NOISE IN RECEIVING SYSTEMS
AT MICROWAVE FREQUENCIES

A Thesis

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Orest Stephen Roscoe

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Chapter I

Introduction

Designers of present day receivers for microwave frequencies are constantly striving to reduce the effects of radio frequency noise on receiver systems. This noise determines the minimum signal level detectable by a receiver. For radar systems, the minimum detectable signal limits the range at which useful information can be provided with a specific accuracy. For space communications and satellite communications systems it determines the transmitter power necessary to provide a sufficient signal-to-noise ratio for reliable communications.

Radio frequency noise can be broadly classified as that arising from the components of the receiver, both active and passive, and that due to sources external to the receiver. Until recently, active devices were always responsible for a very large proportion of the total noise and no serious attention was paid to the noise contributions from the remaining sources. The advent of extremely low-noise receiver front ends, however, such as masers and parametric amplifiers, has made it essential to have a knowledge of all the factors contributing to the noise, since their effect on system sensitivity has increased greatly in significance. These new devices are not thermionic in nature and consequently do not suffer from the thermal noise of vacuum tubes, nor are they subject to shot noise, as are mixer diodes.

Passive devices are also sources of noise, giving rise to a noise voltage which is constant with frequency up to very high frequencies.

Nyquist (1)* was the first to show that this noise voltage followed Planck's formula. He stated that there exists a noise voltage between any two terminals of a passive network, or any resistor, that has a random frequency and amplitude spectrum. The mean square noise voltage, dE^2_n, developed between these two terminals over a frequency interval df is

$$dE^2_n = \frac{4\,hfR\,df}{e^{\frac{hf}{kT}} - 1} \tag{1.1}$$

where

R = resistance between the two terminals

h = Planck's constant

f = frequency

k = the Boltzmann constant (1.38×10^{-23} joules degree^{-1})

and T = absolute temperature of the network.

In almost all radio frequency applications $hf \ll kT$, and the following approximation can be made.

$$e^{\frac{hf}{kT}} \simeq 1 + \frac{hf}{kT}$$

Equation (1.1) then reduces to

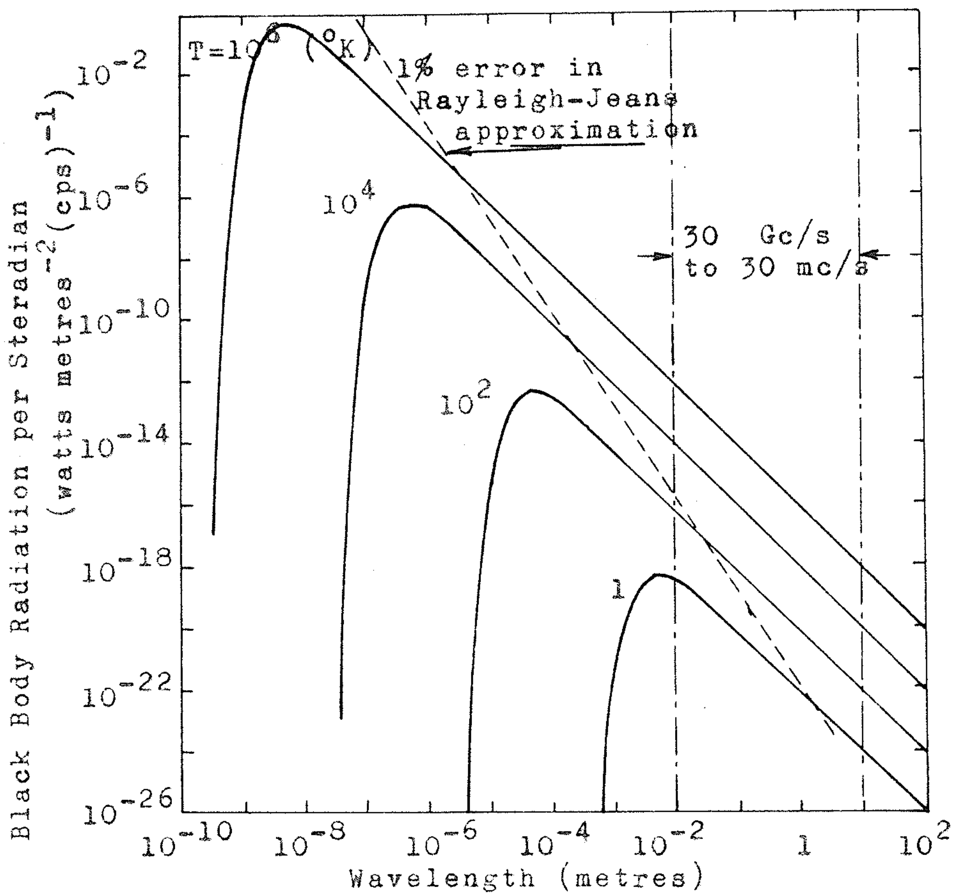
$$dE^2_n = 4kTR\,df. \tag{1.2}$$

This is known as the Rayleigh-Jeans approximation to Planck's law.

* Bracketed numbers refer to corresponding numbers in the list of references.

Figure 1.1 shows plots of Planck's equation for various temperatures and frequencies. The error in the approximation is 1 per cent at the dashed line and generally less in the region of interest, from 30 Mc/s to 30 Gc/s.

The available noise power, dP, over a frequency interval df, which is the maximum power that can be obtained from the two terminals, may be found from (1.2).



VARIATION OF BLACK BODY RADIATION WITH WAVELENGTH FOR A RANGE OF TEMPERATURES

Figure 1.1

$$dP = \frac{dE^2_n}{4R}$$

$$= kT\, df \qquad (1.3)$$

Noise from external sources which must be considered in any calculation of system performance includes that arising from ionospheric and atmospheric absorption, from cosmic and galactic sources, and from black body radiation from the earth. Earth radiation is picked up by the antenna through its side and back lobes and feed spillover. The other sources contribute noise through the main beam as well as through the subsidiary lobes. This antenna noise, as it is commonly called, shows a broad minimum in the 1 Gc/s to 10 Gc/s region. Other sources of external noise which must be included here are man-made noise and transmitter noise.

Such sources have become significantly more important since the invention of low excess-noise radio frequency amplifiers. Under many circumstances, the sensitivity of a receiving system is no longer limited by noise from active receiver components and consideration of their performance alone as a measure of quality is a simplification that is no longer valid.

By accurate calculation of individual noise contributions, it can be shown more readily where system improvement is possible and practical with present-day techniques. This was first done by Friis (2) in regard to the active components of a receiver. He defined a figure of merit for the noise performance of any general four-terminal network and then applied his results to cascaded networks.

Expressions for noise figures and effective noise temperatures for active and passive networks as well as for cascaded networks are developed in chapter II. Chapter III discusses the advantages of using effective noise temperature rather than noise figure as a figure of merit for receiving systems.

Chapter IV describes the noise that arises from sources external to the receiving equipment. An expression for the noise that arises because of absorption in a transmission medium is developed also.

The effective noise temperature of a system is developed from a model of a receiving system in chapter V. The model has the noise producing elements represented in such a manner that their effect on system performance can be examined in detail. Possible ways of system improvement are discussed.

Chapter VI discusses methods of measuring the noise performance of a system and chapter VII describes measurements which were made on a system at 944 Mc/s.

Chapter II

Noise In Active And Passive Devices

Definitions

The definition of noise figure given by Friis (2) is simply the ratio of two power ratios.

$$F = \frac{\left(\dfrac{\text{signal}}{\text{noise}}\right) \text{input}}{\left(\dfrac{\text{signal}}{\text{noise}}\right) \text{output}}$$

$$= \frac{\dfrac{S_i}{N_i}}{\dfrac{S_o}{N_o}} \tag{2.1}$$

This definition assumes maximum available power in each case but does not imply that the actual power transferred in the practical case is maximum. Conditions of mismatch may be desirable if the output noise is reduced to a greater degree than the output signal (3).

An ideal device may be defined as one which generates no noise within itself. Reference to such a device enables the definition of noise figure to be rewritten in terms of input signal power for a specific signal-to-noise ratio. For convenience, this signal-to-noise ratio may be set to unity. Then, for a specific coupling, in both cases the same,

$$F = \frac{\text{mean square signal volts necessary for } S/N = 1 \text{ with a practical device}}{\text{mean square signal volts necessary for } S/N = 1 \text{ with an ideal device}} \tag{2.2}$$

This mean square signal voltage is proportional to the total output noise power for both the practical and ideal device. For the ideal device, however, total output noise power is due to the input noise only. For this reason (2.2) can be alternately expressed as

$$F = \frac{\text{total output noise power}}{\text{output noise power due to input noise}}. \tag{2.3}$$

Input noise may come from an antenna, or the internal resistance of a signal generator coupled to the device. By equation (1.3) the available noise power is given by

$$dP = kT\,df. \tag{2.4}$$

A bandwidth, B, can be defined over which noise power can be found. Then

$$P = kTB \tag{2.5}$$

where

$$B = \frac{1}{G^2}\int_0^{\infty} G_f^2\,df \tag{2.6}$$

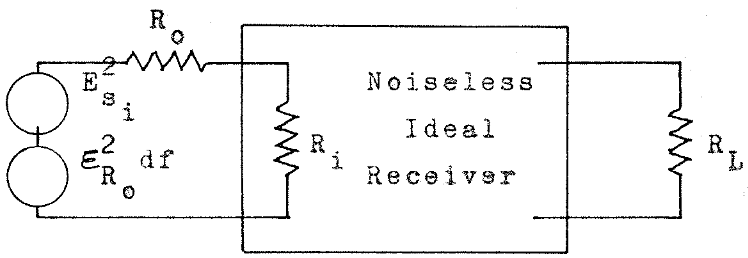
G = maximum voltage gain in the band

and G_f = voltage gain at any frequency f.

Noise power from a resistance is directly proportional to the temperature of the resistance. Therefore, the temperature of a resistance may be used as a measure of the noise power available from it for a specified bandwidth B. The noise output generated internally by any device may be specified in terms of the temperature of a resistance which will produce an equivalent noise power. This is the effective noise temperature of the device.

Noise in Active Networks

Using the definitions given above, noise figure and effective noise temperature of a receiver may be found. The development used here closely follows that of Woonton (4). Consider first the ideal device used in definition (2.2) with a signal generator applied to the input terminals. An equivalent circuit is given in figure 2.1.



EQUIVALENT CIRCUIT OF THE IDEAL RECEIVER

Figure 2.1

The various parameters of the equivalent circuit may be defined as follows:

R_o = equivalent internal resistance of the signal generator.

R_i = equivalent input resistance of the ideal receiver, considered noiseless.

R_L = load resistance which absorbs output power from the receiver, also considered noiseless.

E^2_{Si} = mean square signal voltage due to the equivalent generator.

$\mathcal{E}^2_{R_o}df$ = mean square noise voltage due to the internal resistance of the signal generator over a frequency interval df. By equation (1.2) $\mathcal{E}^2_{R_o}df = 4\ kTR_o df$.

The mean square noise voltage output across R_L at a frequency f and interval df is

$$\mathcal{E}^2_{R_o}\left(\frac{R_i}{R_o + R_i}\right)^2 G^2_f\ df$$

and output noise power is

$$N_o = \mathcal{E}^2_{R_o}\left(\frac{R_i}{R_o + R_i}\right)^2 \int_0^\infty G_f^2\, df \left(\frac{1}{R_L}\right).$$

$$= 4\ kT\, \frac{R_o}{R_L}\left(\frac{R_i}{R_o + R_i}\right)^2 \int_0^\infty G_f^2\, df \qquad (2.8)$$

Output signal power is

$$S_o = E^2_{S_i}\left(\frac{R_i}{R_o + R_i}\right)^2 G^2 \left(\frac{1}{R_L}\right). \qquad (2.9)$$

Maximum voltage gain G is assumed to be signal gain throughout the thesis.

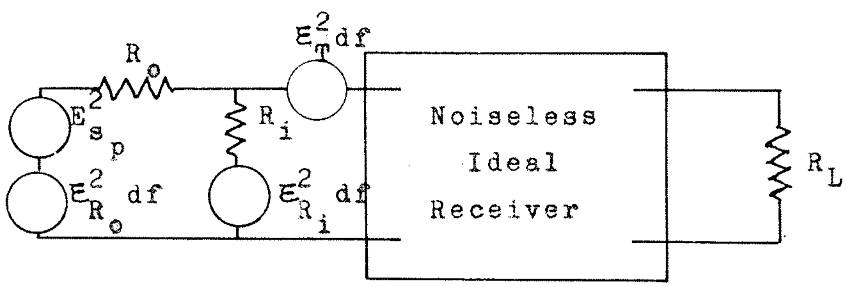
Equating (2.8) and (2.9) to solve for the mean square signal voltage necessary to produce unity signal to noise ratio gives

$$E^2_{S_i} = 4\ kTR_o\ \frac{1}{G^2}\int_0^\infty G_f^2\, df \qquad (2.10)$$

$$E^2_{S_i} = 4\ kTR_o\ B \qquad (2.11)$$

which is simply the mean square noise voltage across the terminals of a resistor with resistance R_o, the equivalent internal resistance of the signal generator, at temperature T. This is the expected result since the ideal device is defined to be noiseless.

The equivalent circuit of the ideal receiver may be modified to represent a practical receiver as in figure 2.2.



EQUIVALENT CIRCUIT OF THE PRACTICAL RECEIVER

Figure 2.2

In figure 2.2, R_o and R_L are as defined for figure 2.1.

R_i = the input impedance of the practical receiver which does generate noise.

$E_{S_p}^2$ = mean square signal voltage due to the equivalent generator.

$\mathcal{E}_{R_o}^2 df$ = as previously defined.

$\mathcal{E}_{R_i}^2 df$ = mean square noise voltage due to the input resistance of the receiver over a frequency interval df. $\mathcal{E}_{R_i}^2 df = 4\ kTR_i df$.

$\mathcal{E}_T^2 df$ = mean square voltage of the excess noise generated within the device referred to the input over a frequency interval df.

The mean square noise voltage output across R_L at a frequency f and over an interval df is

$$\mathcal{E}_{R_o}^2 \left(\frac{R_i}{R_o + R_i}\right)^2 G_f^2\, df + \mathcal{E}_{R_i}^2 \left(\frac{R_o}{R_o + R_i}\right)^2 G_f^2\, df + \mathcal{E}_T^2 G_f^2\, df$$

and output noise power is

$$N_o = \frac{1}{R_L} \left\{ 4\ kTR_o \left(\frac{R_i}{R_o + R_i}\right)^2 + 4\ kTR_i \left(\frac{R_o}{R_o + R_i}\right)^2 + \mathcal{E}_T^2 \right\} \int_0^\infty G_f^2\, df. \qquad (2.12)$$

Output signal power is

$$S_o = E_{S_p}^2 \left(\frac{R_i}{R_o + R_i}\right)^2 G^2 \left(\frac{1}{R_L}\right). \qquad (2.13)$$

Equating (2.12) and (2.13) to obtain unity signal-to-noise ratio gives

$$E_{S_p}^2 = 4\ kTR_o \frac{1}{G^2}\int_0^\infty G_f^2\, df + 4\ kT\frac{R_o^2}{R_i} \frac{1}{G^2}\int_0^\infty G_f^2\, df + \left(\frac{R_o + R_i}{R_i}\right)^2 \frac{\mathcal{E}_T^2}{G^2} \int_0^\infty G_f^2\, df.$$

$$E_{S_p}^2 = 4\ kTR_o B + 4\ kTR_o B \times \frac{R_o}{R_i} + \left(\frac{R_o + R_i}{R_i}\right)^2 \mathcal{E}_T^2 B \qquad (2.14)$$

It is noted that (2.14) consists of the noise generated by the signal generator and two other terms corresponding to what can be called the excess noise. This excess noise is generated by the input impedance and by other circuits of the practical device. An equivalent excess noise generator can be defined so that the equation can be rewritten

$$E_{S_p}^{\;2} = 4\ kTR_oB + E_e^{\;2} \tag{2.15}$$

where $E_e^{\;2}$ = mean square excess input noise voltage.

Available input power due to $E_{S_p}^{\;2}$ is

$$S_i = \frac{E_{S_p}^{\;2}}{4R_o}\ . \tag{2.16}$$

Define power gain $G_p = \dfrac{S_o}{S_i}$. (2.17)

Therefore $$S_o = \frac{E_{S_p}^{\;2} G_p}{4\ R_o}\ . \tag{2.18}$$

Substituting (2.15) into (2.18) and recalling that in deriving (2.15) the signal to noise ratio was assumed to be unity

$$N_o = \frac{G_p}{4\ R_o}\left(4\ kTR_oB + E_e^{\;2}\right). \tag{2.19}$$

Equation (2.19) shows that output noise power is composed of amplified input noise and excess noise, N_e, where

$$N_e = \frac{E_e^{\;2}\ G_p}{4\ R_o}. \tag{2.20}$$

Therefore $$N_o = kTBG_p + N_e\ . \tag{2.21}$$

Noise figure was defined in (2.2) as

$$F = \frac{E_{S_p}^{\;2}}{E_{S_i}^{\;2}}\ .$$

Substituting (2.11) and (2.15) into this definition

$$F = \frac{4\ kTR_oB + E_e^2}{4\ kTR_oB}\ . \tag{2.22}$$

By (2.20)

$$F = \frac{kTBG_p + N_e}{kTBG_p}$$

or

$$N_e = (F - 1)\ kTBG_p\ . \tag{2.23}$$

The excess noise referred to the input at an ambient temperature T_o is then

$$\frac{N_e}{G_p} = (F - 1)\ kT_oB. \tag{2.24}$$

Recall that the effective noise temperature of a device is the temperature of a resistance which will produce a noise power equivalent to that produced internally by the device, or to the excess noise of the device. Noise power from any network is given by (2. 5).

$$P = kTB$$

Therefore the excess noise of the practical network can be written as

$$\frac{N_e}{G_p} = kT_EB \tag{2.25}$$

where T_E is the effective noise temperature of the practical network.

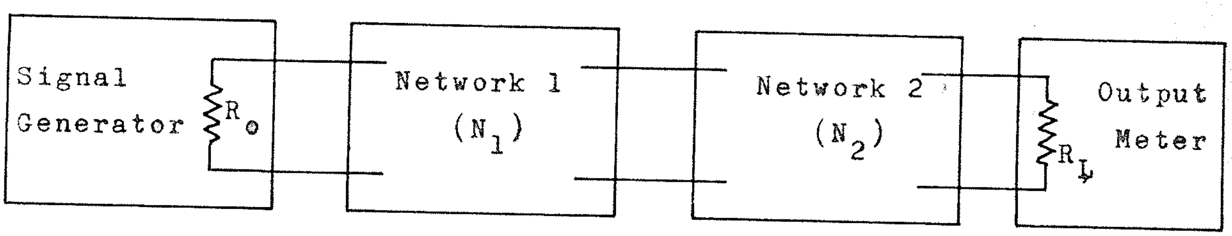
From (2.24) and (2.25) it can be seen that effective noise temperature and noise figure are related as follows:

$$T_E = (F - 1)\ T_o. \tag{2.26}$$

This relation is very useful since it is convenient to use effective temperature in considering noise performance of complete systems involving low noise devices. Measurement of conventional receiver performance is commonly made in terms of the noise figure, F, expressed in decibels.

Cascaded Networks

If a number of active networks are cascaded and their individual noise figures or equivalent temperatures are known, then the noise performance of the chain can be found. Consider two networks cascaded.



CASCADED NETWORKS

Figure 2.3

The definition of noise figure of the system is unchanged from that for one network. By definition (2.3), the noise figure of the system is

$$F_{1,2} = \frac{\text{Total output noise power of the system}}{\text{Noise power at the output of the system due to } R_o} .$$

The parameters of the networks in figure 2.3 are defined below.

R_1 = input resistance of network 1.

G_1 = maximum voltage gain of network 1.

G_{f_1} = voltage gain at any frequency f of network 1.

G_2 = maximum voltage gain of network 2.

G_{f_2} = voltage gain at any frequency f of network 2.

The mean square noise voltage at the output of N_1, in the frequency interval df at the frequency f, due to R_o is

$$\mathcal{E}^2_{R_{o_1}}\, df = 4\, kTR_o \left(\frac{R_1}{R_1 + R_o}\right)^2 G^2_{f_1}\, df \,. \tag{2.28}$$

At the output of N_2 this becomes

$$\mathcal{E}^2_{R_{o_2}}\, df = 4\, kTR_o \left(\frac{R_1}{R_1 + R_o}\right)^2 G^2_{f_1}\; G^2_{f_2}\; df. \tag{2.29}$$

The noise power delivered into a load resistance R_L will be

$$N_o = \frac{1}{R_L}\left\{4\, kTR_o \left(\frac{R_1}{R_1 + R_o}\right)^2 \int_0^\infty G^2_{f1}\; G^2_{f2}\; df\right\}. \tag{2.30}$$

The signal power delivered into a load resistance R_L by a signal voltage $E^2_{S_1}$ from the generator will be

$$S_o = \frac{1}{R_L}\left\{E^2_{S_1}\left(\frac{R_1}{R_1 + R_o}\right)^2 G_1^2\; G_2^2\right\}. \tag{2.31}$$

Solving for the $E^2_{S_1}$ necessary for unity signal-to-noise ratio ,

$$E^2_{S_1} = 4\, kTR_o \int_0^\infty \frac{G^2_{f_1}\; G^2_{f_2}}{G_1^2\; G_2^2}\, df \,. \tag{2.32}$$

This gives the magnitude of a single frequency voltage necessary to produce a signal power at the output which is equal to the noise power caused by the internal resistance of the signal generator.

