atmospheric noise" voltage ratio of 380 (51.6 db) is required with a rf signal bandwidth of 3 kc, to produce an intelligibility of 90% with related words when the noise is referred to a bandwidth of 1 cycle/sec. The corresponding signal-to-rms noise voltage ratio will be 251 (48 db) when the above mentioned correction factor is applied.

The effects of signal bandwidth on required signal-to-noise ratio were studied at Harvard University by members of the Psycho-Acoustic Laboratory and the results have appeared in a recent issue of the Proceedings of the I.R.E.[16] In this study, thermal type noise was generated with a 6D4 gas tube; and impulse noise, which was intended to simulate atmospheric noise, was generated in an irregularly triggered thyratron circuit. The impulse noise consisted of equal amplitude pulses having a duration of approximately 0.02 microseconds spaced irregularly in time with an average of 1000 pulses per second. The percentage copy of spoken words was determined as a function of signal-to-noise ratio for a number of receiver bandwidths. In these tests the noise intensities were measured with an auxilliary receiver with a 10 kc/s bandwidth and an output meter which was calibrated against a thermocouple for each type of noise. The noise measurements were made by substituting a carrier, which was modulated 100% at 400 cycles, and varying its intensity until it produced the same indication on the noise meter as did the noise.

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15/ "A Report of the Marine Section, Safety and Special Services Division, on the Great Lakes Engineering Study of 1941", FCC, May 22, 1942.

16/ W. J. Cunningham, J. S. Goffard, and J. C. R. Licklider, "The Influence of Amplitude Limiting and Frequency Selectivity on the Performance of Radio Receivers in Noise," Proc. I.R.E., vol. 35, Oct. 1947.

The results of these tests have been converted to values of carrier-to-rms noise (B = 1 cycle/sec) that are required to produce 90% intelligibility of related words and are plotted in Fig. 6 as a function of signal bandwidth. In converting these values it was assumed that the calibrating thermocouple was located in the audio circuit of the receiver and, for thermal noise, the correction factor of 1.528 shown in Table I was applied. The conversion factor for the impulse noise is not known but it was assumed that the impulse noise sufficiently approximated atmospheric noise so that the signal-to-noise ratios could be adjusted to correspond to the value determined by the FCC at a signal bandwidth of 3 kc/s. Consequently the level of the impulse noise measurement was adjusted so that the curve gave the same value of required signal-to-noise ratio for a 3 kc signal bandwidth as determined by the FCC in the presence of atmospheric noise. This adjusted curve is shown as a dashed line on Fig. 6.

It may be noted from Fig. 6 that the signal-to-noise ratio curves for the two types of noise cross each other and have a total spread of only a few decibels over a large range of bandwidths. For this reason it seems reasonable to assume that most of the variation in the curves is due to the experimental error in determining intelligibility. It is therefore concluded that a voltage ratio of signal-to-rms noise of approximately 220 (47 db) will be required for 90% intelligibility of related words for both thermal and atmospheric noise, and that this ratio is practically independent of signal bandwidth.

## VIII. THE REQUIRED SIGNAL-TO-NOISE RATIO FOR THE RECEPTION OF L.F. LORAN PULSES.

During the LF Loran study made by the Signal Corps[11/], the percent reliability with which a loran delay reading could be made was determined as a function of noise grade for 180 kc. It was found with sky-wave signals, that readings could be made 90% of the time during the day when the median value of the peak pulse field intensity, corresponding to the weaker signal of the pair to be matched, was 500 times (54 db above) the median value of "average atmospheric noise". When referred to the rms value of the noise this ratio becomes 330 (50.4 db). These figures apply only to 180 kc, however, since the relative distribution of signal and noise will not necessarily be the same on other frequencies. It should be noted that these required signal-to-noise ratios do not apply to individual readings but to the medians of the separate signal and noise distributions. If the two distributions were perfectly correlated, then the ratio of the medians would be equal to the signal-to-noise ratio required for an individual reading. In practice it has been found that some correlation does exist between signal and noise but the exact correlation is not known. In order to estimate the influence of frequency on reliability of loran signals it will be assumed that a good correlation exists and that, as a first approximation, a ratio of 330 (50.4 db) is required for the peak pulse to rms noise to produce a reliability of 90%, regardless of frequency; this is just 1.47 times (3.4 db) stronger than the carrier required for satisfactory telephony. In order for this ratio to be applicable throughout the frequency range, the original receiver band width and pulse length would have to be maintained.

## IX. REQUIRED FIELD INTENSITY

When the available antenna signal power, $S_a$, required for a given type of service has been determined, the field intensity, $F_s$, necessary to produce this power in a short vertical antenna is:

$$F_s = \frac{2}{H_e}\sqrt{S_a R_a} = \frac{79.48}{\lambda}\sqrt{S_a} \quad \text{volts/meter}, \ (h < \lambda/8) \qquad (29)$$

Figs. 7, 8 and 9 have been plotted from (20) and (29) by means of data presented in Figs. 3 and 5, and by assuming a required power ratio of signal-to-noise, $S_o/N_o$, equal to 50,000 (47 db). In these figures, the field intensity required to produce 90% intelligibility of related words has been plotted as a function of frequency for several types of antennas operating in various levels of external noise.

Fig. 7 was plotted for a 5 foot vertical antenna having the characteristics shown in curve 5 of Fig. 3. It may be seen that even in noise grade 3, when such a short antenna is used, the limitation on reception is caused, for a large percentage of the time, by receiver noise and input circuit loss rather than external noise. The difference between the solid and dashed lines indicates the improvement possible at the receiver for the percentages of time shown. When such an antenna is used in the arctic where noise grade 1 exists, reception is limited almost all the time by input circuit loss and receiver noise.

