It can be seen that as d tends to zero or a tends to infinity, the value of U approaches unity corresponding to the dipole on a flat conducting surface.[5]

The series, which can be called the 3rd order curvature corrected series, converges adequately for x less than about 1.5. Writing

$$U = |U| e^{-i\Phi}$$

then $|U|$ and Φ are the amplitude and phase lag, respectively, of the correction factor U. Numerical values are computed from (15) and shown plotted in Fig. 1 for x ranging from 0.1 to 3. Values of $|U|$ and Φ obtained from the residue series formula in (3) are also shown on Fig. 1. The agreement between the two sets of curves is excellent unless x exceeds about 2.0. When x is of the order of 0.1 or less, greater than 100 terms in the residue series are required to obtain three figure accuracy, whereas only the term in x need be retained in the curvature corrected series for U. At larger values of x, say greater than 2 or 3, only several terms in the residue series are required, whereas the curvature corrected series would be very poorly convergent.

Although the preceding theory was developed explicitly for a radial electric dipole source, the results are directly applicable to the current excited on a spherical surface by a narrow slot or its equivalent magnetic dipole. Eq. (2) relating the current I on the curved surface to the current I_0 on a flat surface is only strictly valid in the broadside direction from the narrow slot as

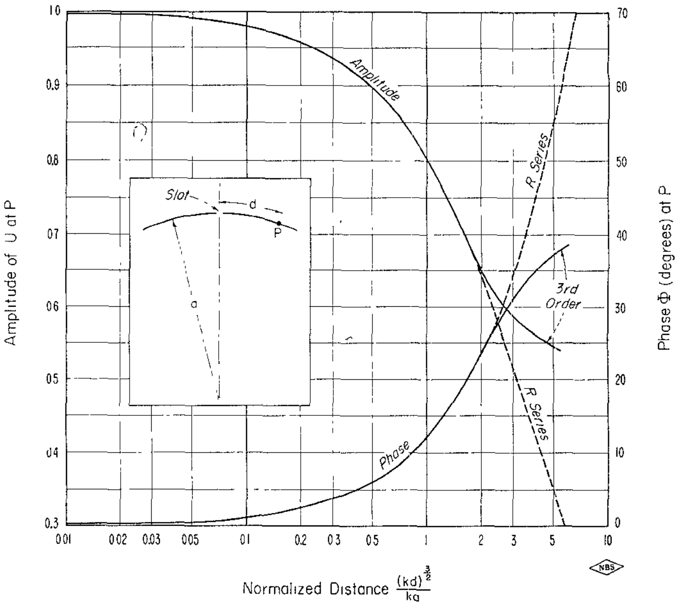

Fig. 1—The ratio of the current induced by a slot on a curved surface to that on a flat surface.

indicated in the inset in Fig. 1. If kd is much greater than unity, however, the equation is also valid in other directions from the slot. It can now be expected that the mutual impedance Z_m between any two slots oriented for other than minimum coupling on a spherical surface of large radius of curvature a is related to the mutual impedance Z_{0m} for the same slots on a flat surface by the formula

$$Z_m \cong UZ_{0m}.$$

In this case, d is taken as the distance between the centers of the slots.

[5] Bremmer, *loc. cit.*, has developed expansion formulas, similar to (15), which are expressed in powers of a factor δ which is approximately proportional to the complex refractive index of the sphere, which in the present analysis is effectively infinite.

A Note on Noise Temperature

PETER D. STRUM†

Summary—**The effective noise temperature of the output impedance of a lossy passive network at an arbitrary noise temperature connected to one or more resistive loads at arbitrary noise temperature lies between the highest and the lowest of these noise temperatures, as determined by the losses between the output terminals and the loads. The determination of the effective noise temperature of a gas-discharge noise generator over a wide frequency range is simplified by the substitution of a loss measurement for the more difficult noise temperature measurement. For minimum-noise radar applications care must be used in considering the excess noise of crystal mixers and gas-discharge duplexers. The influence of galactic radiation on a receiving system is such that there is an optimum frequency in the region of 200 to 600 mc for minimum "operating noise figure." Typical examples of radio-astronomy measurements are amenable to analysis of the type given. Finally, several corrections to measured noise figure are analyzed.**

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Introduction

THE OUTPUT noise power of many widely used devices is conveniently expressed in terms of an equivalent noise temperature—that is, the temperature of a passive resistor that would generate an equivalent available noise power. In the case of directional antennas and gas-discharge noise generators, the term noise temperature is accurately applied because, in one case, the antenna is directed into space, which may have wide temperature variations, and in the other case, the magnitude of the noise output is proportional to the electron temperature of the gaseous discharge. In the case of a crystal mixer, the term noise temperature is often used for describing the output noise ratio as a fictitious normalized temperature.