At the output of N_1, $E^2_{S_1}$ will produce a power S_{o_1}

$$S_{o_1} = 4\, kTR_o \frac{S_2}{E_2^2}\int_0^\infty \left(\frac{G_{f_1}\; G_{f_2}}{G_1\; G_2}\right)^2 df \tag{2.33}$$

where S_2 is the power output of network 1 due to an input voltage E_2. A power gain term can now be defined :

$$G_{p1} = 4\, R_o \frac{S_2}{E_2^2}\,. \tag{2.34}$$

Therefore (2.37) can be rewritten

$$S_{o1} = k\ TG_{p1} \int_{o}^{\infty} \left(\frac{G_{f1}\ \ G_{f2}}{G_1\ \ G_2} \right)^2 df. \tag{2.35}$$

S_{o1} is the input power to network 2 if impedance matching is assumed. Define the output power of N_2 due to E_{S1}^2 as S_{o2}. The gain of N_2 can be written

$$G_{p2} = \frac{S_{o2}}{S_{o1}}. \tag{2.36}$$

Combining (2.36) and (2.33) results in

$$S_{o2} = k\ TG_{p1}\ G_{p2} \int_{o}^{\infty} \left(\frac{G_{f1}\ \ G_{f2}}{G_1\ \ G_2} \right)^2 df. \tag{2.37}$$

This is the signal power which results in unity signal to noise ratio and is equal to the noise output due to the internal impedance of the signal generator.

Output noise power of the system can be found by a similar procedure. Rearranging (2.21) and (2.23) gives

$$N_o = FkTBG_p.$$

Applying this equation to find the noise power due to the signal generator output resistance, network 1, and its output circuits gives

$$N_{o1} = F_1\ kTG_{p1}\ G_{p2} \int_{o}^{\infty} \left(\frac{G_{f1}\ \ G_{f2}}{G_1\ \ G_2} \right)^2 df \tag{2.38}$$

where $G_{p1}\ G_{p2}$ replaces G_p ,

$\int_{o}^{\infty} \left(\frac{G_{f1}\ G_{f2}}{G_1\ G_2} \right)^2$ df replaces B and

F_1 is the noise figure of N_1 .

The noise power from network 2, excluding the power from its input circuits can be considered similar to the excess noise given in (2.23) and can be written

$$N_{o_2} = (F_2 - 1)\, kTG_p \int_0^\infty \left(\frac{G_{f_2}}{G_2}\right)^2 df. \tag{2.39}$$

Total noise power at the output is the sum of equations (2.38) and (2.39).

The noise figure of the system, $F_{1,2}$, can be written by use of (2.23).

$$F_{1,2} = \frac{F_1 kTG_{p_1} G_{p_2} \int_0^\infty \left(\frac{G_{f_1}\, G_{f_2}}{G_1\, G_2}\right)^2 df + (F_2 - 1)\, kTG_{p_2} \int_0^\infty \left(\frac{G_{f_2}}{G_2}\right)^2 df}{kTG_{p_1} G_{p_2} \int_0^\infty \left(\frac{G_{f_1}\, G_{f_2}}{G_1\, G_2}\right)^2 df} \tag{2.40}$$

If the first network has a much greater bandwidth than the second so that G_{f_1} is constant in the passband of network 2, then

$$G_{f_1}^{\;2} = G_1^{\;2}$$

within the limits of the bandwidth integral and

$$\int_0^\infty \left(\frac{G_{f_1}\, G_{f_2}}{G_1\, G_2}\right)^2 df = \int_0^\infty \left(\frac{G_{f_2}}{G_2}\right)^2 df. \tag{2.41}$$

This reduces equation (2.40) to

$$F_{1,2} = F_1 + \frac{(F_2 - 1)}{G_{p_1}}. \tag{2.42}$$

The foregoing procedure may be extended to any number of cascaded networks, provided impedance matching is followed throughout, and provided each network has a much greater bandwidth than that following. The general formula is

$$F_{1,2\ldots n} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1\, G_2} + \frac{F_4 - 1}{G_1\, G_2\, G_3} + \ldots\ldots \tag{2.43}$$

Examination of this formula shows that the noise performance is largely determined by the first network if it has high gain and if the noise figures of the succeeding networks are of the same order as that of the first.

Effective Temperature of Cascaded Networks

It has been previously shown that

$$T_E = (F - 1)\, T_o \; . \tag{2.26}$$

Rearranging, to put noise figure in terms of effective temperature,

$$F = \frac{T_E}{T_o} + 1 \; . \tag{2.44}$$

Now the effective temperature of cascaded networks may be found by substitution of (2.44) into (2.42) and (2.43). For two networks

$$T_{E_{1,2}} = T_{E_1} + \frac{T_{E_2}}{G_{p_1}} \tag{2.45}$$

and for any number of networks

$$T_{E_{1,2\ldots n}} = T_{E_1} + \frac{T_{E_2}}{G_{p_1}} + \frac{T_{E_3}}{G_{p_1}\, G_{p_2}} + \frac{T_{E_4}}{G_{p_1}\, G_{p_2}\, G_{p_3}} + \;\;\ldots\ldots \tag{2.46}$$

Note that effective noise temperature is referred to the input of the system. The effective noise temperature may be referred to any other point in the system by taking network gains into account. For example, in a four network system, the effective noise temperature referred to the input of the third network is

$$T_{E_1}\, G_{p_1}\, G_{p_2} + T_{E_2}\, G_{p_2} + T_{E_3} + \frac{T_{E_4}}{G_{p_3}} \; . \tag{2.47}$$

Noise in Passive Networks

Passive networks in receiver systems include resistive feeds and reflectors, transmission lines and lossy transmission line components, such as rotary joints, circulators, isolators, and duplexers. These contribute to the generation of noise by black body radiation and, as well, produce signal attenuation.

Strum (5) calculated the effective output temperature of a passive network of uniform attenuation and constant temperature. Consider the transmission line in figure 2.4. Assume that it is at ambient temperature

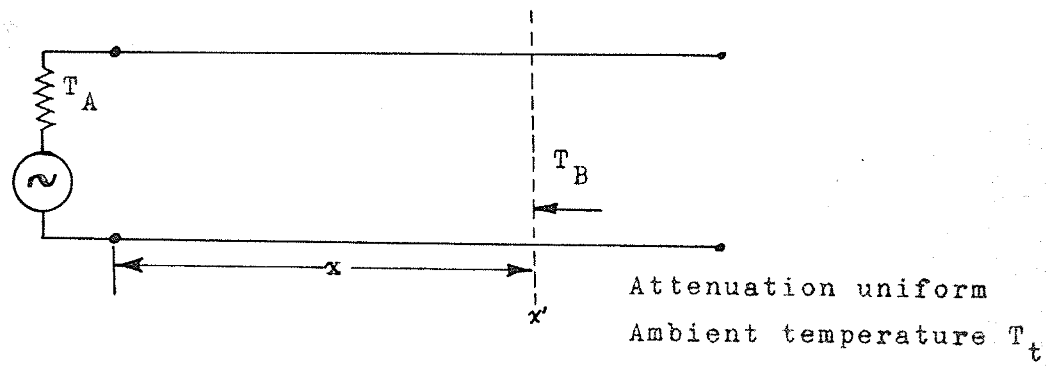


Figure 2.4

T_t and that its characteristic impedance is resistive. Let α be the attenuation constant. T_A is the effective temperature of the noise source connected to the input.

Noise can be treated like a signal, enabling the calculation of T_B, the effective temperature looking back into the line, by means of transmission line theory. At any point x' the effective temperature will consist of the input temperature attenuated by the length of line x and the black body radiation due to the temperature of the line itself, also attenuated.

$$T_B = T_A e^{-2\alpha \ell} + \int_0^{\ell} T_t e^{-2\alpha \ell}\, d\ell$$

$$T_B = T_A e^{-2\alpha \ell} + T_t \left(1 - e^{-2\alpha \ell}\right) \tag{2.48}$$

By Skilling (6), $e^{2\alpha \ell} = L$, the line loss as a power ratio. Then

$$T_B = \frac{T_A}{L} + T_t \left(1 - \frac{1}{L}\right). \tag{2.49}$$

T_B may be referred to the input. This results in an effective input noise temperature

$$T_I = \left\{ \frac{T_A}{L} + T_t \left(\frac{L - 1}{L}\right) \right\} L \tag{2.50}$$

or $$T_I = T_A + T_t \,(L - 1). \tag{2.51}$$

The effective temperature of the line itself is seen to be

$$T_L = T_t \,(L - 1). \tag{2.52}$$

By (2.26)

$$T_E = (F - 1)\, T_o \,.$$

Equating T_E and T_L,

$$(F - 1)\, T_o = T_t \,(L - 1). \tag{2.53}$$

$$F = 1 + \frac{T_t}{T_o} (L - 1) \tag{2.54}$$

If the line is at the reference temperature, i.e., $T_t = T_o$, then

$$F = L. \tag{2.55}$$

Thus the noise figure for a lossy transmission line at temperature T_o is equal to the line loss expressed as a power ratio.

Generally, the same assumptions that were made for the transmission line of figure 2.4 can be made for other transmission line components and therefore the same relations are valid.

Chapter III

Noise Temperature vs. Noise Figure

Use of effective noise temperature as a figure of merit for receivers has become popular since the advent of low noise devices and the need to consider the performance of the entire receiving system. Fundamentally, a receiver is composed of an antenna, an amplifier, a detector, and an indicating device. The antenna is considered by radio astronomers as a device which transposes its radiation resistance, as seen by the receiver input terminals, into a thermal reservoir consisting of the space in the beam of the antenna. The temperature of the radiation resistance is then in equilibrium with this reservoir and produces a power equal to kTB.

The power input at the receiver is equivalent to that from a resistor of the same value as the antenna radiation resistance and at a temperature T. This power input is directly proportional to T and hence radio astronomers refer to values of signal input in units of temperature, namely Kelvin degrees. It becomes a logical extension of this to express the noise contributed by the remainder of the system parts in units of equivalent temperature and to describe the noise power level of the receiver system in terms of its effective temperature. Since the noise power level of the receiver system determines the minimum detectable signal, the effective noise temperature of the system is directly proportional to the minimum detectable signal.

On the other hand, noise figure does not have the convenience of direct proportionately because it is referenced to a temperature other than 0°. The definition of noise figure implies a standard temperature which is taken as 290° K; that is, approximately room temperature. If measurements are made at other than this temperature, a correction must be applied. There has been a tendency in the literature to overlook this correction, thus producing erroneous results.

The use of effective noise temperature as a criterion of receiver performance becomes even more attractive when the receiver noise temperature becomes low. In this case, the noise figure is close to 1 and a small change in noise figure means quite a large percentage change in noise temperature and receiver performance.

By equation (2.26)

$$T_E = (F - 1)\, T_o$$

or

$$F = \frac{T_E}{T_o} + 1. \tag{3.1}$$

The ambient temperature, T_o, is normally taken at 290° K.

Table 3.1

Comparison of Effective Noise Temperature and Noise Figure

T_E (°K)	F	F (db)
1.0	1.0034	0.015
3.0	1.0103	0.045
6.0	1.0207	0.089
10.0	1.0345	0.147
20.0	1.0689	0.289
50.0	1.172	0.690
100	1.34	1.287
200	1.69	2.279
290	2.00	3.00
627	3.16	5.0
1540	6.31	8.0
2610	10.0	10.0

Examination of table 3.1 shows that for the range of effective noise temperatures that can be expected from masers and parametric amplifiers (2° to 100° K), use of effective temperature is much more indicative than noise figure as a figure of merit.

Chapter IV

Noise from External Sources

External radio frequency noise arises from active radiating noise sources and from absorbing regions along the signal path. It enters the receiving system via the antenna and adds to the receiver noise to make up the total noise power against which the signal must compete.

Noise from actively radiating sources includes galactic noise, man-made noise, solar noise and noise from discrete sources beyond our solar system. Observations of this noise are well documented in the literature. With a knowledge of the parameters of the antenna, the amount of this noise from these sources present at the antenna terminals can be calculated.

Absorbing regions which are sources of noise are the ionosphere and the lower atmosphere. The earth also adds noise wherever the antenna pattern intersects with it.

Antenna Patterns and Thermal Noise

The effective temperature, T_A, of the total noise available from an antenna which has no ohmic losses due to thermal sources within its pattern is given by

$$T_A = \frac{1}{4\pi} \int_0^{4\pi} T_\Omega \; G_\Omega \; d\Omega \qquad (4.1)$$

where

G_Ω = gain of the antenna in the direction of the solid angle $d\Omega$.

and T_Ω = temperature of the source in the direction of the solid angle $d\Omega$.

Generally the antenna gain in the direction of the main beam is very much greater than that over the remainder of its pattern. This allows simplifying approximations to be made to (4.1) if the source temperature T_{Ω} is presumed constant over the solid angle subtended by the source. If

ω = solid angle subtended by the source

and Ω_m = solid angle taken up by the antenna main beam,

then for $\Omega_m < \omega$

$$T_A = T_{\Omega} \tag{4.2}$$

and for $\Omega_m > \omega$

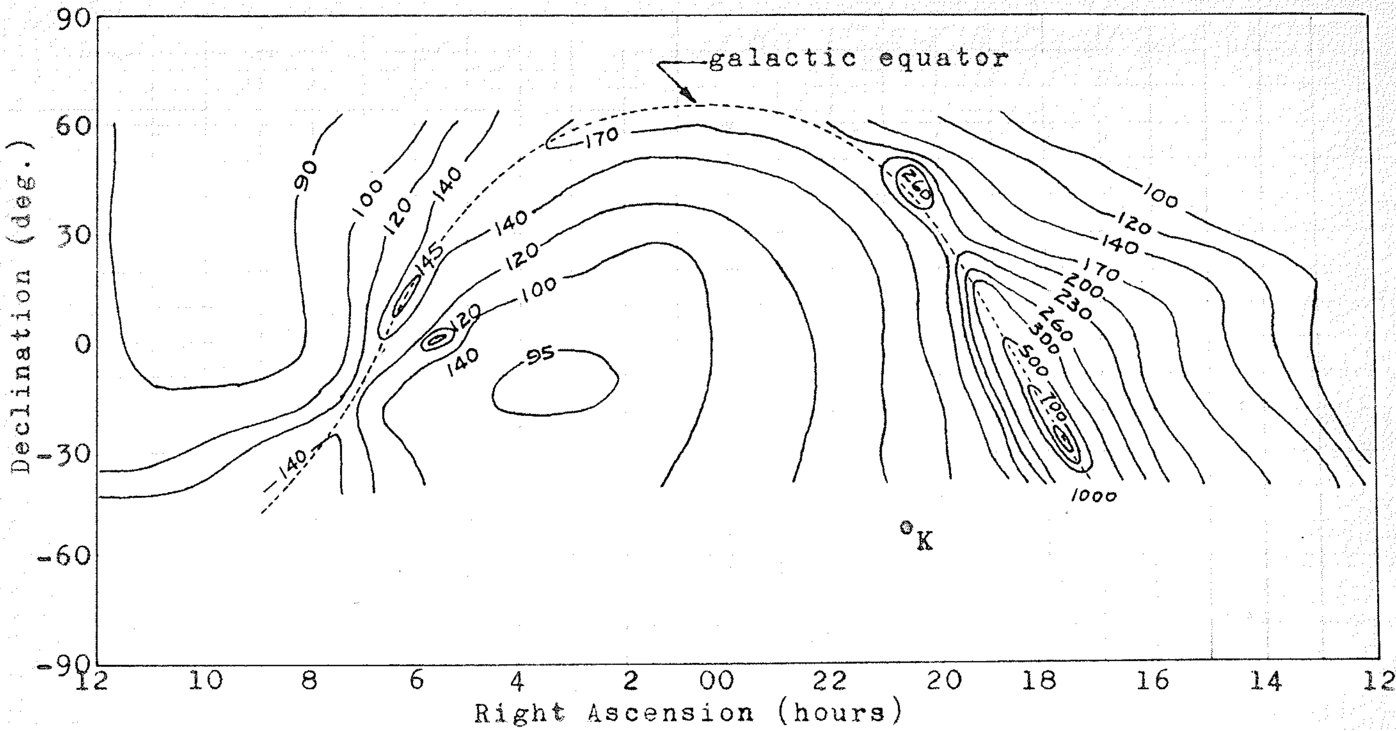
$$T_A = \frac{\omega}{\Omega_m} T_{\Omega}. \tag{4.3}$$

For cases of circular cross sections of both the source and the antenna main beam, plane angles may be used in (4.3).

The approximations given above also assume that 100% of the power pattern of the antenna is in the main beam. This is not true in the practical case so corrections must be made to (4.2) and (4.3) to account for the percentage of power that is distributed in the minor lobe pattern.

Galactic Background Noise

Galactic background radiation originating far beyond the earth's ionosphere appears to be the ultimate noise limitation at frequencies below about 5 Gc/s. Ko (7) gives a collection of sky maps with isothermal contours which show that strong noise-like radiation is concentrated in a small portion of the celestial sphere. Figure 4.1 is such a sky map made by Ko and Kraus (8) at 250 Mc/s. Ko also shows the map redrawn in galactic co-ordinates, demonstrating that the strongest radiation originates from the galactic centre.



ISOTHERMAL CONTOURS OF GALACTIC BACKGROUND RADIATION AT 250 MC/S

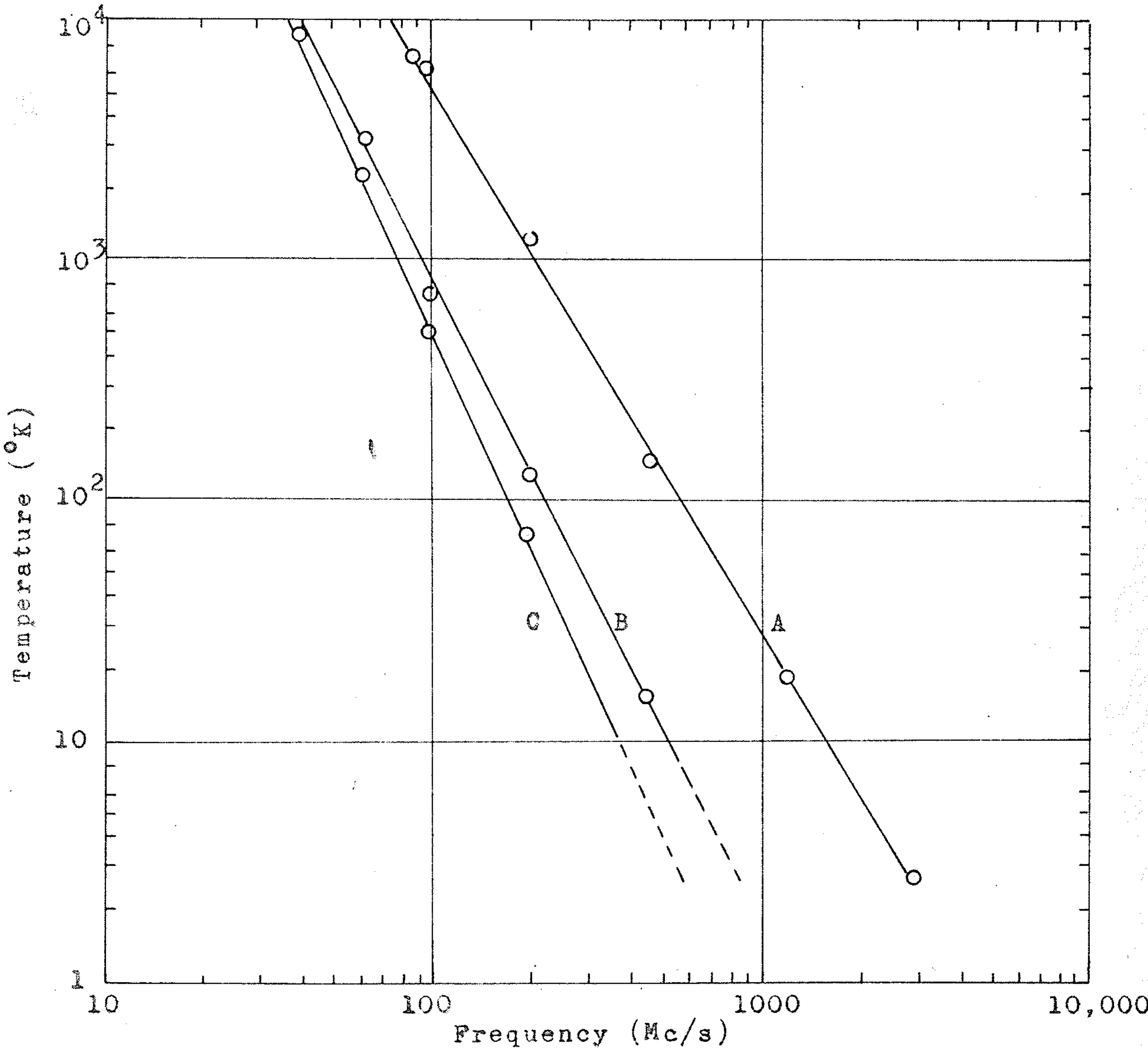
Figure 4.1

Grimm (9) made an approximate numerical integration of a similar sky map at 440 Mc/s and found that only a small percentage of the sky has a relatively high apparent temperature. His results are summarized in table 4.1.

