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Atmospheric noise and its effects on telecommunication system performance

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ATMOSPHERIC NOISE AND ITS EFFECTS ON TELECOMMUNICATION SYSTEM PERFORMANCE

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I. INTRODUCTION

Atmospherics are electromagnetic "signals," impulsive in nature, which means they are spectrally broadband processes. The lightning which radiates these atmospherics radiates most of its energy at frequency at and below HF (3-30 MHz). It is also frequencies at and below HF which are used for long-range communications, since propagation is supported by the earth-ionosphere waveguide. While this means that atmospherics can be used to study this propagation media, 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 is the purpose of this chapter to treat this nature of atmospherics, i.e., the relationships between atmospheric noise and telecommunication systems. It should also be noted that in spite of satellite systems for long-range communications, the use of systems using 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 effecting 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 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 predominate 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 externa` and internal noise, it is convenient to express the resulting noise by means of an overall operating noise factor which characterizes the performance of the entire receiving system. Section II of this Chapter, therefore, defines the receiving system operating noise factor and shows how the internal and external noises must be combined. Section II then gives estimates of the minimum (and maximum) environmental noise levels likely at any location on the earth's surface. The frequency range 0.1 Hz to 100 GHz is covered, and so the interference potential of atmospheric noise can be compared to that of other external noises (e.g., man-made and galactic).

After the broad look of Section II, Section III goes on in much more detail concerning atmospheric noise, giving its level as a function of time and geographic location. In addition, the required statistical characterizations (in addition to level) are defined and examples given. Finally, in Section III, a historical summary of mathematical models for the atmospheric-noise process is given, since, quite often, proper system design requires more information (obtained by modeling) about the process than can be obtained by measurement alone.

The last section (Section IV) summarizes the effects of atmospheric noise on system performance and then gives various means of improving system performance in impulsive noise.

II. WORLDWIDE MINIMUM ENVIRONMENTAL RADIO NOISE LEVELS (0.1 Hz to 100 GHz)

A. Predetection Signal-to-Noise Ratio and Operating Noise Factor

As mentioned in the introduction, it is desirable to express the external noise levels in a form which will allow the external noises to be appropriately combined with noise internal to a telecommunications 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. Also, the noise levels can then be compared to the desired signal leve[l] to determine the predetection signal-to-noise ratio. The predetection signal-to-noise ratio is an important system design parameter and is always required knowled[ge] (required but seldom sufficient) when determining the effects of the external nois[e] 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 which would be observed at the output of block (a) in an actual system (if the terminals were accessible). We can define a receiving syste[m] overall operating noise factor, f, such that $n = fkt_0b$, where k = Boltzmann's constant = 1.38×10^{-23} J/K, t_0 = the reference temperature in K taken as 288K, an[d] 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 dB. The ratio s/n can be expressed:

$$(S/N) = S - N \quad , \qquad (1)$$

where

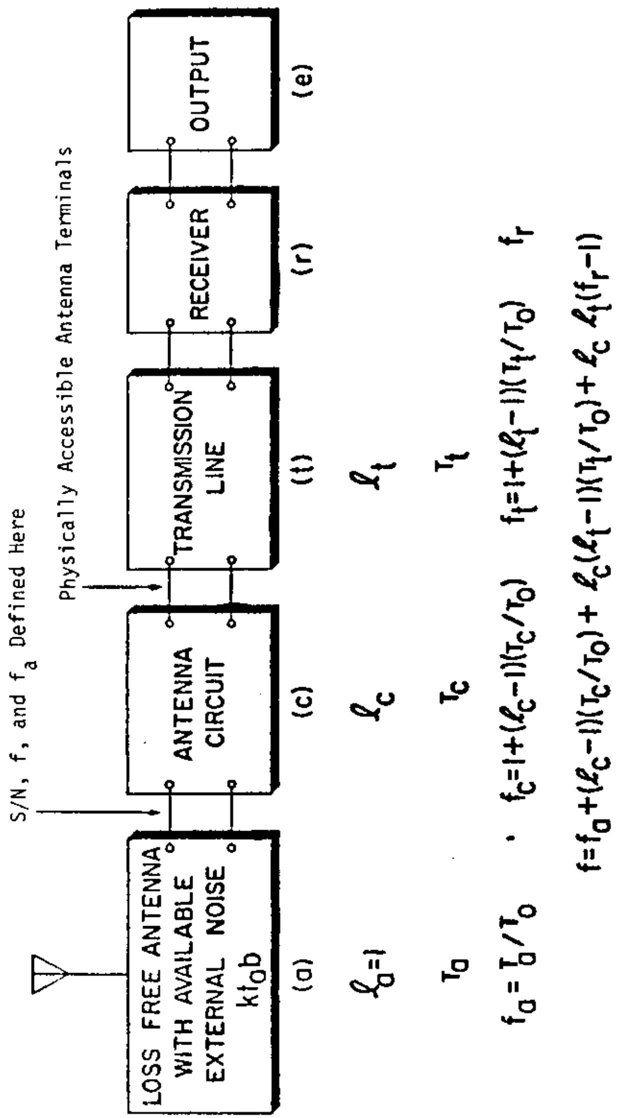


Figure 1. The receiving system and its operating noise factor, f.

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

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

where

f_a = the external noise factor defined as

$$f_a = \frac{p_n}{kt_o b} \quad ; \qquad (3)$$

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 (power available from lossless antenna/power available from actual antenna);

T_c = the actual temperature, in K, of the antenna and nearby ground;

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,

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

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

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

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 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 in bandwidth b and f_{MHz} is the center frequency in MHz. Similar expressions for E_n can be derived for other antennas (Lauber, 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

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

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

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

natural noise are given in Section III of this chapter and on man-made noise in Chapter 7 of this Handbook and CCIR Report 258 (1976).

B. Relationships among F_a, Noise Power, Spectral Density, and Noise Power Bandwidth

Note that f_a is a dimensionless quantity, being the ratio of two powers. The quantity f_a, however, gives, numerically, the available power spectral density in terms of kT_o and the available power in terms of $kT_o b$. The relationship between the noise power, P_n, the noise power spectral density, P_{sd}, and noise power bandwidth, b, are summarized in Figure 2 (from Spaulding, 1976). 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 the minimum value of F_a = 40 dB and b = 10 kHz, then the minimum 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).