This paper will deal with the effective noise temperature of a lossy passive network that has internal noise sources and is connected to loads at arbitrary temperature. Noise generators, crystal mixers, and receiving systems are typical of such networks. The application of the analysis to the computation and measurement of noise figure will also be given.

Noise Temperature

The term noise temperature, when used in the dimensionless or normalized sense, is defined as the ratio of the available noise power at the output of a device to the available thermal noise power that the device would yield if its output impedance were at standard room temperature, 290° Kelvin. This normalized noise temperature is sometimes called noise-temperature ratio or output noise ratio. In other circumstances noise temperature is assigned a value in the Kelvin temperature scale.[1] To distinguish between these two applications of the term noise temperature, the following expression is used:

$$t = \frac{T}{290} \tag{1}$$

where t is the normalized noise temperature, T is noise temperature in the Kelvin scale, and 290° Kelvin is the reference temperature that has been standardized for noise-figure considerations.

In cases where normalized noise temperature is different from unity, it is convenient to deal with excess noise, $t-1$. It should be noted that the excess noise may be greater or less than zero; however, because it is usually considered to be greater than zero, the term excess noise is used.

Transmission Line Analog

The noise temperature of the output resistance of a resistive pad connected at its input to a resistive generator, either of which may be at an arbitrary noise temperature, can be computed with the aid of a transmission line analog. Consider the pad to be a uniform transmission line having losses equally divided between series resistance and shunt conductance, thus having a resistive characteristic impedance. Such a transmission line fed by a resistive generator is shown in Fig. 1. The generator is at normalized noise temperature t_g, and the transmission line (or pad) is at normalized noise temperature t_p and has an attenuation constant α. The effective excess noise "seen" when looking to the left at

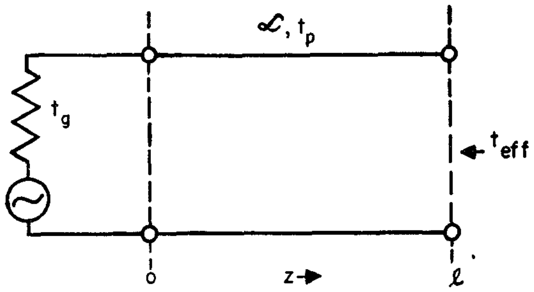

Fig. 1—Transmission-line analog of noisy, or "hot," pad.

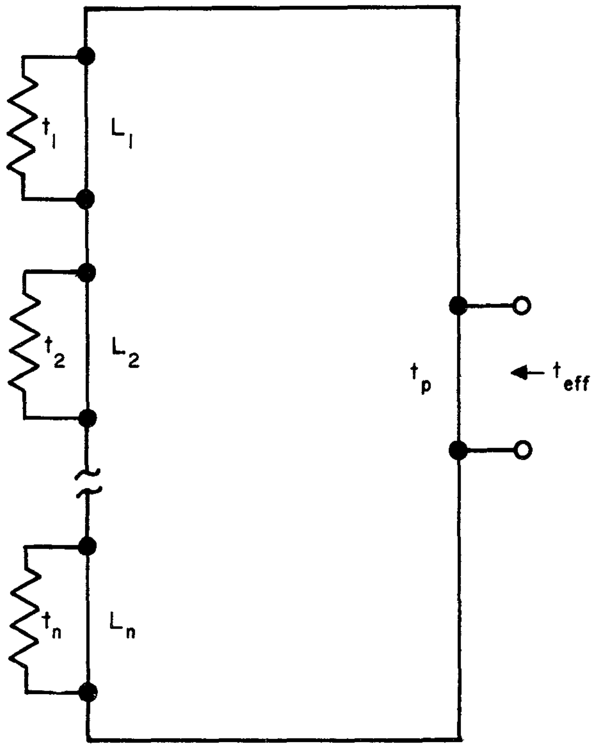

Fig. 2—Noisy pad matched to an arbitrary number of noisy terminations.

any point z in Fig. 1 can be determined on the basis of transmission-line theory, if one bears in mind that noise powers add linearly [hence the factor 2 in the exponentials of (2)] and that excess noise can be otherwise treated like a signal. Therefore,

$$(t_{eff} - 1)_z = (t_g - 1)e^{-2\alpha z} + (t_p - 1)(1 - e^{-2\alpha z}). \tag{2}$$

If one then traverses all z from 0 to 1, one "sees" the excess noise of the generator gradually modified by the loss and excess noise of the transmission line until at $z=1$ the excess noise is that of the generator attenuated by the total loss plus that of the line reduced by that fraction lost into the generator. Thus at $z=1$

$$t_{eff} - 1 = (t_g - 1)/L + (t_p - 1)(1 - 1/L) \tag{3}$$

where L is the total loss in power ratio.

