ATMOSPHERIC RADIO NOISE: WORLDWIDE LEVELS AND OTHER CHARACTERISTICS

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The determination of radio communication system performance is a matter of proper statistical treatment of both the desired signal and the real-world noise (or interference) processes. System performance is highly dependent on the detailed statistical characteristics of both the signal and the noise as well as the single parameter: signal-to-noise ratio (which is sometimes the only parameter considered). Generally, the computation of the desired signal characteristics over a given path can be made reasonably accurately. This is not the case when it comes to estimating the noise level and other required noise characteristics. Existing noise models consist primarily of the worldwide atmospheric noise maps contained in CCIR Report 322 and estimated man-made noise levels given in CCIR Report 258. In addition, there are numerous other special purpose models.

There is a need for an overall, comprehensive usable noise model for application to telecommunication problems. One needed task that has been accomplished toward the goal of obtaining such an overall model is the development of an improved atmospheric noise model. The existing worldwide atmospheric noise model (CCIR Report 322) was developed from approximately 4 years of measurements from a worldwide network of 16 measurement stations. This network made measurements for 5 years (longer in a few cases) past the completion of CCIR Report 322 in 1963. Also, additional data are now available from other locations, primarily many years of data from 10 Soviet measurement stations. All these additional data have been analyzed and an updated worldwide atmospheric noise model has been prepared in both graphical and numerical forms. Results of this analysis show substantial "corrections" (on the order of 20 dB for some locations) to the 1 MHz noise level values given by CCIR Report 322. It is the purpose of this report to present and discuss this new model for atmospheric noise levels and other characteristics.

Key words: amplitude probability distributions; atmospheric noise characteristics; atmospheric radio noise; diurnal and seasonal noise variations; worldwide noise levels

1. INTRODUCTION AND DEFINITIONS

Atmospherics are electromagnetic "signals," impulsive in nature, which means they are spectrally broadband processes. The lightning that radiates these atmospherics radiates most of its energy at frequencies at and below HF (3-30 MHz). It is also frequencies at and below HF that are used for long-range communications, since propagation is supported by the Earth-ionosphere waveguide. While this means

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that atmospherics can be used to study this propagation medium, the density and location of thunderstorms and other geophysical phenomena, it also means that long-range communications systems can receive interference from these atmospherics. At any receiving location, atmospherics can be received from the entire Earth's surface (at low enough frequencies). Therefore, the satisfactory design of a radio communications system must take into account the level and other characteristics of this atmospheric noise. It should also be noted that in spite of satellite systems, the use of the ionosphere to achieve long-range communications is continually increasing.

The satisfactory design of a radio communications system depends on consideration of all the parameters affecting operation. This requires not only the proper choice of terminal facilities and an understanding of propagation of the desired signal between the terminals, but also a knowledge of the interference environment. This environment may consist of signals that are intentionally radiated, or of noise, either of natural origin or unintentionally radiated from man-made sources, or various combinations of these. It has long been recognized that the ultimate limitation to a properly designed communication link will usually be the radio noise.

There are a number of types of radio noise that must be considered in any design; though, in general, one type will be the predominant noise and will be the deciding design factor. In broad categories, the noise can be divided into two types--noise internal to the receiving system and noise external to the receiving antenna. Noise power is generally the most significant parameter (but seldom sufficient) in relating the interference potential of the noise to system performance. Since the noise level often results from a combination of external and internal noise, it is convenient to express the resultant noise by means of an overall operating noise factor that characterizes the performance of the entire receiving system. In so doing, it is then possible to make decisions concerning required receiving system sensitivity; that is, a receiver need have no more sensitivity than that dictated by the external noise. Indeed, worldwide minimum noise levels have been estimated for this purpose (CCIR Report 670, 1978). Also, the noise levels can then be compared to the desired signal level to determine the predetection signal-to-noise ratio. The predetection signal-to-noise ratio is an important system design parameter and is always required knowledge (required but seldom sufficient) when determining the effects of the external noise on system performance. It is useful to refer (or translate) the noise from all sources to one point in the system for comparison with the signal power (desired signal). A unique system reference point exists: the terminals of an equivalent lossless antenna having the same characteristics (except efficiency) as the actual antenna (see CCIR Report 413).

Consider the receiving system shown in Figure 1. The output of block (a) is this unique reference point. The output of block (c) represents the actual (available) antenna terminals to which one could attach a meter or a transmission line. Let s represent the signal power and n the average noise power in watts that would be observed at the output of block (a) in an actual system (if the terminals were accessible). We can define a receiving system overall operating noise factor, f, such that $n = fkT_0 b$, where k = Boltzmann's constant = 1.38×10^{-23} J/K, T_0 = the reference temperature in K taken as 288K, and b = the noise power bandwidth of the receiving system in Hertz.

We can also define a system overall operating noise figure $F = 10 \log_{10} f$ in decibels. The ratio s/n can be expressed in decibels:

$$(s/n)_{dB} = S - N \tag{1}$$

where

S = the desired average signal power in dB (1W)
= $10 \log_{10} s$, and
N = the average system noise power in dB (1W)
= $10 \log_{10} n$.

Let us now explore the components of n in greater detail with emphasis on environmental noise external to the system components.

