RADIO NOISE

Radio noise can be defined as unwanted and unavoidable electromagnetic fluctuations that tend to obscure the information content of a desired radio signal. In a radio receiver, the noise disturbances are fluctuating voltages and currents that alter the desired signal's original frequency, amplitude, or phase in some unpredictable, unwanted manner. In early radios, much of the "noise" stemmed from the quality of the equipment; for example, poor contacts and unreliable connections, sensitivity to mechanical vibrations, and unstable detectors and amplifiers all contributed to the degradation of the radio signal. Over the years, there was steady progress in improving transmitters and receivers and greatly reducing or completely eliminating these and other noise sources. It was soon realized, however, that all sources of noise could not be totally eliminated and that a fundamental residual noise remained as a lower limit. This article focuses on such noise emanating from both natural sources and human activities that affect the performance of *narrowband* radio frequency (RF) communications systems.

Typically radio noise is divided into two components—internal or *receiver* noise (that is, intrinsic noise generated by the receiving system components) and external or *environmental* radio noise (noise collected by the receiving system antenna). Receiver noise is largely due to natural processes such as *thermal noise,* arising from the motion of thermally agitated free electrons in resistors, and *shot noise,* resulting from current fluctuations superimposed on the steady current flow in both vacuum tubes and solid-state devices. Environmental noise is an intrinsic part of a wireless communications channel and consists of *natural radio noise* (i.e., noise originating from natural sources such as atmospheric noise and sky noise), and *unintentional* RF emissions due to human activity, which are commonly referred to as *man-made* noise. Atmospheric noise is largely due to lightning and related phenomena, such as precipitation static. *Sky noise* is a generic term used to describe noise from a variety of terrestrial and extraterrestrial sources, such as cosmic noise and absorption of radio waves in the earth's atmosphere due to rain, water vapor, and oxygen. Intentional RF emissions that result in adjacent- and co-channel radio interference, including intermodulation and jamming, are not covered in this article.

While such noise cannot be completely eliminated, understanding the character of radio noise allows engineers and system designers to evaluate radio system performance and devise means to lessen the adverse effects. The most important design parameter used to characterize noise performance is the predetection signal-to-noise ratio (SNR), and hence, noise power is generally the most significant parameter in relating the interference potential of noise to system performance. Noise power calculations must include noise generated in all components of the receiving system as well as the radio channel. This is usually accomplished by determining a single parameter, the *operating system noise factor,* which is essentially the ratio of the receiving system predetection noise power referenced to the terminals of an equivalent lossless receiving antenna and the noise power available from a resistor at standard temperature (288 K).

In this article, important sources of receiver noise are described and the concept of receiver noise factor is developed. The noise factor concept is then extended to cover the entire radio receiving system, including the receiving antenna and environmental noise. This is followed by a description of important environmental noise sources.

RECEIVER NOISE AND NOISE FACTOR

The two most important receiver noise sources, used as noise standards and for noise characterization, are thermal and shot noise. Thermal noise is characterized as the spontaneous fluctuations in voltage across a resistor due to the random motion of thermally agitated electrons. Thermal noise is always present in any radio system and often establishes the lower limit of signal detection. Shot noise, on the other hand, originates in a flow of discrete charges not in equilibrium where the mean-square noise current is proportional to the product of elementary charge, the average current, and the bandwidth or $2e\bar{I}b$ (1). The cathode-to-anode stream of a temperature-saturated thermionic diode is an example of a pure shot noise generator. Shot noise currents in semiconductors such as diodes and transistors are due to the diffusion of charge carriers in *p–n* junctions.

Since thermal and shot noise may be described as being the sum of a very large number of random, short-lived disturbances, it follows from the central limit theorem that the processes are Gaussian. More precisely, observed voltages are white Gaussian noise. It was shown experimentally by Johnson (2) and theoretically by Nyquist (3) that the mean thermal noise power density available from a resistor is simply

kT, where $k = 1.38 \times 10^{-23}$ W/Hz/K is Boltzmann's constant and T is the absolute temperature of the resistor. The characterization as white noise is an approximation valid for typical narrowband RF communication systems operating at or near the standard ambient temperature $T_0 = 288$ K. When quantum mechanical considerations are included, the mean power density kT is replaced by the more accurate expression obtained by Max Planck (4):

$$\frac{h\nu}{e^{h\nu/kT} - 1}\ (\text{W/Hz}) \tag{1}$$

where $h = 6.626176 \times 10^{-34}$ J/Hz is Planck's constant and ν represents frequency. Clearly, the flat power spectral density approximation is inaccurate when high frequencies are combined with cryogenic temperatures. Such systems are beyond the scope of this article.

Since both thermal and shot noise constitute white Gaussian noise sources, the properties of the noise voltage they deliver to an output circuit are indistinguishable. The significant difference is that thermal noise is proportional to temperature and shot noise is proportional to the average current. Hence, an equivalent noise temperature T_e can be used to characterize the noise of a device with thermal sources at temperature T and shot noise sources with mean power dw_s in an incremental bandwidth $d\nu$ as follows:

$$kT_e = kT + \frac{dw_s}{d\nu} \tag{2}$$

Solid-state shot noise sources such as noise diodes are commonly used in noise measurements. To achieve the required precision in T_e, these devices are calibrated against a primary standard. Noise diodes are commonly characterized in terms of excess noise ratio defined as

$$N_R = 10\log_{10}\left(\frac{T_e}{T_0} - 1\right)\ (\text{dB}) \tag{3}$$

Thermal noise generated within or passing through a band-limited receiver circuit is colored and perhaps amplified. Since thermal noise power is independent of frequency over the bandwidth of most narrowband RF communication systems, it is useful to define a *noise-equivalent bandwidth* b_0. When a resistor is attached to the input terminals of a linear receiver with gain $g(\nu)$, the total noise power available to the receiver w_a in the system band can be expressed in terms of the noise equivalent bandwidth as follows:

$$w_a = kT\int_0^\infty \frac{g(\nu)}{g_0}\, d\nu = kTb_0 \tag{4}$$

where g_0 is the nominal gain in the system bandwidth.

Statistical Characterization of Narrowband White Gaussian Noise

If the receiver input termination is a resistor, the receiver output noise voltage is a random function of time whose behavior can only be described statistically. For a typical RF communication system, the signal is narrowband with respect to a central radio frequency ν_c and the output noise voltage $V(t)$ can be written as

$$V(t) = Re\{v(t)e^{j2\pi\nu_c t}\} = E(t)\cos(2\pi\nu_c t - \Phi(t)) \tag{5}$$

where $v(t)$ is the complex baseband representation, $E(t)$ is the amplitude, and $\Phi(t)$ is the phase. In this representation, $v(t)$ is a complex random process and the pair $(E(t), \Phi(t))$ are two associated real random processes. When the observed voltages are white Gaussian noise, their baseband representations are 0-mean complex Gaussian processes with a flat power spectral density. This means that the co- and quad phases of v are independent and Gaussian distributed with 0 means and identical variances. It also means that voltages at different times are independent—a statement that must be emended by the fact that the receiver is narrowband, so that the actual observed power spectral density is proportional to the power spectrum of the receiver.

For these complex Gaussian processes, it is also true that the resulting amplitude and phase are independent of each other and that the phase is uniformly distributed over the complete circle. The amplitude is then *Rayleigh distributed.* In terms of the *instantaneous noise power* (which is proportional to the square of the amplitude), the cumulative distribution function (more precisely, the exceedance distribution function) is

$$\Pr\{\text{noise power} > w > 0\} = e^{-w/w_o} \tag{6}$$

where w_o is the average output noise power. This average equals the total area under the power spectral density curve and is equal to the sum of the mean power of the input noise amplified by the receiver and the mean noise power added by the receiver w_r or

$$w_o = g_0 kTb_0 + w_r \tag{7}$$

where T is the temperature of the resistor connected to the input terminals.