C. Estimates of Minimum (and Maximum) Environmental Noise Levels

The best available estimates of the minimum expected values of F_a along with other external noise levels of interest are summarized in this section as a function of frequency. Figure 3 covers the frequency range 0.1 Hz to 10 kHz. The solid curve is the minimum expected values of F_a at the earth's surface based on measurements (taking into account all seasons and times of day for the entire earth), and the dashed curve gives the maximum expected values. Note that in this frequency range there is very little seasonal, diurnal, or geographic variation. The larger variability in the 100-10,000 Hz range is due to the variability of the earth-ionosphere waveguide cutoff.

Figure 4 covers the frequency range 10^4 - 10^8 Hz, i.e., 10 kHz - 100 MHz. The minimum expected noise is shown via the solid curves and other noises that

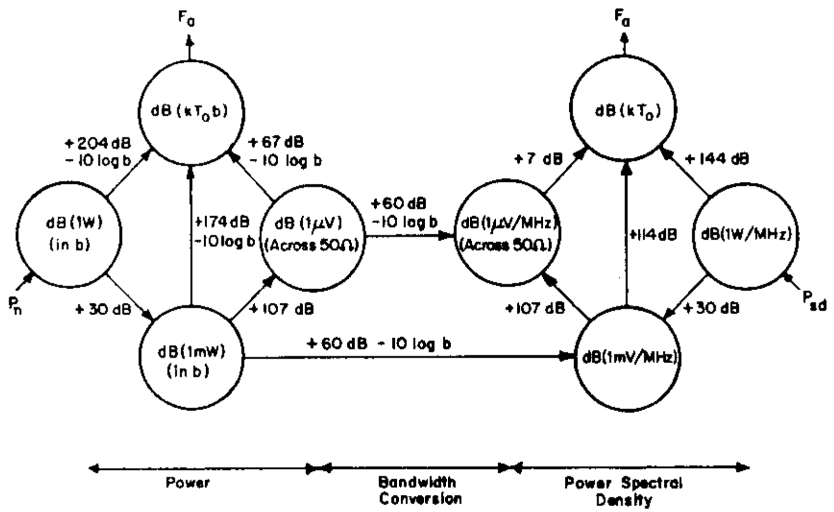
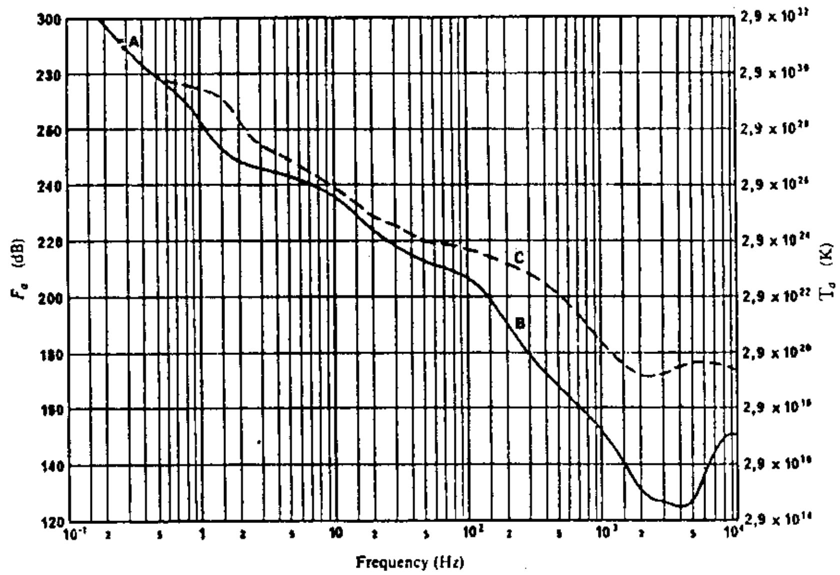
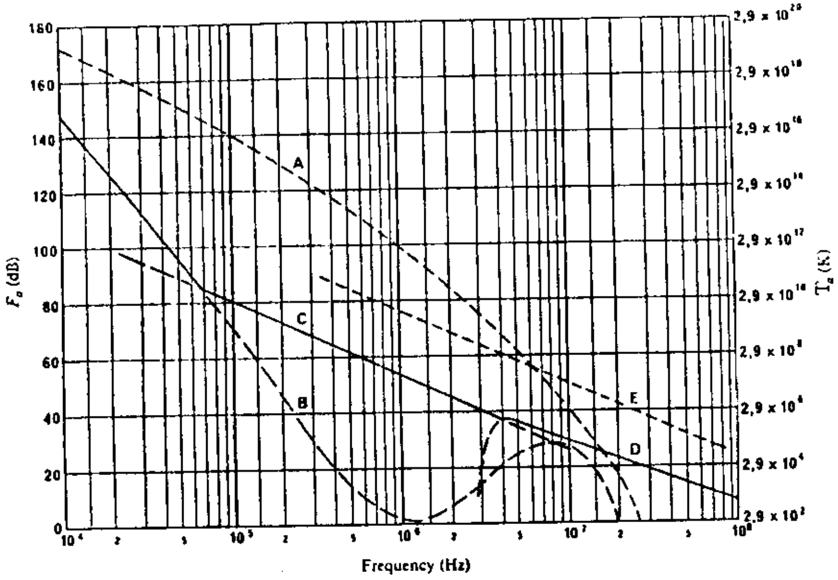


Figure 2. Relationships between power, power spectral density, and noise bandwidth (rms detector).



A: Micropulsations
B: Minimum value expected of atmospheric noise
C: Maximum value expected of atmospheric noise

Figure 3. F_a, minimum and maximum, versus frequency (0.1 to 10^4 Hz).