Fig. 8 was plotted in a similar way for a 30 foot vertical antenna with characteristics shown in curve 3 of Fig. 3. When operating in noise grade 1, the losses associated with this antenna determine the required field intensity rather than external noise for large percentages of the time; however, in noise grade 3, external noise controls most of the time. As in

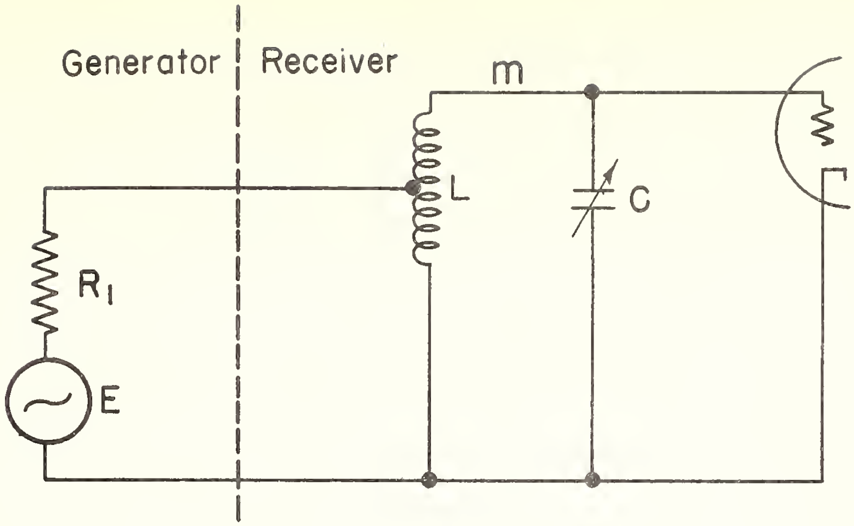
Fig. 7, the difference between the solid and dashed curves shows the improvement in reception possible by reducing the losses.

Fig. 9 shows the field intensity required for a quarter-wave antenna operating in noise grade 1. With this antenna, reception is limited only in extremely low noise fields by antenna losses and set noise. These low noise fields are not likely to be encountered, however, because thermal radiation from the ionosphere at a temperature of about 300°K will prevent values of $\overline{EN}$ from going appreciably below 1 (0 db) within the frequency range shown. Thus when a quarter-wave antenna is used, reception is determined almost always by external noise.

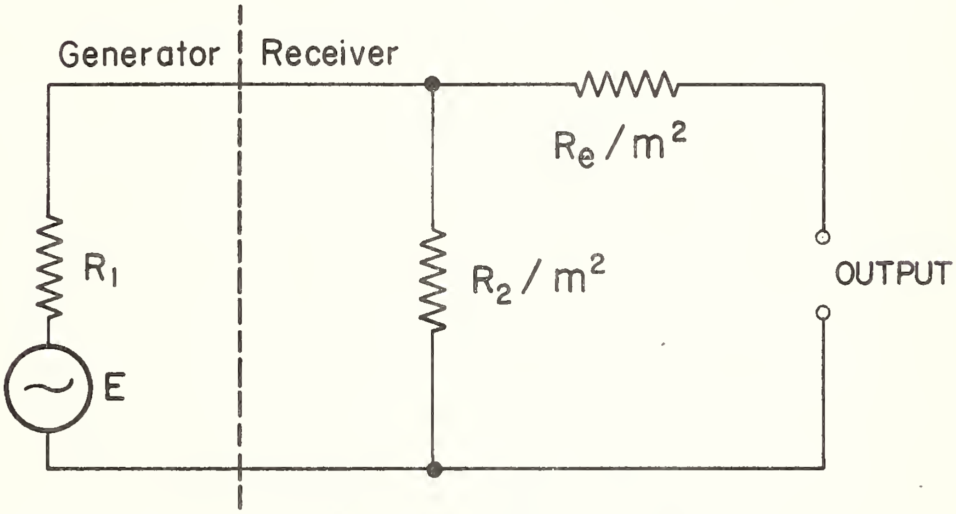
The curves of Figs. 7, 8 and 9 may also be used to obtain the pulse field intensity required for Loran reception. If the values of field intensity shown by the curves are multiplied by 1.47 (increased by 3.4 db) an estimate is obtained of the peak pulse field intensity required to produce 90% reliability for an individual delay reading. As was pointed out before, this assumes close correlation between the signal and noise distributions since the required signal-to-noise ratio was determined when both signal and noise were variable. The median value of pulse field intensity required for 90% reliability may be determined by increasing by a factor of 1.47 (adding 3.4 db to) the 50% curves shown. In this case the only assumption regarding the signal and noise correlation is that the same correlation exists that was obtained when the Loran study was made.

Fig. 10 has been plotted to show more clearly the percentage of time that reception is limited by receiver noise rather than external noise. The curves were plotted for 5 foot, 30 foot, and quarter-wave vertical antennas operating in noise grades 1 and 3 during summer daytime. No curve is shown for a quarter wave antenna in noise grade 3 since reception is limited by receiver noise for less than 1 percent of the time. These curves are subject to error since, as before, the distribution of external noise was assumed to be the same for all frequencies as the measured distribution on 180 kc.

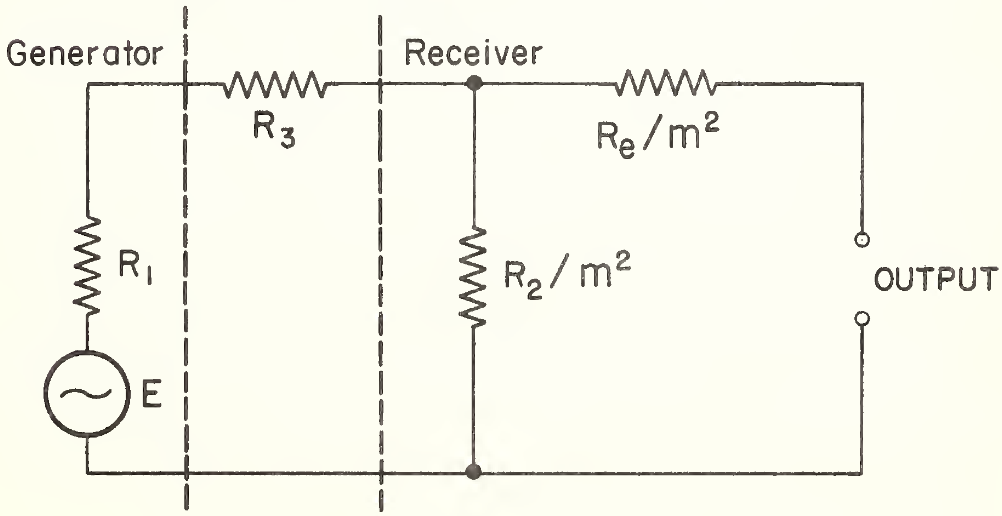
Using methods presented here, the field intensity required for other services may be determined under various operating conditions. The parameters which limit reception will then become evident and when the limitation is due to equipment shortcomings, some improvement usually may be obtained by equipment modifications.