To obtain this result, the receiver noise is assumed to be Gaussian and white, as would be the case when thermal and shot noise are dominant. More generally, Eq. (7) is valid for any random processes. If the receiver noise is not Gaussian, however, the instantaneous power distribution would not be Rayleigh, as given in Eq. (6). The white Gaussian thermal noise assumption is reasonable for most narrowband RF receivers. In general, however, w_r will depend on frequency.

In noise calculations, it is important to define clearly what is meant by gain. There are many possible definitions of gain. Assuming that a signal generator is connected to the receiver input terminals and a power meter is connected to the receiver output terminals, an obvious choice would be to use the ratio of the input and output powers, or so-called *power gain.* Clearly, power gain depends on the impedance of both the signal generator as well as the impedance of the power meter, and hence a noise characterization based merely on power gain is ambiguous. To circumvent this difficulty, the gain used in noise calculations is usually taken to be the *available power gain* (5), defined as the ratio of the available power from the receiver to the available power from a signal generator connected to the receiver input terminals so that any mismatch losses are included. With this definition, the gain does not depend on the receiver load; however, it does depend on the impedance of the signal generator.

In determining noise performance, the signal generator is often matched to the receiver so that the maximum power is delivered to the receiver. This is a reasonable choice for most RF applications, where signal generators, connecting cables, the loads, and so on are usually 50 Ω devices, or they are matched waveguide interfaces. It should also be noted that when there is a complete match at the input and output, the available gain and the power gain are equal.

The Receiver Noise Factor

In radio engineering it is desirable to have a simple, yet unambiguous method of characterizing the noise properties of a radio receiver. For this purpose, the concept of noise factor was developed and defined. There are a variety of ways to define noise factor. The basic idea is to relate the available noise power at the input of an active or passive two-port linear network to the noise power available at its output terminals. Assume that a CW signal generator is connected and matched to the input terminals of a receiver. Let w_g be the available signal generator power, w_l be the signal power available at the load, and w_0 be the available noise power at the load; the International Radio Consultative Committee (CCIR) (6) definition of noise factor is given as follows: The noise factor f_r of a radio receiver is defined to be the ratio of the available CW signal-to-reference noise power w_g/kT_0b_0 at the terminals of the signal generator to the corresponding total signal-to-noise power ratio w_l/w_o available to the load of the linear portion of the receiver with the CW signal tuned to the maximum response of the receiver bandpass characteristic and with the signal generator output impedance at the reference temperature T_0:

$$f_r \equiv \frac{w_g/kT_0b_0}{w_l/w_o} = \frac{w_g}{w_l}\frac{w_o}{kT_0b_0} \tag{8}$$

The ratio w_l/w_g is simply the maximum available power gain and hence,

$$f_r = \frac{w_o}{g_o kT_0b_0} \tag{9}$$

If it is assumed that the receiver bandwidth is very narrow $b_0 \to d\nu$ so that the receiver noise is constant over the bandwidth, Eq. (9) gives the spot noise factor

$$f_s(\nu) = \frac{\dfrac{dw_0}{d\nu}}{g(\nu)kT_0} \tag{10}$$

which is essentially a single-frequency value based on a unit bandwidth. It should be noted that the noise factor is simply the available output noise power referred to the input terminals (i.e., divided by the nominal gain) in units of kT_0b (i.e., the noise power available from a resistor at standard temperature).

The spot noise factor as given in Eq. (10) is equivalent to the Institute of Radio Engineers (IRE) definition (7). In practice, for narrowband linear receivers, the weighted average spot noise factor over the system bandwidth $\overline{f}$ is the quantity commonly used to characterize receiver noise performance:

$$\overline{f} = \frac{\int_0^\infty f_s(\nu)g(\nu)\,d\nu}{\int_0^\infty g(\nu)\,d\nu} = \frac{w_0}{kT_0\int_0^\infty g(\nu)\,d\nu} = \frac{w_o}{kT_0g_0b_0} \tag{11}$$

which is precisely f_r defined previously.

Noise Factor for a Passive Two-Port Linear Network

Communications receivers use transmission lines, attenuators, and other devices that can be generally classified as passive two-port linear networks. It is important to consider the effects of such devices operating in tandem with the actual receiver to characterize properly the noise performance of the receiving system.

The spot noise factor of a linear two-port network is obtained by calculating the power density ratio given in Eq. (10) when a resistor at reference temperature T_0 is connected to the input terminals of the network. If the network is at the ambient temperature T_0, the available output noise power density is just kT_0. If the network temperature is $T_n \neq T_0$, a correction arising from the temperature difference $T_0 - T_n$ must be included; hence

$$\frac{dw_0}{d\nu} = kT_n + gk(T_0 - T_n) \tag{12}$$

where g is the available gain. From Eq. (10), the spot noise factor is

$$f_s = 1 + \frac{T_n}{T_0}(1/g - 1) = 1 + \frac{T_n}{T_0}(\ell - 1) \tag{13}$$

where $\ell = 1/g$ is the available loss factor. Note that the spot noise factor depends on the input resistance used to determine the available gain (or loss).

Noise Factor for Cascaded Linear Networks

The noise factor for a linear receiving system can be calculated from the noise factors for its individual components. Understanding the relationship between the system noise factor and the noise factors for various components is important in system design since it shows which components contribute most significantly to the noise factor.

Assume that two networks are connected together: network a with spot noise factor f_a and gain g_a, and network b with spot noise factor f_b and gain g_b. Further assume that a resistor is connected to the input of network a and the entire system is at temperature T_0. The power density available at the output of network b is equal to the sum of the power density available at the input of network b scaled by g_b and the available noise power density due only to network b or

$$\frac{dw_o}{d\nu} = f_a g_a g_b kT_0 + (f_b - 1)g_b kT_0 \tag{14}$$

Using Eq. (10), the spot noise factor for two cascaded networks is

$$f_{ab} = f_a + \frac{f_b - 1}{g_a} \tag{15}$$

which is the result originally obtained by Friis (8). Spot noise factors will usually vary somewhat across the band of an actual network and, for a particular system, the effects of nonuniform noise and gain may require additional consideration. As described previously, the weighted average spot noise factor is often used to characterize the receiving system.

This analysis is readily extended to several linear networks in cascade. For example, if network c is connected to the output terminals of network b, the system noise factor is

$$f_{abc} = f_{ab} + (f_c - 1)/g_{ab} = f_a + (f_b - 1)/g_a + (f_c - 1)/g_a g_b \tag{16}$$

and so on for additional networks. This result shows that if network a has a high gain, its noise factor will be the most important in determining the overall noise factor for the system. High-gain low-noise amplifiers are often used to reduce the noise factor in receiving systems.

Noise Factor for the Linear Portion of a Receiving System

In addition to the actual receiver, a typical radio receiving system is composed of an antenna, transmission lines, and other circuits, all of which contribute noise and must be included in the analysis of the system noise performance. Of particular importance for wireless systems is the receiving antenna, which collects environmental noise. By using the results of the previous sections, the noise factor can be extended to characterize any specified portion of an operating system at any specified set of input terminals. For a radio receiving system, the most useful reference point for noise factor calculations is the input to the terminals of an equivalent loss-free receiving antenna (6). This reference point provides an appropriate and unique measure of the performance of the entire receiving system.

Typically, the linear portion of a receiving system can be divided into a series of cascaded two-port networks, as shown in Fig. 1. The receiving antenna is modeled as an equivalent loss-free antenna connected to an antenna circuit network. A section of transmission line connects the antenna to the receiver. Using Eq. (16), the noise factor for the receiving system is

$$f = f_a + \frac{f_c - 1}{g_a} + \frac{f_t - 1}{g_a g_c} + \frac{f_r - 1}{g_a g_c g_t} \tag{17}$$

where f_a, f_c, and f_t are the spot noise factors; and g_a, g_c, and g_t are the gains of the antenna, antenna circuit, and transmission line, respectively; and f_r is the spot noise factor of the receiver.