For receivers free from spurious responses, the system noise factor is given by

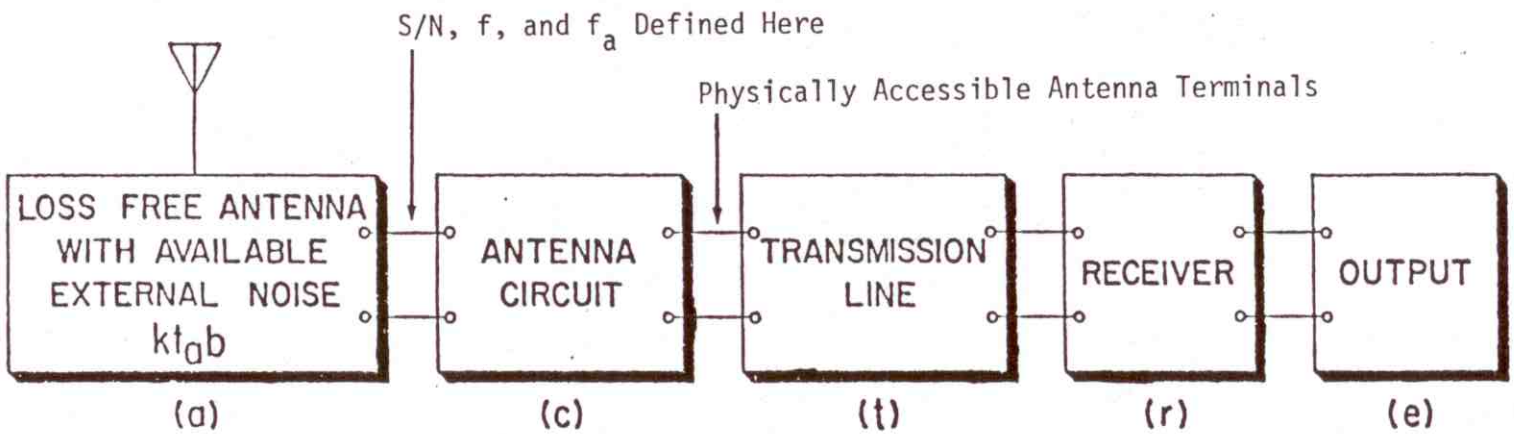
$$f = f_a + (\ell_c - 1) \frac{T_c}{T_o} + \ell_c(\ell_t - 1) \frac{T_t}{T_o} + \ell_c \ell_t (f_r - 1) \quad , \tag{2}$$

where

f_a = the external (i.e., antenna) noise factor defined as

$$f_a = \frac{p_n}{kT_0 b} \quad ; \tag{3}$$

F_a = the external noise figure defined as $F_a = 10 \log f_a$;
p_n = the available noise power from a lossless antenna [the output of block (a) in Figure 1];
ℓ_c = the antenna circuit loss (available input power/available output power);
T_c = the actual temperature, in K, of the antenna and nearby ground;



(a)	(c)	(t)	(r)
$\ell_a = 1$	ℓ_c	ℓ_t	
T_a	T_c	T_t	
$f_a = T_a/T_o$	$f_c = 1 + (\ell_c - 1)(T_c/T_o)$	$f_t = 1 + (\ell_t - 1)(T_t/T_o)$	f_r

$$f = f_a + (\ell_c - 1)(T_c/T_o) + \ell_c(\ell_t - 1)(T_t/T_o) + \ell_c \, \ell_t (f_r - 1)$$

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

ℓ_t = the transmission line loss (available input power/available output power);

T_t = the actual temperature, in K, of the transmission line; and

f_r = the noise factor of the receiver ($F_r = 10 \log f_r$ = noise figure in dB).

Let us now define noise factors f_c and f_t, where f_c is the noise factor associated with the antenna circuit losses,

$$f_c = 1 + (\ell_c - 1) \frac{T_c}{T_o} \quad , \tag{4}$$

and f_t is the noise factor associated with the transmission line losses,

$$f_t = 1 + (\ell_t - 1) \frac{T_t}{T_o} \quad . \tag{5}$$

If $T_c = T_t = T_o$, (2) becomes

$$f = f_a - 1 + f_c f_t f_r \quad . \tag{6}$$

Note specifically that even when $f_c = f_t = 1$ (lossless antenna and transmission line), then $F \neq F_a + F_r$.

Relation (3) can be written

$$P_n = F_a + B - 204 \text{ dB(1W)} \quad , \tag{7}$$

where $P_n = 10 \log p_n$ (p_n = available power at the output of block (a) in Figure 1, in watts); $B = 10 \log b$; and $-204 = 10 \log kT_o$. For a short ($h << \lambda$) grounded vertical monopole, the vertical component of the rms field strength is given by

$$E_n = F_a + 20 \log f_{MHz} + B - 95.5 \text{ dB(1 } \mu\text{V/m)} \quad . \tag{8}$$

where E_n is the field strength [dB(1 μV/m)] in bandwidth b (Hz) and f_{MHz} is the center frequency in MHz. Similar expressions for E_n can be derived for other antennas (Lauber and Bertrand, 1977). For example, for a halfwave dipole in free space,

$$E_n = F_a + 20 \log f_{MHz} + B - 98.9 \text{ dB(1 } \mu\text{V/m)} \quad . \tag{9}$$

The external noise factor is also commonly expressed as a temperature, T_a, where by definition of f_a

$$f_a = \frac{T_a}{T_o} , \tag{10}$$

and T_o is the reference temperature in K and T_a is the antenna temperature due to external noise (in K).

More detailed definitions and discussions (including the case with spurious responses) are contained in CCIR Report 413 (1966).

Note that f_a is a dimensionless quantity, being the ratio of two powers (or, equivalently, two temperatures). The quantity f_a, however, gives, numerically, the available power spectral density in terms of kT_o and the available power in terms of kT_ob. The relationships between the noise power, P_n, the noise power spectral density, P_{sd}, and noise power bandwidth, b, are summarized in Figure 2. When F_a is known, then P_n or P_{sd} can be determined by following the steps indicated in the figure. For example, if value of F_a = 40 dB and b = 10 kHz, then the value of noise power available from the equivalent lossless antenna is P_n = -124 dB(1W).

If ℓ_c = 3, then the noise power available from the actual receiving antenna is -128.8 dB(1W).