Table 4.1

Degrees above General Background	Per cent of Sky
300°	0.01
100°	2.7
25°	7

The frequency dependence of the apparent temperature of galactic background radiation is given by Piddington (10) and shown in figure 4.2. Curve A shows the equivalent temperature near the galactic centre. Curve B shows the equivalent temperature in the region of the milky way and curve C shows the temperature in the coldest region of the sky. Using the results of table 4.1, it can be concluded that more than 90% of the sky exhibits an apparent temperature that must lie somewhere between that shown by curves B and C.



EQUIVALENT TEMPERATURE OF GALACTIC RADIATION

Figure 4.2

The relationship between frequency and equivalent temperature defined by these curves is given by

$$T \propto f^{-\gamma} . \tag{4.4}$$

From figure 4.2, it can be seen that γ, the slope of the curve, varies from 2.5 to 2.7, and that galactic radiation becomes very low at frequencies beyond about 1000 Mc/s.

<u>Noise from Discrete Sources</u>

Discrete celestial sources of noise consist of the sun, radio stars and planets. The sun is by far the strongest contributor but for very low noise systems, the weaker sources must also be considered. Discrete sources are not normally troublesome at UHF and higher frequencies, however, because of the small angles subtended by these sources. Since the beam widths of the antennae used at these frequencies are narrow, the probability of intercepting discrete sources is small.

The intensity and position of many radio stars has been tabulated by Kraus and Ko (11), and Pawsey (12). The flux density vs. frequency of some of the more prominent radio stars is shown in figure 4.3, which is reproduced from Millman (13). The spatial distribution of these sources is shown in figure 4.4. Star temperature, T_{Ω}, in terms of flux density, S, is given by

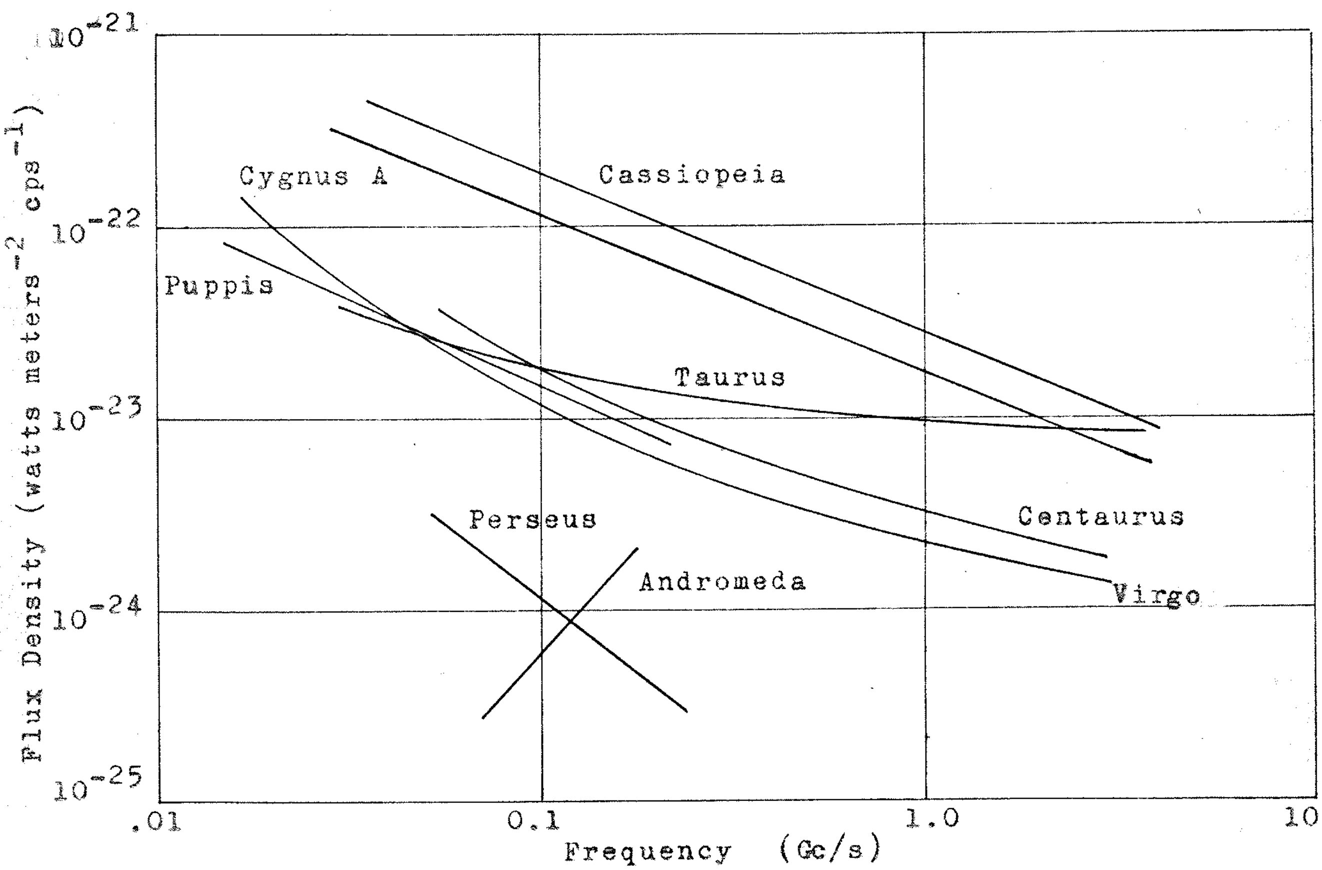
$$T_{\Omega} = \frac{S\lambda^2}{2k\omega} \tag{4.5}$$

where ω is the solid angle subtended by the star. In most cases the solid angle subtended by the star is less than the solid angular beamwidth of the antenna and equation (4.3) may be applied to find the contribution of the source to the effective noise temperature, T_A, of the antenna. Combining

(4.3) and (4.5) gives

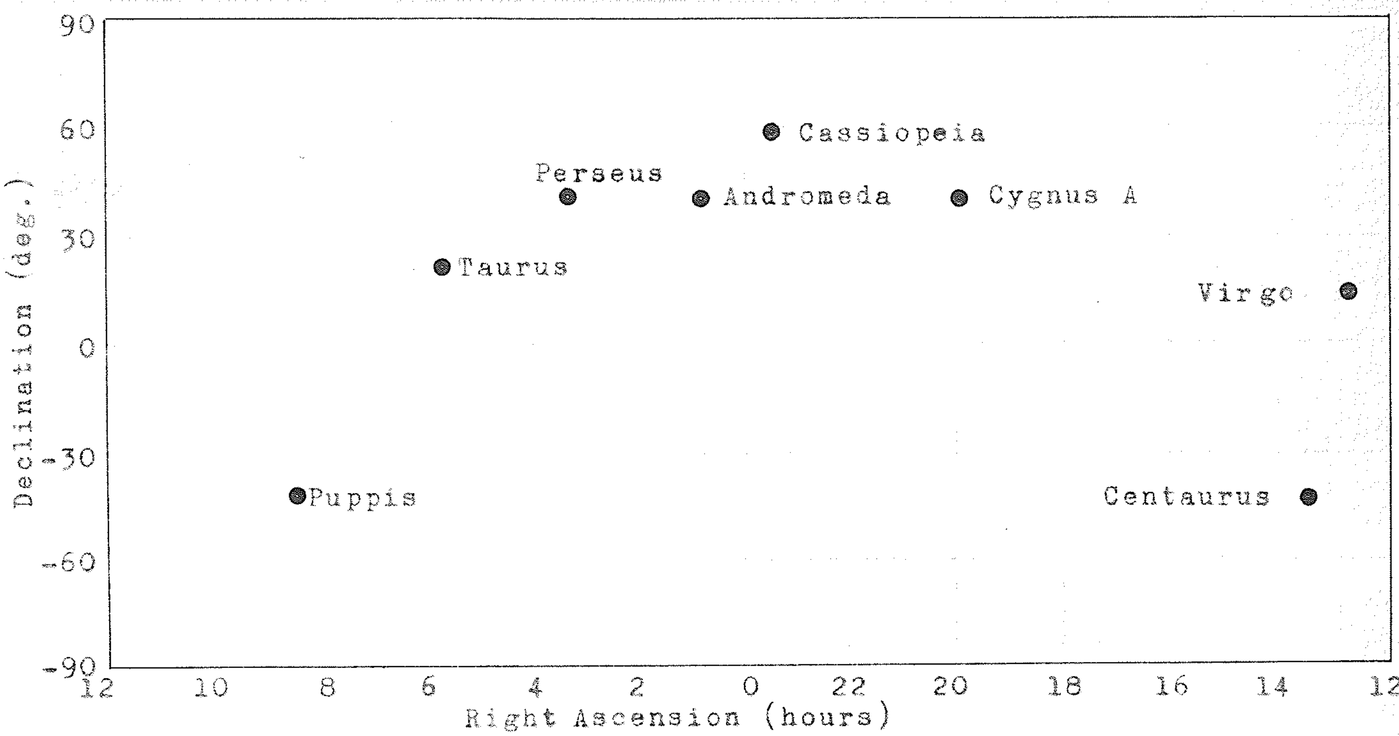
$$T_A = \frac{S\,\lambda^2}{2\,k\,\Omega_m} \quad . \tag{4.6}$$

Hansen and Stephenson (14) have tabulated the surface temperatures of the most important planets which contribute to antenna noise. Their table is reproduced in table 4.2, along with the angles subtended by the planets. This allows calculation of their contribution to antenna temperature by the use of equation (4.3).



FLUX DENSITY OF DISCRETE STELLAR NOISE SOURCES

Figure 4.3



SPATIAL DISTRIBUTION OF SOME DISCRETE STELLAR NOISE SOURCES

Figure 4.4

Table 4.2

Planetary Radiation Temperatures

Planet	Subtended Angle (Milliradians)	Frequency (Gc/s)	Surface Temperature (°K)
Venus	.05 to .32	35	410
		9.5	590
		3	580
Jupiter	.16 to .25	9.5	145
		2.9	640
		1.4	3000
		0.97	5500
		0.44	50,000
Mars	.02 to .12	9.5	218

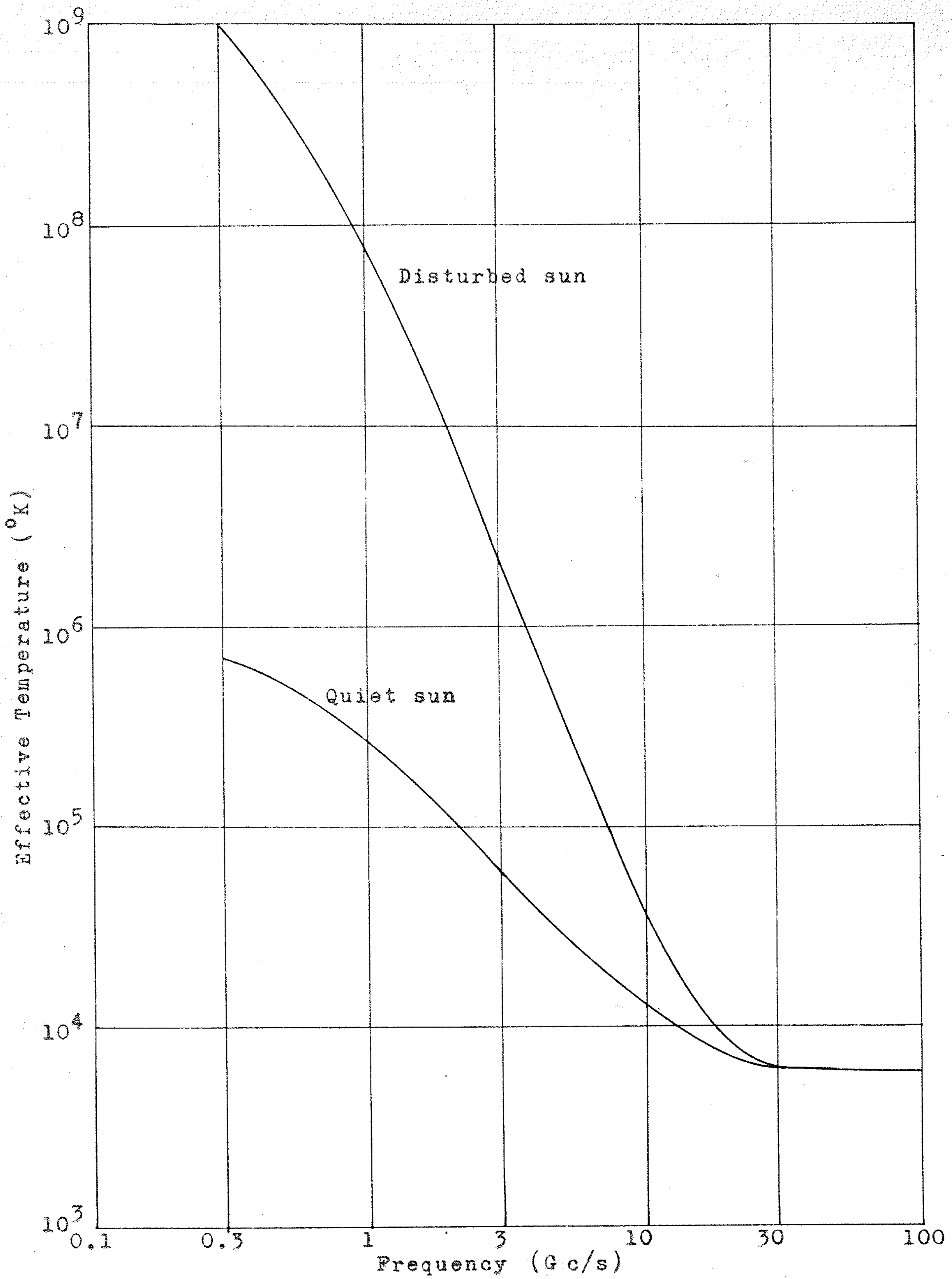
Solar Noise

The sun is the most important of the discrete sources of noise. When in the main beam of the antenna, it can greatly increase the effective noise temperature at the receiver input, and it is important to be able to evaluate its effect.

Figure 4.5, obtained from (35), shows the effective temperature of the quiet and disturbed sun as a function of frequency. For quiet conditions the effective solar temperature can be seen to decrease with increasing frequency up to 30 Gc/s before levelling off at 6000° K. The radiation may rise considerably above the quiet values for short periods during disturbed conditions up to the maximum temperature indicated by the upper curve. Such enhancements occur most frequently near the maximum in the sunspot cycle (23).

The plane angular width subtended by the solar disk varies from 1° at 100 Mc/s to $\frac{1}{2}^{\circ}$ at 50 Gc/s. For antennae with greater beam widths, solar noise contribution to the effective temperature in the main beam may be found by equation (4.3).

It is obvious that the sun's contribution will be very high when it is in the main beam of the antenna and in fact may be far greater than the combined contributions of all other noise. In any particular mode of operation it is necessary to know the percentage of time that the receiver will be solar noise limited. Hartz (15) has made such a calculation for an antenna used for 24-hour all-sky surveillance. He considers receiver limitation to occur whenever solar noise causes the noise temperature at the antenna terminals to exceed receiver noise temperature. System parameters used in his calculation are:

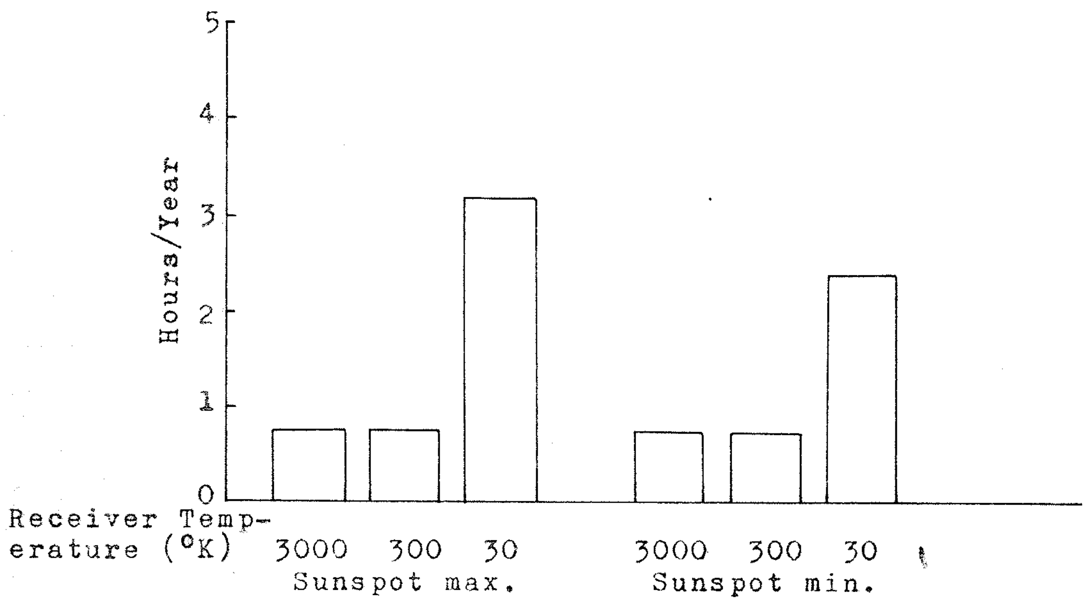


EFFECTIVE NOISE TEMPERATURE OF THE SUN

Figure 4.5

frequency	1500 Mc/s
antenna	80 foot paraboloidal reflector with first side lobe gain 25 db below main beam second side lobe gain 30 db below main beam all other side lobe gains 35 db or more below the main beam

Other assumptions are that the sun is visible for half the time and that receiver recovery time is so short as to be unimportant.



TOTAL TIME THAT SOLAR NOISE EXCEEDS RECEIVER NOISE
IN AN ALL-SKY SCAN MODE OF OPERATION

Figure 4.6

Figure 4.6 shows the relative time that various receivers would be solar noise limited under these conditions. It is significant to note that the relative time is several times greater for the low noise receiver because noise contribution when the sun is in the near side lobes may be as great as receiver noise. It is also significant that for such a general mode of operation as the one chosen, the total time of receiver limitation by solar noise is low. No serious deterioration of the surveillance capacity of the antenna would occur if it were programmed to avoid the sun. The total time that the receiver would be noise limited would, of course, be different for other modes of operation and would have to be calculated in each case. In general, however, it would be very low.

Man-made Noise

Man-made noise is not easily predictable and it is very difficult to determine how receiver performance will be affected by it. It is continually increasing and for this reason it is becoming a more and more serious problem. This noise arises from domestic appliances, motor vehicles, and industrial machinery, as well as from the growing number of intentional transmissions of energy from amateur and commercial radio stations, television stations, radars, active satellites, and communication links of all kinds. The best way to avoid this noise is by site location as far away as possible from sources of man-made noise. This is becoming increasingly difficult, however, as civilization creeps into even the most remote areas.

Propagation Through an Absorbing Medium

Absorbing regions through which signals may be passing include the ionosphere and the atmosphere. Propagation through an absorbing region is similar to propagation through a passive network except that the temperature and attenuation factor may be variable instead of constant, since they are functions of path position. Pawsey and Bracewell (16) have derived an expression for the effective black body temperature of such a region, taking into account both absorption and emission processes, viz.

$$T_b = \int_0^\infty e^{-\delta} T_p \, d\delta \qquad (4.5)$$

where

T_b = effective black body temperature of an absorbing medium extending to infinity from the point of observation.

T_p = thermal equilibrium temperature of the absorbing medium. T_p varies along the path.

δ = the attenuation depth = $\int_{\infty}^{s} \alpha ds$, where s is the elemental position.

α = the attenuation factor per unit length. It also varies with path position.

ds = an element of path length.

$d\delta = \alpha ds$, the attenuation thickness for an element of absorbing region.