The external noise power in the band $d\nu$ that is available at the terminals of the loss-free receiving antenna can be expressed as $kT_a\, d\nu$, where T_a is the noise temperature of the radiation resistance of the receiving antenna at the center frequency of the receiver. The antenna noise factor f_a is equal to the ratio T_a/T_0. Since the antenna circuit and transmission line are passive two-port networks, the spot noise factor can be expressed as

$$f = T_a/T_0 + (\ell_c - 1)T_c/T_0 + \ell_c(\ell_t - 1)T_t/T_0 + \ell_c\ell_t(f_r - 1) \tag{18}$$

where the gains have been replaced by the corresponding loss factors. Strictly speaking, this result is meaningful for narrowband systems where the noise factors do not vary significantly over the operating frequency range. It should be understood that all of the spot noise factors and loss factors are determined with generator impedances that are the same as those in the actual receiving system. Also, the formula for cascaded networks is applicable regardless of the degree of match or mismatch between the output impedance of one network and the input impedance of the following network. The magnitudes of these mismatch losses do influence the values of the spot noise factors and loss factors and will thus affect the noise factor.

The quantity of interest for finite bandwidth systems is the weighted average spot noise factor, which is often referred to as the operating noise factor f_{op} (6). The operating noise factor can be expressed in terms of the weighted average noise factors of the receiving system components as follows:

$$f_{op} = \overline{f}_a + \overline{f}_{ct} - 1 + (b_r/b)(g_r/g_0)(\overline{f}_r - 1) \tag{19}$$

where, denoting the overall system gain at frequency ν as $g(\nu)$, the weighted average antenna noise factor is

$$\overline{f}_a = \frac{\int_0^\infty T_a(\nu) g(\nu)\, d\nu}{T_0 \int_0^\infty g(\nu)\, d\nu} \tag{20}$$

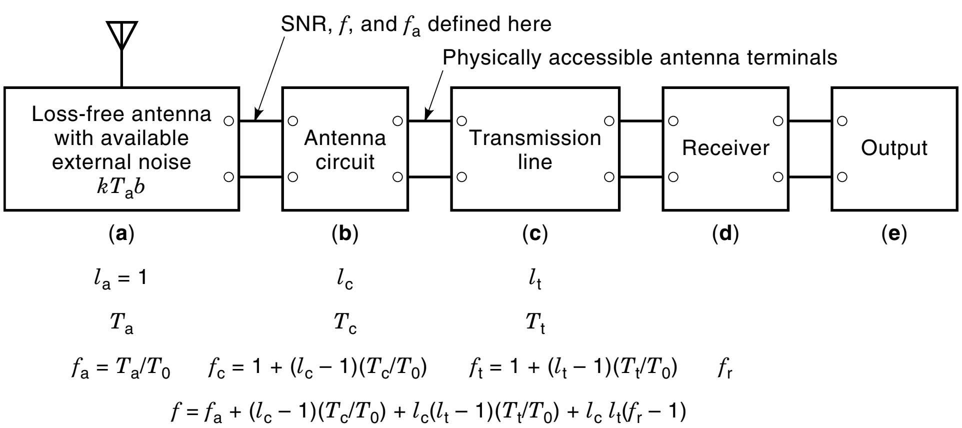

Figure 1. The receiving system and its operating noise factor, f.

$\overline{f}_{ct}$ is the weighted average combined noise factor of the antenna circuit and transmission line network,

$$\overline{f}_{ct} = \frac{\int_0^\infty f_{ct}(\nu)g(\nu)\,d\nu}{\int_0^\infty g(\nu)\,d\nu} \tag{21}$$

b is the equivalent bandwidth of the system, b_r is the equivalent bandwidth of the receiver, g_0 is the nominal gain of the system, g_r is the maximum gain of the receiver, and $\overline{f}_r$ is the weighted average receiver noise factor, as given in Eq. (11) and using the receiver gain function.

To apply the foregoing results, noise factors for the receiver, related electronic components, and an equivalent lossless antenna must be determined. Using the definitions given in the previous sections, measurement methods can be readily devised and implemented to calculate accurately noise factors for receivers and other electronic components (see, for example, Ref. 9). The determination of the antenna noise factor is, in general, much more difficult. For RF communication systems, the antenna noise factor is often a nonstationary random process that varies with time, frequency, geographical location, and receiving antenna characteristics. As a consequence, researchers have spent many years measuring and compiling statistics that can be used to estimate the antenna noise factor for various environmental noise sources. In the case of man-made noise, not only is there a fast time dependence over fractions of an hour to days, but there is also a relatively slow time dependence based on advances in technology. Significant changes in the background noise for a particular environment may occur within a few years, and as a consequence published data can become outdated. Antenna noise factors based on published noise statistics are described in the following sections.

So far in this article, lowercase letters have been used to represent noise factors, gains, and bandwidths. In noise analysis, it is common to express these quantities as decibels and to use uppercase letters to denote that the quantity is in decibels. Also, when given in decibels, the noise factor is usually referred to as *noise figure;* for example, the antenna noise figure is

$$F_a = 10\log_{10} f_a\ (\text{dB}) \tag{22}$$

and in decibels, the notations for gain and bandwidth are

$$G = 10\log_{10} g\ (\text{dB});\ B = 10\log_{10} b\ (\text{dB/Hz}) \tag{23}$$

This notation and terminology is used in the following sections.

ENVIRONMENTAL NOISE AND ANTENNA NOISE FIGURE

Environmental noise emanates from both natural and man-made sources and is collected by the receiving system antenna. The determination of noise parameters, such as the antenna noise figure F_a, requires careful measurement programs that must account for temporal, spatial, and frequency variations of the particular noise source. In this section, some of the more important sources of environmental noise are described. The statistical data presented are based on many years of measurements of natural and man-made noise over the entire radio spectrum.

F_a for Blackbody Radiation

All objects at temperatures above absolute zero radiate energy in the form of electromagnetic waves. A blackbody is a perfect absorber and a perfect radiator of electromagnetic energy. It absorbs all incident radiation at all wavelengths, and the radiation from it is a function of only temperature and wavelength. Although the concept of a blackbody is an idealization, it can be used to estimate the radio noise emitted by a variety of objects. For example, the cosmic background, thought to be the lingering echo of the creation of the universe, is equivalent to radiation from a blackbody at 2.7 K.

The *brightness* β of radiation from a blackbody radiator at temperature T and frequency ν is given by Planck's radiation law (10):

$$\beta = \frac{2h\nu^3}{c^2(e^{h\nu/kT} - 1)}\ (\text{W/m}^2\text{/Hz/sr}) \tag{24}$$

where $c = 2.99792458 \times 10^8$ (m/s) is the speed of light in free space. For typical radio frequencies and standard temperatures, where, $h\nu \ll kT$, this reduces to the Rayleigh–Jeans approximation

$$\beta \cong \frac{2kT}{\lambda^2} \tag{25}$$

where λ is the free space wavelength. As in the case of thermal noise in a resistor, the radiation power is directly proportional to temperature.

The power received by an antenna from an incremental blackbody of area dA at temperature T in bandwidth $d\nu$ is

$$dw = \frac{1}{2}\beta\frac{\lambda^2}{4\pi}\gamma(\Omega)\,d\Omega\,d\nu \cong \frac{kT}{4\pi}\gamma(\Omega)\,d\Omega\,d\nu \tag{26}$$

where $d\Omega$ is the element of solid angle subtended at the receiver by dA and $\gamma(\Omega)$ is the directive gain of the antenna. Note that the antenna only collects half the power since only a single polarization is received. The total power collected when the blackbody radiation at temperature T is received from all directions is

$$w = kT\,d\nu\left(\frac{1}{4\pi}\int_{4\pi}\gamma(\Omega)\,d\Omega\right) = kT\,d\nu \tag{27}$$

which is the same as the total power available from a resistor at temperature T. Hence, the antenna temperature is simply T and $f_a = T/T_0$ independent of the antenna gain.