Fig. 2 shows a lossy network to which an arbitrary number of resistive loads is connected. In the network of Fig. 2, t_n is the normalized noise temperature of the nth load resistance, t_p is the normalized noise temperature

[1] See "Standards on electron devices: methods of measuring noise," Proc. IRE, vol. 41, pp. 890–896; July, 1953.

of the resistive components of the pad, and L_n is the loss from the output terminals to the nth load resistor when the output terminals are fed by a generator of resistance equal to the image impedance of the pad at the output terminals. The result given in (3) can be expanded to apply to the multiterminal network of Fig. 2. The expression then becomes[2]

$$t_{eff} - 1 = (t_1 - 1)/L_1 + (t_2 - 1)/L_2 + \cdots (t_n - 1)/L_n$$

If $t_1 = t_2 = \cdots t_n + (1 - L_1^{-1} - L_2^{-1} - \cdots L_n^{-1})(t_p - 1)$. (4)

$$t_{eff} - 1 = [(t_1 - 1)/L_1](1 + L_1/L_2 + \cdots L_1/L_n) + (1 - L_1^{-1} - L_2^{-1} - \cdots L_n^{-1})(t_p - 1). \quad (5)$$

It should be noted that in (4) and (5) it may seem possible for the factor containing $(1 - L_n^{-1})$ to become negative. This eventuality is impossible in a passive network, however, because the total gain cannot exceed unity.

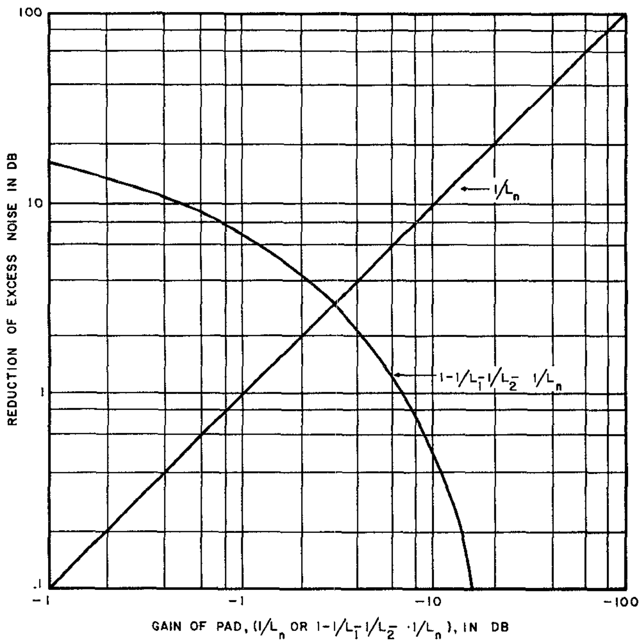

Fig. 3—Reduction of excess noise as a function of loss of pad.

Fig. 3 shows the reduction in excess noise as a function of the losses of the pad in db. In the case of the function $(1 - L_1^{-1} - L_2^{-1} - \cdots L_n^{-1})$ where two or more losses are to be considered, the gains $(1/L_n)$ should be summed. If this summed gain is then converted to decibels, it can be used to enter the abscissa of Fig. 3.

Applications of Analysis

Noise Generators

There are two types of standard noise generators in widespread use at the present time: gas-discharge noise generators and temperature-limited diode noise generators.

[2] This general result agrees with the two particular cases given by W. L. Pritchard, "Notes on a crystal mixer performance," Trans. IRE, vol. MTT-3, pp. 37–39; January, 1955.

In the usual gas-discharge noise generator, t_n is near unity, t_p is large (normalized electron temperature of discharge), and the loss to be considered is the loss induced by the ionized gas. Such a noise generator usually has a matched termination on one end. From (3) it is seen that nearly the entire excess noise will be available at the output provided the induced loss is sufficiently great. In fact, the effective excess noise may seem to be several times larger than the excess noise of the discharge if the receiver under test has appreciable response at more than one channel. In the general case involving responses at several sidebands, the relationship is

$$t_{eff} - 1 = (1 - L_1^{-1})(t_p - 1) + (1 - L_2^{-1})(t_p - 1)r_2 + \cdots (1 - L_n^{-1})(t_p - 1)r_n \quad (6)$$

where L_n is the loss through the discharge at the frequency of the nth response of the receiver and r_n is the relative power response of the receiver at the nth response. If the loss through the discharge is uniform at all response bands, (6) will reduce to

$$\begin{aligned} t_{eff} - 1 &\cong (1 - L^{-1})(t_p - 1)B_0/B_u \\ &\cong (t_p - 1)B_0/B_u, \qquad L \gg 1 \end{aligned} \quad (7)$$

where B_0 is the total bandwidth of the receiver including all sidebands and B_u is the bandwidth of the useful channel.