(a) TYPICAL RECEIVER INPUT CIRCUIT




(b) EQUIVALENT INPUT CIRCUIT




(c) EQUIVALENT INPUT CIRCUIT
INCLUDING ANTENNA AND LOADING INDUCTOR LOSS

FIGURE 1

# RECEIVER "NOISE FIGURE"

PLOTTED AS A FUNCTION OF THE MISMATCH FACTOR REQUIRED FOR MINIMUM "NOISE FIGURE"

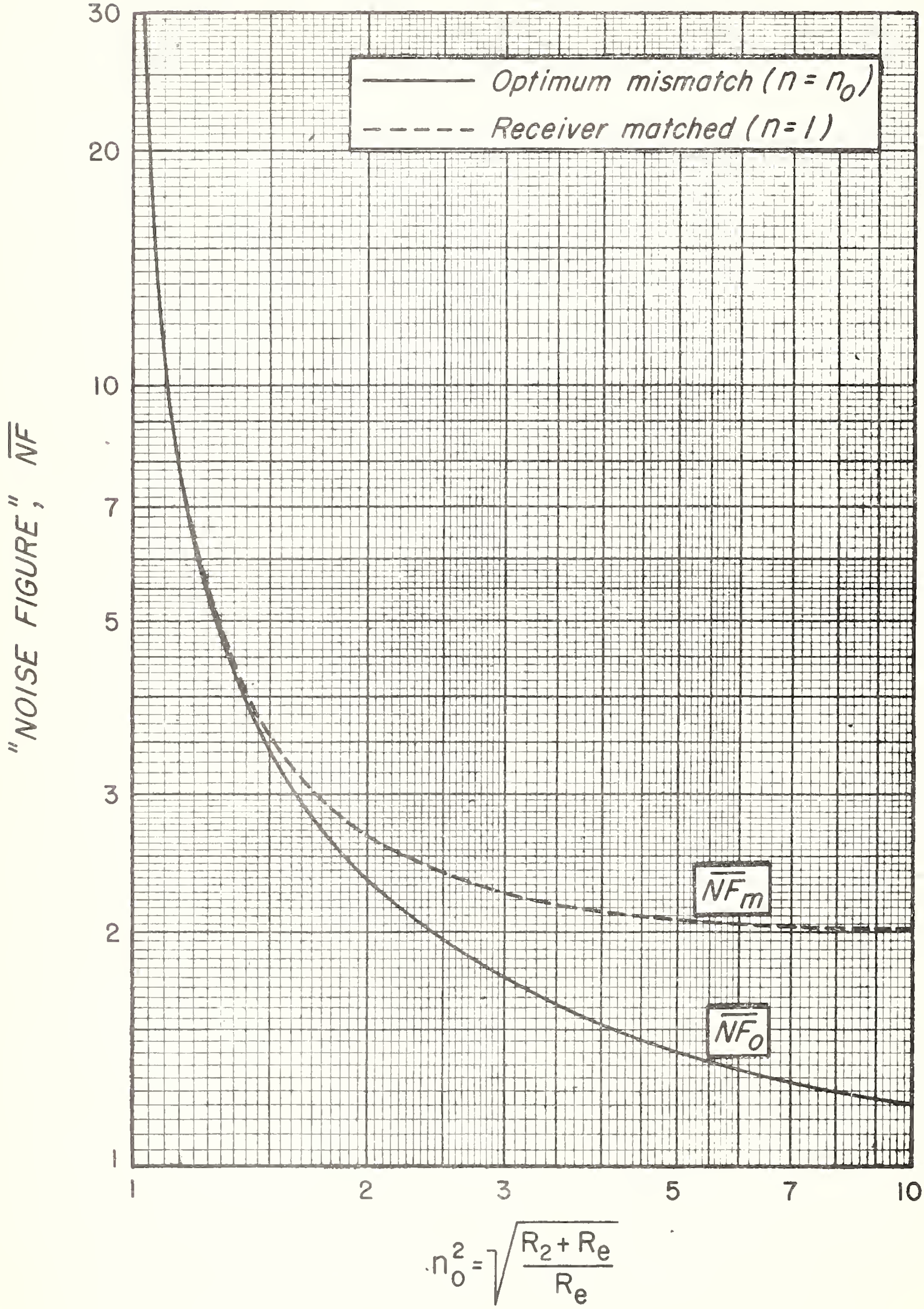



FIGURE 2

## $L\,\overline{NF}$ VS FREQUENCY FOR SEVERAL VERTICAL ANTENNAS

Noise Figure = 2.5 (4 db); Ground Loss = 5 Ohms; Loading Inductor Q = 100
Base Insulator Capacitance = 50 $\mu\mu$f; Base Insulator Shunt Resistance = 1 Megohm