Where T_p and α are functions of s

$$T_b = \int_0^{\infty} e^{\left(-\int_0^{s} \alpha(s)\ ds\right)} T_{p(s)}\, \alpha_{(s)}\ ds. \tag{4.6}$$

This equation enables the calculation of the effective temperature of a path through a non-uniform absorbing region such as the atmosphere.

Consider a special case where the path is of finite length P and is isothermal with a temperature T_p. Let the attenuation depth for the path be $\Delta = \int_0^{P} \alpha\ ds$. Then its effective temperature is

$$T_b = T_p \int_0^{\Delta} e^{-\delta}\, d\delta \tag{4.7}$$

or
$$T_b = T_p\,(1 - e^{-\Delta}). \tag{4.8}$$

But

$$e^{\Delta} = L, \text{ the loss factor.}$$

Therefore

$$T_b = T_p\left(1 - \frac{1}{L}\right). \tag{4.9}$$

Comparing (4.9) with the second term of equation (2.49), it is evident that the effective black body temperature of an absorbing medium is equivalent to the re-radiated transmission line effective temperature.

Noise from Ionospheric Absorption

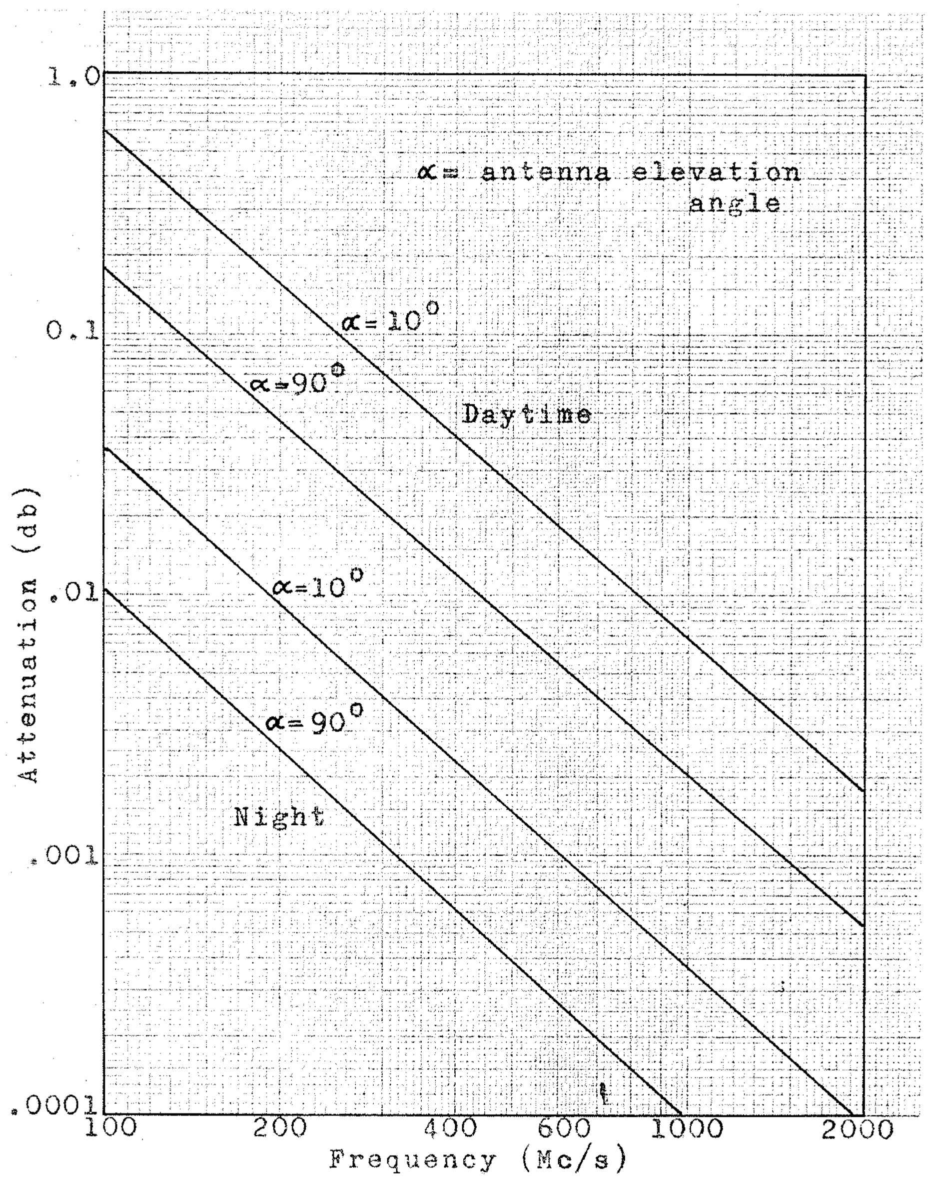
For noise contribution purposes, the ionosphere may be considered as an isothermal passive network with a loss equal to its absorption. Millman (17) has calculated the loss assuming the Chapman distribution of electron density and a collision frequency model based on an ionosphere that is chemically homogeneous and isothermal. His results for typical night-time and daytime electron densities and for elevation angles of 10° and 90° are illustrated by figure 4.7. By geometry the path through the ionosphere is longer at low angles of elevation and is characterized by greater attenuation.

Even in the most severe case, however, ionospheric attenuation is not high and for UHF or higher frequency systems, it will contribute only a fraction of a degree to the effective noise temperature.

Under abnormal conditions of the ionosphere, such as during the occurrence of aurora, absorption is increased due to increases in the electron density. Observations made at 440 Mc/s (18), however, failed to show any detectable increase in absorption of an UHF signal traversing an auroral disturbance.

Noise from Atmospheric Absorption

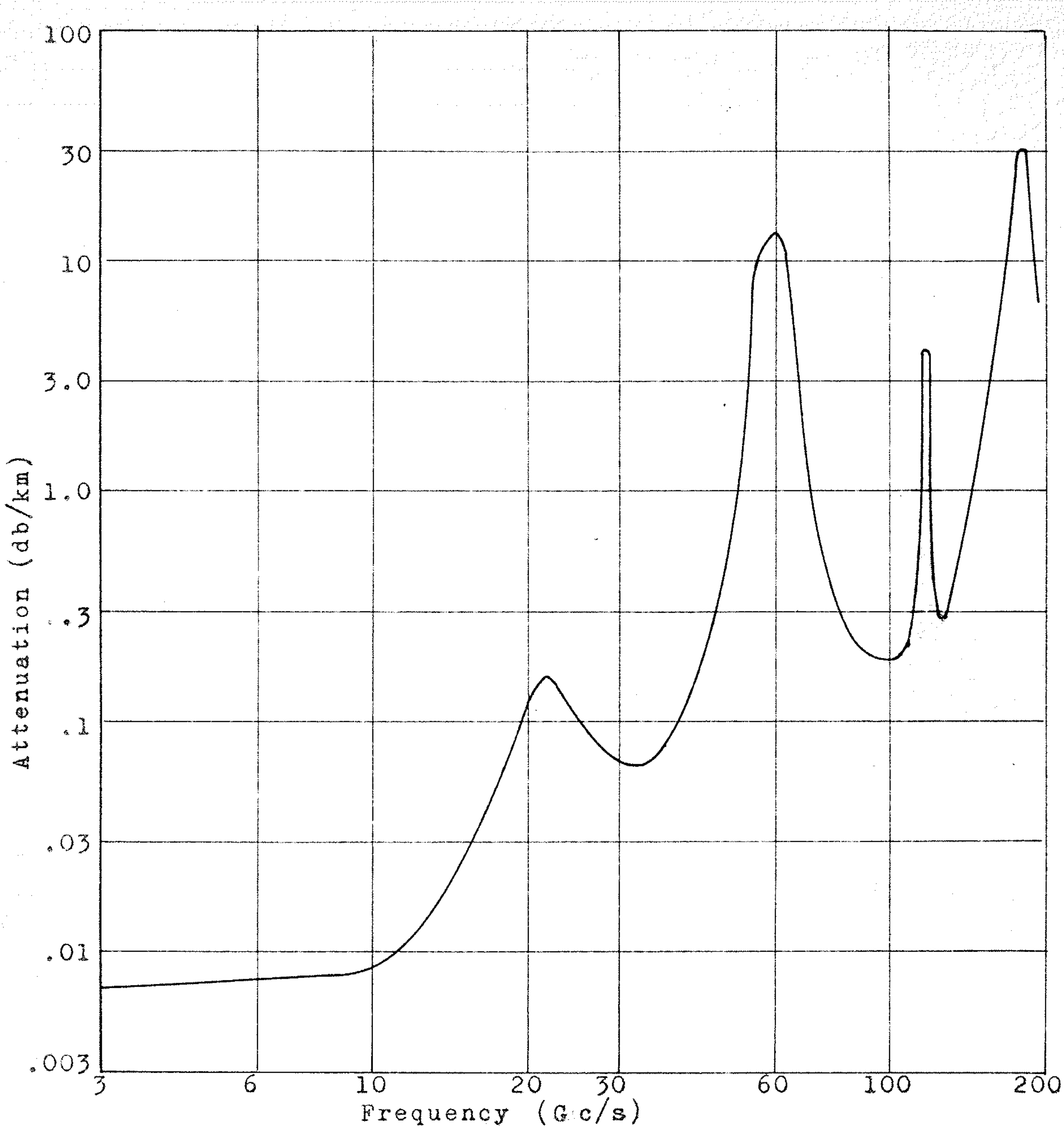
Atmospheric absorption due to oxygen and water vapour becomes predominant as frequency is increased into the gigacycle region. The absorption by these two gases becomes a maximum at frequencies associated with the dipole moments of their molecules because of resonance effects. For oxygen



ONE-WAY IONOSPHERIC ATTENUATION vs. FREQUENCY

Figure 4.7

this is due to its magnetic moment and occurs at wavelengths in the vicinity of 0.25 cm and 0.5 cm. For water vapour this is due to its electric dipole moment at an approximate wavelength of 1.35 cm. These maxima are apparent in figure 4.8, which shows the attenuation per kilometer by an atmospheric water vapour content of 1% and normal atmospheric oxygen content, at sea level and a temperature of 20° C.

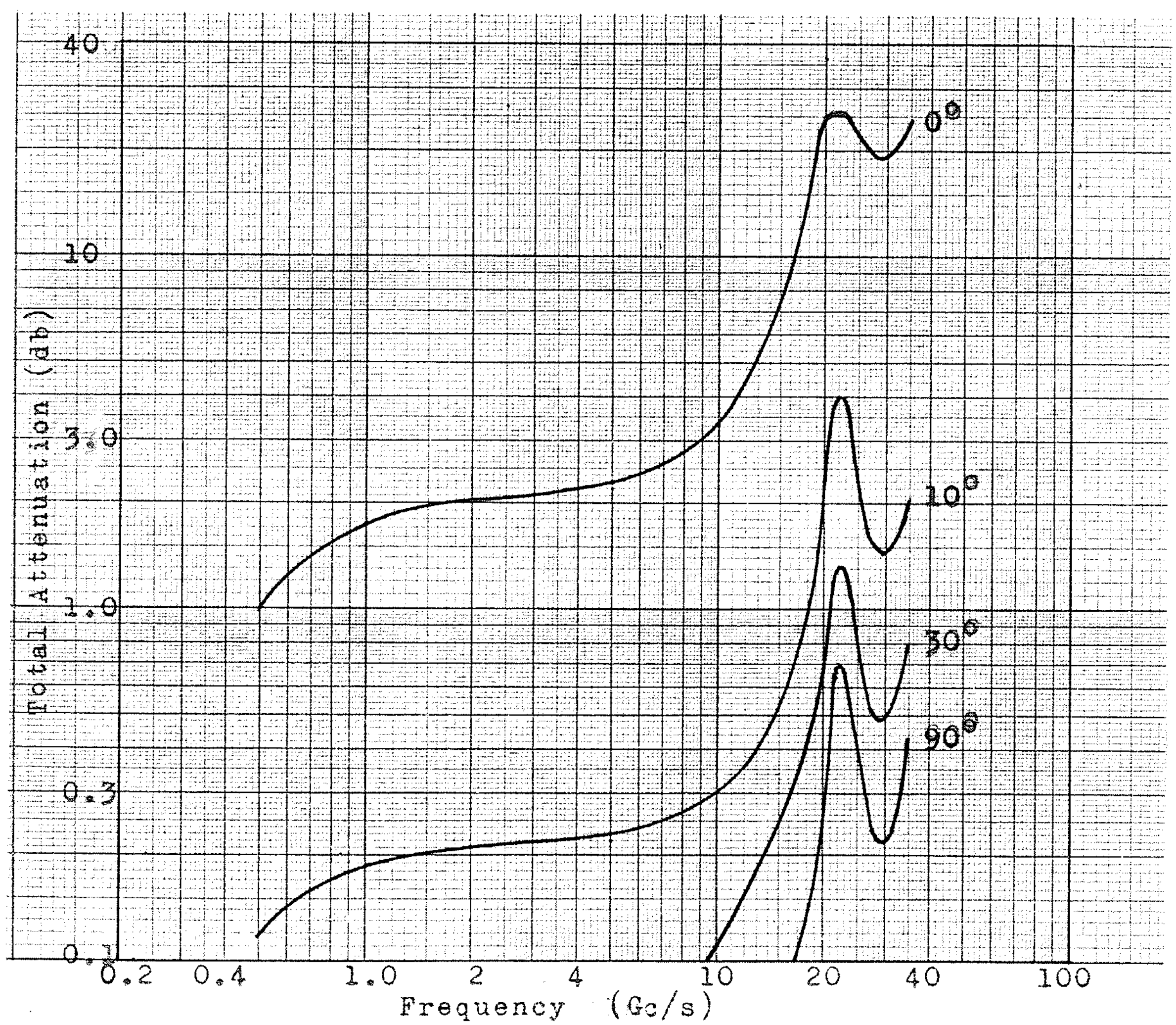


ATMOSPHERIC ATTENUATION AT GROUND LEVEL
DUE TO OXYGEN AND 1% WATER VAPOR

Figure 4.8

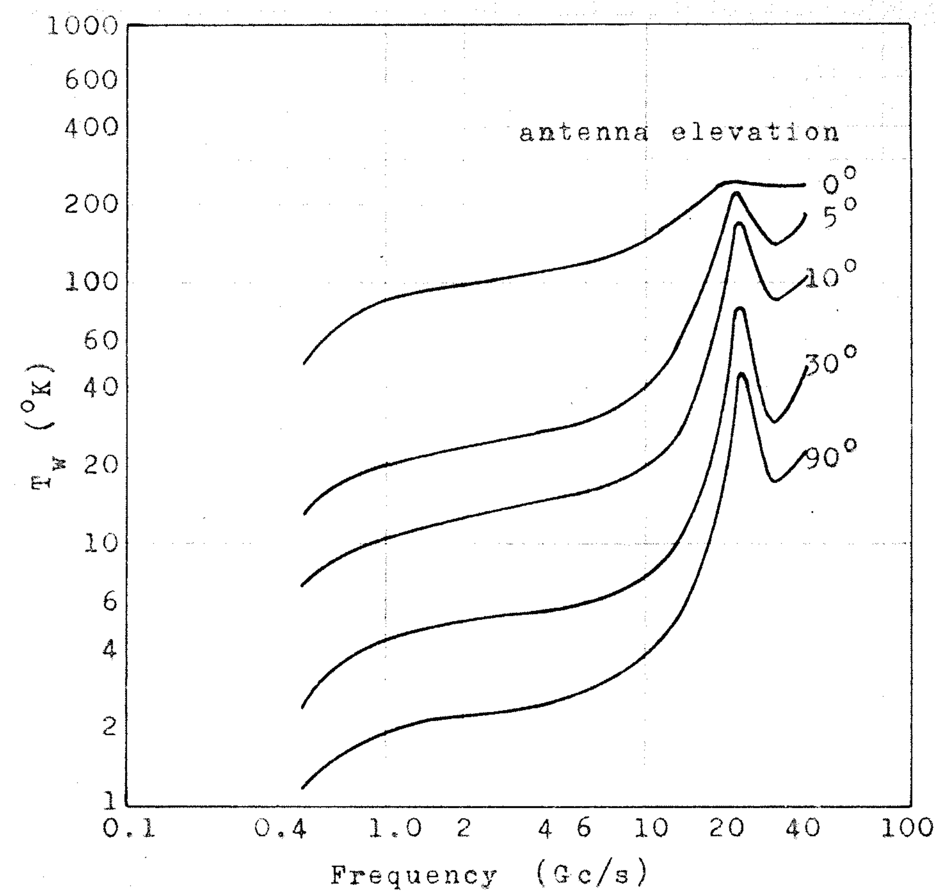
Figure 4.8 is the result of ground measurements. Radio astronomy measurements by Aarons, Barron and Castelli (19) at a wavelength of 3.2 cm have yielded an attenuation of 0.00585 db/km, and at 0.87 cm an attenuation of 0.033 db/km, in reasonable agreement with the ground measurements.

The total absorption that is suffered by a signal passing through the atmosphere is affected by the path length and atmospheric density and temperature. These are functions of height and the antenna elevation angle. Therefore, calculations of absorption presuppose the assumption of a suitable atmospheric model. Hogg (20) has taken a typical summer atmosphere twenty kilometers in height and has calculated its attenuation characteristic due to water vapor and oxygen. His results are shown in figure 4.9. Hogg has compared his results with measurements made by various workers in the field and has concluded that his calculated data is of satisfactory accuracy.



ONE-WAY ATTENUATION DUE TO ATMOSPHERIC OXYGEN AND WATER VAPOR

Figure 4.9



ANTENNA TEMPERATURES DUE TO OXYGEN AND WATER VAPOR

Figure 4.10

The noise temperature contribution of the atmosphere may be calculated by employing the method outlined in this chapter. Figure 4.10 shows the results of such a calculation made by Hogg, based on his calculated attenuation curves and an assumed model of atmospheric temperature.

Noise due to Warm Earth

The warm earth contributes to antenna noise temperature when the antenna pattern intersects the earth's surface because the earth is generally a good absorber in the frequency range of interest. Hansen (21), and Feiner and Savage (22) have calculated its contribution to the antenna temperature by applying the concept of reciprocity which states that the noise power received through any particular small solid angle of the pattern of an antenna is proportional to the power absorbed in that direction when the antenna is transmitting, and to the temperature of the absorbing body. The total effective temperature of the noise incident on the antenna is the summation of the noise received through each elemental solid angle.

$$T = \sum T_i \, p_i \tag{4.10}$$

where p_i is the fraction of total power absorbed through the i^{th} element of solid angle.

T_i is the temperature of the absorbing surface in the i^{th} element of solid angle.

Applying equation (4.10) to earth absorption, with an assumed earth temperature of 290° K, the noise contribution of the warm earth to the antenna temperature becomes

$$T = 290^\circ \, p \tag{4.11}$$

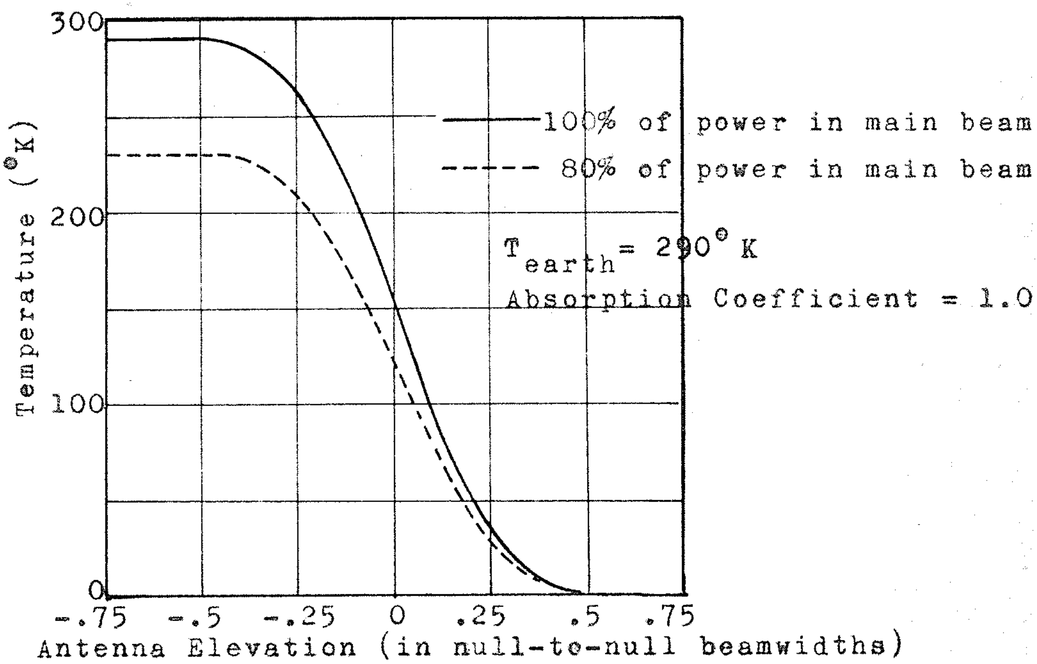
The fraction of total power absorbed by the earth, p, can be found from the integral

$$p = \frac{\int \frac{G_\Omega}{4\pi} K_\Omega \, d\Omega}{\int \frac{G_\Omega}{4\pi} \, d\Omega} \tag{4.12}$$

where G_Ω is the antenna gain in the direction of the element of solid angle $d\Omega$.