Temperature-limited diode noise generators are well known to have an excess noise of $20IR$, where I is the temperature-limited diode current and R is the resistive component of impedance. For superheterodyne measurements, again, multiple responses should be considered, in which case

$$t_{eff} - 1 = 20I(\tau_1 R_1 + \tau_2 R_2 r_2 + \cdots \tau_n R_n r_n) \quad (8)$$

where τ_n is a transit-time reduction factor and R_n is the effective resistive component of impedance at the plane of the diode current. At low frequencies all R_n may be equal, but at uhf where there may be a significant distance between the diode and its termination, R_n may be quite variable.

The effect of imperfect (nonunity) swr is usually insignificant in the gas-discharge noise generator because the dissipative match is provided by the "hot" gas column. In the diode noise generator nonunity swr has a first-order effect on accuracy inasmuch as the resistive component of impedance at the plane of the diode current determines the excess noise directly.

Crystal Mixer

Eq. (4) can be applied to a crystal mixer. In this case L_n is the loss from the IF terminals to the nth pair of rf terminals. For ordinary noise-figure considerations, t_n is unity and t_p is the crystal noise temperature. For a high-Q mixer, L_1 is the loss to the signal terminals, and $L_2, L_3, \cdots, L_n$ are sufficiently great that they can be considered to be infinite. In a broad-band mixer, the losses to the signal and the image terminals are equal; therefore, L_1 and L_2 are equal to the fundamental conversion loss. In certain broad-band mixers, the higher-order sidebands are reasonably well matched; therefore, L_3 and L_4 are the losses to the lower and upper sidebands of the second harmonic of the local-oscillator frequency, and so forth. Usually conversion loss for the second harmonic is greater than that for the fundamental by about 4 to 6 db, and conversion loss for the third harmonic is higher than that for the second by about 6 to 8 db, and so forth. If reasonably good matches are achieved at these high-order sidebands, a significant reduction in noise temperature can occur. However, since the fundamental conversion loss is also dependent on these terminations, receiver noise figure may either rise or fall as a function of the terminations.[3,4]

TR Switch

The duplexer in a microwave receiver usually incorporates a tr switch in which a keep-alive current is maintained. Since the keep-alive discharge is similar to that utilized in gas-discharge noise generators, it is apparent that excess noise may be introduced from this source if there is coupling to the rf circuit. Coupling between the keep-alive discharge and the rf circuit is usually specified in terms of interaction loss, which is the loss introduced into the signal path by the discharge.

Noise figure with keep-alive current will be

$$F_{ka} = L_i F + L_{rk}(1 - L_i^{-1})(t_D - 1)(B_0/B_u) \qquad (9)$$

where F_{ka} is noise figure with keep-alive current, L_i is interaction loss, L_{rk} is the loss from the rf input terminals to the plane of the keep-alive interaction, F is noise figure without keep-alive current, t_D is the noise temperature of the discharge, B_0 is the total bandwidth including all sidebands that are matched to the antenna, and B_u is the useful bandwidth.

To estimate the magnitude of the increase in noise figure that may occur, typical values can be assumed for the excess noise of the discharge and the interaction loss, 16 db above thermal noise and 0.1 db, respectively. On the basis of the assumed values, the excess noise from the discharge is 0.9 or 1.8, depending on whether B_0/B_u is 1 for a high-Q tr switch or 2 for a broadband tr switch. If the assumed values of excess noise and interaction loss occur in actual receivers, a significant increase in noise figure may be experienced.

In certain receiver installations, it may be desirable to incorporate a simple means for checking noise figure. For such an application, it may be possible to use the keep-alive discharge or a discharge directly across the rf gap as a standard source of noise.

Receiving System

The foregoing concepts can be applied to noise figure of a receiving system. In particular, these concepts are applicable to a receiver whose antenna is effectively at a temperature other than room temperature. Typical examples of such receivers are radar and radio-astronomy receivers. It has been well established that the apparent temperature of the sky varies widely, whereas the earth and black-body radiators on the earth exhibit a temperature near 290° Kelvin.[5] Since the term noise figure is standardized in such a way that the excess noise of a receiver is referred to the available noise from a resistor at room temperature (290° Kelvin), it is desirable to use the term "operating noise figure" to define the sensitivity of a receiver in its normal operating environment.[6] For a single-band receiver, operating noise figure can be defined as