Above, we have f_a (and T_a), the most useful and common way of specifying the external noise level. When one is concerned with determining the effects of the external noise (e.g., atmospheric noise) on system performance, more information about the received noise process than just its energy content (level) is almost always required. An exception would be if the external noise were a white Gaussian noise process, but this is almost never the case. Other parameters useful in determining the degradation effects of noise or interference are defined below.

Atmospheric noise (and man-made noise) is a random process. The fact that we are dealing with a random process means that the noise can be described only in probabilistic or statistical terms and cannot be represented by a deterministic waveform or by any collection of deterministic waveforms. Of course, deterministic waveforms can be treated as "random" and described in probabilistic terms also. But the opposite is not true; that is, random processes, such as atmospheric noise, must be described probabilistically.

The basic description of any random process is its probability density function (pdf) or distribution function. The first-order pdf of the received interference process is almost always required in order to determine system performance (i.e., it is always necessary but sometimes not sufficient). The received atmospheric noise

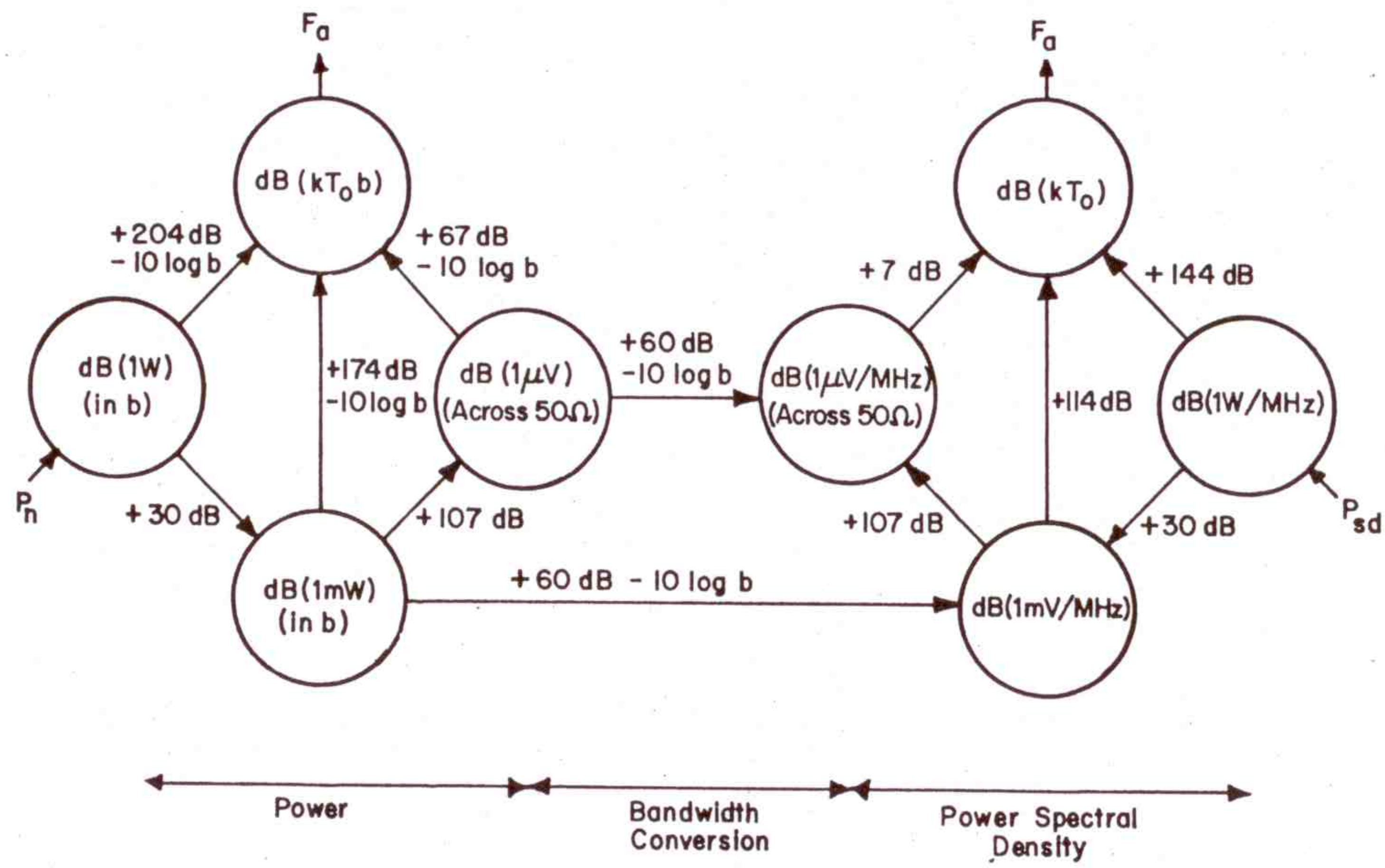


Figure 2. Relationships between power, power spectral density, and noise bandwidth (rms detector). (Presentation developed by G. H. Hagn.)

process under consideration here is a bandpass process in that it is describable by an envelope process and a phase process. Since the phase process is known (phase uniformly distributed), the required pdf of the instantaneous amplitude can be obtained from the envelope amplitude pdf. Usually, also, the envelope pdf can be used directly in system performance analyses. The atmospheric noise envelope statistic is usually given as (and measured as) a cumulative exceedance distribution, termed the "amplitude probability distribution" or APD. For some envelope level, E_i, the APD is the fraction of the total measurement time, T, for which the envelope was above level E_i;

$$D(E) = \mathrm{Prob}[E \geq E_i] = 1 - P(E) \quad , \tag{11}$$

where P(E) is the cumulative distribution function. The pdf of E is given by the derivative of P(E).