K_Ω is the fraction of power in the element of solid angle $d\Omega$ that is absorbed.

Applying the concept of reciprocity to the main beam only, a curve of antenna temperature due to the earth's contribution was obtained and is shown in figure 4.11. It was calculated on the basis of per cent of antenna main beam volume intercepted by the earth, assuming that the antenna pattern was produced by a uniform aperture illumination with its typical narrow beam and that the main beam provided all the power received by the antenna. To apply it to a practical antenna, the curve must be multiplied by the appropriate fraction of the total power received by the main beam. The broken curve is an example of temperature when 80% of the power is in the main beam. A further assumption that was made was that the earth is a perfect absorber. It is evident from the figure that antenna temperature rises rapidly when the main beam intersects the earth's surface.



EFFECTIVE TEMPERATURE OF EARTH NOISE
PICKED UP BY THE MAIN BEAM OF AN ANTENNA

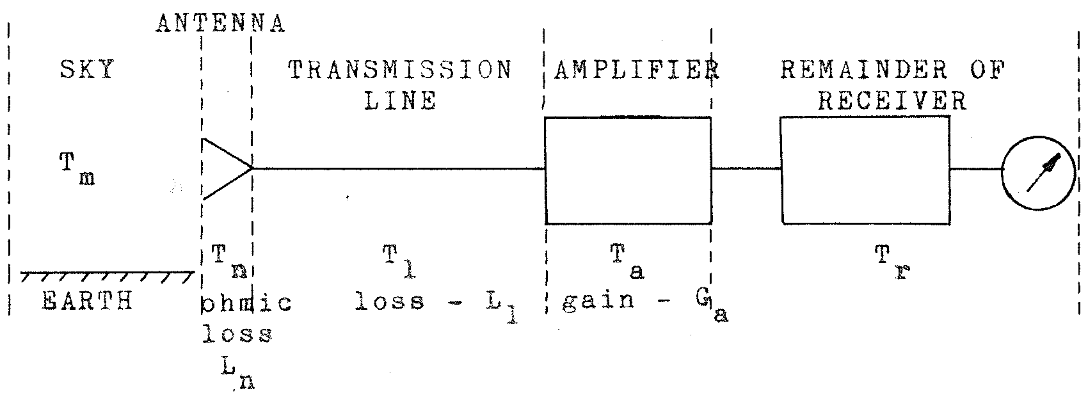
Figure 4.11

Chapter V

Complete Receiving System Noise

Model of a Receiving System

A model of a receiving system may be devised in which all of the noise producing elements are represented as separate entities. An appropriate configuration is shown in figure 5.1.



MODEL OF A RECEIVING SYSTEM

Figure 5.1

The model includes noise contributed by the antenna, the receiver, and the transmission line linking the two. Antenna noise is divided into that over which the designer has no control and that which is affected by antenna design. Receiver noise is divided into that which arises from the first active stage and that which comes from the remainder of the receiver. Such a receiver is a suitable representation for a modern microwave receiver employing a high gain low noise front end. In the figure

T_m = effective temperature of all noise sources in the main beam of the antenna.

T_n = effective temperature of all noise which is controlled by antenna design.

T_l = effective temperature due to transmission line losses.

T_a = effective noise temperature of the preamplifier.

T_r = effective temperature of the remainder of the receiver.

T_m includes the composite effects of galactic background radiation, radiation due to ionospheric and atmospheric losses, radiation from discrete sources, and earth radiation in the main beam. It is the result of noise sources which cannot be avoided. These are often small, depending on the frequency range of interest, and are a function of the antenna beam position.

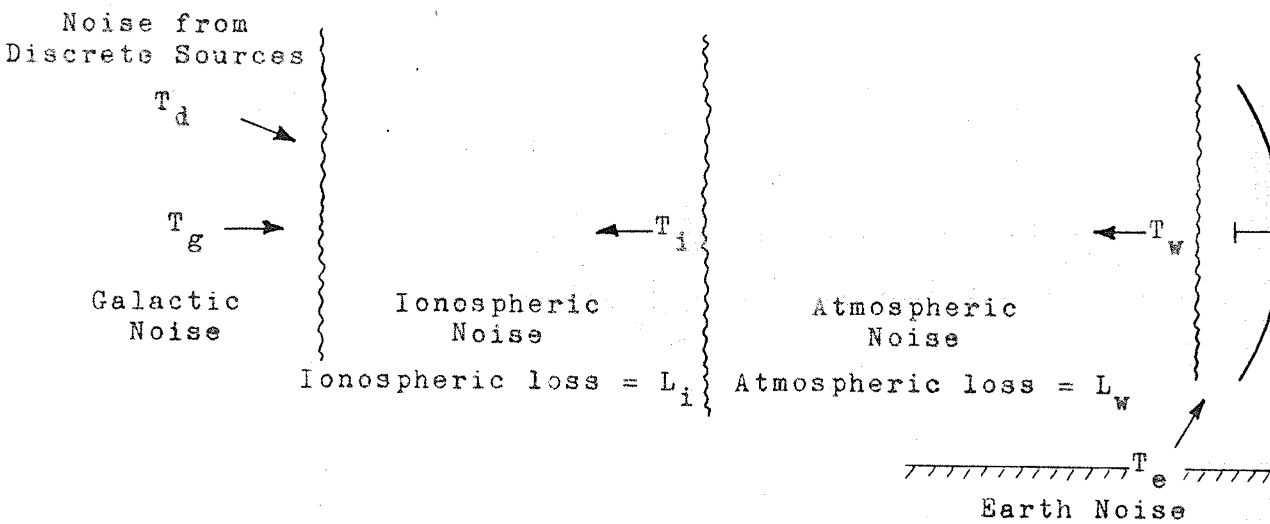
T_n is composed of noise due to antenna ohmic losses, sky background and earth radiation into the antenna back and side lobes, and feed spillover. Noise due to ohmic losses is generally low, but noise due to subsidiary lobes in the antenna pattern can be significant. This noise can be reduced by antenna design.

T_l consists of transmission line noise and noise from all passive components which form part of the line, such as rotary joints, circulators and duplexers.

T_a and T_r may be classified as receiver noise. They are considered individually because the noise figure of a receiver is determined largely by the noise in the first active, high gain stage. T_r consists of noise from the converter, intermediate frequency amplifiers and any other noise producing components. The effect of T_r can be expected to be small in a good system.

Main Beam Noise

Main beam noise, T_m, has been subdivided into several components. These are shown in figure 5.2. It is strongly dependent on antenna elevation and frequency. At very low elevation angles the earth may lie in the main beam of the antenna and contribute noise by thermal radiation. At low elevation angles also, atmospheric and ionospheric paths are longer. Galactic background radiation varies widely across the sky, and hence its effect on system noise also depends on beam position.



ORIGIN OF MAIN BEAM NOISE

Figure 5.2

The composite effects of all continuous sources which are contributors to main beam temperatures may be calculated by reference to figure 5.2. When referred to the antenna primary feed

$$T_m = \frac{T_d}{L_i\ L_w} + \frac{T_g}{L_i\ L_w} + \frac{T_i}{L_w} + T_w + T_e . \qquad (5.1)$$

T_g, L_i, L_w, T_w and T_e are available from graphs and T_d may be calculated from tables and graphs in the preceding chapter.

$T_i = \frac{(L_i - 1)}{L_i} T_{ionosphere}$, and is negligible in the UHF and higher frequency regions.

T_g, T_d, T_i, T_w and T_e are effective temperatures with reference points as indicated in the diagram.

Figure 5.3 shows the variation of main beam temperature versus frequency for various elevation angles. In the calculation of the figure, the following conditions were assumed:

(i) there are no discrete sources in the main beam.

(ii) galactic temperature is that given by curve A of figure 4.2, the worst condition. Minimum galactic temperature is shown by the dotted curve.

(iii) the earth is a perfect absorber at 290° K.

(iv) earth noise is subject to negligible atmospheric attenuation.

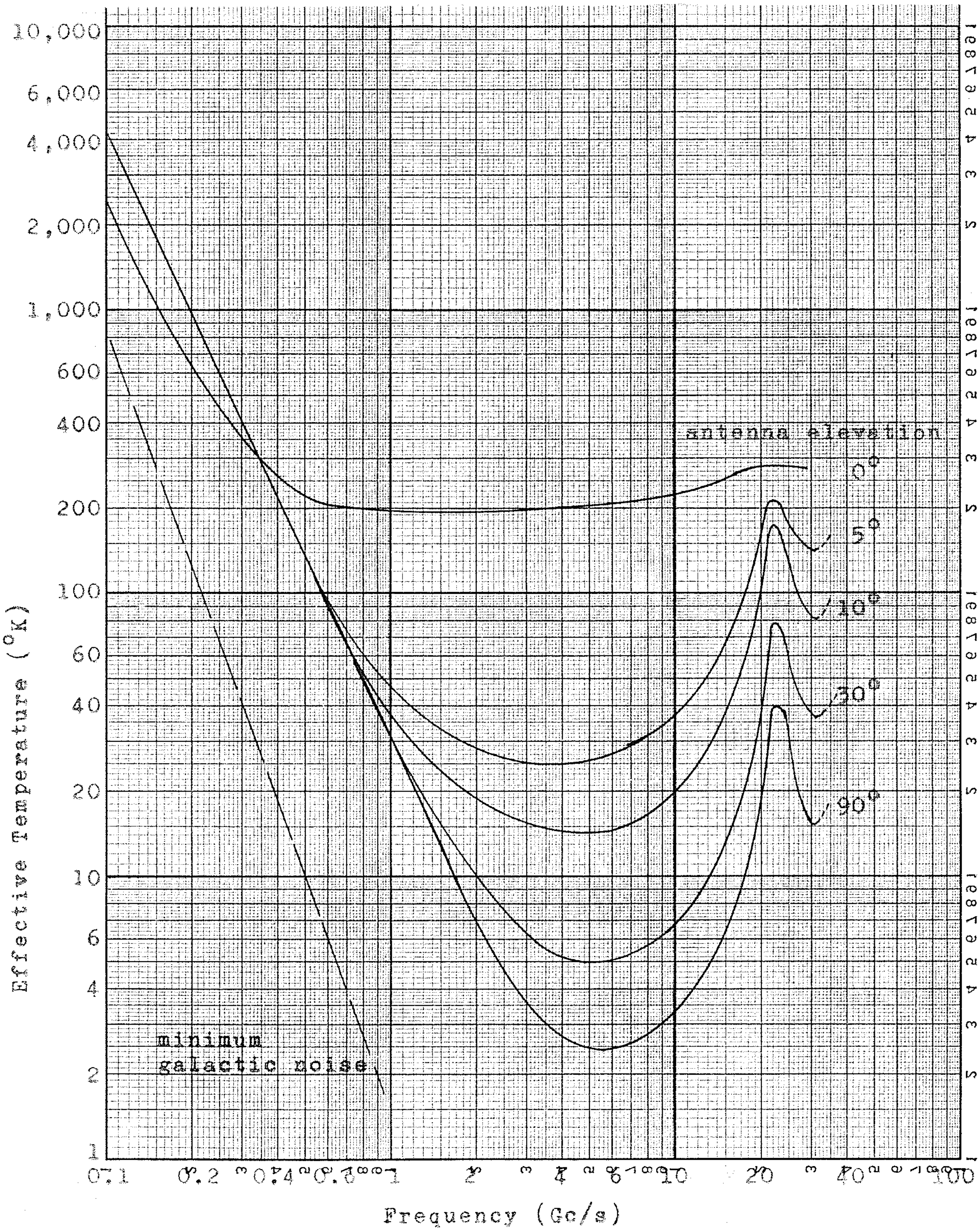
(v) the main beam is less than 5° wide.

(vi) 100% of the power received by the antenna is received through the main beam. For a practical antenna, the appropriate correction factor must be applied.

(vii) conditions are those typical for summer.

Noise Dependent on Antenna Design

Calculation of the total effective noise temperature available at the terminals of an antenna is made difficult by the complexity of the antenna radiation pattern with its multitudinous back and side lobes. These are caused by spillover, diffraction at the reflector edge and supporting structures, leakage through the mesh, etc., and are not easily predictable. To facilitate computation, an idealized pattern has been generally assumed (21) (22), in which the solid angle occupied by the main



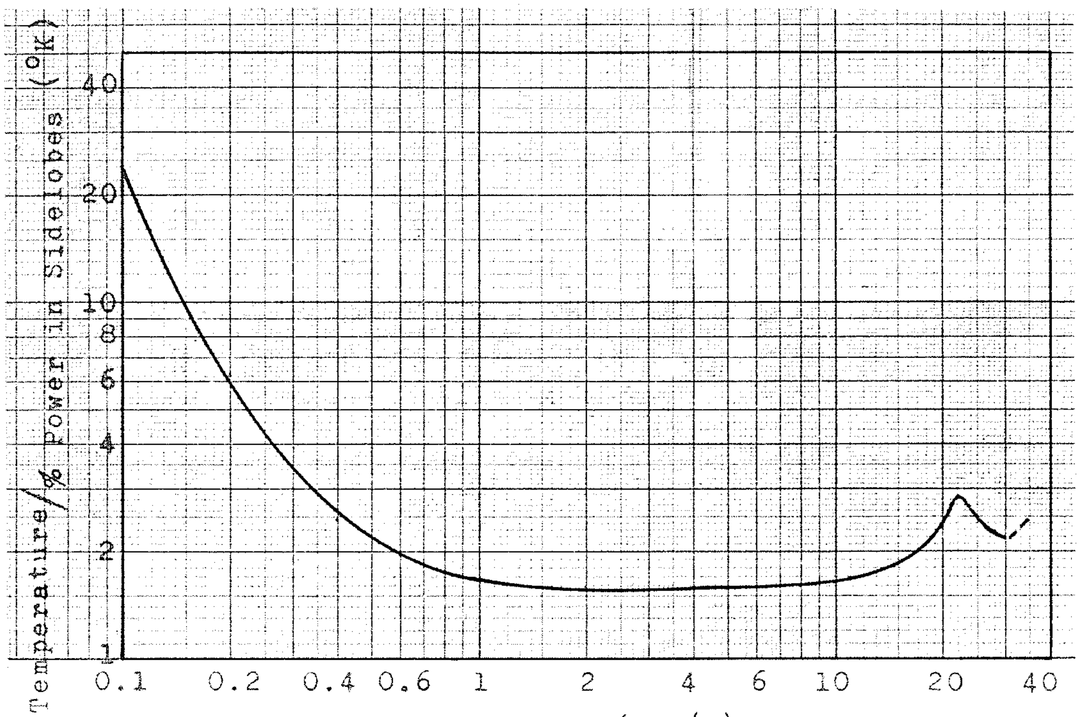
SKY NOISE TEMPERATURE DUE TO GALACTIC SOURCES AND ATMOSPHERIC ABSORPTION

Figure 5.3

beam is negligible with respect to the total solid angle of the minor lobes. The gain of the minor lobes is assumed to be constant and equal to the average minor lobe gain. This provides a spherical minor pattern, with half the pattern illuminating the sky and the other half illuminating the earth.

Applying the concept of reciprocity, the temperature of the noise contribution by the minor lobes can be calculated. The assumption is made that the earth is a perfect absorber at 290° K and that it fills the lower half of the minor lobe pattern. The average temperature of the sky filling the upper half of the minor lobe pattern is assumed to be the same as that given for an elevation angle of 5° in figure 5.3. The result of this calculation is figure 5.4, which is a curve of minor lobe noise temperature contribution versus frequency for an antenna in which the minor lobes account for 1% of the total received power. For most practical antennas this percentage is higher and the actual side lobe temperature contribution may be found by multiplying the curve by the proper factor.

Antenna ohmic losses also account for some of the absorption in a typical antenna. Since antennas are usually at an ambient temperature of 290° K, a loss of one per cent accounts for a 2.9° increase in effective noise temperature. It can readily be appreciated that increased ohmic losses would raise effective noise temperatures rapidly and that antenna and feed designers should endeavour to keep such losses as low as possible. Typical ohmic losses for paraboloidal reflectors quoted by the Airborne Instruments Laboratory in their study of antenna noise temperature (23) are about 0.05 db or 1%.

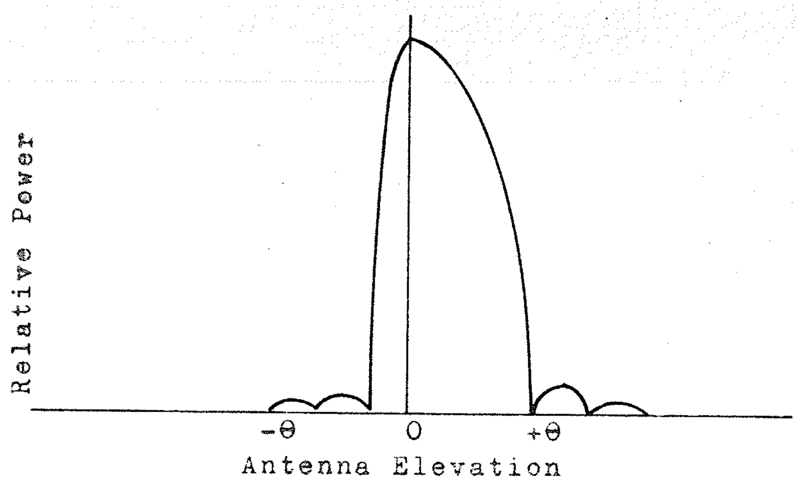


CONTRIBUTION OF SIDELOBES TO ANTENNA NOISE TEMPERATURE

Figure 5.4

Over the frequency range shown in figure 5.4 warm earth radiation makes the larger contribution to minor lobe noise. Antenna noise temperature improvement could be effected by lowering the level of the entire minor lobe pattern, or at least that portion which impinges upon the warm earth. This can be done by proper feed design so that feed spillover is minimized and by using an antenna aperature illumination which produces low side lobes. This is adequately discussed in the Airborne Instruments Laboratory Report.

To lower the side lobes directed earthward, a feed producing an assymmetrical beam, with a sharp drop off and low level side lobes at the lower side of the elevation pattern, such as that shown in figure 5.5, could be used. Hanson (21) reports such techniques to be under development.



ELEVATION PATTERN OF ANTENNA WITH MAIN BEAM
SHAPED TO REDUCE EARTH NOISE PICKUP
Figure 5.5

Another technique used to lower the temperature seen by the side lobes is to place a reflecting mesh beneath the antenna so that the apparent temperature within the side lobe pattern is that of the cold sky. Care must be taken, however, to see that side lobe levels are not appreciably enhanced.

Other methods of reducing side lobes directed earthward include the use of Cassegrain and Gregorian feeds for antennas. A study of Cassegrainian systems with respect to their low noise properties is found in reference (24).

Transmission Line Noise

Transmission line noise may be calculated by the methods of Chapter 2 if the line loss and ambient temperature are known. Understandably, the loss must be kept as low as possible so that T_1 does not increase the total noise temperature of the system significantly. Special transmission line components, such as duplexers, circulators and rotary joints may also be considered as passive noise generating networks. Here extra care must be taken to keep the loss low, particularly with high average-power radars, since dissipation in a lossy component will tend to raise the ambient temperature and hence increase the effective noise temperature of the component. Frictional heating in rotary joints will have a similar effect.