$$F_{op} = S_i N_{290}^{-1} S_0^{-1}[(F - 1)N_{290} + N_a] \qquad (10)$$
$$= F + t_a - 1$$

where S_i is the available input signal power, N_{290} is the available noise power from a resistor at 290° Kelvin, S_0 is the available output signal power referred to the input, and N_a is the available noise power from a resistor at the effective antenna temperature. If a broad-band mixer is matched to the antenna at sidebands other than the desired signal frequency, this relation will be altered as follows:

$$F_{op} = F + (t_a - 1)(1 + L_1L_2^{-1} + L_1L_3^{-1} + \cdots L_1L_n^{-1}) \qquad (11)$$
$$= F + (t_a - 1)B_0/B_u$$

where L_n has the same definition as applied to the crystal mixer above, and F is the noise figure of the receiver and includes all effects that result from $B_0/B_u > 1$

[3] P. D. Strum, "Some aspects of mixer crystal performance," Proc. IRE, vol. 41, pp. 875–889; July, 1953.

[4] In passing, it should be noted that care should be exercised in using quoted specifications on noise temperature for crystal mixers. Standard noise-temperature test sets, for example, measure S-band crystal noise temperature at a power level of 0.5 mw and most other crystals at a power level of 1 mw. Most microwave receivers use a local-oscillator power of about 0.3 milliwatt. The noise temperature of a mixer crystal may, therefore, be less than that quoted by the manufacturer in many cases. A functional relationship between excess crystal noise and local-oscillator power has been found experimentally to be

$$t_{x'} - 1 \cong KP^n,$$

where P is the absorbed local-oscillator power, K is an arbitrary constant, and n lies between 1 and 2, 1.3 being a typical value. Other factors that must be considered when determining mixer noise temperature are excess local-oscillator noise and the variation of crystal noise with frequency. See Strum, *op. cit.*, Fig. 9.

[5] J. L. Lawson and G. E. Uhlenbeck, "Threshold Signals," vol. 24, Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N.Y.; pp. 103–108; 1950.

H. V. Cottony and J. R. Johler, "Cosmic radio noise intensities in the vhf band," Proc. IRE, vol. 40, pp. 1053–1060; September, 1952.

J. D. Kraus and E. Ksiazek, "New Techniques in radio astronomy," *Electronics*, vol. 26, pp. 148–152; September, 1953.

H. I. Ewen, "Radio waves from interstellar hydrogen," *Scientific Amer.*, vol. 189, pp. 42–56; December, 1953.

J. L. Pawsey and R. N. Bracewell, "Radio Astronomy," Oxford Univ. Press, New York, N.Y.; 1955.

[6] The concept of "operating noise figure" was introduced by North.

D. O. North, "The absolute sensitivity of radio receivers," *RCA Rev.*, vol. VI, pp. 332–343; January, 1942.

D. O. North and H. T. Friis, "Discussion on 'noise figures of radio receivers'," Proc. IRE, vol. 33, pp. 125–127; February, 1945.

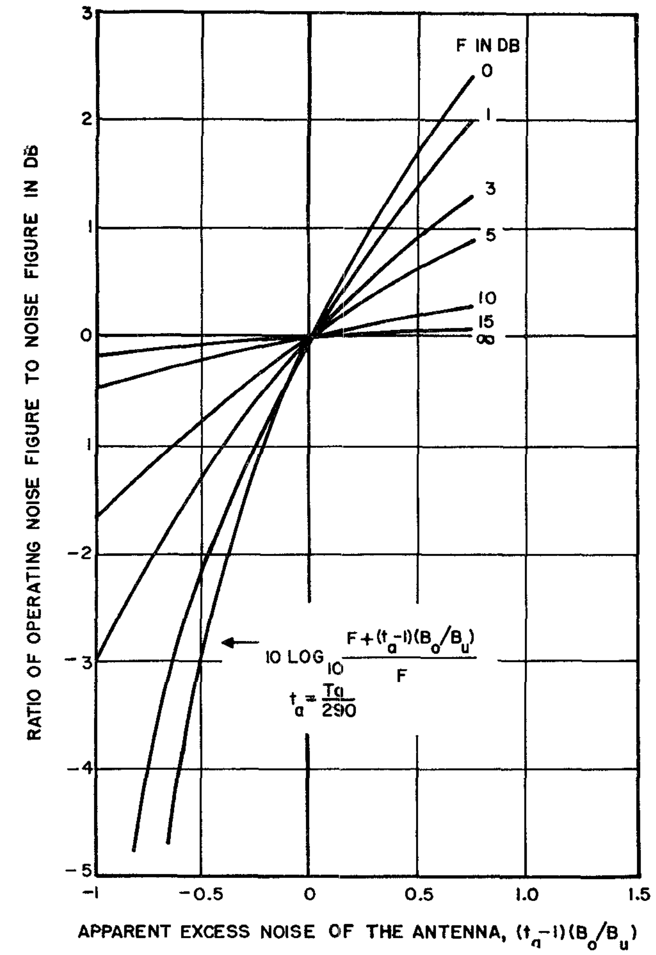

Fig. 4—Ratio of operating noise figure to noise figure.

except for the effect of antenna temperature. Fig. 4 shows the relation of (11).