Over many years, various statistical moments of the received atmospheric noise envelope were measured and, on occasion, continue to be measured. These statistical moments are defined as follows:

The average envelope voltage is termed the expected value of E or E[E];

$$E_{av} = E[E] = \frac{1}{T}\int_0^T E(t)dt = -\int_0^\infty E dD(E) \quad , \tag{12}$$

where $-dD(E) = p(E)dE$; the rms voltage squared (proportional to energy or power), $E[E^2]$, is

$$E_{rms}^2 = E[E^2] = \frac{1}{T}\int_0^T E^2(t)dt = -\int_0^\infty E^2 dD(E) \; ; \tag{13}$$

and the average logarithm of the envelope voltage, E[logE], is

$$E_{log} = E[\log E] = \frac{1}{T}\int_0^T \log E(t)dt = -\int_0^\infty \log E dD(E) \quad . \tag{14}$$

Because the rms voltage level can be given in absolute terms (i.e., rms field strength or available power), it is common to refer the other envelope voltage levels to it. The dB difference between the average voltage and the rms voltage is termed V_d,

$$V_d = -20 \log \frac{E_{av}}{E_{rms}} \quad . \tag{15}$$

The dB difference between the antilog of the average log of the envelope voltage and the rms voltage is termed L_d,

$$L_d = -20 \log \frac{10^{E_{\log}}}{E_{rms}} \quad . \tag{16}$$

Of course, many other statistical descriptors (e.g., average crossing rate characteristic, autocorrelation function, pulse spacing distributions, pulse width distributions, etc.) have been measured and/or modeled. The ones defined above are the main ones of concern here. How these parameters (e.g., f_a) vary with time and location is also required knowledge.

Research pertaining to atmospheric noise dates back to at least 1896 (A. C. Popoff); however, the research leading to the first publication of predictions of radio noise levels was carried out in 1942 by a group in the United Kingdom at the Interservices Ionosphere Bureau and in the United States at the Interservice Radio Propagation Laboratory (I.R.P.L., 1943). Predictions of worldwide radio noise were published subsequently in RPU Technical Report No. 5 (1945) and in NBS Circular 462 (1948), NBS Circular 557 (1955), and CCIR Report 65 (1957). All these predictions for atmospheric noise were based mainly on weather patterns and measurements at very few locations and over rather short periods of time.

Starting in 1957, average power levels (f_a) of atmospheric noise were measured on a worldwide basis starting with a network of 16 identical recording stations. Figure 3 shows the locations of these recording stations. The frequency range 13 kHz to 20 MHz was covered, and measurements of F_a, V_d, and L_d were made using a bandwidth of 200 Hz. In addition, APD measurements were made at some of the stations.

The data from this worldwide network were analyzed by the Central Radio Propagation Laboratory (CRPL) of NBS and the results published in the NBS Technical Note Series 18. The first in this series was published in July 1959 and covered July 1957-December 1958. After this, one in the series was published every quarter until No. 18-32 for September, October, and November 1966. These Technical Notes gave, for each frequency and location, the month-hour median value of F_a along with D_μ and D_ℓ, the upper and lower decile values; i.e., the values exceeded 10 percent and 90 percent of the time. The median values of V_d and L_d were also given. In addition, the corresponding season-time block values were given for the four seasons, winter (December, January, and February; June, July, and August in the southern hemisphere), spring (March, April, May), summer (June, July, August), and