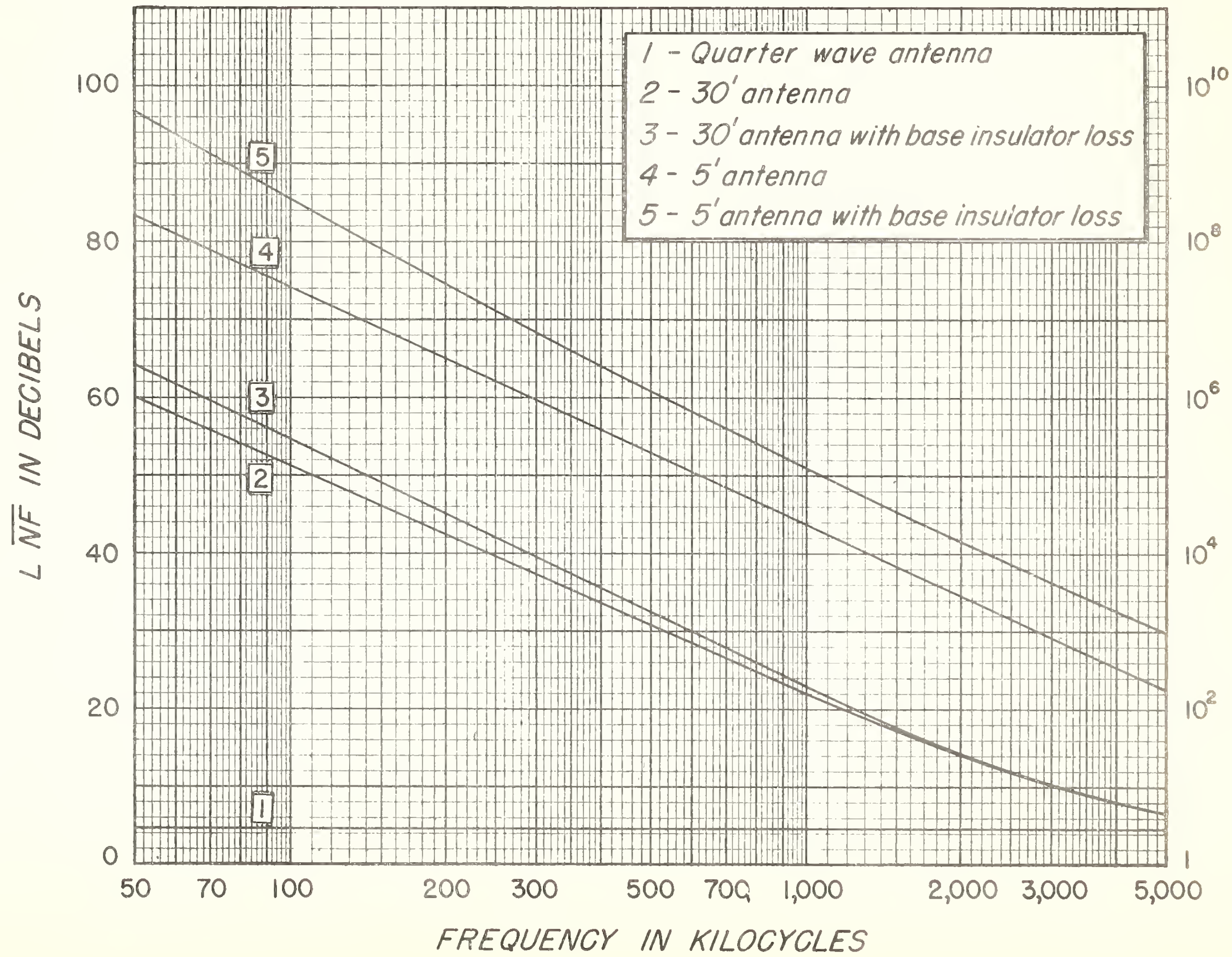
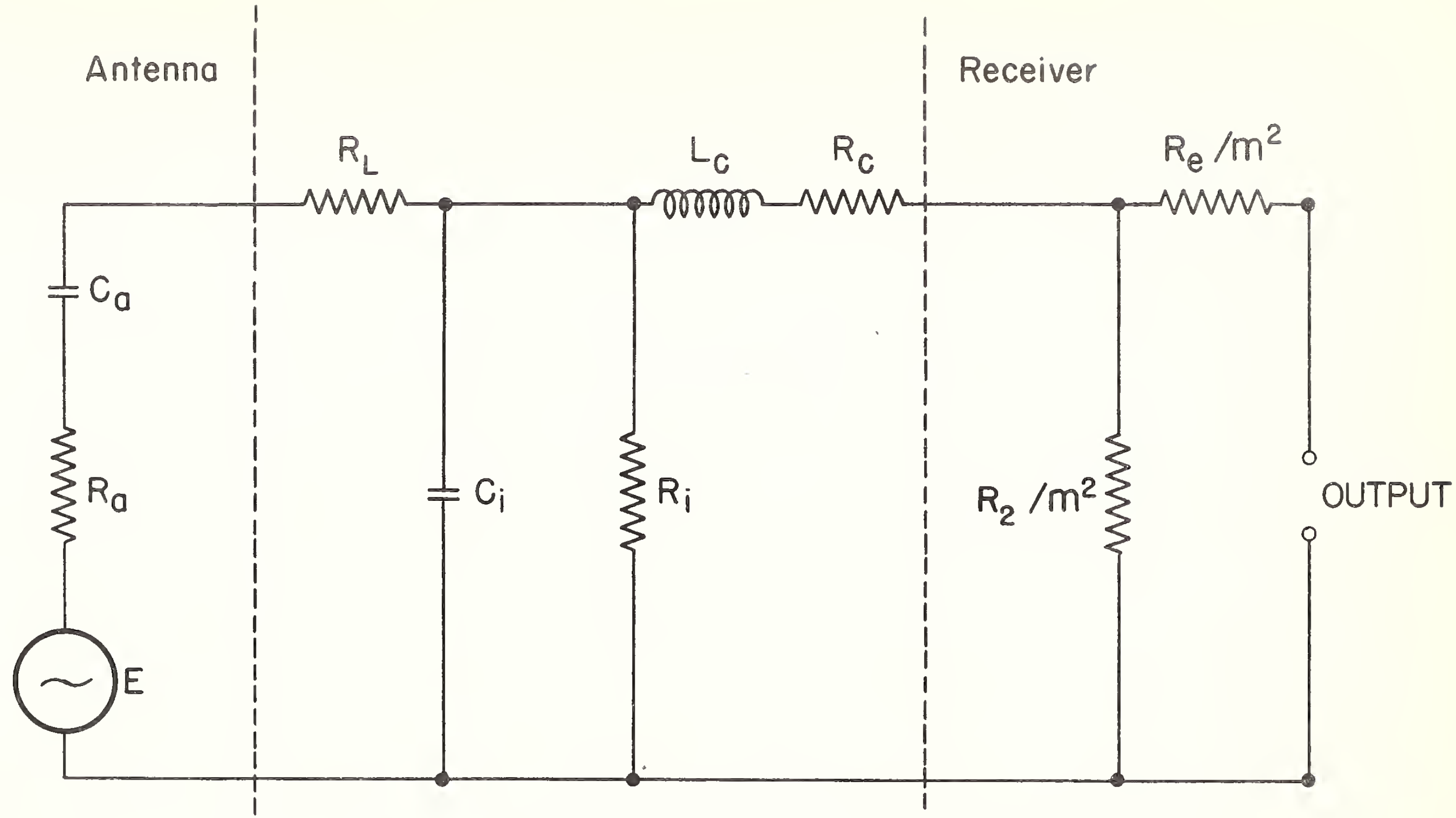