It should be noted that the operating noise figure as defined in (10) and (11) gives directly a basis for comparison of the abilities of receivers to detect a fixed magnitude of signal power available from the antenna. This case is analogous to the radar case in which a fixed magnitude of echo power is available at the antenna terminals and to the radio-astronomy case in which a fixed magnitude of celestial noise power is available at the antenna.

It should be noted that this result is considerably different from that obtained by using "effective noise figure," as defined by Goldberg.[7,8] Effective noise figure, according to Goldberg's definition, compares the excess noise of the receiver with the noise of a resistor at the temperature of the antenna as follows:

$$F_{eff} = 1 + (F - 1)/t_a. \qquad (12)$$

It should be noted that this relation does not give a direct measurement of the ability of a receiver to detect a signal power of fixed magnitude. As an example of the confusion that may occur, consider a receiver having a 10 db noise figure and an antenna oriented in such a way that t_a equals 0.33. The operating noise figure of such a receiving system will be 9.7 db, the 0.3 db improvement resulting from the fact that less over-all system noise is available in this case in comparison with the room-temperature case. A fixed magnitude of signal power will be slightly more easily discerned in this receiving system than would be the case if the antenna were at room temperature. If, however, one computes effective noise figure, the result will be 14.5 db. Such a result might imply that a particular signal will be less easily discerned. In this case, it is necessary to remember that, for a fixed signal power, the input signal-to-noise ratio is larger by a factor t_a^{-1} than in the room-temperature case.

The concept of operating noise figure gives a basis for including the effects of galactic noise on the receiving system.[5] Galactic noise is usually specified in terms of an apparent temperature, which is applied to the background radiation received from outer space. This background noise has a smooth spectrum, which varies at a rate somewhat greater than with the inverse square of frequency (about $f^{-2.5}$). Discrete noise sources may have much higher noise temperatures than the background, but they are confined in angle of arrival, and may usually be disregarded as sources of interference.

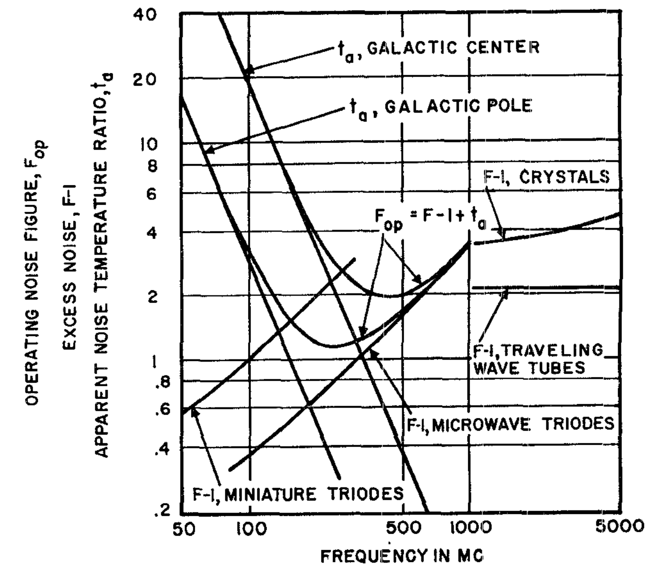

Fig. 5—Influence of galactic noise on operating noise figure.

Fig. 5 shows normalized galactic noise temperature as given by Ewen[5] plotted together with the excess noise of some typical receivers (as specified by their first-stage active circuit elements). It is seen that good microwave triodes provide the best obtainable noise figures at frequencies less than about 1,000 mc. At these frequencies, however, the galactic noise has a pronounced effect on operating noise figure. For these particular receiver types an optimum frequency for mini-

[7] H. Goldberg, "Some notes on noise figures," Proc. IRE, vol. 36, pp. 1205–1214; October, 1948.

[8] Lawson and Uhlenbeck, *loc. cit.*, applied the term "effective noise figure" to the "operating noise figure."

mum operating noise figure is seen to be in the region of 200 to 600 mc. For Fig. 5, it is assumed that the antenna beam is highly directional. If an appreciable portion of the beam intercepts earthbound black-body radiators at about 290° Kelvin, the effective antenna temperature will lie between the galactic noise curve and the horizontal line at unity; and the optimum frequency will be lower. In Fig. 5, man-made interference and atmospherics are not considered, though they are frequently important at frequencies below the ultra-high frequencies.