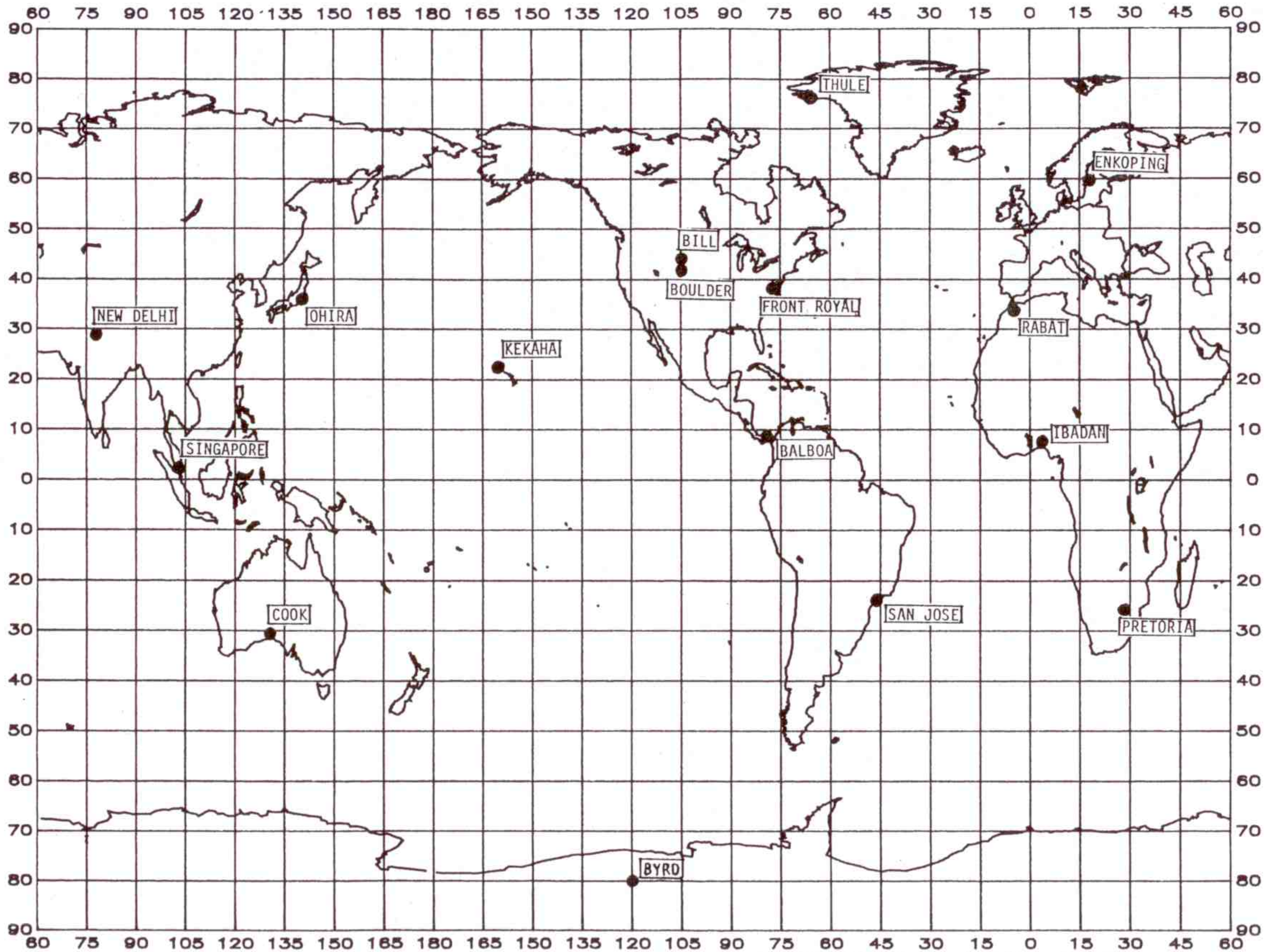


Figure 3. Radio noise recording stations used to obtain most of the data used for CCIR Report 322.

fall (September, October, November) and six four-hour time blocks (0000-0400, etc.).

In 1964, CCIR Report 322, World Distribution and Characteristics of Atmospheric Radio Noise, was published by the International Telecommunication Union (ITU) in Geneva. This report (small book, actually) presents the worldwide predictions of F_a, V_d, and their statistical variations for each season-time block and is based on all the available measurements to that date, primarily the recording network shown in Figure 3. In 1983, CCIR Report 322 was reprinted as CCIR Report 322-2 with a revised text and title, but with the same atmospheric noise estimates.

Figure 4 shows Figure 19A of CCIR Report 322. This figure gives F_{am} at 1 MHz as a function of latitude and longitude for the summer season and the time block 2000-2400. Since this map is for local time, there is a discontinuity at the equator (corresponding to summer being 6 months apart in the northern and southern hemispheres). World maps of atmospheric radio noise in universal time are also available (Zacharisen and Jones, 1970). To obtain F_{am}, Figure 19B (given as Figure 5 here) is used to convert the 1 MHz value to any frequency between 10 kHz and 30 MHz. Finally, the median value of V_d, V_{dm}, and the statistical variations of F_a about its median value F_{am}, are given via Figure 19C (Figure 5 here). Also, numerical representation of CCIR Report 322 is available (Lucas and Harper, 1965). While the title of Lucas and Harper says that only HF (3-30 MHz) is covered, the results there will cover the frequency range 10 kHz to 30 MHz. This numerical representation is also contained in the ITU HF propagation prediction programs. The numerical representation of Lucas and Harper was obtained by the numerical mapping of values obtained from the CCIR 322 1-MHz maps, rather than by numerically mapping of the original data points (84 longitude, 100 latitude grid points), which produced the CCIR 322 maps. This procedure gave an rms error of approximately 2 dB (typically for each of the 24 maps) with maximum errors up to approximately 10 dB being noted between the CCIR 322 maps and the Lucas and Harper numerical representation. The numerical representation of the frequency variation of F_{am} (e.g., Figure 19B of Figure 5) and the D_μ and D_ℓ variation (e.g., Figure 19C of Figure 5) given by Lucas and Harper are "precise," being the same numerical routines used to produce these parts of CCIR 322. The universal time "maps" of Zacharisen and Jones (1970) were obtained by numerical mapping using the "original" Report 322 data. Also, using the original data to plot the contour maps in Report 322, Sailors and Brown (1982,1983) developed a simplified atmospheric noise numerical model suitable for use on minicomputers.