A: Atmospheric noise, value exceeded 0.5% of time
B: Atmospheric noise, value exceeded 99.5% of time
C: Man-made noise, quiet receiving site
D: Galactic noise
E: Median business area man-made noise
____: Minimum noise level expected

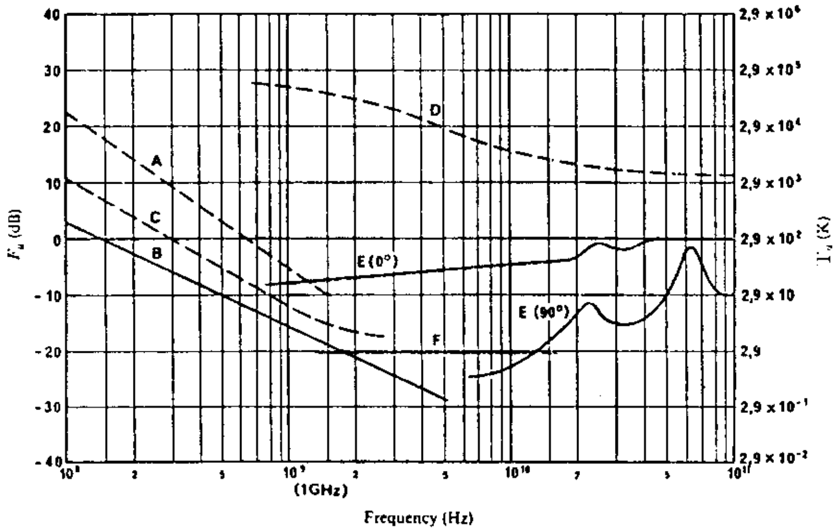
Figure 4. F_a versus frequency (10^4 to 10^8 Hz).

could be of interest as dashed curves. For atmospheric noise ($f > 10^4$ Hz), the minimum values expected are taken to be those values exceeded 99.5% of the time, and the maximum values are those exceeded 0.5% of the time. For the atmospheric noise curves, all times of day, seasons, and the entire earth's surface have been taken into account. More precise details (geographic and time variations) can be obtained from CCIR Report 322 (1963), which is discussed in Section III of this chapter. These atmospheric noise data are average background. Local thunderstorms can cause higher noise levels. The man-made noise (quiet receiving site) is that noise measured at carefully selected, quiet sites worldwide as given in CCIR Report 322. The atmospheric noise below this man-made noise level was, of course, not measured, and the levels shown are based on theoretical considerations [CCIR, 1963, and references therein] and engineering judgment (Crichlow, 1966). Also shown is the median expected business area man-made noise. Further details concerning man-made noise and its variation can be obtained from Chapter 7, CCIR Report 258 (1976), Spaulding and Disney (1974) and references therein, and Hagn and Shepherd (1974).

On Figure 5, the frequency range 10^8 - 10^{11} is covered, i.e., 100 MHz - 100 GHz. Again, the minimum noise is given by solid curves while some other noises of interest are again given by dashed curves.

The majority of the results shown on the three figures is for omni-directional vertically polarized antennas (except as noted on the figures). The average value of F_a for directional antennas will be the same if we assume random direction. Studies have indicated that at HF (for example), for atmospheric noise from lightning, there can be as much as 10 dB variation (5 dB above to 5 dB below the average F_a value shown) with direction for very narrowbeam antennas.

For galactic noise, the average value (over the entire sky) is given by the solid curve labeled galactic noise (Figures 4 and 5). Measurements indicate a ±2 dB variation about this curve. The minimum galactic noise (narrowbeam antenna towards galactic pole) is 3 dB below the solid galactic noise curve shown on Figure 5. The maximum galactic noise for narrowbeam antennas is shown via a dashed curve on Figure 5.



A: Estimated median business area man-made noise
B: Galactic noise
C: Galactic noise 9toward galactic center with infinitely narrow beamwidth)
D: Quiet sun (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: Black body (cosmic background), 2.7 K
_____: Minimum noise level expected

Figure 5. F_a versus frequency (10^8 to 10^{11} Hz).

D. Example Determination of Required Receiver Noise Figure

We now want to consider a simple example to show how to determine the required receiver noise figure. At 10 kHz, for example, the minimum external noise is F_a = 145 dB (see Figure 4). If we assume $t_c = t_t = t_o$, and $\ell_c = \ell_t = 1$ (that is, no antenna or transmission line losses), then

$$f = f_a - 1 + f_r \quad . \tag{11}$$

We can take f_r to be that value which will increase F by only 1 dB. This gives us a noise figure, F_r, of <u>140 dB</u> or an overall noise figure, F, of 147 dB. Any smaller noise figure, F_r, no matter how small, cannot decrease F below 146 dB. Consider now that $\ell_c = \ell_t$ = 100--i.e., 20 dB antenna losses and 20 dB transmission losses. Then,

$$f = f_a - 1 + 10000\, f_r \quad . \tag{12}$$

In order to raise the F no more than 1 dB (to 147 dB) for the above situation, F_r can only be as large as <u>100 dB</u>. As this example shows, it makes no sense to attempt to use sensitive receivers at low frequencies.

As another example, consider a VHF receiver at 100 MHz. The minimum noise level is now due to galactic noise and is approximately an F_a of 7 dB. Suppose that ℓ_c = 100 and ℓ_t = 1; now, in order not to raise F more than 1 dB, F_r can only be as large as <u>-19.8 dB</u>.

In the first example above, the interfering noise was atmospheric noise, and in the second example the noise was galactic. These two types of noise are quite different in character--atmospheric noise being very impulsive and galactic noise being white Gaussian. Correspondingly, these two types of noise will affect system performance quite differently, even if they have the same level (i.e., available power). In specifying system performance, the detailed statistical characteristic of the noise must be taken into account. One consequence of this is that the external noise can still limit performance even though the receiver noise

(Gaussian in character) is made as high as possible so as not to increase the overall operating noise factor f. System performance depends on more than the noise level, and so far we have considered only noise level via f_a. In Sections III and IV of this chapter, then, we continue on, taking a closer look at the character of atmospheric noise and its effects on system performance as well as some techniques to overcome degradation caused by impulsive noise.

III. WORLDWIDE ATMOSPHERIC RADIO NOISE ESTIMATES

A. Introduction

In the previous section we defined f_a (and t_a), the most useful and common way of specifying the external noise level. We also noted that 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. In Section B following, then, we will define these more detailed statistics which are required and show, via examples for atmospheric noise, their general characteristics. Having the definitions in hand, Section C will discuss CCIR Report 322, which gives the available worldwide estimates for atmospheric noise, its level, f_a, and also the most useful statistic, the amplitude probability distribution of the received noise envelope along with the time, frequency, and geographic variations of these parameters.