F_a for Common Natural and Man-Made Radio Noise Sources

Both natural and man-made radio noise have been measured and carefully studied by many scientists and engineers in the latter half of the twentieth century. The results of these efforts have been published in various journals, conference proceedings, and reports and recommendations of radio engineering organizations, such as the International Telecommunication Union (ITU) (11–14). In this article, statistical data from these studies are presented for what are considered to

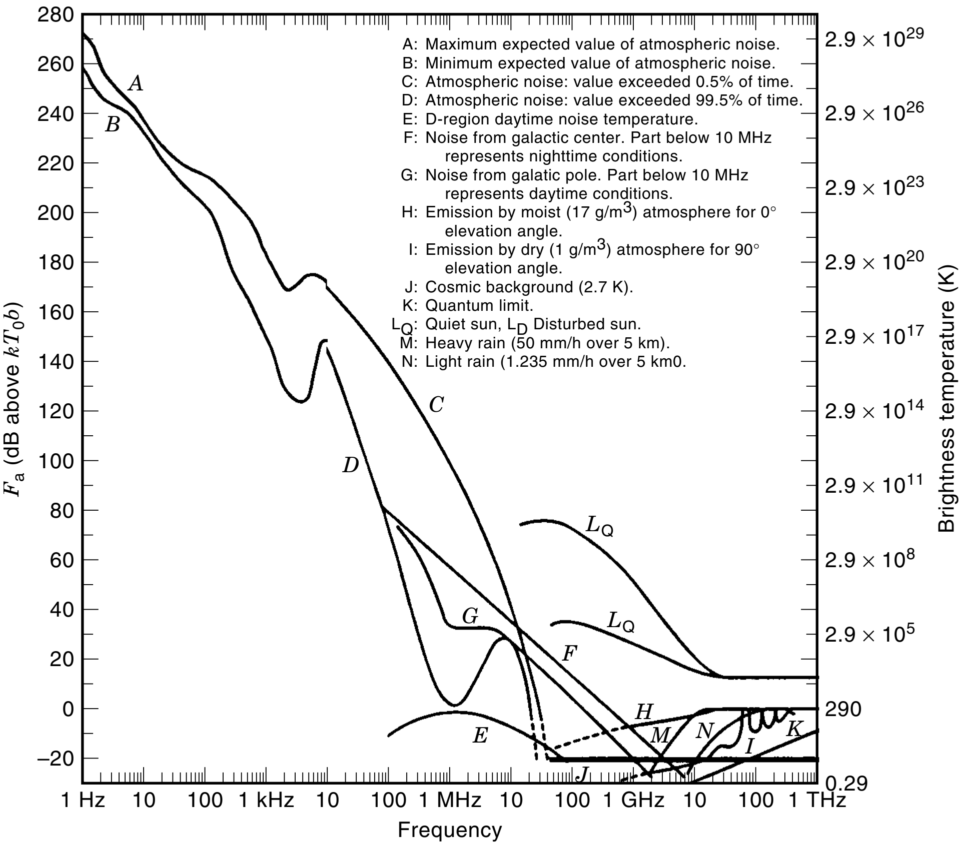

Figure 2. Natural radio noise (1 Hz to 1 THz) (15).

be some of the more important environmental radio noise sources. For a more detailed treatment of these and other sources of radio noise, the reader is referred to the references.

The antenna noise figure F_a for background natural radio noise from 1 Hz to 1 THz is illustrated in Fig. 2 (15). These data show that natural radio noise depends strongly on frequency over the radio spectrum (nominally 3 kHz to 300 GHz). In addition, several noise sources are nonstationary in time and space (e.g., atmospheric, sun, rain). Of particular interest for communications systems operating at or below about 30 MHz is atmospheric noise, where F_a is random and is characterized by its statistics. Atmospheric noise is also non-Gaussian. The other noise sources shown in this figure are essentially Gaussian.

For RF systems operating at frequencies of several hundred megahertz and below, man-made noise is an important source of radio noise. Like atmospheric noise, man-made noise is both nonstationary and non-Gaussian. Figure 3 (16) shows the median antenna noise figure F_{am} for man-made noise in four environments and galactic noise as compared with the expected day-time and night-time levels for atmospheric noise. Man-made noise is strongly dependent on frequency and, in general, the F_{am} curves have a slope of -27.7 dB/decade of frequency.

Figure 4 (15) shows the details of natural radio noise over the frequency range of 100 MHz to 100 GHz. The estimated median business-area man-made noise has also been included. The $E(90°)$ curve shows sky noise measured with a narrow beam antenna at zenith. The water and oxygen absorption bands are clearly visible. The $E(0°)$ curve is sky noise with a narrowbeam antenna directed along the earth's surface.

It was shown that when an antenna receives blackbody radiation at a uniform temperature from all directions, F_a does not depend on the receiving antenna gain. For most environmental noise sources, however, F_a does depend on the antenna gain and on several other factors. Appropriate corrections must be applied when the radio system-receiving antenna differs significantly from that used to measure the noise.

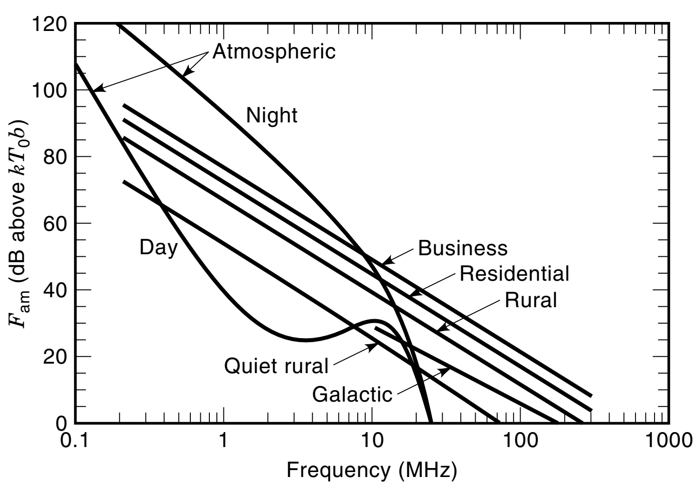

Figure 3. Median values of F_a (16).

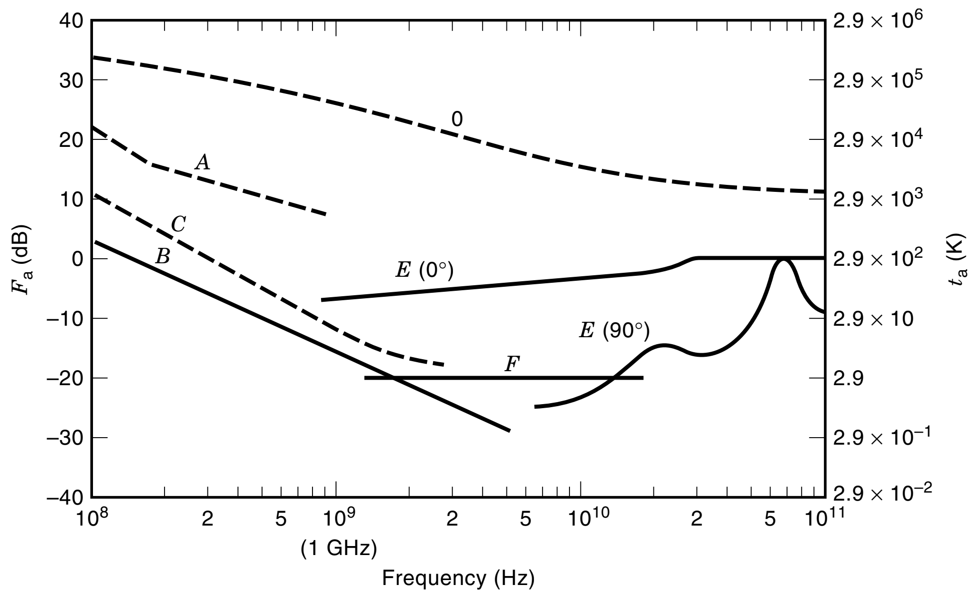

Figure 4. F_a versus frequency (100 MHz to 100 GHz), where A = estimated median business area man-made noise, B = galactic noise, C = galactic noise (toward galactic center with infinitely narrow beamwidth), D = quiet sun ($\frac{1}{2}$ degree beamwidth directed at sun), E = sky noise due to oxygen and water vapor (very narrow beam antenna); upper curve 0° elevation angle, lower curve 90° elevation angle, F = cosmic background, 2.7 K (15).