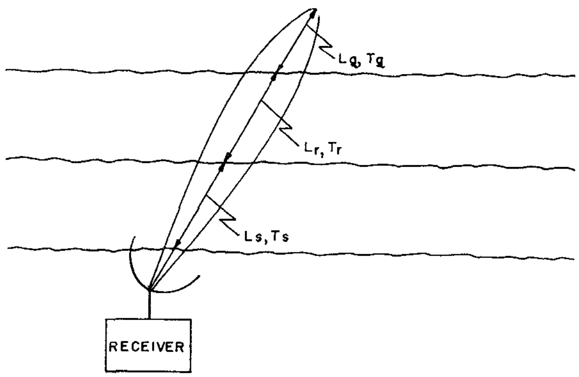

Fig. 6—The radio-astronomy situation.

Radio Astronomy

Galactic and other extraterrestrial noise, besides being forms of interference in certain receiving systems, are subjects of study for radio astronomers. Fig. 6 shows the radio-astronomy situation. The antenna beam intercepts one or more regions that have different values of loss and noise temperature. By solving (4) at successive boundaries, starting at the farthest, the net result at the receiver can be determined. If a narrow-angle source is also to be considered, a correction must be made for the reduced relative solid angle. Several cases can be cited.

The simplest is the case in which the beam of a directive antenna is directed through a semi-infinite absorbing medium at a temperature that is to be measured. In this case, the antenna will effectively exhibit th temperature of the absorbing medium.

Another case is similar to the first except that an absorbing medium is interposed between the antenna and the medium of interest. Such a case occurs when observations are made at frequencies at which the ionosphere exhibits absorption. The ionosphere should then be assigned an effective loss and temperature to permit corrections to be made to the observations. Other such cases occur whenever two or more absorbing mediums in space fall along the center of the antenna beam.

A particularly interesting case is met in observations of the absorption line of galactic hydrogen at 21 cm. In such observations a radio star beyond the hydrogen may raise the background radiation over an appreciable frequency range. At frequencies other than resonance frequencies, the hydrogen is virtually loss-free, or "transparent." At 21 cm, the resonance frequency, the hydrogen becomes highly absorptive, or "opaque." Besides the absorption aspect of the 21 cm line, in directions where background radiation is small, the effective temperature will be raised by radiation from the hydrogen at 21 cm. The 21 cm radiation from galactic hydrogen, first observed by Ewen and Purcell in 1951, has opened one of the largest avenues presently being explored by the astronomers.[9]

It is of interest to note that the image response, which is considered a nuisance in most applications, can be used to improve the sensitivity of a receiver in the measurement of "white" noise, or noise that has negligible difference in magnitude at the two principal sidebands of the local-oscillator frequency. That is, a receiver with equal image and signal responses will be 3 db more sensitive in detecting a single white noise source than a comparable receiver having image rejection. For instance, a two-channel receiver having a 10 db noise figure when rated on the basis of one useful channel would effectively have a 7 db noise figure when used to measure "white" noise. In this case, the factor $B_0 B_u^{-1}$ is unity instead of two. If the signal and image channels are sufficiently close together, this fact can be used in measurements of sloping spectra such as that of the galactic radiation.

It was brought to my attention by Ewen that there frequently is the situation in which a weak white noise source is to be detected in a strong background of white noise. In such a case the advantage of the image response is reduced and may virtually disappear, depending upon the relative magnitudes of the background noise and the excess noise of the receiver according to the three following cases:

1) If the background noise is much greater than the excess receiver noise, receiver characteristics such as image rejection, noise figure, and the like have relatively little influence on the output signal-to-noise ratio; therefore, there is little sensitivity advantage in admitting the image sideband.

2) If the background noise is much smaller than excess receiver noise, virtually the full 3-db advantage is obtained.

3) If background noise and excess receiver noise are comparable, there will be a sensitivity advantage between zero and 3 db.