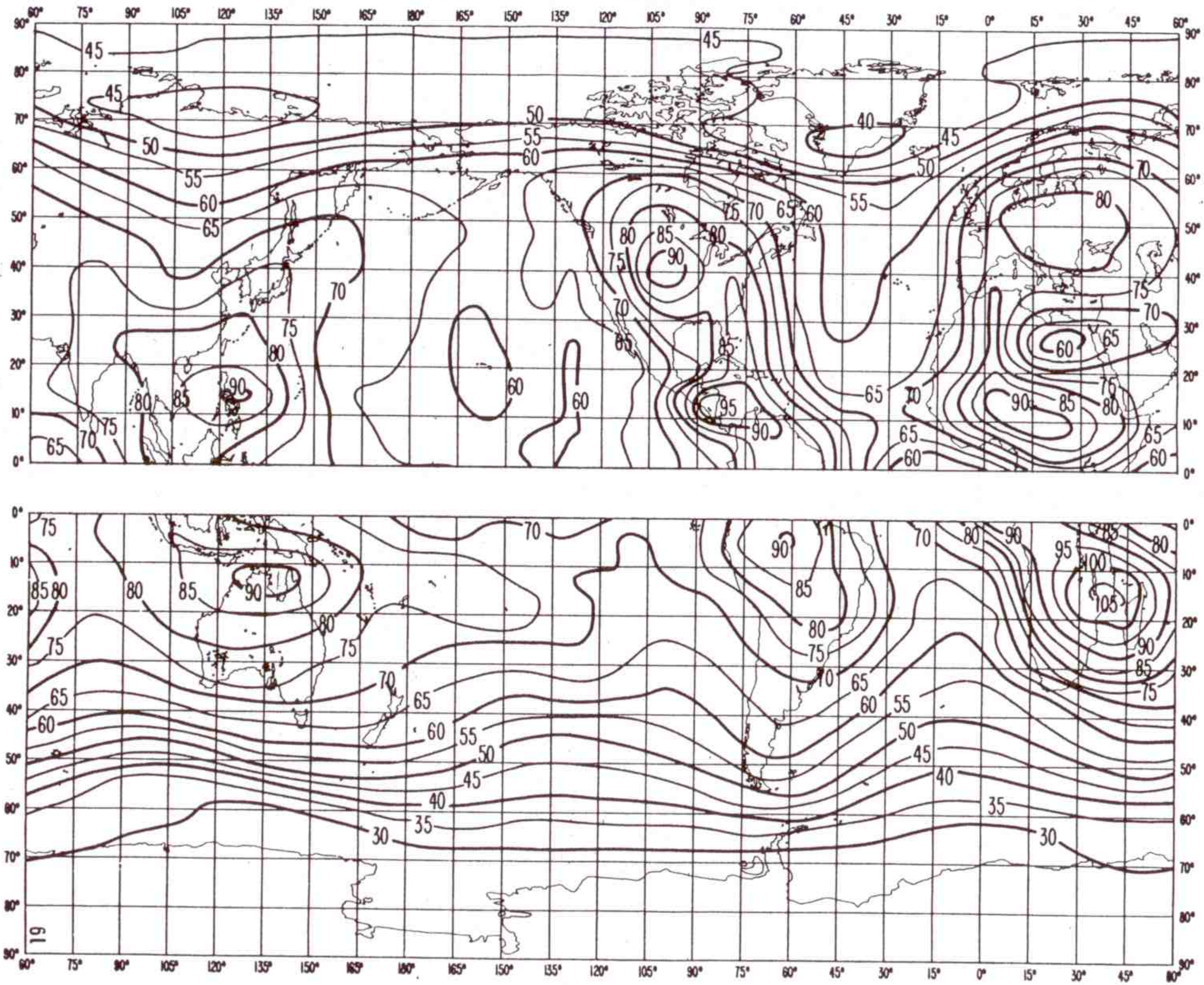
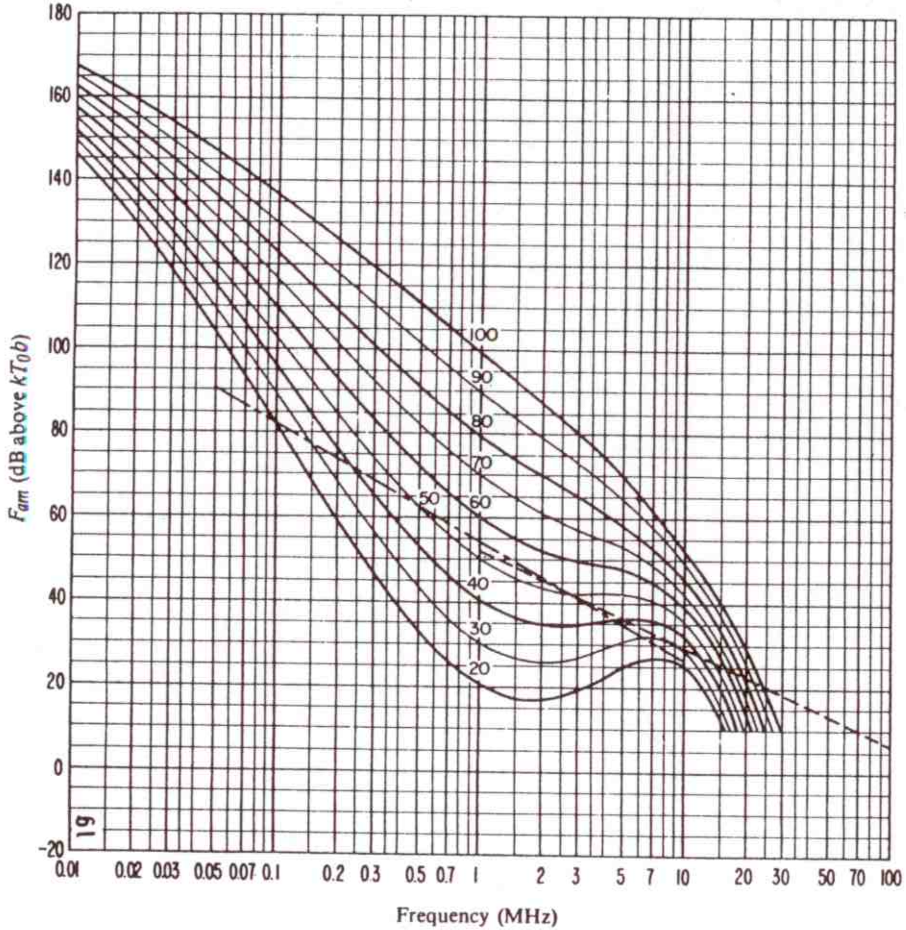


FIGURE 19a – *Expected values of atmospheric radio noise, F_{am} (dB above kT_0b at 1 MHz)*
(Summer; 2000-2400 h)

Figure 4. Figure 19A from CCIR Report 322.