FIGURE 3




EQUIVALENT ANTENNA AND RECEIVER INPUT CIRCUIT

FIGURE 4

## "EXTERNAL NOISE FACTOR" VS FREQUENCY

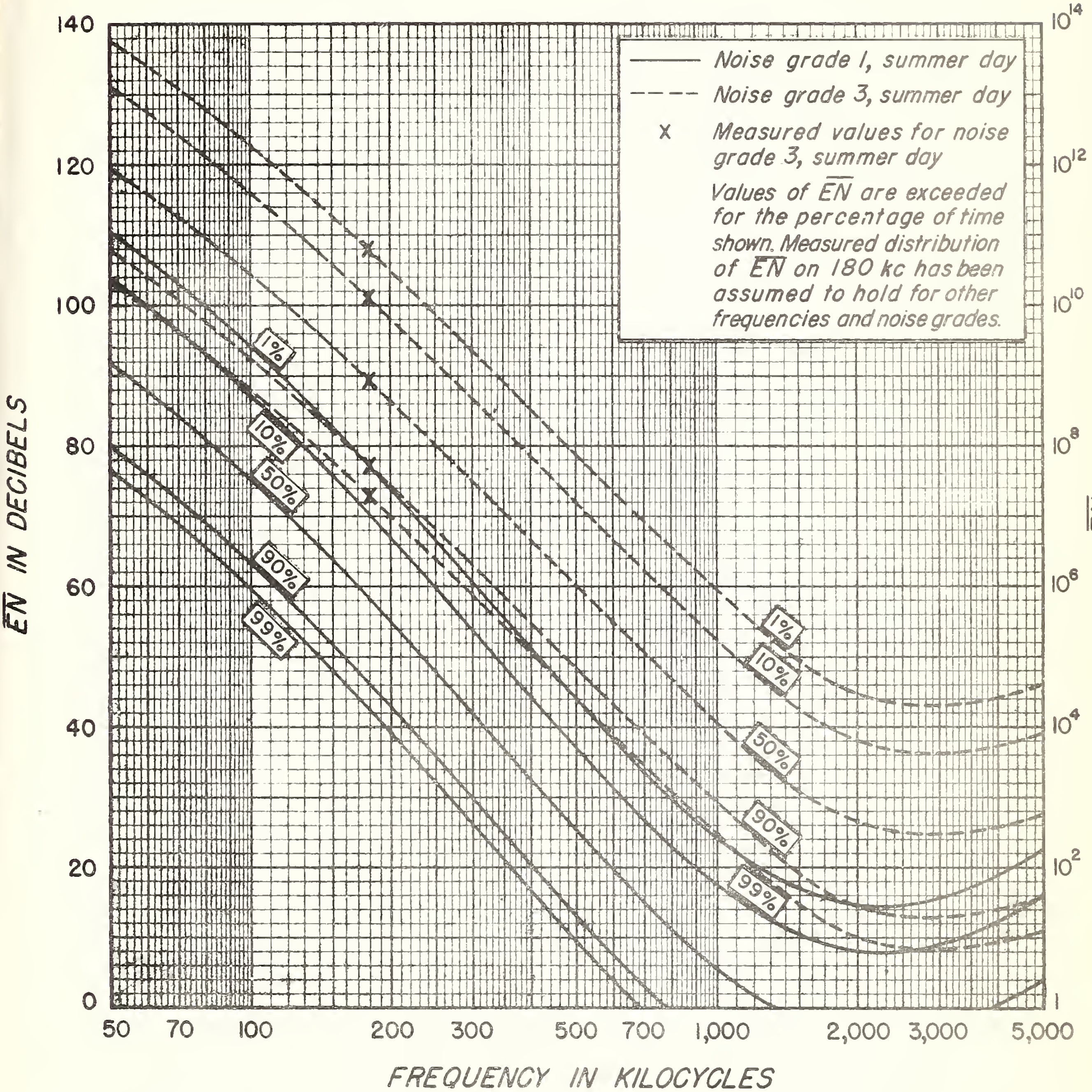



FIGURE 5

RATIO OF CARRIER-TO-NOISE IN A ONE CYCLE BANDWIDTH
REQUIRED FOR 90% INTELLIGIBILITY OF RELATED WORDS
(60% INTELLIGIBILITY FOR NON-RELATED WORDS)
VS
SIGNAL BANDWIDTH