Noise Figure Measurement

Whenever noise figure is measured utilizing a generator at a temperature different from room temperature (when not intentionally emitting excess noise), the

[9] H. I. Ewen and E. M. Purcell, "Radiation from hyperfine levels of interstellar hydrogen," *Phys. Rev.* vol. 83, pp. 881–883; August 15, 1951.

numerical result will be in terms of operating noise figure unless a correction is made for the temperature of the noise generator. The difference between operating noise figure and noise figure in Fig. 4 can be used as a correction to the measured noise figure. The reading from Fig. 4 should be subtracted from the result that is obtained from the measurement. A typical case in which this sort of correction is important is that of environmental testing of receiving equipment. If the environmental testing is done at elevated or reduced temperature the following results can be obtained: 1) If the noise generator is at the ambient temperature imposed upon the receiving equipment, the resulting noise figure will be an operating noise figure, and the correction should be made to give noise figure, and 2) if the receiving equipment is at the environmental test temperature, but the noise generator is at room temperature, no correction is required. In the case of an amplifier with extremely low noise figure, the resulting temperature changes that occur when a noise generator is allowed to warm up become important and must be considered if accurate results are to be obtained. For instance, from Fig. 4 it is seen that for an amplifier with a 1 db noise figure, there is a correction of about 0.1 db for each 10 degrees at temperatures near room temperature.

When a broad-band noise generator is used to measure the noise figure of a superheterodyne receiver in which the mixer is matched to the antenna at sidebands other than the signal frequency, the apparent excess noise is higher than for the single-channel case. For the broad-band receiver, the apparent excess noise is that given by (6) and (7). The result given in (6) and (7) has been used frequently in the past to the extent that the image frequency has been considered. From the plot in Fig. 7, it is seen that significant errors may result if the upper and lower sidebands of the second and third harmonics are not considered. In considering Fig. 7, however, it should be noted that few mixer structures have sufficiently broad response characteristics to require the full correction that is indicated. It is intended here only to indicate that the possibility exists for such corrections. In waveguide structures it may be necessary to consider modes other than the dominant mode when considering the effects of these high-frequency sidebands. Three usual cases can be postulated:

1) High-Q mixer—$B_0 B_u^{-1} = 1$.
2) Mixer utilizing band-pass filter matching both signal and image, but rejecting other sidebands —$B_0 B_u^{-1} = 2$.
3) Broad-band mixer providing a match to signal, image, and several other sidebands—$B_0 B_u^{-1} > 2$.

To eliminate the necessity for correcting for the extra sidebands, it might seem that, for measurement purposes, a band-pass filter could be interposed between the noise generator and the mixer. If such a filter is used, however, it is necessary to provide resistive padding between it and the mixer to prevent the possibility of seriously altering the sideband terminations, thereby altering conversion loss, impedances, and noise temperature of the mixer.[10]

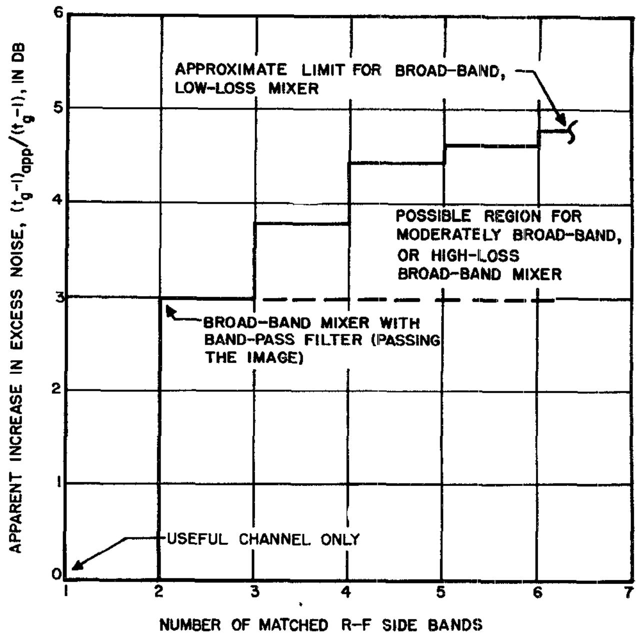

Fig. 7—Apparent increase in excess noise in a typical broad-band mixer.

Conclusion

Expressions have been given for the noise temperature of a lossy pad at an elevated temperature connected to an arbitrary number of terminations at arbitrary temperatures. The application of these expressions was shown for several receiving-system components.

It was shown that the noise temperatures of various components of a receiving system including its antenna can seriously affect noise figure and its measurement. In particular, consideration of galactic noise indicates that an optimum frequency for minimum operating noise figure lies in the region of hundreds of megacycles. Methods were given to account for the effect of the temperature of the test equipment when noise figure is to be measured and for the spurious sidebands in a superheterodyne receiver that has broad-band characteristics.

Acknowledgment

The author wishes to express his appreciation to A. J. Hendler and M. T. Lebenbaum of Airborne Instruments Laboratory, and H. I. Ewen of Ewen Knight Corp. for many stimulating discussions and suggestions which have helped to clarify some of the concepts presented here.

[10] See Strum, *loc. cit.*, for a discussion of the magnitudes of these effects.