Curves L_D, L_Q, F, H, and M in Fig. 2 all refer to very narrowbeam antennas pointing directly at the source. Noise from such sources (sun, atmospheric gasses, the earth's surface) are also expressed in terms of brightness temperature. These curves can be used to calculate the antenna temperature of a particular receiving antenna by integrating Eq. (25) in terms of temperature over the region occupied by the noise source:

$$T_a = \frac{\gamma_0}{4\pi} \int_{\text{sources}} T(\Omega) p(\Omega)\, d\Omega \tag{28}$$

where γ_0 is the gain and $p(\Omega)$ is the pattern of the receiving antenna; that is, $\gamma(\Omega) = \gamma_0 p(\Omega)$. For example, the sun has a beamwidth of about $\frac{1}{2}^\circ$. If a receiving antenna with gain γ_0 is aimed at the sun and the pattern is essentially constant over the intersection with the sun's beam, the antenna temperature is

$$T_a = \frac{\gamma_0}{4\pi} \int_{\text{Sun}} T(\Omega) p(\Omega)\, d\Omega \cong \gamma_0 T_s \left(\frac{\pi}{1440}\right)^2 \tag{29}$$

where T_s is the brightness temperature of the sun at the desired frequency.

In Fig. 4, there are two curves associated with galactic noise. Curve B is for an omnidirectional antenna, while curve C is for an infinitely narrow beam aimed toward the galactic center. Because of the relative motion of the earth and galaxy, galactic noise is not constant in time. A more accurate determination of galactic noise for other types of antennas can be obtained by using published radio sky data, which gives the brightness temperature as a function of position in the sky. Such data are available in CCIR Report 720-2 (14), which contains maps of the brightness temperature of the radio sky at 408 MHz and an approximate expression for the frequency dependence of the temperature.

Atmospheric and Man-Made Noise

The most significant sources of environmental radio noise at frequencies below 1 GHz are man made and atmospheric. For these sources, the noise data were measured with a grounded electrically short monopole antenna. Since this type of noise most probably arrives at the receiver at relatively low elevation angles and from random directions, such an azimuthally omnidirectional antenna is well suited for noise measurements. Predicting the antenna noise figure for other types of receiving antennas requires an assessment of the differences between the ideal short monopole antenna and the desired receiving antenna. Factors that should be considered are antenna efficiency, directivity, polarization, and height above the ground.

The direction of arrival for both atmospheric and man-made noise has been shown to be nonuniform, varying by as much as 10 dB with direction (17). Since the noise is nonstationary, predicting F_a for high-gain antennas would likely be arduous if worst-case estimates based on the measured data do not provide sufficient accuracy. For azimuthally symmetric antennas such as a half-wave dipole, a correction factor based on the ratio of the desired antenna gain to the reference antenna gain can be applied to obtain the appropriate value for F_a.

Since these noise processes are nonstationary, the usual design parameter, SNR, is random and the underlying statistics of the noise process as a function of time and geographical location must be understood to assess radio performance properly. These characteristics are discussed in more detail in the following sections.

Another important consideration is that both atmospheric and man-made noise are non-Gaussian. Typically, communication system performance is calculated based on Gaussian noise. A more detailed analysis incorporating the statistics of the actual non-Gaussian noise process may be required in radio design and performance evaluations. Several publications listed in the references provide information regarding the impulsive nature of these noise sources and its effect on radio receivers.

Statistics of F_a for Atmospheric Noise. Atmospheric noise is an important consideration for wireless communication systems operating below 30 MHz. The main source of atmospheric noise is lightning. The electromagnetic energy emitted by electrical storms couples into the earth-ionosphere waveguide, and hence, local noise levels can be significantly influenced by distant thunderstorms. Because of ionospheric interactions, overall atmospheric noise levels are greater at night, as shown in Fig. 3.

In Fig. 2, curves *A*, *B*, *C*, and *D* represent the expected range of F_a at the surface of the earth. These data are of the average background, taking into account all times of the day, seasons, and the entire surface of the earth. Curves *A* and *B* give the maximum and minimum values of F_a from 1 Hz to 10 kHz. In this frequency range, there is very little seasonal, diurnal, or geographic variation. Note that the variation of F_a begins to increase significantly at about 100 Hz. This is due to the variability of the Earth-ionosphere waveguide cutoff. Curves *C* and *D* give the atmospheric noise from 10 kHz to about 30 MHz, above which the noise levels are quite low. Curve *C* is the value of F_a exceeded 0.5% of the time, and curve *D* is the value of F_a exceeded 99.5% of the time. These results are derived from background atmospheric noise and do not include effects of "nearby" electrical storms. A compilation of measurements showing the peak field strength for 1 mile distant lightning as a function of frequency is given in Fig. 5 (18).

The variability of F_a, particularly in the medium frequency (MF) and high frequency (HF) communication bands (300 kHz to 30 MHz), is so large that the bounds given in Fig. 2 alone cannot be used to obtain a useful characterization of radio system performance. It is important, therefore, to know how F_a and other noise statistics vary with time and location. Starting in 1957, the average power levels and other relevant statistics were measured on a worldwide basis using a network of 15 stations. These measurements spanned 13 kHz to 20 MHz and considered both the time of day and the season. The results of several years of measurements were published in the National Bureau of Standards (NBS) Technical Note Series 18 (19) and later published in CCIR Report 332 (12). A numerical representation of the data contained in Report 332 is also available (20).

The published data give, for each frequency, location, season, and time of day (measured in 4-h increments), the month-hour median value of F_a along with values exceed 10% (upper decile, D_u) and 90% (lower decile, D_l) of the time. As an example of these data, Fig. 6 shows worldwide values for the median antenna noise figure F_{am} in the winter between 0000 and 0400 local time. The median noise figure at other frequencies, D_u, D_l, and related statistics are obtained using the curves shown in Fig. 7.

The statistical distribution of F_a and hence the radio system SNR is readily obtained from the published data. For a given season and measurement time block (4 h) it has been shown that F_a is adequately represented by two log-normal distributions (21), one above the median value and one below. As an example, the distribution of F_a for 3 MHz at Boulder, Colorado in the winter at 0000 to 0400 can be determined using the data from Figs. 6 and 7. First, the 1 MHz value of F_{am} at the geographic location of interest is obtained from Fig. 6 and corrected to 3 MHz using Fig. 7. Then D_u and D_l as well as their standard deviations are obtained from Fig. 7. Using normal probability paper, these three points define the two intersecting lines that give the two desired log-normal distributions. The resulting distribution is shown in Fig. 8. Hence, if a radio system is operating at 3 MHz, the system performance can be conveniently specified in terms of the percent of time that the required SNR will be available at a particular geographic location, season, and time.

Statistics of F_a for Man-Made Noise. In 1974, Spaulding and Disney (22) presented results from many years of measure-