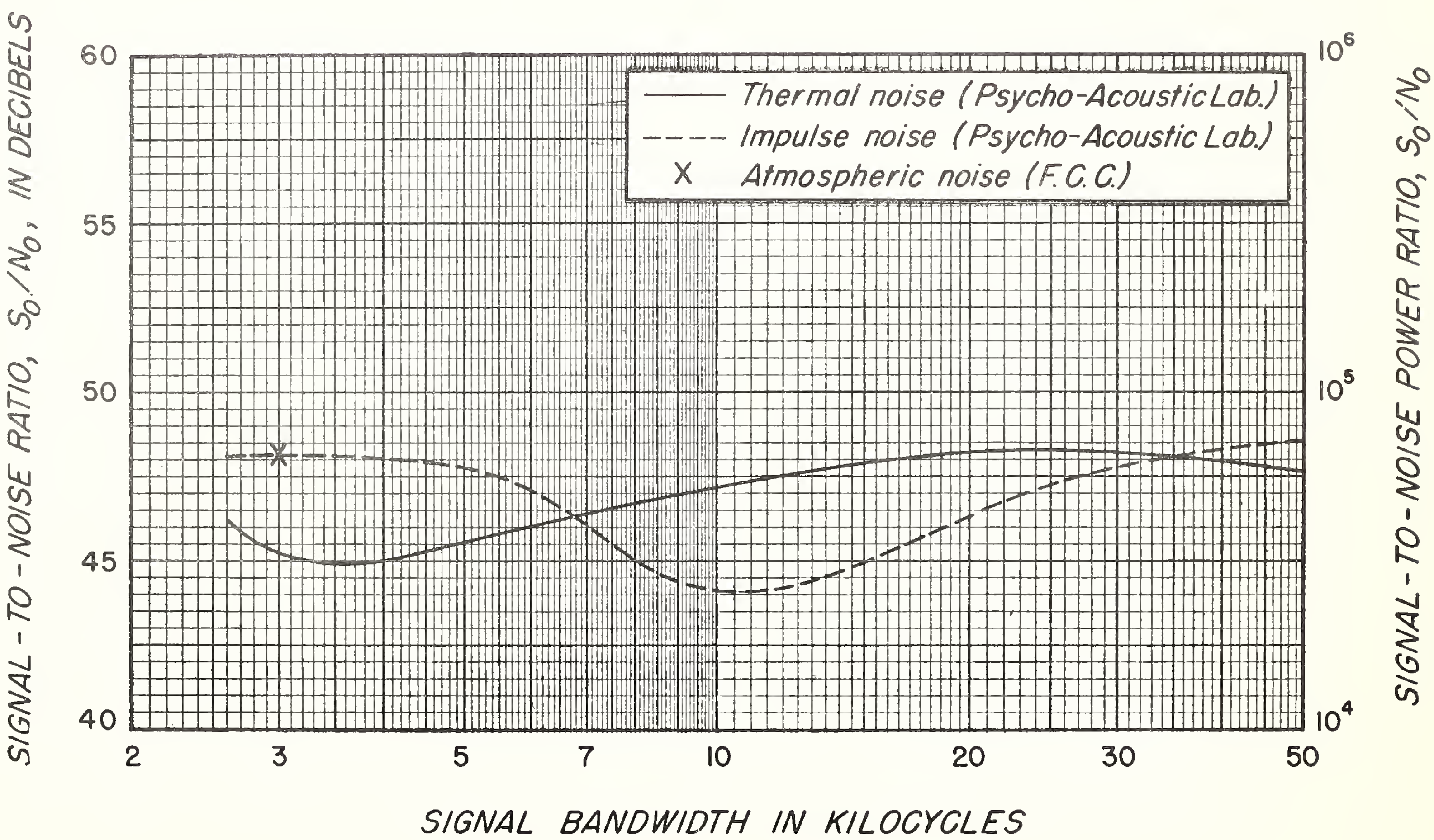



FIGURE 6

FIELD INTENSITY REQURED FOR 90% INTELLIGIBILITY OF RELATED WORDS (60% INTELLIGIBILITY OF NON-RELATED WORDS) VS FREQUENCY

(With a 5' vertical antenna in noise grade 3, summer day)

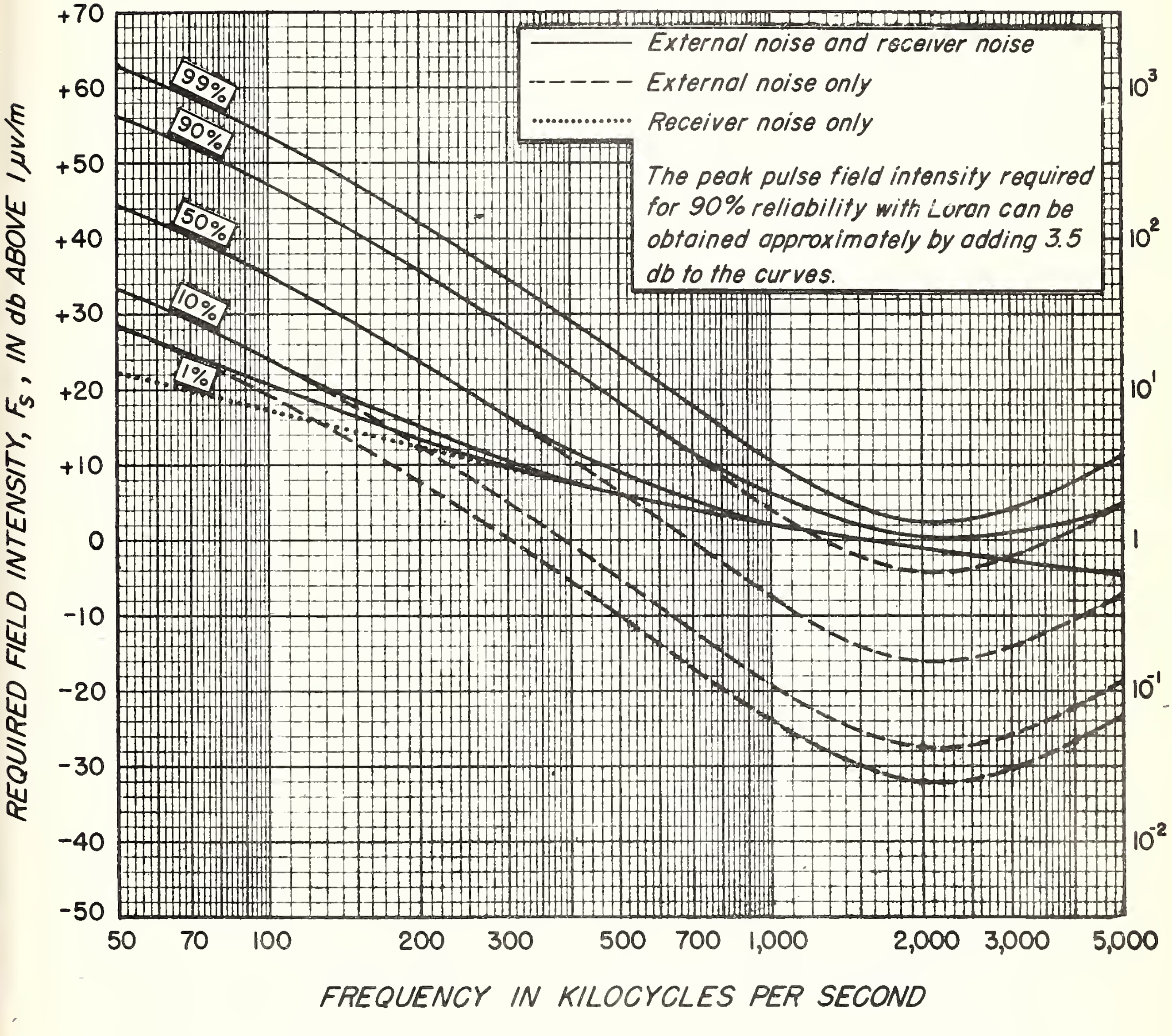



FIGURE 7

FIELD INTENSITY REQUIRED FOR 90% INTELLIGIBILITY OF RELATED WORDS
(60% INTELLIGIBILITY OF NON-RELATED WORDS)
VS
FREQUENCY