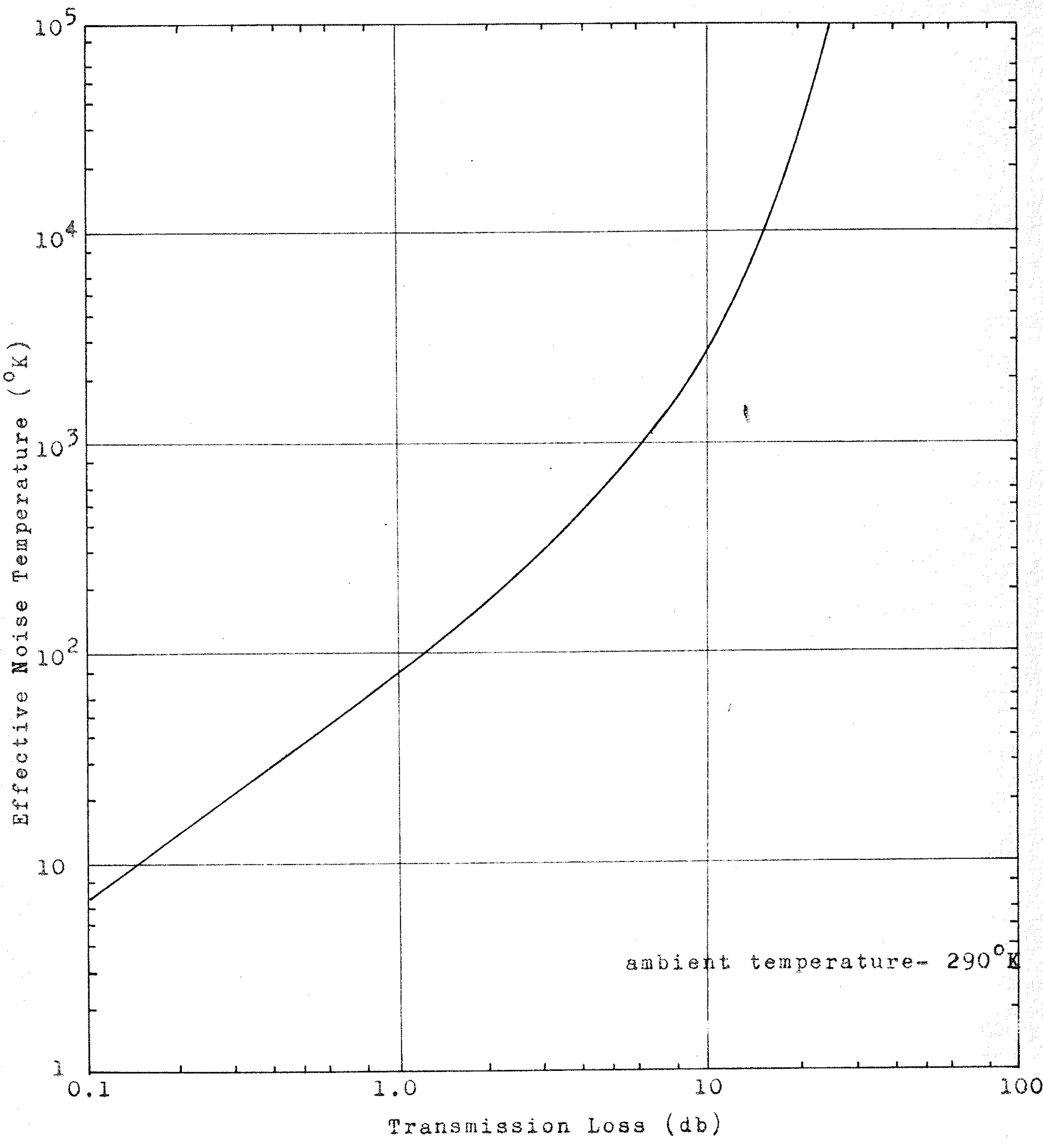
Figure 5.6 shows the relation between loss in a passive network at an ambient temperature of 290° K and the effective input noise temperature of the network.

Amplifier Noise

The noise contribution of the amplifier which is the first active stage of a microwave receiver, or the receiver front end, depends largely on the type of front end. The effective noise temperature that can be expected from the best planar triode vacuum tubes, as reported by McCoy (25), are shown as a function of frequency in figure 5.7. Plotted on the same figure are the reported noise temperatures of other types of front ends, including masers, parametric amplifiers, travelling wave tubes, tunnel diode amplifiers and crystal mixers (33).

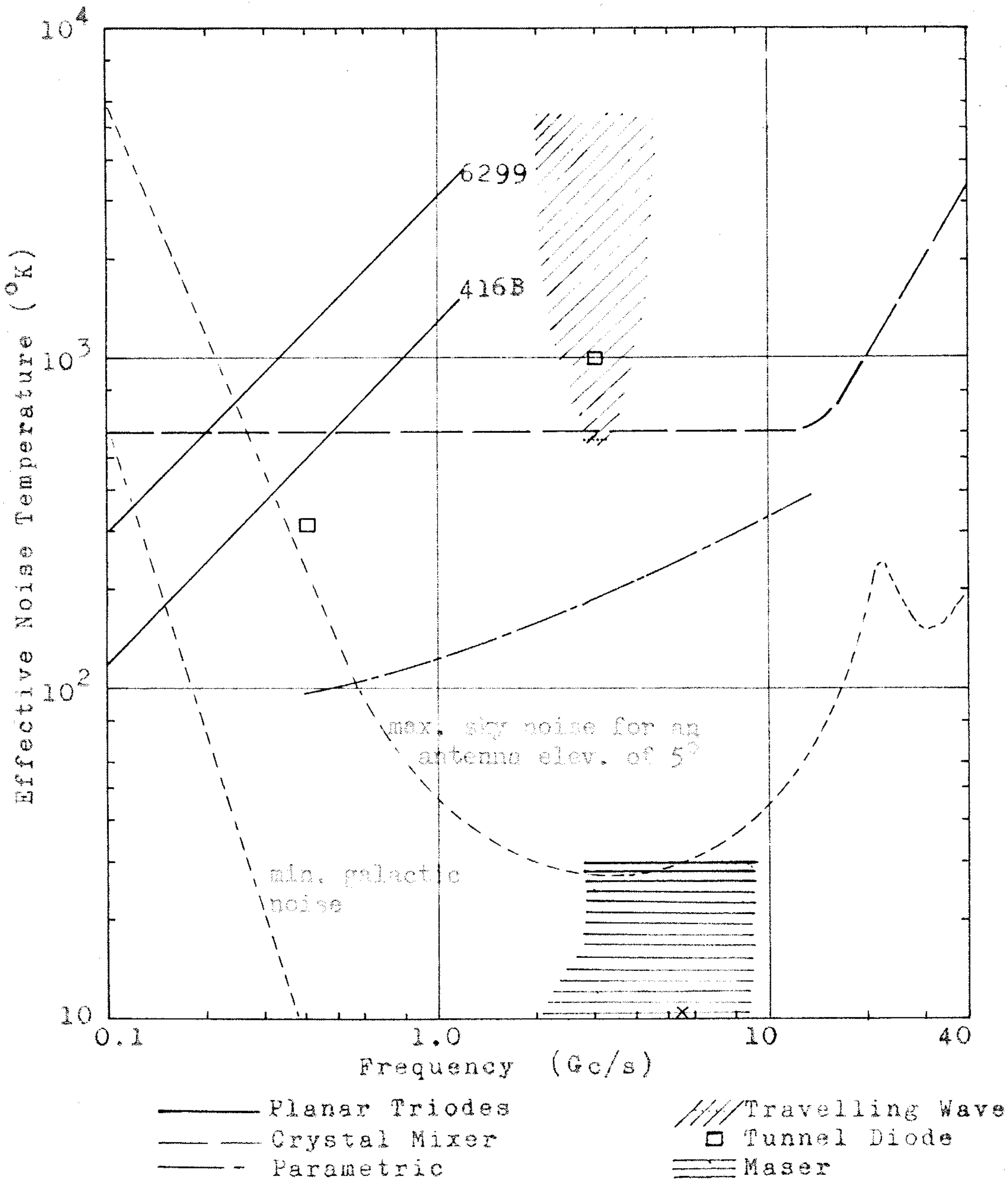
It can be seen that planar triodes and travelling wave tubes generally yield high effective noise temperatures in their region of usefulness. Crystal mixers are somewhat better, but in the practical case, the signal suffers attenuation upon conversion and hence the noise figures of the following stages become significant.

Masers, on the other hand, provide a very low effective temperature. Parametric amplifiers and tunnel diodes fall between the very low temperature masers and the planar triodes. The choice of amplifier for a receiver front end must be made on the basis of the expected improvement in overall system sensitivity and on practical considerations.



EFFECTIVE NOISE TEMPERATURE OF A PASSIVE NETWORK vs. TRANSMISSION LOSS

Figure 5.6



MEASURED EFFECTIVE NOISE TEMPERATURES
OF VARIOUS TYPES OF RECEIVERS

Figure 5.7

Noise From the Remainder of the Receiver

The remainder of the receiver has been lumped together for its contribution to the effective noise temperature because it may be treated as one active network composed of a number of cascaded active stages. T_r should be kept as low as possible to keep its effect on receiver noise temperature small. To examine possible methods of reducing T_r, the effect of the various stages may be considered separately.

At microwave frequencies the receiver front end is normally followed by a crystal converter. The converter noise contribution merits special attention since signals usually suffer a loss when passed through a crystal converter. Equation (2.46) shows

$$T_{E_{1,2\ldots n}} = T_{E_1} + \frac{T_{E_2}}{G_{p_1}} + \frac{T_{E_3}}{G_{p_1} G_{p_2}} + \frac{T_{E_4}}{G_{p_1} G_{p_2} G_{p_3}} + \cdots\cdots$$

and if the loss is large and approaches the front end gain in magnitude, it could nullify much of the advantage of a low noise front end. The IF circuits of the receiver would then have a greater effect on overall noise temperature.

Under the circumstances of high converter loss the effective noise temperatures of IF amplifiers become important. Low noise temperature IF amplifiers are readily available, however. A study of the components of a particular receiver with respect to the required sensitivity will determine the maximum permissible IF amplifier noise temperature.

Another portion of the receiver that may contribute noise is the local oscillator. Noise at the signal frequency and the image frequency may be generated within the local oscillator and appear at the IF output of the mixer. Since this noise comes from an independent source, however, it may be suppressed without affecting the signal. Various circuitry useful in this regard include tuned filters at the local oscillator frequency and balanced mixers, such as the magic-T ([illegible]), and the short slot hybrid (26), which utilize phase cancellation of the unwanted signal.

System Noise Temperature

The total noise temperature of the system may be found if the pertinent antenna and receiver parameters are known. From the model

$$T_s' = \frac{T_m}{L_n\, L_l} + \frac{T_n}{L_n\, L_l} + \frac{T_l}{L_l} + T_a + \frac{T_r}{G_a}. \qquad (5.2)$$

This assumes that the antenna is at a temperature T_o and that the earth and discrete sources of noise do not lie within the main beam of the antenna.

The reference point in use here is the input terminal to the front end. To change the reference point to the input of the transmission line, consider the line cascaded with the front end and the receiver proper. Then

$$T_s = \frac{T_m}{L_n} + \frac{T_n}{L_n} + T_l + T_a\, L_l + \frac{T_r\, L_l}{G_a}\ . \qquad (5.3)$$

To study the effects of the contributions of the antenna, transmission line and receiver to total system noise, it is convenient to combine additive factors and thus make the equation less cumbersome. Let

$T_m + T_n \equiv T_A$ ... noise present at the antenna output terminals

$T_a + \dfrac{T_r}{G_a} \equiv T_R$ ... noise added by the active networks of the system

Then

$$T_s' = \frac{T_A}{L_n\, L_l} + \frac{T_l}{L_l} + T_R \qquad (5.4)$$

and

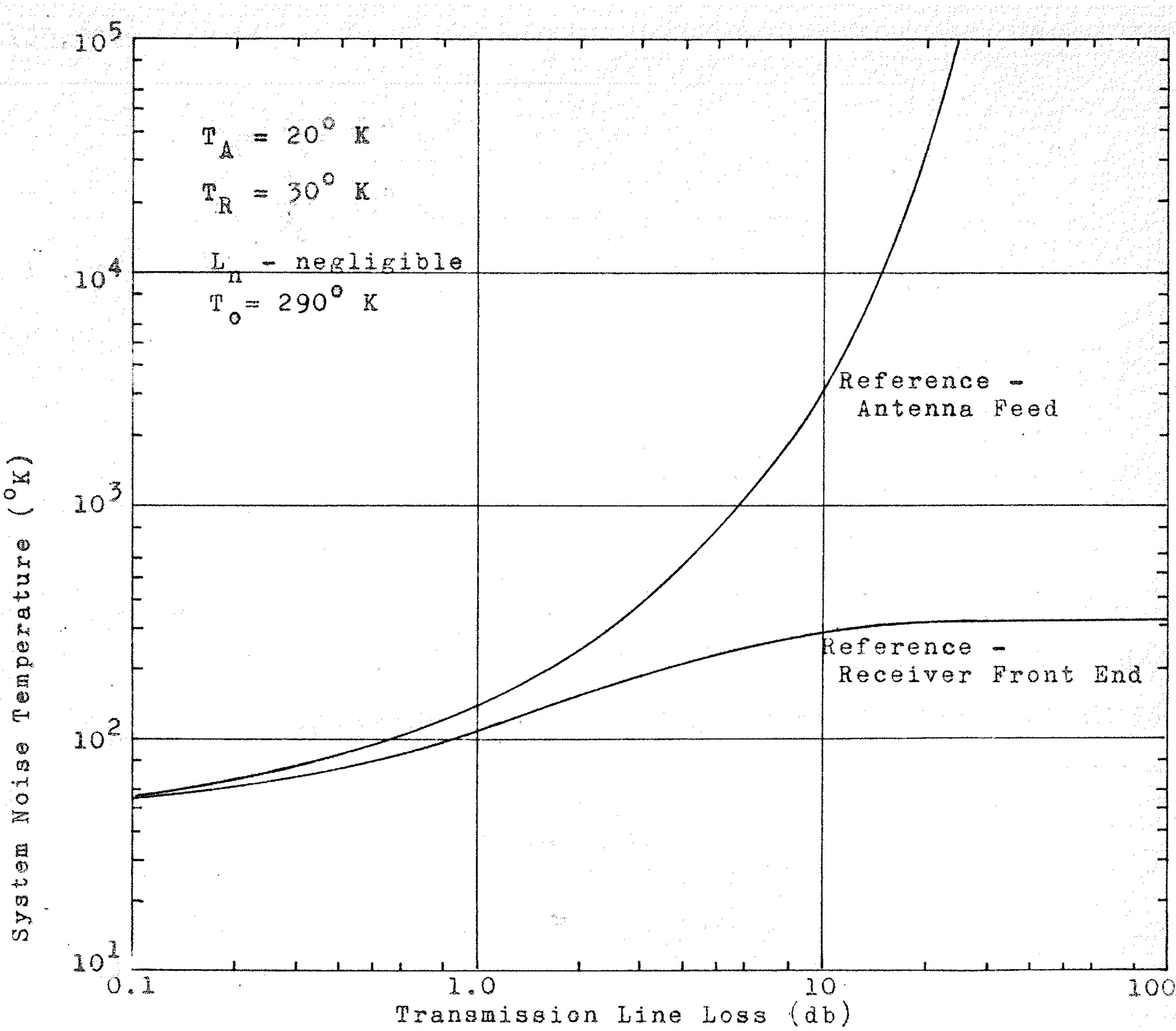
$$T_s = \frac{T_A}{L_n} + T_l + T_R\, L_l. \qquad (5.5)$$

Note that changing the reference point from the output of the transmission line to the input increases the total system noise temperature by a factor which is equal to the loss of the line. The effect of the reference point on the significance of total noise temperature as a measure of system sensitivity is illustrated in figure 5.8.

If the input terminal to the front end is used as a reference, system degradation due to signal attenuation is not accounted for. In the case of infinite loss the transmission line appears as a black body at temperature T_o and contributes T_o to the total noise of the system, at the same time completely absorbing any noise and signal that might appear at its input. A more realistic picture is obtained by taking the antenna feed as the reference point. Signal attenuation is now taken into account and the total noise temperature as a measure of system sensitivity is placed in proper perspective.

Improving System Sensitivity

The importance of minimizing transmission line loss can be illustrated with figure 5.8. For the system shown a 2 db line loss results in a system noise temperature of 230° K at the antenna feed. For no line loss system noise temperature is 50° K. For a given signal-to-noise ratio at the receiver output, signal strength would have to be increased in the ratio of 230 to 50, resulting in a difference in system sensitivity of 6.6 db, far more than just the 2 db due to the line loss. This is due to the fact that the line adds noise to the system as well as reduces signal strength. This effect becomes less pronounced as antenna and receiver noise contributions increase, but must be taken into account in low noise systems.



EFFECT OF REFERENCE POINT ON SYSTEM NOISE TEMPERATURE

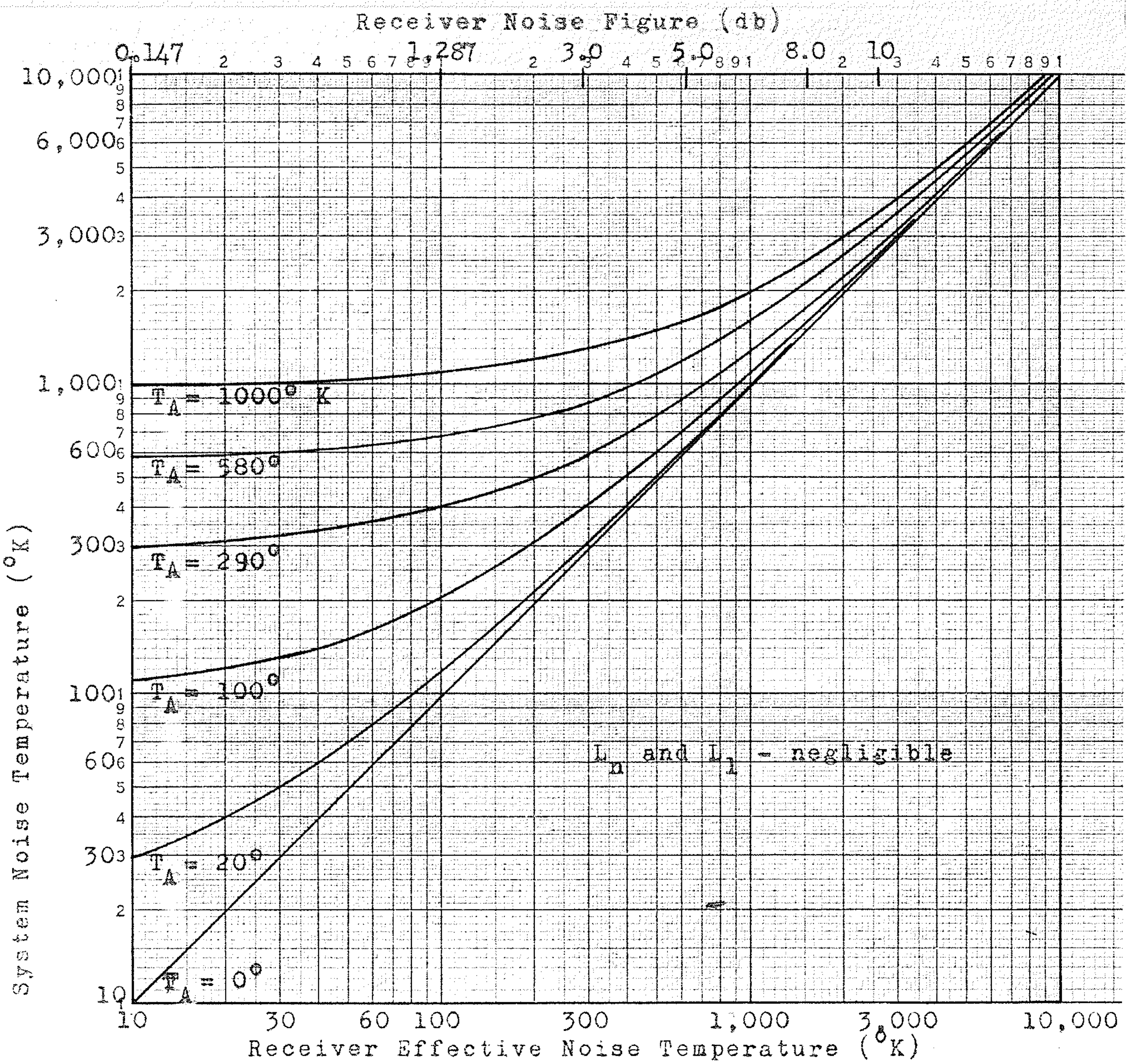
Figure 5.8

The necessity of keeping noise received by the antenna feed low if there is to be any important benefit from low receiver noise is demonstrated in figure 5.9 which shows the effect of receiver effective noise temperatures on system noise temperatures and hence on sensitivity for a range of antenna temperatures. As an example, it can be seen from the figure that a reduction in receiver effective noise temperature from 1000° K to 10° K will give a 15 db improvement in sensitivity for an antenna temperature of 20° K but only a 3 db improvement for an antenna temperature of 1000° K. For cases where the antenna noise contribution is high, the effort required to reduce receiver noise temperature may not be justified since total system noise temperature will not be significantly decreased.

The noise figure scale on figure 5.9 can be used to point out the effect of the use of 290° as the reference temperature in the definition of noise figure. A specific decrease in noise figure in db does not reflect a corresponding decrease in system noise temperature except for an antenna temperature of 290° K. For a higher antenna temperature, total system noise decreases less than does the noise figure and for a lower antenna temperature, it decreases more than the decrease in noise figure. For example, with a T_A of 100° K and a receiver noise figure improvement of 4 db from 5 db to 1 db, system noise temperature decreases from 700° K to 175° K, or approximately 6 db. This apparent greater improvement in sensitivity is due to the fact that the temperature seen by the receiver at its input is less than the reference temperature used in the measurement of the receiver noise figure.