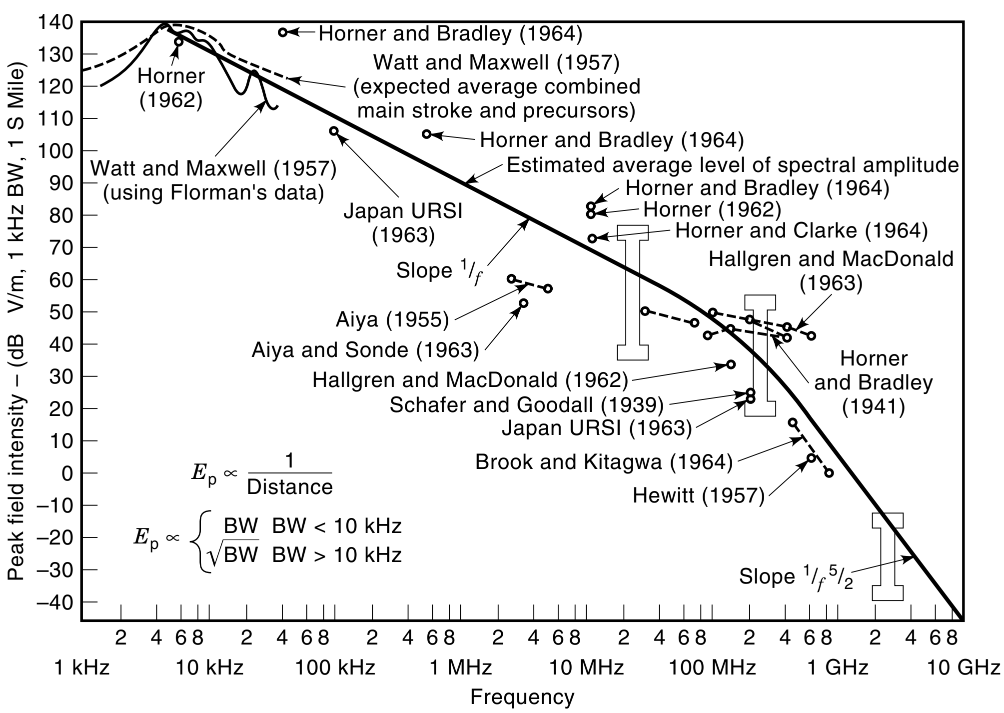

Figure 5. Lightning emission peak field strength, 1 mile distant. (Reprinted from p. 369 of Ref. 18, by permission, © 1982 IEEE.)

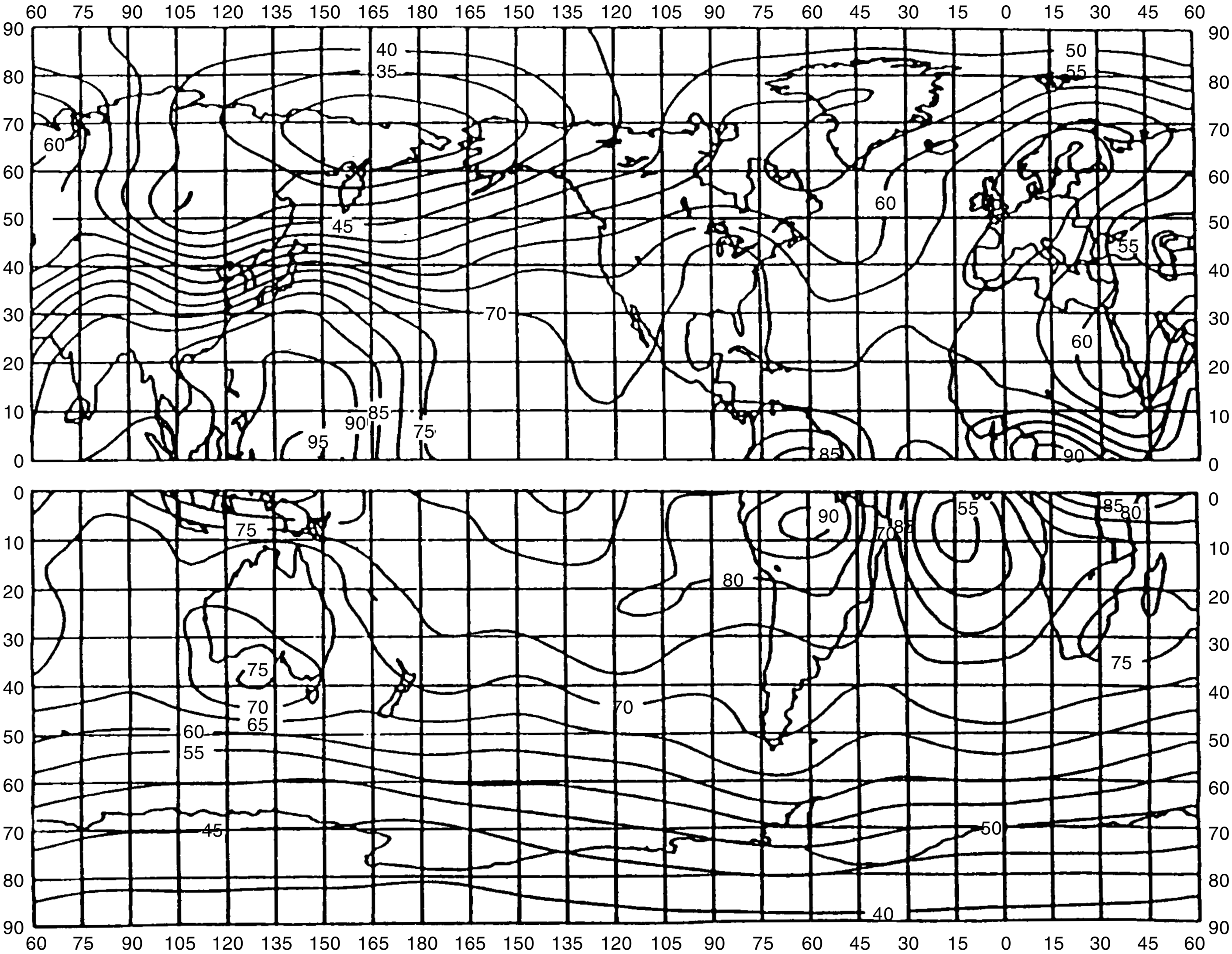

Figure 6. Expected values of atmospheric radio noise, F_{am} (dB above kT_0b at 1 MHz) (Winter 0000–0400 LT) (12).

ments of man-made radio noise. They devised methods for estimating the noise power and noise amplitude statistics that are important in the design of radio systems. These methods are described in the CCIR Reports (13) and have been widely used by industry. Figure 3 summarizes these results in terms of the median antenna noise figure F_{am}. As with atmospheric noise, man-made noise is both nonstationary and non-Gaussian and is a significant source of radio noise for frequencies below a few hundred megahertz. The antenna noise figure F_a varies both in time and location. The noise level depends on the type and extent of human activities, which are conveniently classified into four man-made noise environments (13) described in Table 1.

The within-the-hour time variability of F_a is commonly described by two log-normal distributions (21), as described previously for atmospheric noise. Values of D_u and D_l are given in CCIR Report 258 as a function of frequency and environment. More recently, Spaulding and Stewart (21) have analyzed the data used to obtain these decile values and have found that it is appropriate to use the values D_u = 9.7 dB and D_l = 7 dB, independent of environmental category and frequency. Other proposed noise models described in Report 258 include a simple Gaussian model that does not describe the skewness observed in measured noise data and a more complex χ-square model.

As an example, the distributions of F_a using D_u = 9.7 dB and D_l = 7 dB at 137 MHz for business, residential, rural, and quiet rural noise environments are shown in Fig. 9. These data include the contribution of Galactic noise, which is only significant in the quiet rural noise environment.

Location variability is also an important consideration when characterizing F_a. The usual assumption (22) is that F_{am} is the noise figure exceeded 50% of the time at 50% of the locations. Hence, the time distribution of F_a as shown in Fig. 9 is the noise power exceeded at 50% of the locations for a particular environment. If it is assumed that the location variability is Gaussian, then the value $\tilde{F}_a$ that is exceeded at other than 50% of locations is obtained from

$$\tilde{F}_a = F_a + \sqrt{2}\sigma_L \operatorname{erfc}^{-1}\left[\frac{\%\,\text{locations}}{50}\right] \quad (30)$$