(With a 30' vertical antenna in noise grade I, summer day)

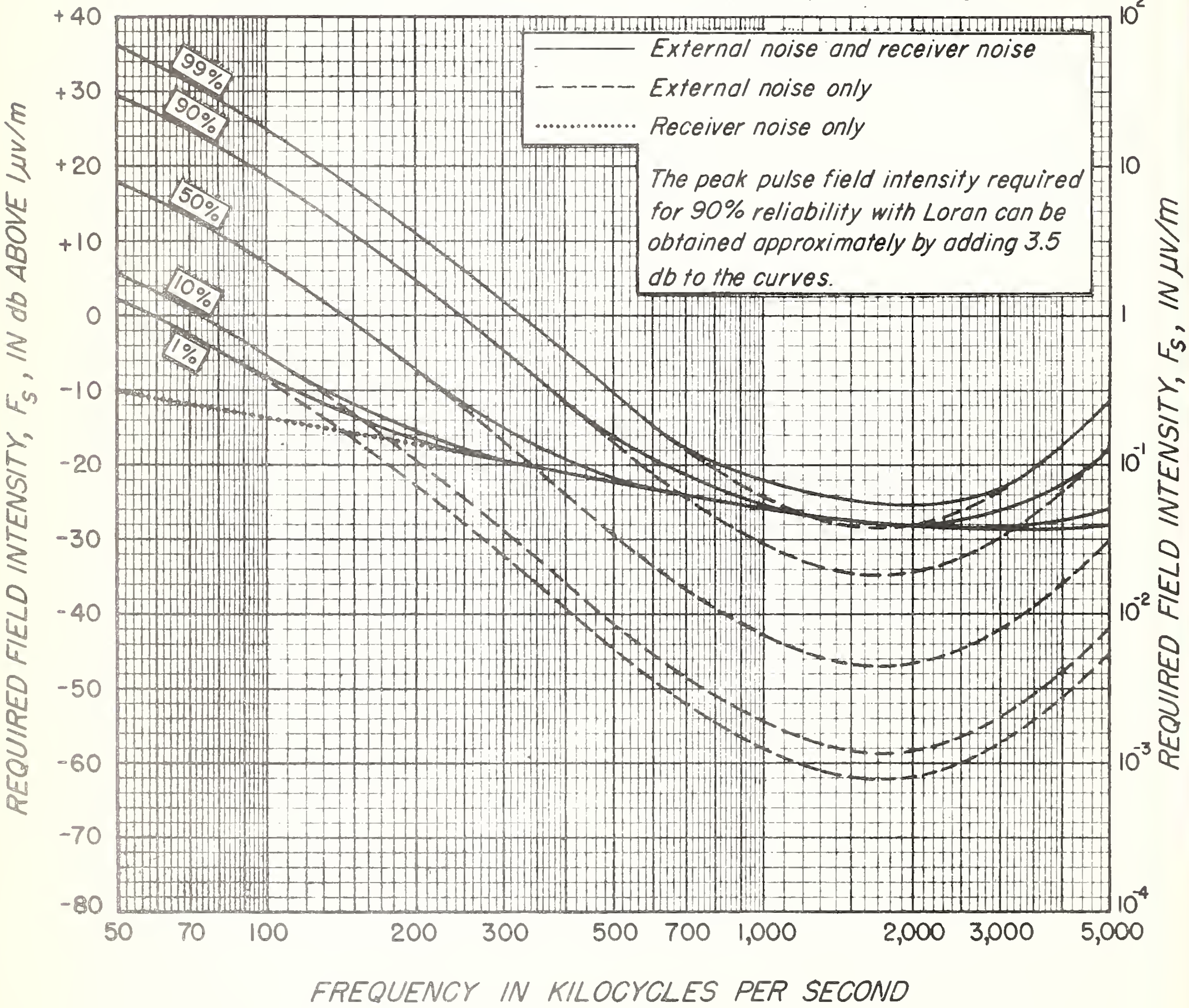



FIGURE 8

FIELD INTENSITY REQUIRED FOR 90% INTELLIGIBILITY OF RELATED WORDS
(60% INTELLIGIBILITY OF NON-RELATED WORDS)
VS
FREQUENCY

(With a $\frac{\lambda}{4}$ vertical antenna in noise grade I, summer day)