<u>Low Noise Amplifiers</u>

The performance that can be expected from various types of amplifiers was shown in figure 5.7. Choice of amplifier must be made on the expected improvement in sensitivity, on practical considerations, and on the intended use of the system. A surveillance radar would be used at low antenna elevation angles for a large percentage of the time, with increased antenna noise added by the main beam as a consequence. Under such circumstances, use of a parametric amplifier might be indicated. If the system is to be



SYSTEM NOISE TEMPERATURE vs. RECEIVER NOISE TEMPERATURE FOR VARIOUS ANTENNA NOISE CONTRIBUTIONS

Figure 5.9

used for satellite tracking or for radio astronomy where the antenna is used at high elevation angles, antenna noise is kept at a minimum and sensitivity is important, a maser would be useful. The use of a maser would also be profitable with an antenna with very low side lobe levels and hence low antenna noise, such as that described by De Grasse et al . (27).

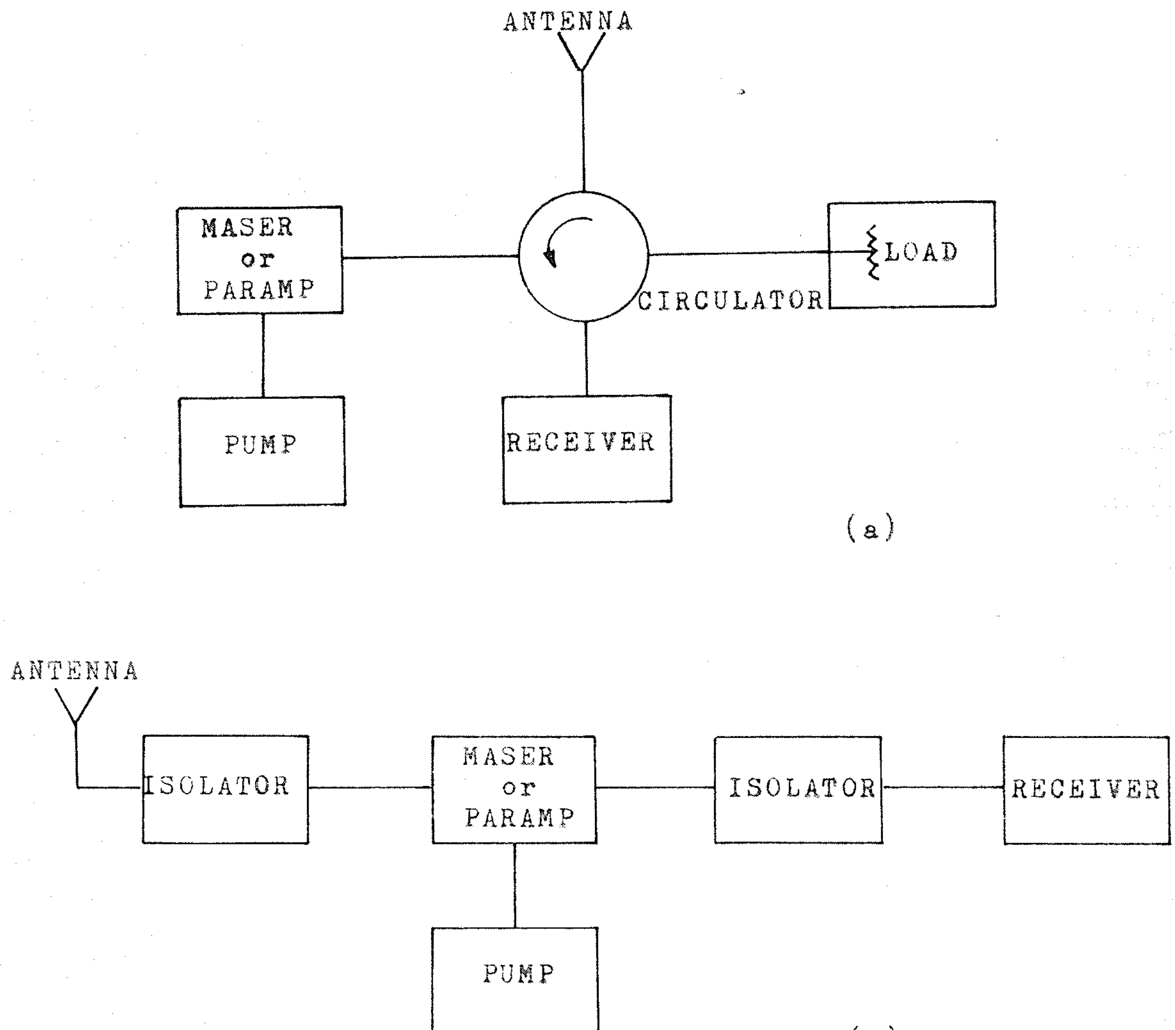
Amplifier characteristics and the amount of auxiliary equipment necessary to operate the amplifier are among the practical considerations which must be taken when making a choice of amplifier. The use of a maser generally involves cooling the apparatus with liquid helium which must be replenished frequently and which is expensive to produce. Its recovery time after saturation is long, making it undesirable for applications such as in surveillance radar systems.

Masers and some parametric amplifiers, because of their negative resistance characteristics require the use of isolators or circulators for stable operation. Configurations are shown in figure 5.10. Some form of isolation is necessary because the gains of the amplifiers are sensitive to impedance changes. The impedance presented by the antenna might change with change in position, thereby affecting amplifier gain. Isolation at the output is necessary because of the bilateral characteristic of these devices. Noise generated or reflected by the load input network would be amplified and added to the total noise output from the amplifier.

A supply of power at gigacycle frequencies (pump power) is a requirement common to both masers and parametric amplifiers. For gain stability, pump power and frequency must be stable.

In general, maser amplifiers have found their greatest use in the scientific field and parametric amplifiers are best for use in an operational system. Both are sufficiently compact that they may be mounted at the antenna feed, thereby eliminating transmission line loss. Only experimental models of travelling wave tubes have approached the noise performance of parametric amplifiers and tunnel diode amplifiers have not yet reached a suitable state of development.

Other low noise amplifiers in the research and development stage include parametric amplifiers cooled with liquid nitrogen and electron beam parametric amplifiers (31). These have exhibited effective temperatures in the neighbourhood of 30^{o} K to 50^{o} K at UHF frequencies.



DIAGRAMS OF RECEIVING SYSTEMS EMPLOYING AMPLIFIERS WITH NEGATIVE RESISTANCES

Figure 5.10

Chapter VI

Measurement of System Noise Performance

In cases where total system noise is dominated by receiver noise, measurement of receiver noise figure is generally considered an adequate indication of system noise performance. However, standards of measurement which have been adopted can be extended to include the measurement of noise performance of solid state low noise receivers as well as conventional types.

Standards on methods of measuring noise in linear twoport networks were published by the Institute of Radio Engineers in 1959 (28). Three methods are described: the CW signal generator method, the broad band noise generator method and the comparison method. These methods will be discussed briefly in the following paragraphs. Emphasis is placed on variations of these methods wherever these variations result in practical improvements in the ease or precision with which measurements can be made.

Receivers with negative resistance characteristics present special problems of measurement, but these can be circumvented by providing adequate isolation by means of circulators or isolators at the input and output of such receivers when performing measurements.

The CW Signal Generator Method

The theory of this method can be derived from the definition of noise figure first given .

$$F = \frac{\left(\frac{\text{signal}}{\text{noise}}\right)_{\text{input}}}{\left(\frac{\text{signal}}{\text{noise}}\right)_{\text{output}}}$$

The noise available at the input is the thermal noise voltage generated by the output impedance of the generator or antenna connected to the receiver, which is

$$E_n^2 = 4\, R_o kTB \tag{6.1}$$

Where R_o is the output impedance of the signal generator and k, T and B are as defined previously.

Then

$$\left(\frac{\text{signal}}{\text{noise}}\right)_{\text{input}} = \frac{E_s^2}{4\, R_o kTB} \tag{6.2}$$

where E_s is the open circuit voltage of the generator.

If a signal voltage E_o, at frequency f_o, is now injected at the input of the receiver so that receiver power output is twice that with noise output only, then the signal-to-noise ratio at the output is unity.

E_o is defined as the sensitivity of the receiver and is related to E_s by

$$E_o = E_s \left(\frac{R_i}{R_o + R_i}\right) \tag{6.3}$$

where R_i is the input impedance of the receiver.

With unity output signal-to-noise ratio the noise figure of the receiver becomes

$$F = \frac{E_s^2}{4\, R_o kTB}\ . \tag{6.4}$$

Substituting for E_s

$$F = \frac{E_o^2 \left(\dfrac{R_o + R_i}{R_i}\right)^2}{4\, R_o kTB}\ . \tag{6.5}$$

Usually $R_o = R_i$, for maximum power transfer, and

$$F = \frac{E_o^2}{R_o kTB} \, . \tag{6.6}$$

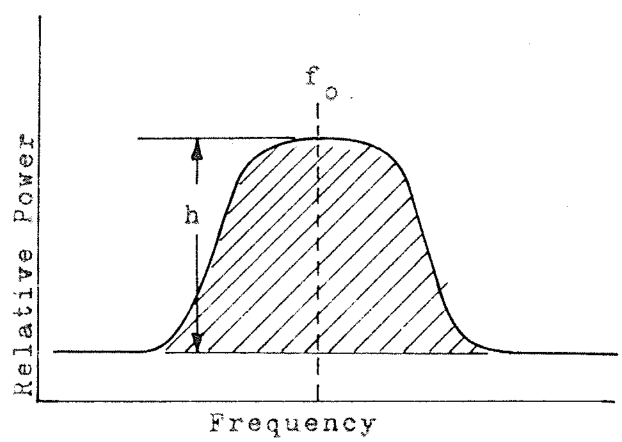
$$F = \frac{P_o}{kTB} \tag{6.7}$$

The output power, P_o, is known for any good, calibrated signal generator, T is 290°, and only B remains to be determined.

Noise bandwidth has been defined in (2.5) as

$$B = \frac{1}{G^2} \int_0^\infty G_f^2 \, df \, .$$

In the practical case it can be measured by plotting receiver power output versus frequency over the principal response of the receiver, as in figure 6.1. The area under the curve and above the general noise level outside the response of the receiver is then used to construct a rectangular response curve of the height h and same area as the actual response curve at f_o. The bandwidth of this rectangular response curve is the noise bandwidth B.

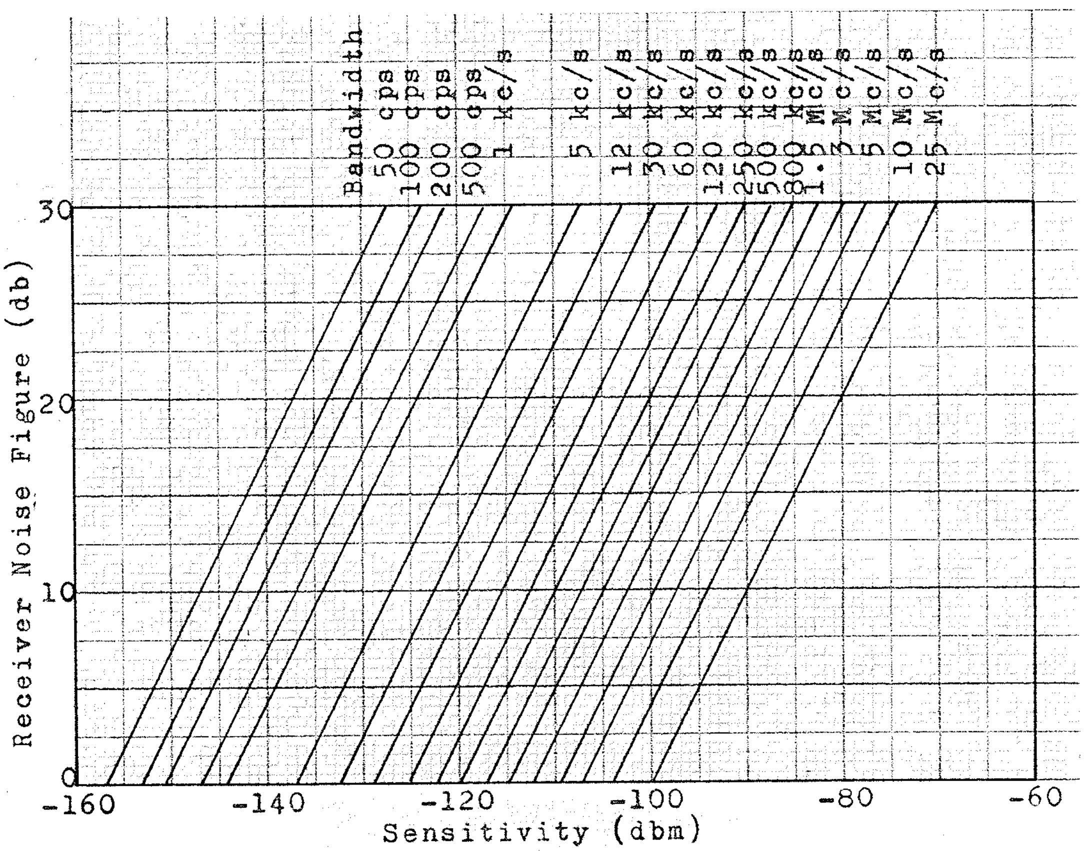


RECEIVER FREQUENCY RESPONSE
USED TO FIND NOISE BANDWIDTH

Figure 6.1

Receiver sensitivity is most conveniently obtained by measuring power output at an IF stage. An accurate power meter can be used for this purpose or a three db attenuator can be inserted between the receiver output and the indicating meter. In the latter method the output from the signal generator is increased until the meter returns to its previous reading and any non-linearity in the meter has no effect on the measurement.

Knowing receiver sensitivity and noise bandwidth, receiver noise figure can be calculated, or readily found from figure 6.2, which is reproduced from a paper by Saul and Luloff (29).



RECEIVER NOISE FIGURE vs. SENSITIVITY FOR VARIOUS RECEIVER BANDWIDTHS

Figure 6.2

Sources of error in this method include errors in the calibration of the signal generator, attenuator or power meter, and inaccuracy in determining the noise bandwidth. Signal generator inaccuracy is by far the most serious, since the signal generator output power required is directly proportional to noise figure, as seen in (6.7).

The Broadband Noise Generator Method

The greatest drawback to the signal generator method is the inconvenience of having to make a measurement of the receiver noise bandwidth. This inconvenience is avoided in the broadband noise generator method. In this method, signal-to-noise ratios are effectively changed by changing source noise level rather than signal level. This can be accomplished by changing the temperature of the noise source. In an ideal receiver a change in the noise power at the input will result in a corresponding change at the output. In a practical receiver, a constant amount of noise power proportional to the effective temperature of the receiver is added to the output, causing a deviation from a direct correspondence. This deviation allows the effective temperature of the receiver to be calculated (32).

A method of obtaining receiver effective temperature by using noise sources at two temperatures can be found from (2.21) and (2.25). Noise power at the output of a receiver when a generator at temperature T_1 is connected to the input is

$$N_1 = kT_1BG + N_e \tag{6.8}$$

where

T_1 = temperature of the noise generator

N_1 = the corresponding output noise power

and N_e = excess noise added by the receiver.

Similarly, for a generator at a temperature T_2

$$N_2 = kT_2BG + N_e \quad . \tag{6.9}$$

Subtracting ,

$$N_2 - N_1 = kBG\ (T_2 - T_1) \tag{6.10}$$

or $$kBG = \frac{N_2 - N_1}{T_2 - T_1} \quad . \tag{6.11}$$

From (2.25)

$$T_E = \frac{N_e}{kBG} \tag{6.12}$$

and

$$N_e = N_1 - kT_1BG . \tag{6.13}$$

Substituting (6.11) and (6.13) into (6.12)

$$T_E = \frac{N_1\ (T_2 - T_1) - T_1\ (N_2 - N_1)}{N_2 - N_1} \quad . \tag{6.14}$$

$$T_E = \frac{N_1\ T_2 - N_2\ T_1}{N_2 - N_1} \tag{6.15}$$

Dividing by N_1 gives T_E in terms of noise generator temperatures and output power ratio .

$$T_E = \frac{T_2 - \left(\frac{N_2}{N_1}\right)\ T_1}{\left(\frac{N_2}{N_1}\right) - 1} \tag{6.16}$$

Define $\frac{N_2}{N_1} = Y$, the so-called Y factor which is in common use. Then

$$T_E = \frac{T_2 - YT_1}{Y - 1} \quad . \tag{6.17}$$

A similar derivation may be followed to obtain F, the noise figure of the receiver in terms of Y factor. From Maxwell and Leon (30)

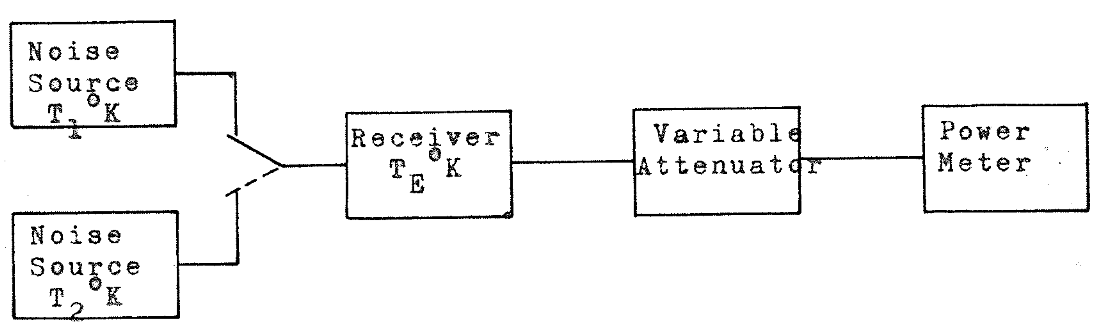
$$F = \frac{\frac{T_2}{T_o} - 1 - Y\left(\frac{T_1}{T_o} - 1\right)}{Y - 1} \tag{6.18}$$

where T_1 and T_2 are other than the standard temperature T_o.

If one of the noise sources is simply a matched load at room temperature, as is common practice, then (6.18) reduces to

$$F = \frac{\frac{T_2}{T_o} - 1}{Y - 1} \quad . \tag{6.19}$$

The accuracy of the method depends on the calibration of the noise source in use and upon the precision of measurement of Y. Accurate measurement is possible if Y is not too close to 1. Figure 6.3 shows a common arrangement for determining Y. With a matched source at the input, the receiver gain is adjusted to give a convenient indicator reading. The second matched noise source is then connected to the input and an accurately calibrated variable IF attenuator adjusted to return the indicator to its previous reading. The difference in the attenuator setting is the power ratio, or Y factor, desired.



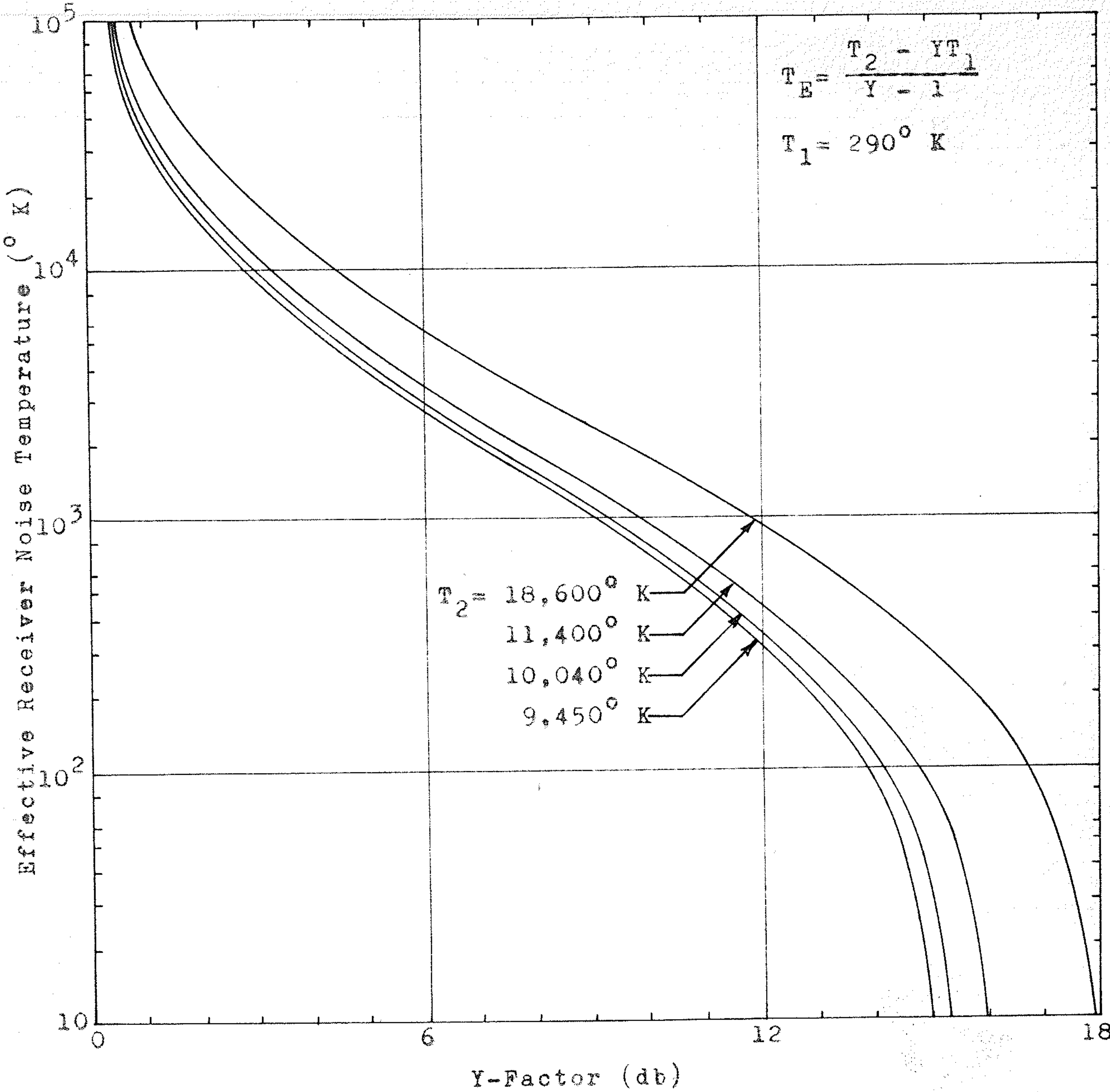
Y-FACTOR METHOD OF MEASURING EFFECTIVE NOISE TEMPERATURE

Figure 6.3

A precaution which must be taken is to ensure that only that noise which passes through the principle passband of the receiver is measured. In superheterodyne receivers image passbands may exist and contribute to the total output noise power. If the image passband is identical to the principle passband, 3 db must be added to the measured noise figure. In other cases, the most practical solution is to eliminate the problem by the use of filtering.