Since the impulsive atmospheric noise can have serious effects on the performance of communication systems, various techniques can be used to minimize these effects. This means that receiving systems must be designed to function as well as possible in impulsive noise. In general, in order to carry out such system designs, more knowledge about the noise process is required than can be obtained by measurement alone. Therefore, Section D gives a summary of the mathematical models that have been developed for the atmospheric noise process. In addition to system performance and design problems, some of these models can be used, coupled with measured noise data, to study various geophysical phenomena such as radio wave propagation, thunderstorm occurrence rates, the nature of lightning, etc.

B. Definition and Examples of Measured Received Atmospheric Noise Envelope Statistics

Atmospheric 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 any collection of deterministic waveforms. In addition, atmospheric noise is basically nonstationary; therefore, great care must be exercised in the planning and making of measurements and in the interpretation of the results. We must measure long enough to obtain a good estimate of the required parameter but be certain that the noise remains "stationary enough" during this period. This is no small point and is frequently overlooked in the design of measurement experiments. We assume that the random noise process is stationary enough over some required time period for us to obtain the required statistics. Of course, how these statistics then change with time, as from day to day, as well as with location, now becomes important.

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

Although a random process, X(t), is said to be completely described if its hierarchy of distributions is known, there are other important statistical properties (important to communications systems) which are not immediately implied by this hierarchy. Moments and distributions of level crossings of X(t) within a time interval, moments and distributions of the time interval between successive crossings, distribution of extremes in the interval, and so on are typical examples.

We now want to define, in a unified way, the atmospheric noise parameters that have been measured and their interrelationships.

For analysis of a communication system, the noise process of interest is the one seen by our receiving system. This means that we are almost always interested in "narrowband" noise processes. A narrowband process results whenever that bandpass of the system is a small fraction of the center frequency, f_c, and means that the received noise is describable in terms of its envelope and phase as shown on Figure 6. The noise process, x(t), at the output of a narrowband filter is given by

$$x(t) = v(t) \cos[\omega_c t + \phi(t)] \quad ,$$

where v(t) is the envelope process and $\phi(t)$ is the phase process. For atmospheric noise in the absence of discrete signals, ϕ is uniformly distributed; that is

$$p(\phi) = \frac{1}{2\pi} \quad , \quad -\pi \le \phi < \pi \quad .$$

Therefore, we will concentrate on the statistics of the envelope process, v(t). In general, for system analysis, the required statistics that determine performance are either the envelope statistics directly or are obtainable from the envelope and phase statistics. For noise from some discrete sources or for general background atmospheric noise plus interfering signals, $\phi(t)$ is not uniformly distributed, and the statistics of the $\phi(t)$ process must also be known.

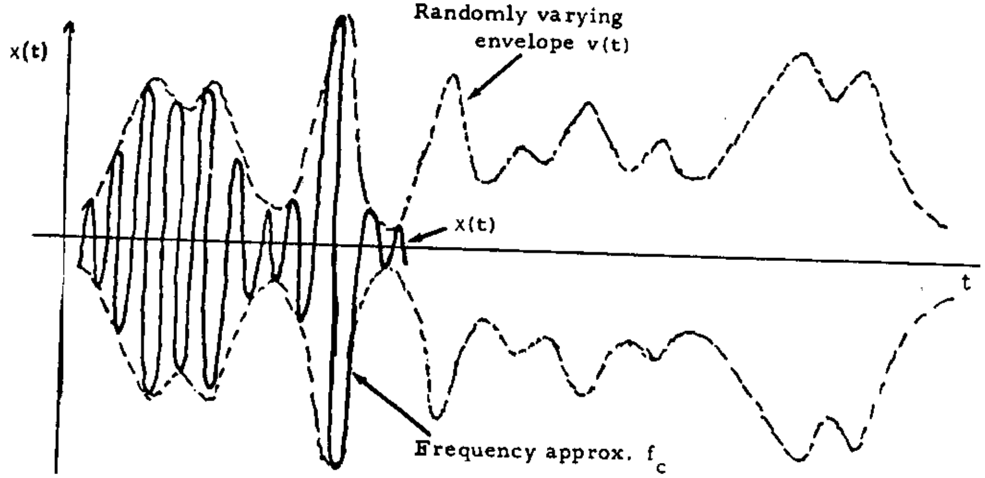


Figure 6. Noise at the output of a narrowband filter.

As an example, let x(t) (Figure 6) be a white Gaussian process, then the pdf's for x, v, and ϕ are

$$p(x) = \frac{1}{\sqrt{\pi N_0}} \exp\left[-\frac{x^2}{N_0}\right] ,$$

$$p(v) = \frac{2v}{N_0} \exp\left[-\frac{v^2}{N_0}\right] , \quad v \geq 0 ,$$

$$p(\phi) = \frac{1}{2\pi} , \quad -\pi \leq \phi < \pi ,$$

where N_0 is the noise power spectral density (watts/Hz). That is, the envelope voltage v is Rayleigh distributed and the phase is uniformly distributed.

Figure 7 shows the noise envelope of a sample of atmospheric noise along with definitions of the various noise parameters that have been measured. From Figure 7 we have:

The amplitude probability distribution (APD) is the fraction of the total measurement time, T, for which the envelope was above level v_i;

$$D(v) = \text{Prob}[v \geq v_i] = 1 - P(v) ,$$

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

The average crossing rate characteristic (ACR) is the average number of positive crossings of level v_i = total number/T. For impulsive noise and at high envelope voltage levels, an average noise pulse rate (pulses/sec) at the receiver input can be inferred from the ACR. The requirement for the pulse rate to be essentially equal to the ACR is that the noise envelope (at the level v_i) be composed of isolated filter impulse responses (URSI, 1962).

The pulse spacing distribution (PSD) for level v_i is the fraction of pulse spacings at level v_i that exceeds time τ. That is, the PSD is the distribution for the random variable τ.