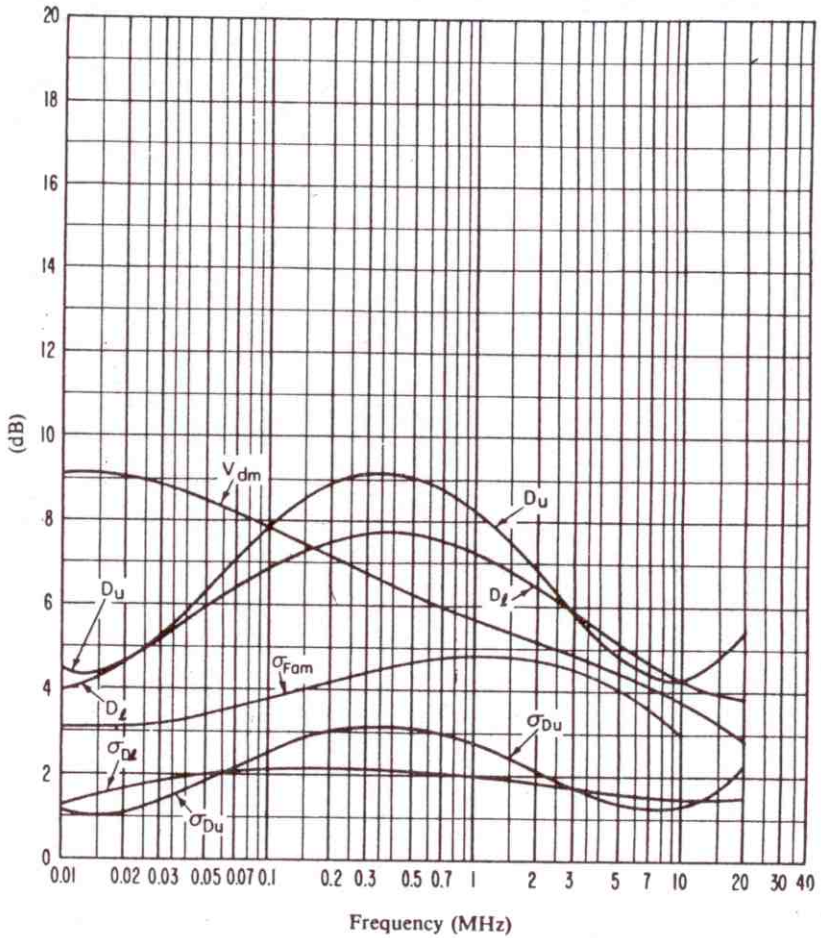
Frequency (MHz)

FIGURE 19b – *Variation of radio noise with frequency*
(Summer; 2000-2400 h)

[solid line] Expected values of atmospheric noise

[dot-dash line] Expected values of man-made noise at a quiet receiving location

[dashed line] Expected values of galactic noise



Frequency (MHz)

FIGURE 19c – *Data on noise variability and character*
(Summer; 2000-2400 h)

σ_{Fam} : Standard deviation of values of F_{am}
D_u : Ratio of upper decile to median value, F_{am}
σ_{Du} : Standard deviation of values of D_u
D_l : Ratio of median value, F_{am}, to lower decile
σ_{Dl} : Standard deviation of value of D_l
V_{dm} : Expected value of median deviation of average voltage. The values shown are for a bandwidth of 200 Hz.

Figure 5. Figure 19B and 19C from CCIR Report 322.

It has been shown that the variation of f_a for a given season and time block can be adequately represented by two log-normal distributions (i.e., dB values normally distributed), one above the median value and one below. Therefore, the variation is given by F_{am}, D_μ, and D_ℓ. This is best explained with an example. Suppose we want F_a and its variation for the summer season, 2000-2400 time block for Boulder, Colorado, at 500 kHz. From Figure 4, the 1 MHz F_{am} value is 90 dB. From Figure 5 then, the 500 kHz F_{am} is 102 dB with D_u = 9.0 dB, D_L = 7.7 dB, σ_{Du} = 3.1 dB, and $\sigma_{D\ell}$ = 2.0 dB. A value for $\sigma_{F_{am}}$ is also given (4.7 dB) and is designed to account for the difference between observations and the results obtained by the numerical mapping routines that produced CCIR Report 322, to account for year-to-year variations, and also to account for the expected variation in the median value when extrapolations were made to geographic areas where measurements did not exist. Figure 6 shows the distribution of F_a values estimated via the data above (F_{am}, D_u, D_ℓ, σ_{Du}, and σ_{D_ℓ}). On Figure 6, all the measured values of F_a measured at Boulder at 500 kHz will essentially lie between the two dotted lines with the solid line being the estimate of the distribution of F_a for this season and time block. The σ_{D_ℓ} and σ_{D_u} values account for the year-to-year variation in D_ℓ and D_μ and also the geographic variation, since only one value of D_u is given for the entire Earth's surface. Now the value of F_a exceeded any percent of time for this season-time block can be determined.

CCIR Report 322 was originally published in 1964 and was an output document of the CCIR Xth Plenary Assembly held in Geneva in 1963. The atmospheric noise data used were the data from the worldwide network of recording stations (Figure 3) through 1961; that is, the data were from July 1957 through October 1961. Since then, much additional data have become available. Data from the worldwide network through November of 1966 and many years of data from 10 Soviet measurement locations are now available along with data from Thailand from March 1966 to February 1968 (Chindahporn and Younker, 1968). All these data have been analyzed and an updated set of atmospheric radio noise estimates produced, essentially in the CCIR Report 322 format. Section 2 of this report covers this analysis and presents, both in graphical and numerical forms, these updated estimates. These estimates are new 1 MHz contour maps (corresponding to Figure 4, for example).