Noise sources of various temperatures are available or can be constructed. Low temperature sources can be made at the 4.2° K temperature of liquid helium or the 77° K temperature of liquid nitrogen. A good, easily obtained source is any matched passive load at 293° K, room temperature. Other accurate sources at 273° K and 373° K have been suggested (31). Electric furnaces have been constructed at 1000° K (30) and argon discharge tubes have an output at about $10,000^{\circ}$ K. Figure 6.4 gives curves of T_E versus Y for one generator at various temperatures and the other generator at 290° K.

If an antenna capable of celestial tracking is available and its system parameters are known, the sky can be used to provide sources at assorted temperatures, since measurements have been made both of the cold sky and of discrete hot sources at many frequencies. For discrete sources a correction must be made if the beam is not filled which may make the use of the sky for hot sources inconvenient. Large areas of the cold sky are of constant temperature, however, and the problem of the antenna beam being only partially filled does not arise, making the sky a very convenient cold source.



EFFECTIVE RECEIVER NOISE TEMPERATURE vs. Y-FACTOR
FOR NOISE GENERATORS AT VARIOUS TEMPERATURES

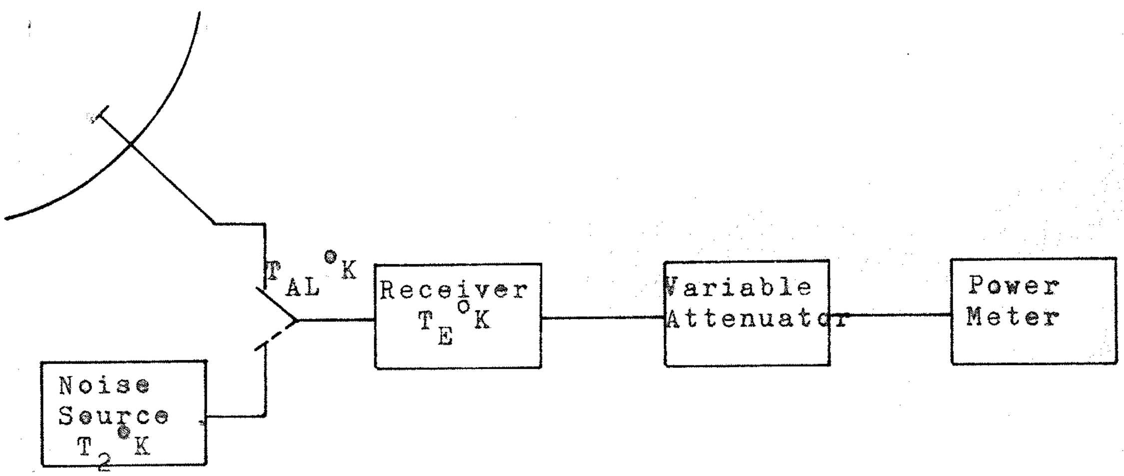
Figure 6.4

The Comparison Method

The comparison method is most useful for production testing, where approximate noise figure determination is adequate, and will not be discussed in detail. This method consists of comparing the receiver with a standard receiver of known effective noise temperature. It requires that the characteristics of the receiver under test and the associated test equipment duplicate to close limits the standard receiver and the equipment used with it.

Measurement of Noise Contribution by the Antenna

The Y factor method can be used to measure the noise temperature contributed by the antenna if the antenna is used as one of the noise sources in (6.17). Figure 6.5 gives a test arrangement.



MEASURING NOISE CONTRIBUTED BY THE ANTENNA

Figure 6.5

Define T_{AL}, the noise contributed by the antenna and the transmission line.

$$T_{AL} = \frac{T_A}{L_1} + \frac{T_o\ (L_1 - 1)}{L_1} \qquad (6.20)$$

where

T_A = total noise received by the antenna feed.

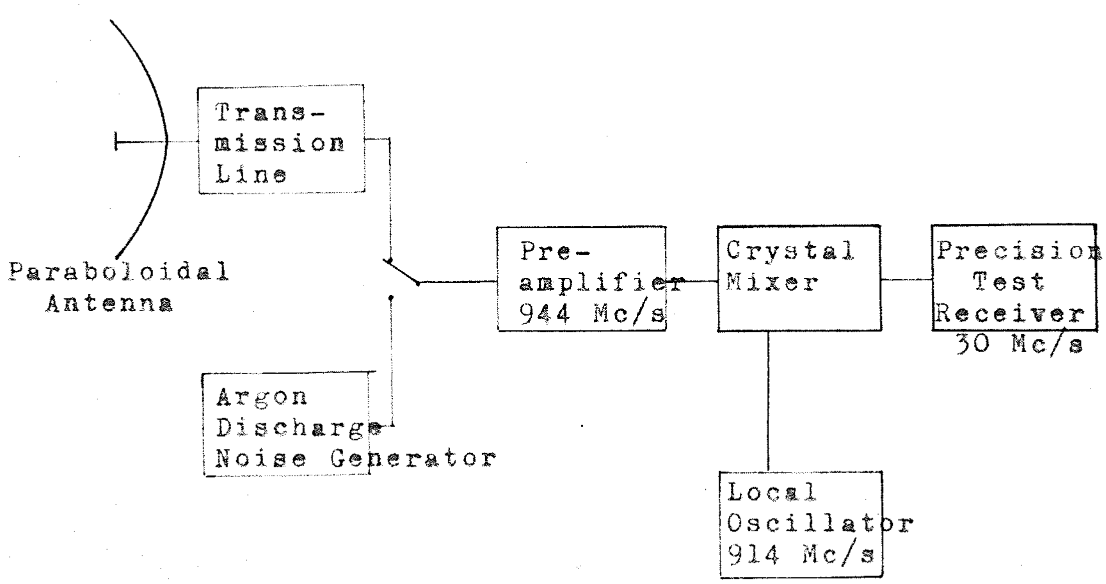
L_1 = transmission line loss.

With T_E and L_1 measured or known, T_{AL} can be measured and T_A found. With a knowledge of power distribution in the antenna pattern, it is possible to separate the noise contributions from the antenna main beam and side lobes.

Chapter VII

Measurements of System Noise Temperature

Measurements of system noise temperature have been carried out on a receiving system at 944 Mc/s. A block diagram of the system and measuring apparatus is given in figure 7.1. Referring to the figure, the receiver consists of a vacuum tube preamplifier connected to a paraboloidal antenna through a transmission line. A crystal mixer which converts the signal to 30 Mc/s follows the preamplifier. The 30 Mc/s signal is then fed to a test receiver where it is further amplified and then detected. The test receiver has a precision IF attenuator incorporated in it. An argon discharge noise generator which could be connected directly to the preamplifier is used as a noise source. All system parameters are listed in table 7.1.



A RECEIVING SYSTEM AT 944 MC/S

Figure 7.1

Table 7.1

Receiving System Parameters

1. Antenna - paraboloidal reflector

   Diameter 60 feet
   Gain 43 db over isotropic radiator (estimated)
   Beamwidth (half power) 1.2°
   Power distribution (estimated)
      Main beam 70%
      Side lobes 29%
      Ohmic losses 1% (0.05 db)
   Feed 944 Mc/s dipole, polarization vertical

2. Transmission Line

   190 feet of 3 1/8" coaxial line, type 462
   6 feet of .405" coaxial line, type RG-8/U
   2 rotary joints
   Total measured loss 1.25 db

3. Receiver

   Preamplifier using 2 GL6299 coplaner triodes
      Gain 26 db
      Effective noise temperature 1546° K (measured)
   Crystal mixer using 1N21F diode
      Conversion loss 6 db
      Noise temperature 870° K
      Overall noise temperature (mixer and IF amplifier) 1495° K (measured)
   IF amplifier
      30 Mc/s precision test receiver with built in attenuator
      Noise temperature 120° K

4. Noise Generator

   Coaxial argon discharge noise generator
      ON condition temperature $10{,}060^{\circ}$ K
      OFF condition temperature 293° K

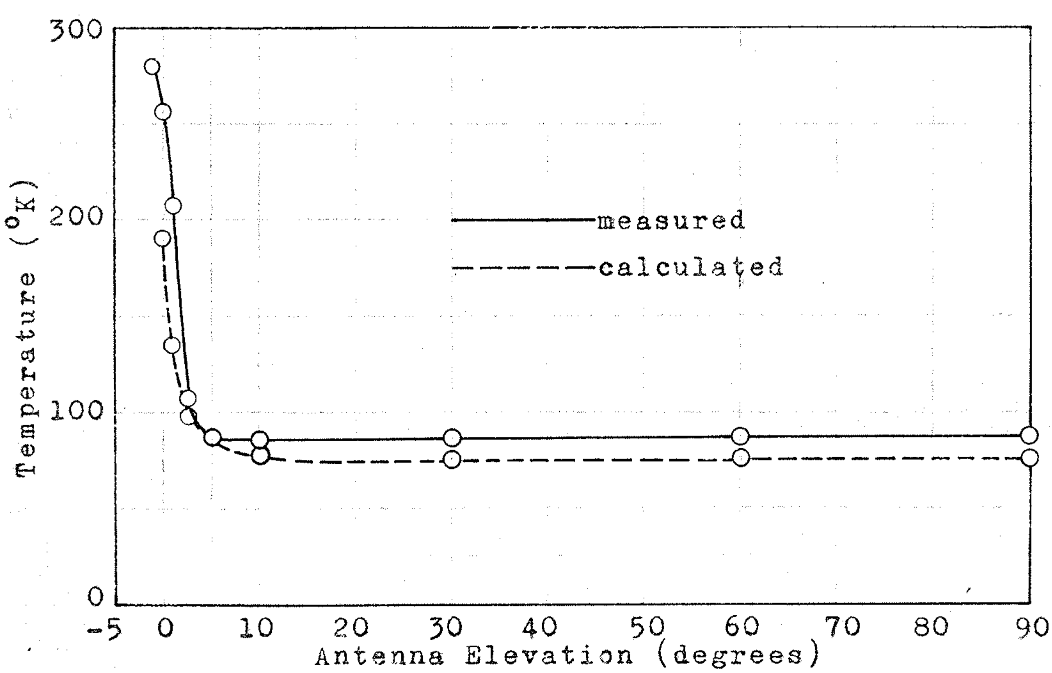
Noise temperatures were found by the noise generator method outlined in the preceding chapter. The temperature of the argon noise source was $10{,}060^{\circ}$ K $\pm$ 40° K in the ON condition and 293° K $\pm$ 2° K in the OFF state. These temperatures were used as T_2 and T_1, respectively, in equation 6.17, in the calculation of receiver noise temperature. The precision test receiver enabled the Y factor to be measured to an accuracy of $\frac{1}{2}$%.

Overall noise temperature of the receiver was found to be 1550° K ± 1.2%. Measured noise temperature of the mixer and IF amplifier was 1495° K. It was calculated that the high gain of the amplifier, however, reduced the contribution of the rest of the receiver to the overall receiver noise temperature to 4° K.

The effective temperature of the noise contributed by the antenna and transmission line can be found if it is substituted for T_1 in equation (6.17), which can be rearranged to give

$$T_1 = \frac{T_2 - T_E (Y - 1)}{Y} . \qquad (7.1)$$

Such measurements were made at various elevation angles. Noise contributed by the antenna alone was then found by equation (6.20) and is shown in figure 7.2.



EFFECTIVE NOISE TEMPERATURE AT ANTENNA OUTPUT TERMINALS

Figure 7.2

Antenna noise temperature at 944 Mc/s was also computed from the antenna parameters and figures 5.3 and 5.4. This computed antenna noise is also plotted in figure 7.2. Reasonable agreement with the antenna noise found from measurement is evident. The possible error in the measured antenna noise is high, however, ($\pm$ 25%) because of the use of a receiver with a high effective noise temperature. If an amplifier with an effective noise temperature of 100° K were located at the feed point of the antenna and the loss in the transmission line components associated with it were 0.5 db or less, then the possible error would be reduced to $\pm$ 6%. A low noise receiver, therefore, is essential for accurate measurements of noise received by the antenna by this method at frequencies where this noise is low. If greater accuracy is desired, radiometric techniques must be used.

The sum of antenna noise, transmission line noise and receiver noise referred to the transmission line input is the effective noise temperature of the system. This is plotted in figure 7.3. Also shown in the figure is the system noise temperature that would result if a parametric amplifier with an effective noise temperature of 100° K were connected to the system through a circulator with a loss of 0.5 db. Two cases are shown. The first is the case where the parametric amplifier is inserted into the system between the transmission line and the vacuum tube preamplifier and the second is where the amplifier is located at the feed point of the antenna and there is a negligible amount of transmission line loss.

Figure 7.3 shows clearly that the increase in system noise temperatures at low antenna elevation angles becomes less significant when the noise temperature of the receiver is several times greater than the noise at the antenna output terminals. For either of the two cases involving the use of parametric amplifiers, however, the minimum detectable signal is deteriorated by several db at low elevation angles. This deterioration would be even greater at higher frequencies.

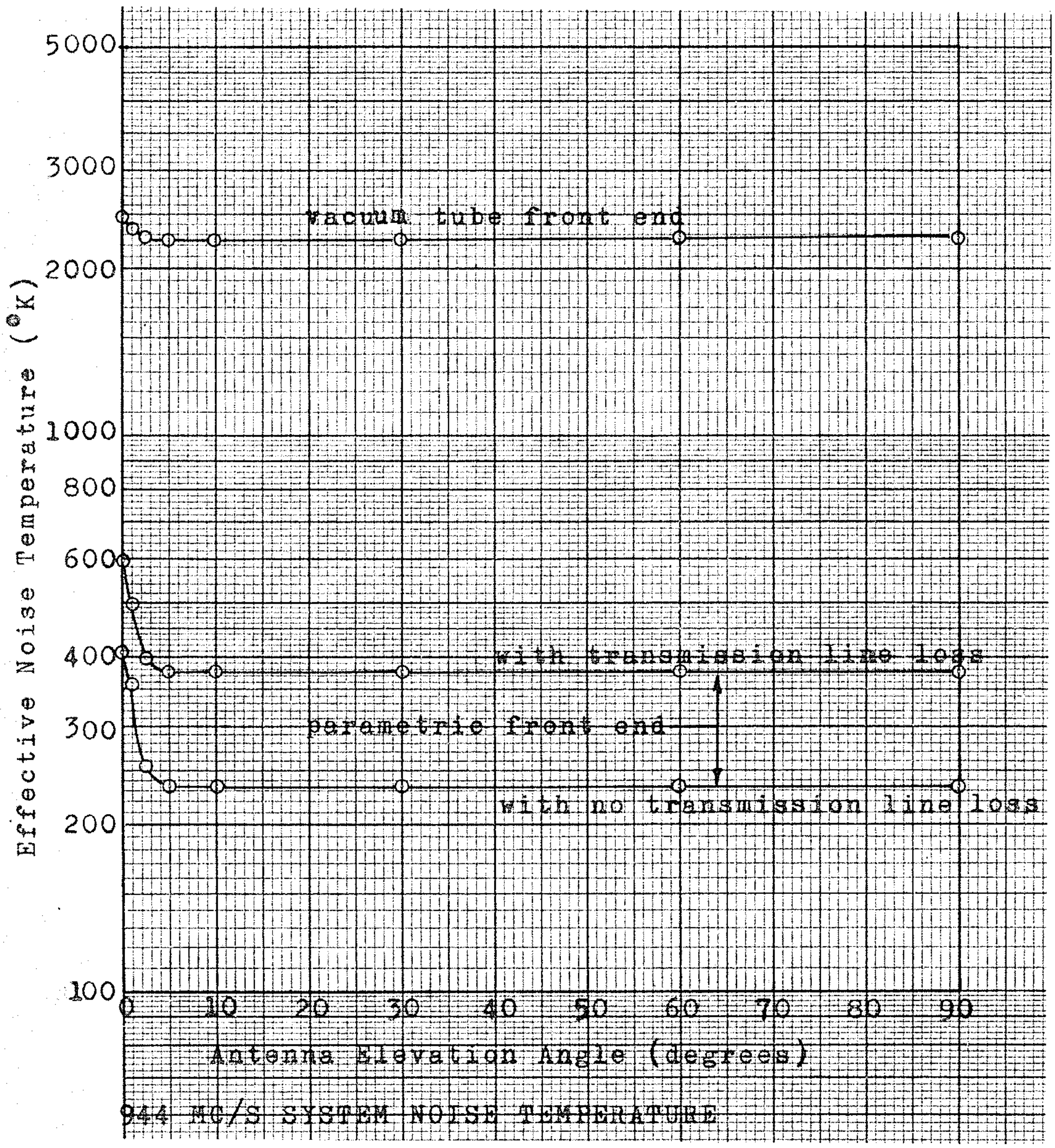


Figure 7.3

Chapter VIII

Summary

Receiver design is now advanced to a state where the antenna, the transmission medium, and the background upon which the signal is superimposed must be included as part of the receiving system in considerations of system sensitivity. For this reason a model of a receiving system has been proposed which includes all sources of system noise and allows analysis of these sources to show where improvement of the system is possible.

Background noise appears to be the ultimate limitation on system sensitivity. A minimum in this noise appears between 1 Gc/s and 15 Gc/s and it is in this frequency range that the capabilities of low noise receivers may be realized. Up to a frequency of about 600 Mc/s, galactic noise imposes a lower limit on sensitivity. At higher frequencies, atmospheric absorption begins to have increasing effect. The effect of ionospheric absorption is negligible at UHF and higher frequencies.

In certain parts of the sky background noise may be increased because of discrete sources such as the radio stars and the sun. Radio star positions are well known, however, and their effect can be taken into account if this is found necessary. Solar noise can impose a severe limitation on receiver performance, but again it can be taken into account, or avoided in some circumstances.

The effect of earth and sky noise picked up by subsidiary lobes in the antenna pattern can be reduced by improving the pattern of the antenna. Transmission line noise is a source that can be virtually eliminated if necessary. Noise resulting from the active components of the receiver can also be reduced by employing various techniques for this purpose as well as by taking full advantage of a low-noise high-gain receiver front end.

In systems which have good noise performance, the use of effective noise temperature as a measure of performance is more meaningful than the use of noise figure because the former is directly proportional to system sensitivity.

The choice of reference point used in the determination of system noise temperature is an important consideration. This reference point must precede any dissipative networks in the signal path, such as transmission lines or transmission line components to take into account signal deterioration due to losses, as well as noise added by these networks. Losses due to such networks must be minimized particularly in low noise systems where the effect of losses on system noise temperature becomes more pronounced.

The decision to include a particular low noise amplifier in a receiving system must be based on two considerations. One of these is the practical problem of operating such an amplifier. The other is the expected improvement in system sensitivity. To determine the improvement, the noise contributed to the system by the antenna can be predicted with a knowledge of the antenna radiation pattern.

The measurement of receiver noise temperature is most convenient by the Y-factor method. This method can be extended to measure the noise temperature available at the terminals of an antenna. For frequencies where this noise is low, however, suitable accuracy by this method can only be obtained if the receiver also has a low effective noise temperature.

Measurements of the effective noise temperature of a system at 944 Mc/s have been described. The effect of earth radiation into the antenna main beam is demonstrated and two receivers are compared to show the effect of high and low noise front ends on system sensitivity.

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