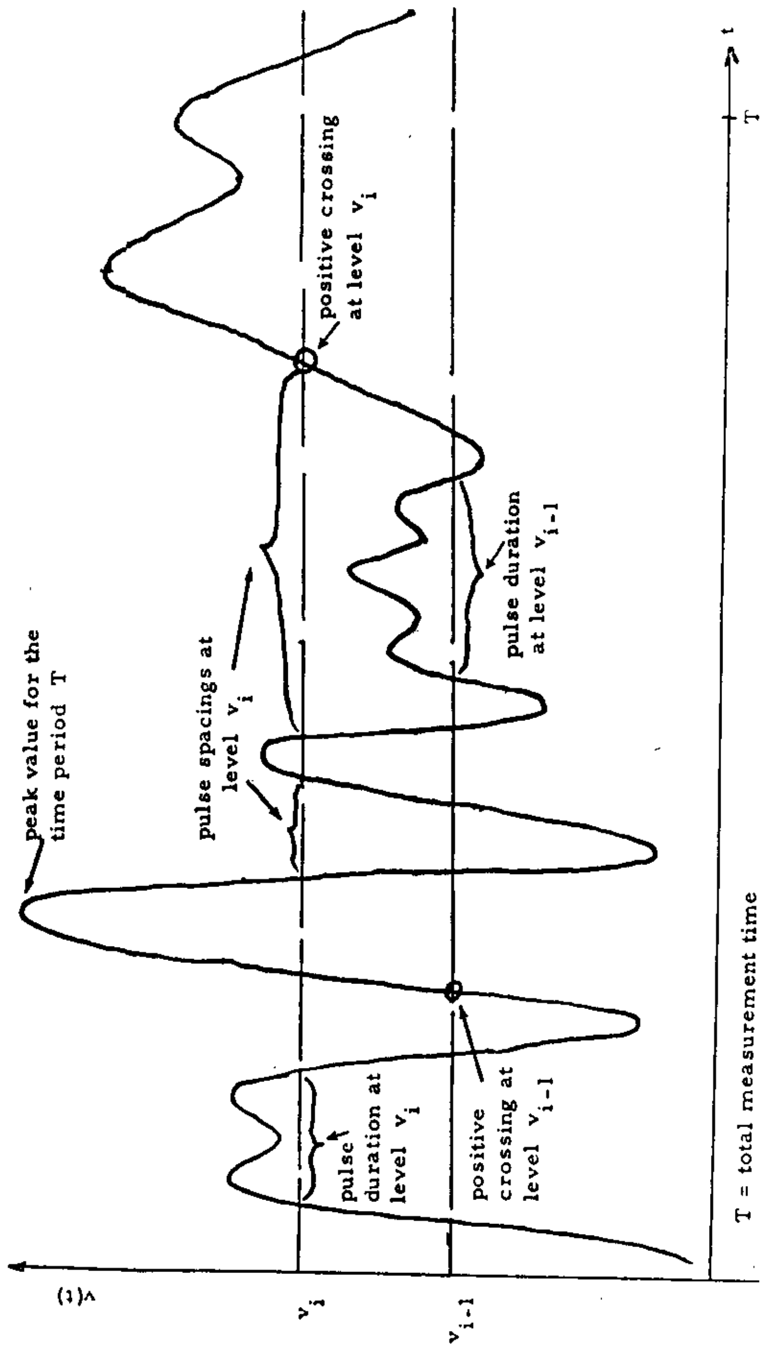


Figure 7. Noise envelope of a sample of atmospheric noise.

The pulse duration distribution (PDD) for level v_i is the fraction of pulse durations at level v_i that exceeds time τ.

To specify time dependence in the received waveform, the autocorrelation function, $R(\tau)$, is used.

$$R(\tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v_1 v_2 \, p_2(v_1,v_2,\tau) \, dv_1 dv_2$$

$$= \lim_{T \to \infty} \frac{1}{T} \int_0^T v(t) \, v(t+\tau) \, dt \quad ,$$

where v_1 is $v(t)$ at time t_1, v_2 is $v(t)$ at t_2, and $\tau = t_2 - t_1$, with $p_2(v_1,v_2)$ the 2nd order pdf of $v(t)$. The autocovariance of $v(t)$ is the covariance of the random variables $v(t_1)$ and $v(t_2)$. For zero mean processes, the autocorrelation and autocovariance are identical.

The power spectral density, $S(\omega)$, for a stationary random process is given by the Fourier transform of $R(\tau)$. This is similar to the Fourier transform pair relationship between the time domain representation and the frequency domain representation of deterministic waveforms. Note, however, that while for deterministic waveforms the spectrum gives the amplitude of each frequency component and its phase, no phase information is possible for the spectrum of a random process. If the process is time independent (correlated only for τ=0), then

$$R(\tau) = N_0 \, \delta(\tau - 0)$$

and

$$S(\omega) = N_0 \quad .$$

Noise with the above property is termed "white."

The average envelope voltage is termed the expected value of v, $E[v]$;

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

where

$$-dD(v) = p(v) \, dv \quad .$$

The rms voltage squared (proportional to energy or power), $E[v^2]$, is

$$v^2_{rms} = E[v^2] = \frac{1}{T}\int_0^T v^2(t) \, dt = -\int_0^{\infty} v^2 \, dD(v) \quad .$$

The average logarithm of the envelope voltage, $E[\log v]$, is

$$v_{\log} = E[\log v] = \int_0^T \log v(t) \, dt = -\int_0^{\infty} \log v \, dD(v) \quad .$$

The peak voltage for time period T is the maximum of $v(t)$ during T.

Because the rms voltage level can be given in absolute terms (i.e., rms field strength or available power as given in Section 2.1), 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,

$$V_d = -20 \log \frac{v_{av}}{v_{rms}} \quad .$$

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

$$L_d = -20 \log \frac{10^{v_{\log}}}{v_{rms}} \quad .$$

Knowledge of the behavior of the above statistics with time and location is also important.