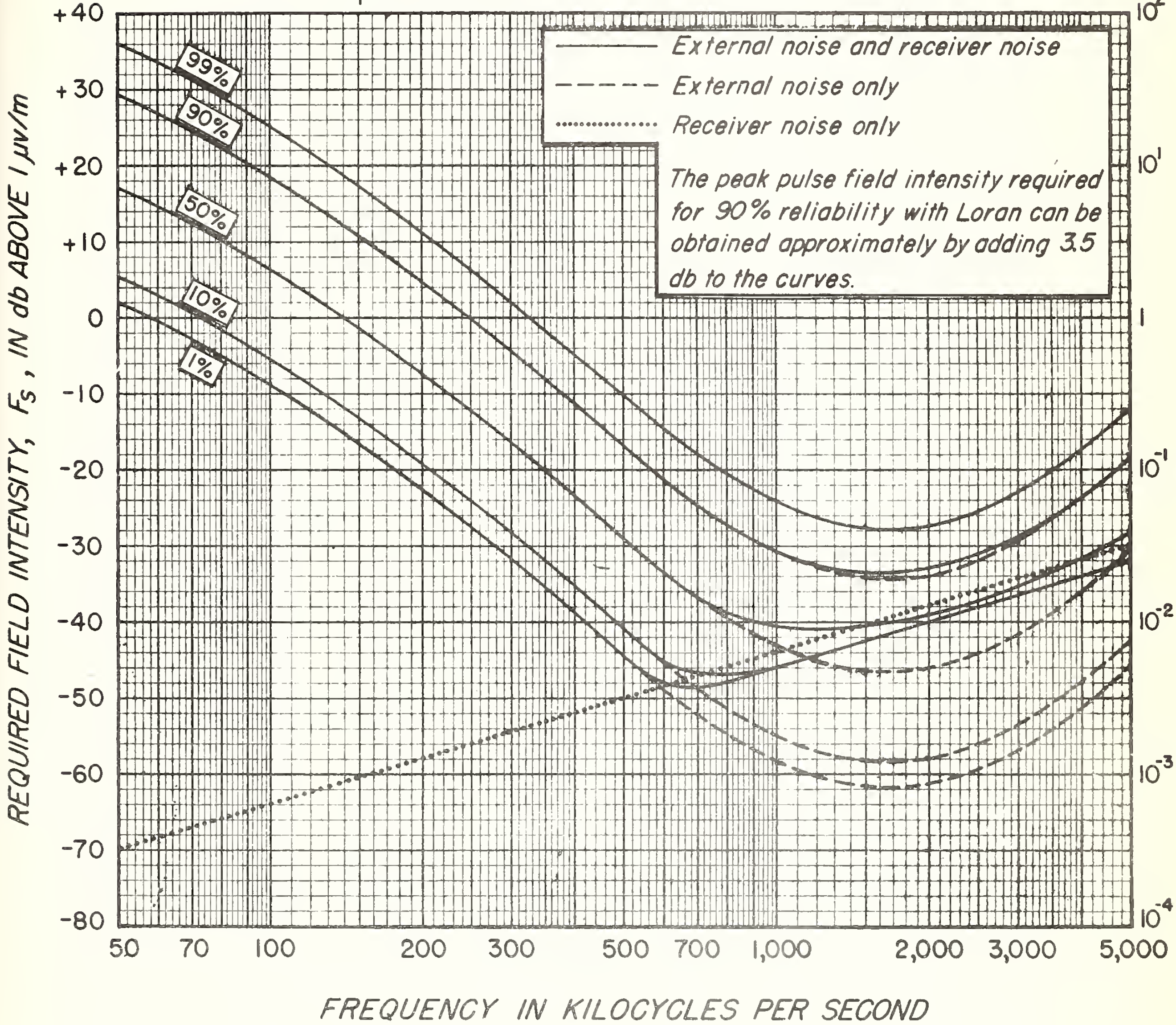



FIGURE 9

PERCENTAGE OF TIME RECEIVER NOISE
EXCEEDS EXTERNAL NOISE
VS
FREQUENCY

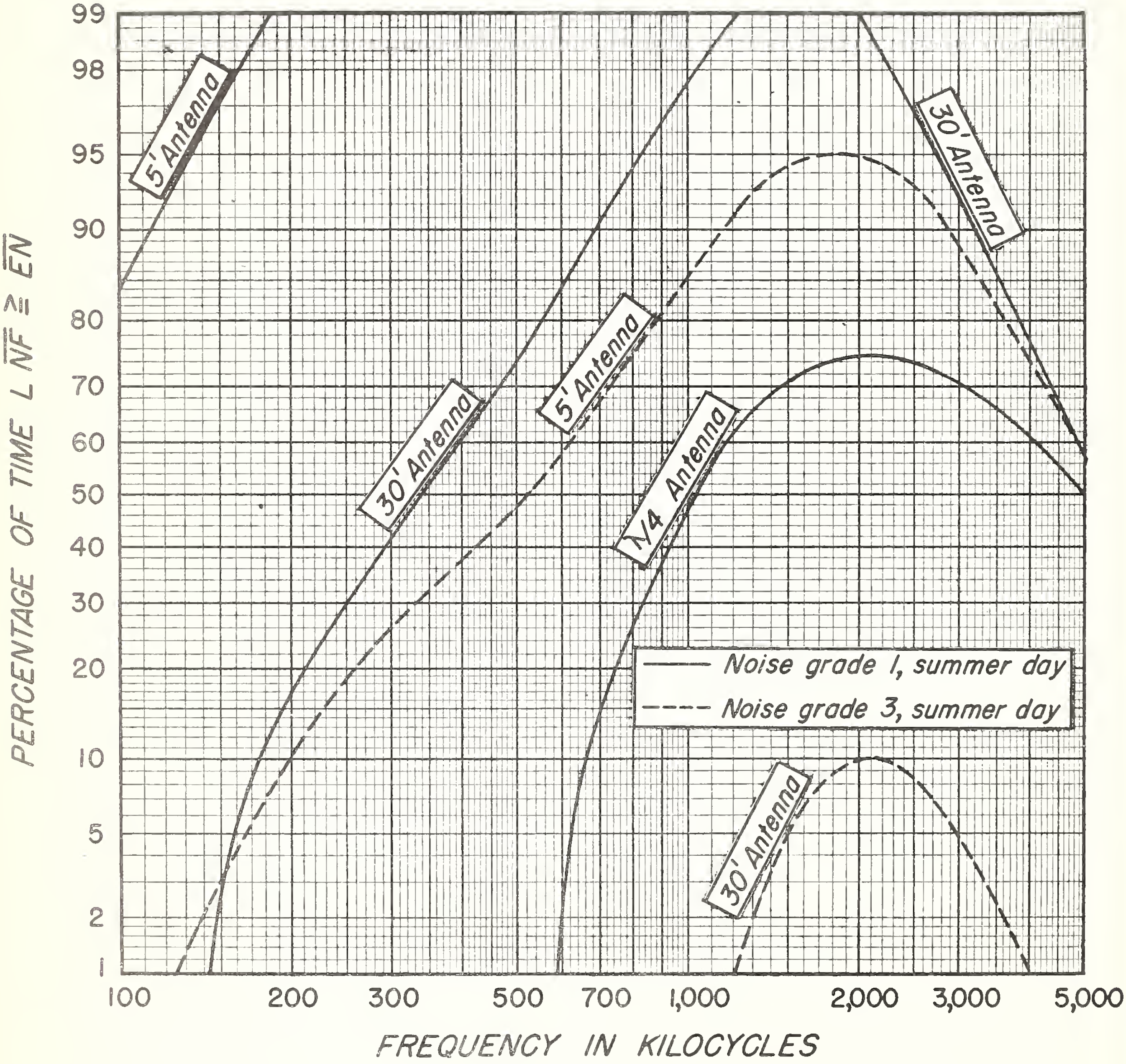



FIGURE 10