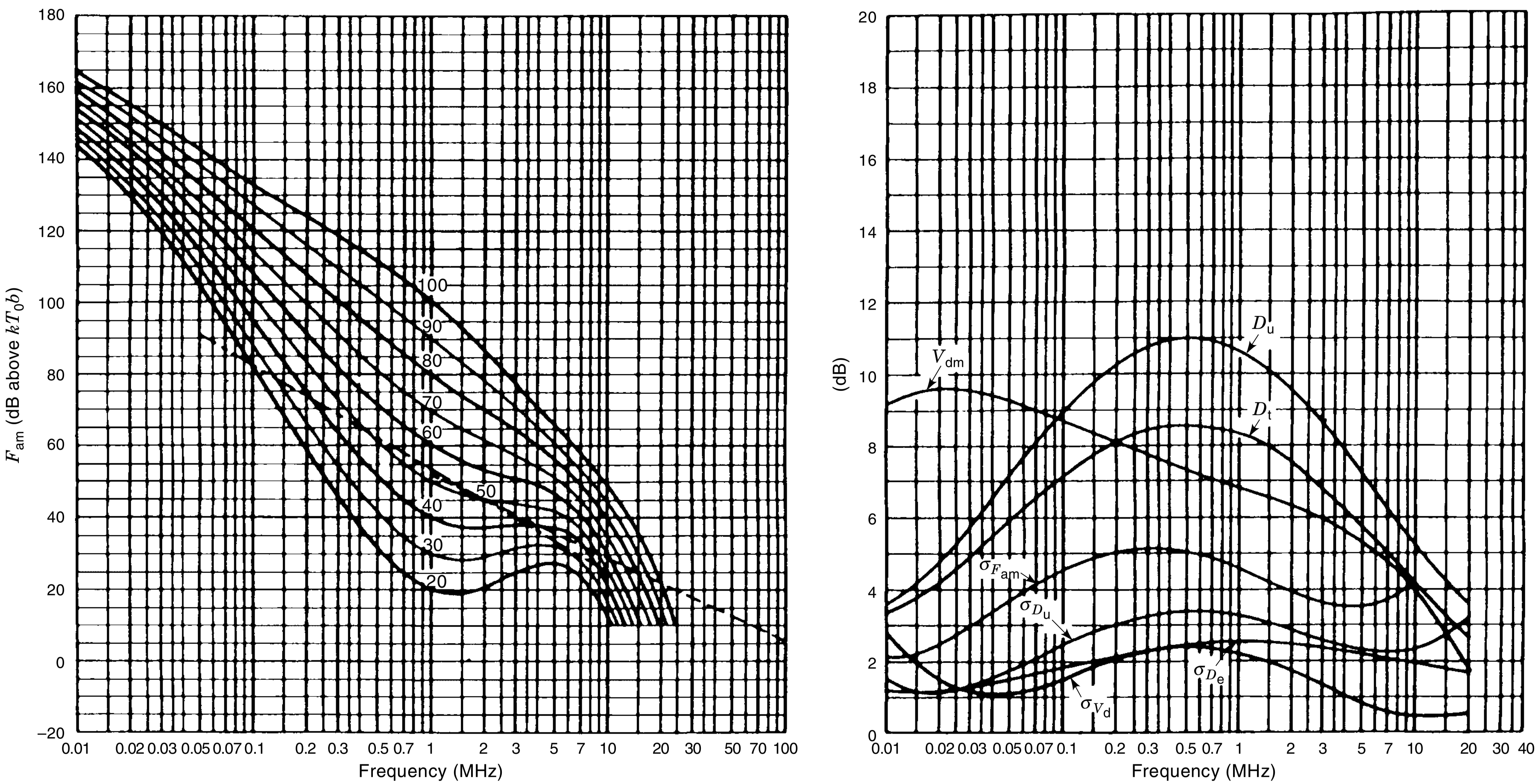

Figure 7. (a) Variation of radio noise with frequency (winter; 000–0400 LT) (12). ———— Expected values of atmospheric noise. — — — — — Expected values of galactic noise. (b) Data on noise variability and character (winter; 000–0400 LT) (12). $\sigma_{F_{am}}$: Standard deviation of values of F_{am}. D_u: Ratio of upper decile to median value, F_{am}. σ_{D_u}: Standard deviation of values of D_u. D_l: Ratio of median value, F_{am}, to lower decile. σ_{D_l}: Standard deviation of values of D_l. V_{dm}: Expected value of median deviation of average voltage. The values shown are for a bandwidth of 200 Hz. σ_{V_d}: Standard deviation of V_d (12).

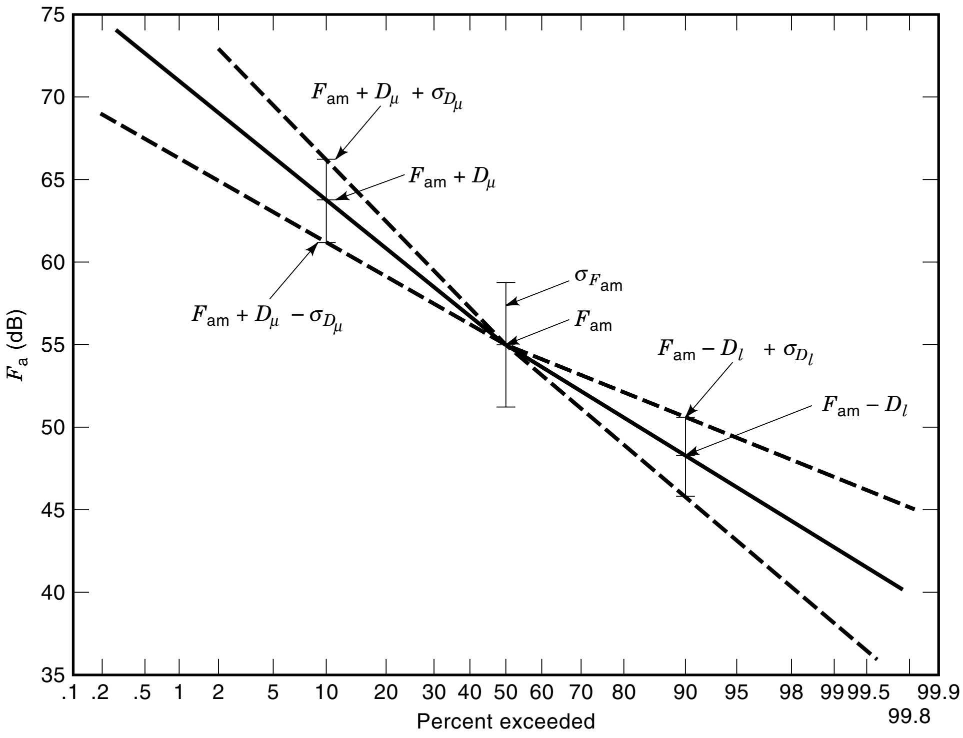

Figure 8. The distribution of F_a values for atmospheric radio noise at Boulder, Colorado. 3 MHz, for the winter season, 0000–0400 hours (21).

Table 1. CCIR Report 258 Definitions of Man-Made Noise Environments

Environment	Characteristics
Business	Areas where predominant usage is for any type of business
Residential	Areas used predominantly for single or multiple family dwellings (at least five single-family units per hectare), no large or busy highways
Rural	Areas where dwelling density is no more than one every two hectares
Quiet Rural	No definition given

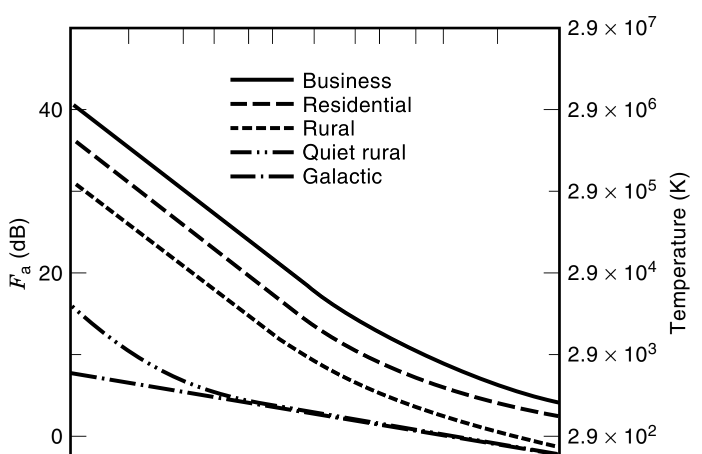

Figure 9. Distribution of F_a for man-made and galactic noise.

where $erfc^{-1}$ is the inverse complimentary error function and σ_L is the standard deviation of the location distribution.

The location variability in terms of the standard deviation σ_L of the median value as a function of frequency and environment is given in Table 2 (13). As may be expected, σ_L for the business environment is much larger than either the residential or rural environment.