Figures 8 and 9 show a 200 ms sample of atmospheric noise taken from a 6minute noise recording at 2.5 MHz in a 4 kHz bandwidth and the autocorrelation for this sample. Note from the autocorrelation that some time correlation (for small τ) is indicated. While some samples of atmospheric noise show no time correlation, the situation depicted in Figure 9 can be considered to be typical for atmospheric noise. Figures 10, 11, 12, and 13 show the APD, ACR, PDD, and PSD for this 6-minute

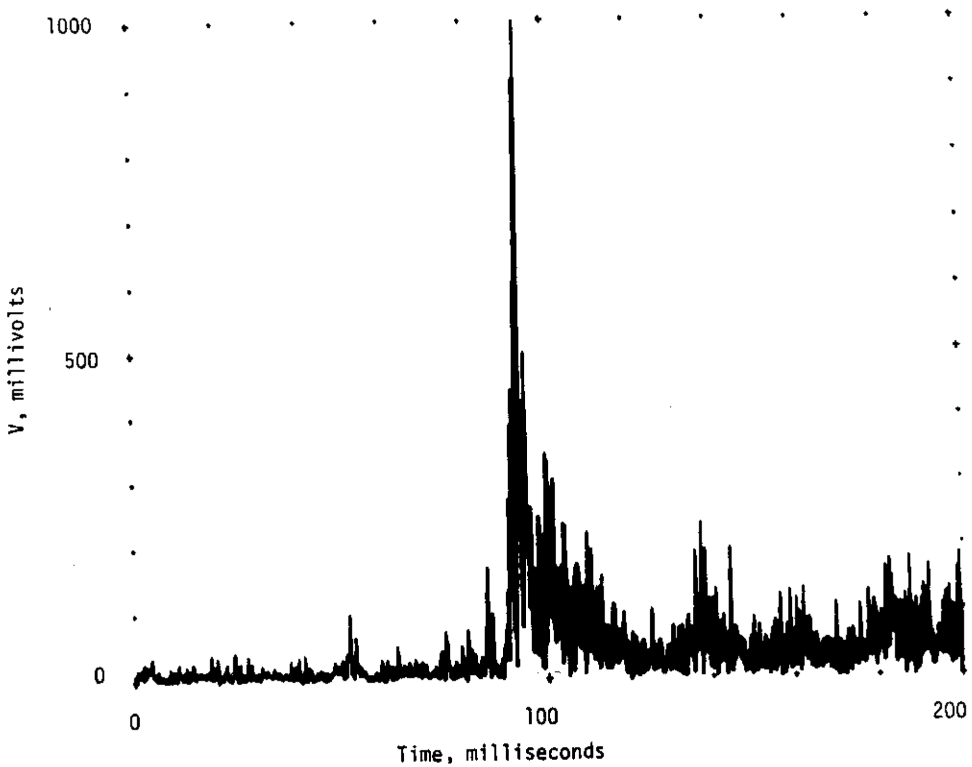


Figure 8. Randomly selected 200 ms sample of atmospheric noise envelope from a 6-min noise recording at 2.5 MHz in a 4 kHz bandwidth.

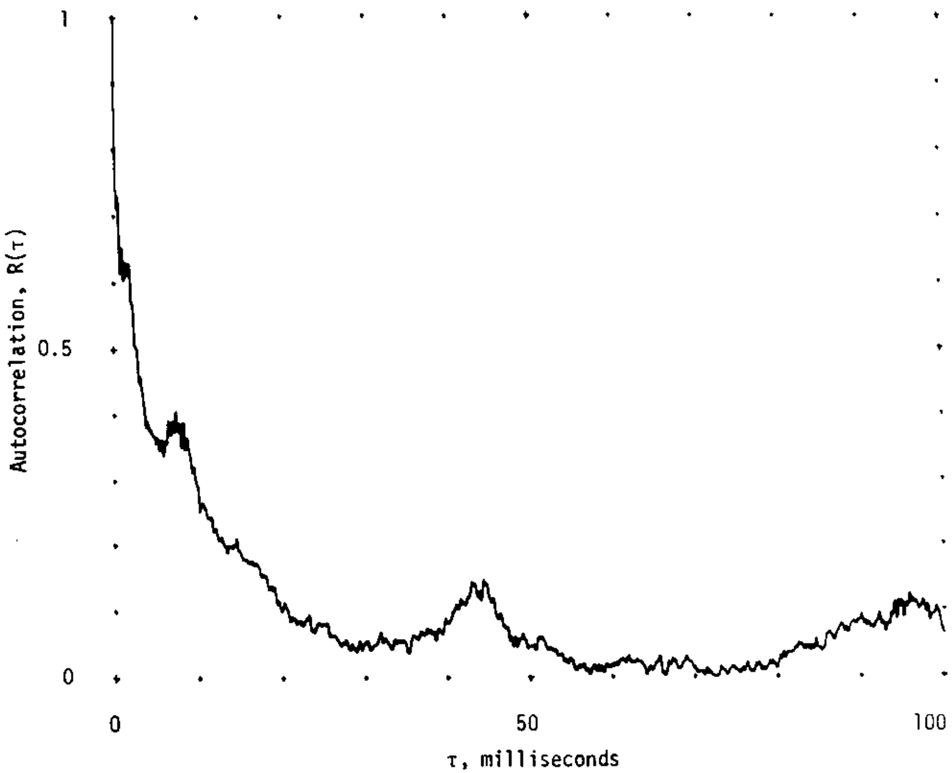


Figure 9. Autocorrelation for the noise sample of Figure 8.