Section 3 reproduces the 24 sets of characteristics from Report 322, of which Figure 5 here is an example, and gives the coefficients for the mathematical version of these characteristics. This is done for completeness, to make this report self-contained, and also, some of these sets of coefficients (e.g., for σ_{Du}) were

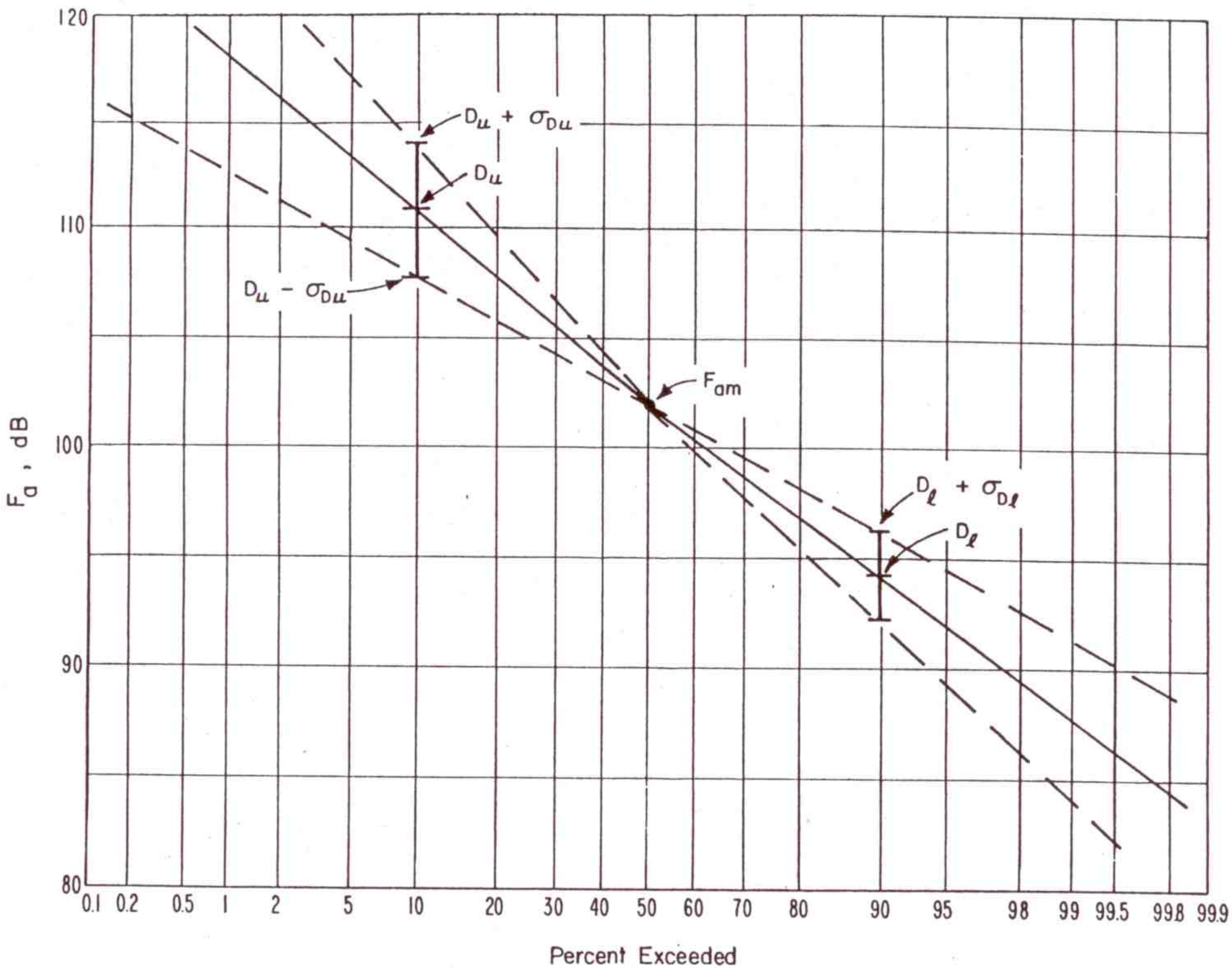


Figure 6. The distribution of F_a values expected at Boulder, Colorado, 500 kHz, for the summer season, 2000-2400 hrs.

not available before. Analysis of the totality of data from the worldwide network of recording stations obtained no significant changes in these characteristics, so this portion of the "new" model is the same as the current CCIR Report 322 model.

Crichlow et al. (1960a) developed a "model" or method for obtaining the APD of the received atmospheric noise envelope from the measured statistical moments V_d and L_d, defined previously. A "most likely" subset of this model became the "CCIR 322" model. Section 4 reviews this model and presents a numerical representation, including bandwidth relationships, since the received APD is a function of receiver bandwidth.

Section 5 then gives a brief summary and Section 6 contains the references. Various computer algorithms (programs) are given throughout the report, where appropriate, that will reproduce all the atmospheric noise characteristics. These programs are given in FORTRAN.

2. THE NEW 1 MHz ATMOSPHERIC RADIO NOISE F_{am} ESTIMATES

As noted in the last section, the existing estimates of atmospheric noise levels and characteristics are contained in CCIR Report 322. These estimates were obtained from measurements made by a worldwide network of 16 recording stations (Figure 3). The measurements were made in a 200 Hz bandwidth on frequencies of essentially .013, .051, .160, .495, 2.5, 5, 10, and 20 MHz. There were some small variations in these frequencies between stations and not all stations had all frequencies for the entire period of measurement. The measurements made from July 1957 through October 1961 were used to produce Report 322. The network continued to operate through November 1966 and longer still for some locations. All these data are contained in the series of NBS Technical Notes No. 18 (July 27, 1959) through 18-32 (October, 1967). This means that there is a great deal of additional analyzed data available from this network to use in producing an updated "322." Data from portions of the network exist past November 1966, but only the analyzed data contained in the NBS Technical Note Series (July 1957-November 1966) are used here. Also, after the publication of Report 322, it was shown that the data from Thule, Greenland, and Byrd Station, Antarctica, were generally contaminated by high levels of local man-made noise. Therefore, data from Thule and Byrd Station were not used in this present analysis.

For a number of years the Soviet Union operated a network of ten noise measurement stations. Data from these measurement locations within the Soviet Union are available from the World Data Center (National Oceanic and Atmospheric Administration, Boulder, Colorado 80303). Raw data are available on microfilm for periods