APPLICABILITY OF PUBLISHED MAN-MADE NOISE STATISTICS TO CONTEMPORARY ENVIRONMENTS

The man-made noise statistics presented are largely based on measurements that were made more than 20 years ago in North America by Spaulding and Disney (22). More recently, Spaulding has warned that the CCIR data may now be inaccurate due to technological advances (23). This is largely based on the fact that emissions from newer automobile ignition systems, a major contributor to man-made noise in urban

Table 2. Location Variability in Terms of the Standard Deviation for Various Environments

Frequency (MHz)	σ_L Business	σ_L Residential	σ_L Rural
0.25	6.1	3.5	3.9
0.50	8.2	4.3	4.4
1.00	2.3	2.5	7.1
2.50	9.1	8.1	8.0
5.00	6.1	5.5	7.7
10.00	4.2	2.9	4.0
20.00	4.9	4.7	4.5
48.00	7.1	4.0	3.2
102.00	8.8	2.7	3.8
250.00	3.8	2.9	2.3

areas, have decreased dramatically over the years. After reviewing more recent measurements and trend analyses, Spaulding concluded (23) that in the business environment "at 100 MHz in the 1970's time-frame, F_{am} was on the order of 20 dB but now is probably approximately 20 dB less." This conclusion, however, is not based on a comprehensive set of noise measurements as would be necessary to update the previous survey described in Ref. 23.

While the improvements in automobile ignition systems have likely affected the noise levels in business and residential environments, emissions from gap discharge and corona in power transmission and distribution lines have probably not decreased with time. Figure 10 (22) shows F_{am} under, and one-quarter mile from, a 115 kV line in rural Wyoming. It is interesting to note that the noise measured one-quarter mile from the power line is about the same as that predicted for a rural environment. A possible conclusion is that if power and distribution lines are the primary noise source in rural environments, rural man-made noise is not likely to have decreased. However, one would not expect noise in an urban environment to be less (than rural), as would be the case with the estimated 20 dB reduction in F_{am}.

Another factor that could significantly affect the level and character of man-made radio noise is the proliferation of electronic devices (e.g., computers, electronic switching devices, microwave ovens, etc.) that are unintentional RF emitters. Such devices have become ubiquitous in business, residential, and rural environments and could affect both the magnitude of the noise power as well as its frequency dependence.

The man-made noise data presented in the previous sections are applicable to North America; the validity of extension to other parts of the world cannot be determined precisely. CCIR Report 258 describes very high frequency (VHF) measurements made in business and residential areas of the United Kingdom where the noise power was found to be some 10 dB below that shown in Fig. 3 (16). This is attributed to differences in patterns of utilization of electric and mechanical appliances and regulation of interference. The report also states that due to such differences, the noise statistics should be used with caution. It should be noted, however, that if an overall 10 dB reduction in urban noise can be justified, the man-made noise environments near 100 MHz would be bounded by what are now classified as rural (worst) and quiet rural (best) environments, as shown in Fig. 3.

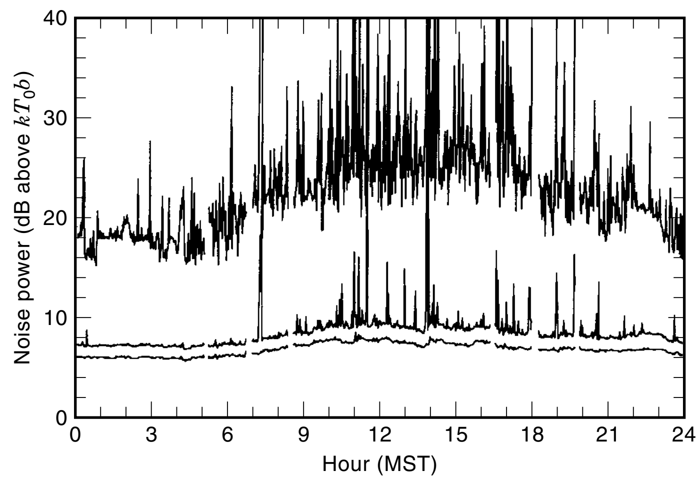

Figure 11. Median, mean, and peak noise power near an office park (24).

Relatively recent noise measurements at 137 MHz (24) show that the statistics of man-made noise are significantly different from what is predicted by CCIR Report 258. For example, Fig. 11 shows the median, mean, and peak (exceeded 0.01% of the time) values of F_a measured over a 24-h period in a business environment. Diurnal variations corresponding to human activity are clearly evident. The relatively steady within-the-hour values of the mean power (F_a) are not consistent with the predicted within-the-hour distribution of F_a for a business environment (see Fig. 9). Figure 12 shows the distribution of F_a measured at six urban sites plotted on normal probability paper. The distribution at a particular site was obtained by collecting statistics measured within two-minute intervals spaced about an hour apart from hours of continuous measurements made at that particular location. Hence, the results should correspond to the hour-to-hour time variability, which, for the most part, is relatively low at most of

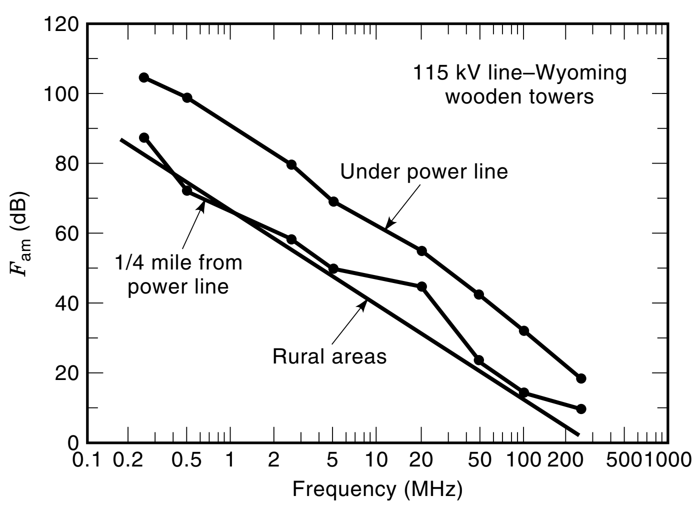

Figure 10. Power line noise measurements near a 115 kV line in rural Wyoming (22).

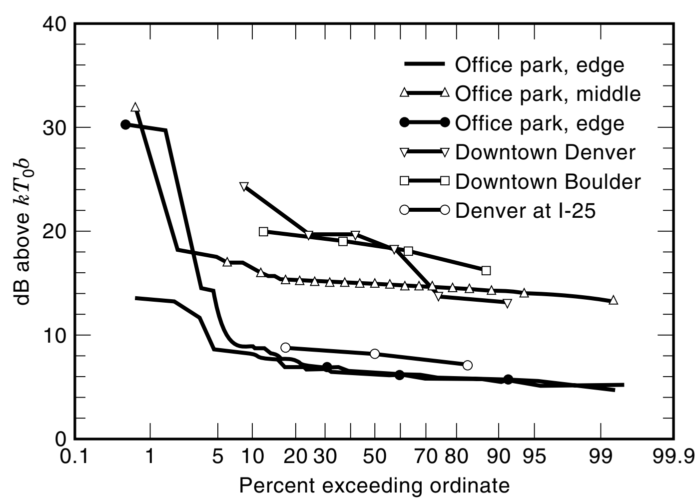

Figure 12. Power averages from measurements at six urban sites (24).

the locations. Location variations however are quite large, exceeding 12 dB in some cases. More importantly, these measurements show that there are business environments (downtown urban areas) where F_{am} is still nearly 20 dB.

In summary, the 137 MHz measurements demonstrate that important changes have occurred in both the level and character of man-made noise since the comprehensive noise survey described by Spaulding and Disney (22). While these measurements can only be considered as a "spot check," they do show that standard methods used to predict man-made radio noise are probably outdated. It is concluded that additional comprehensive man-made noise measurements at RF frequencies into the ultrahigh frequency (UHF) band will be necessary to provide radio system designers and engineers with the required tools to effectively design modern radio systems.

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