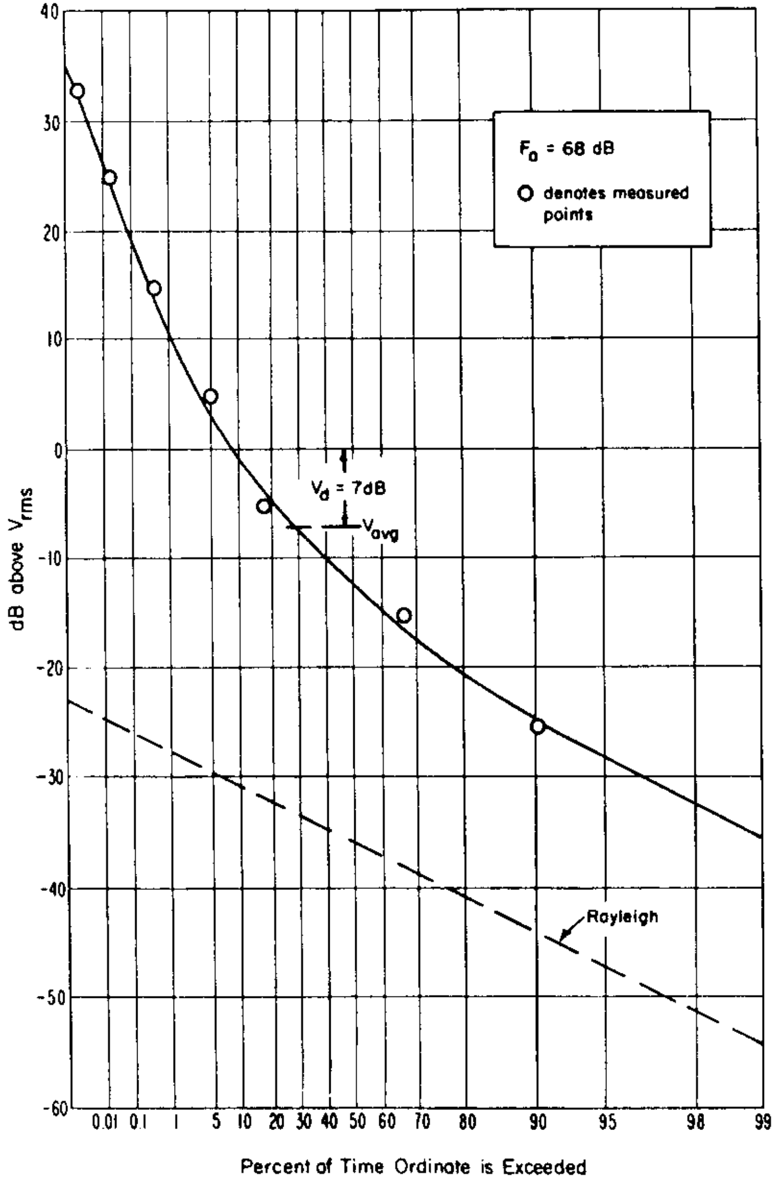


Figure 10. Amplitude probability distribution for a 6-min sample of atmospheric noise recorded at 2.5 MHz in a 4 kHz bandwidth.

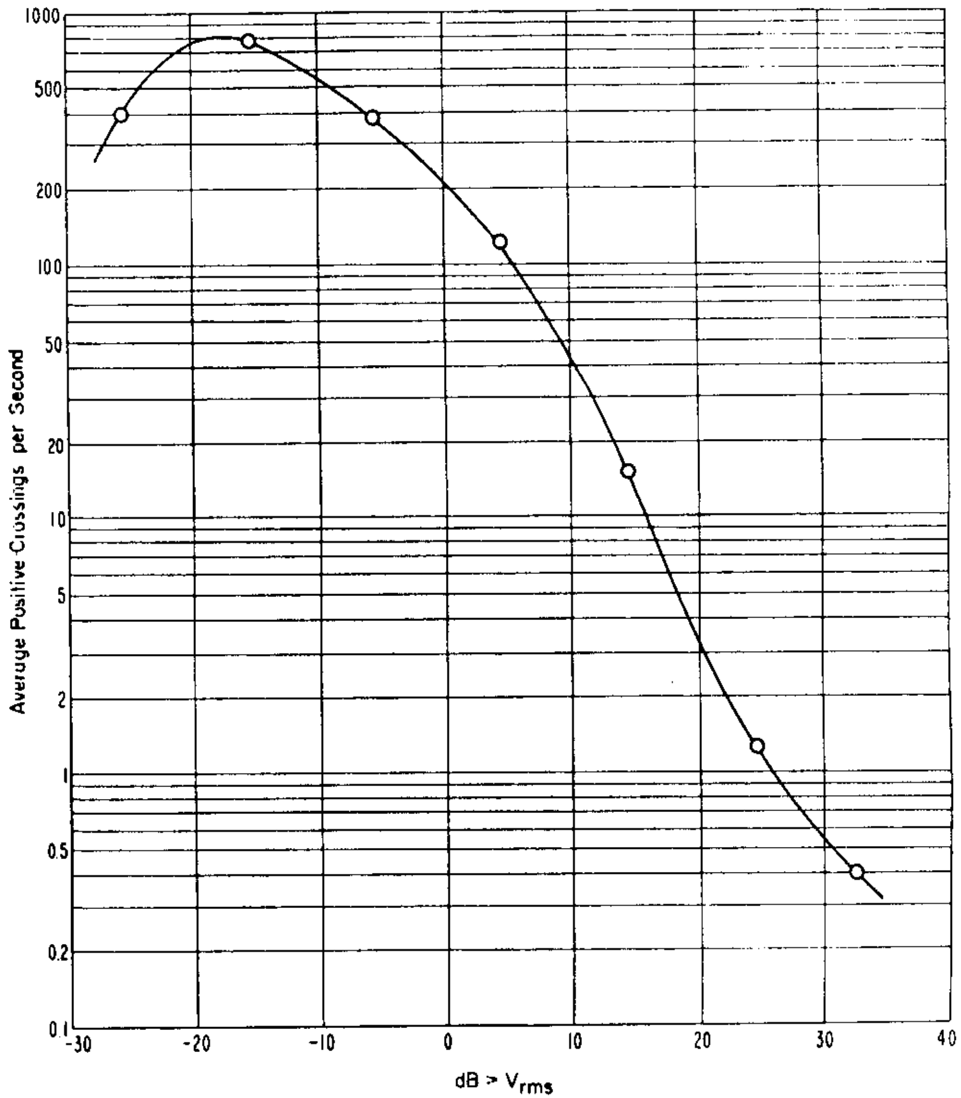


Figure 11. Average positive crossing rate characteristic for the sample of noise of Figure 10.

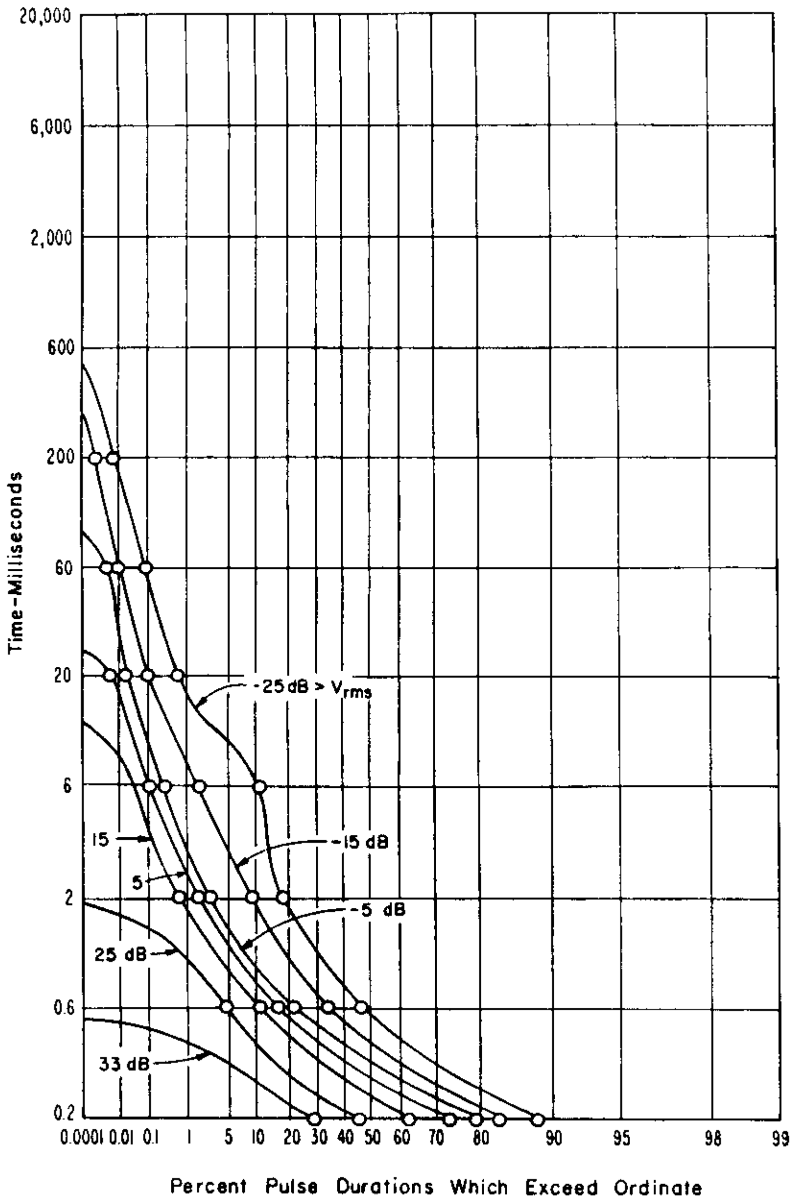


Figure 12. Pulse duration distributions for the sample of noise of Figure 10.

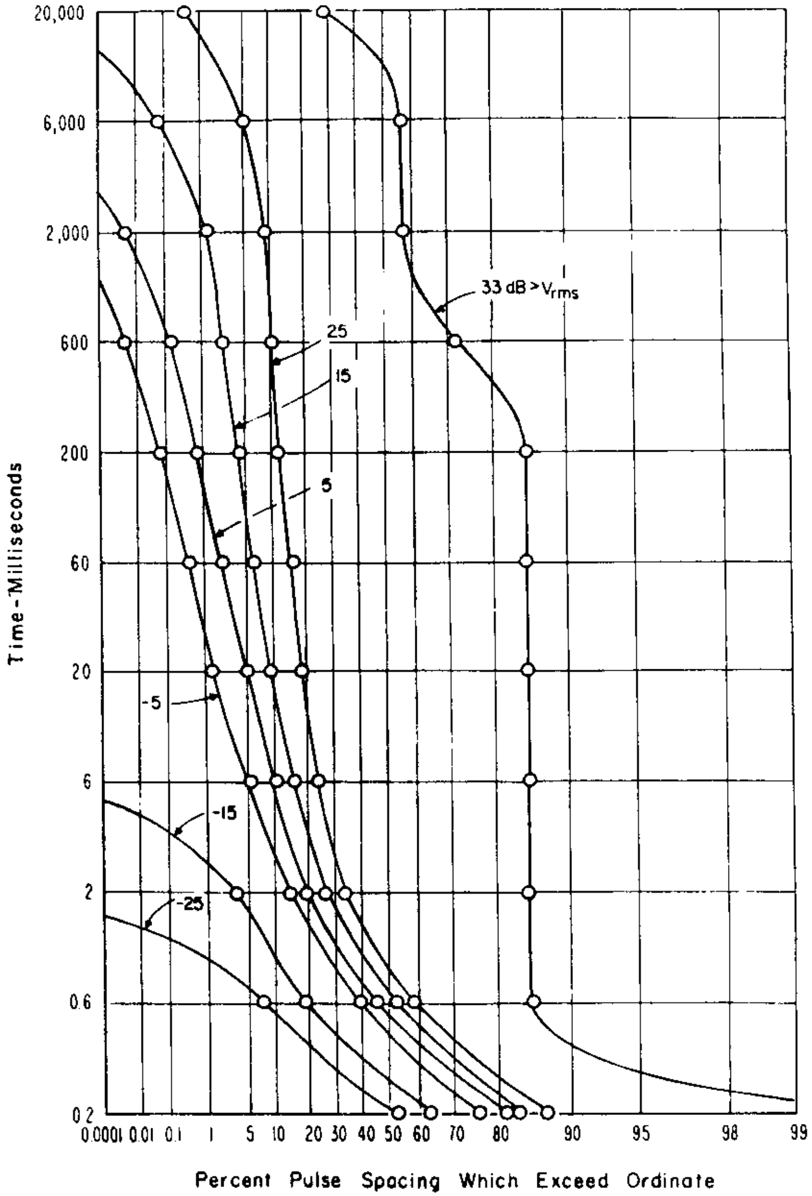


Figure 13. Pulse spacing distributions for the sample of noise of Figure 10.

sample of atmospheric noise. In Figure 10 the dashed curve is that for a Rayleigh distribution (envelope of Gaussian noise). The impulsive nature of atmospheric noise at 2.5 MHz can easily be seen from Figure 10. In general, atmospheric noise is much more impulsive still (larger dynamic range) at lower frequencies (e.g., LF, MF, etc.). This example of the statistics of the received atmospheric noise was selected to only give a general "feel" of the statistical nature of atmospheric noise. Even so, the example shown is quite typical.

C. CCIR Report 322

Previously, the various atmospheric noise parameters that have been measured were defined and examples given. 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 15 identical recording stations. Figure 14 shows the location 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_u and D_ℓ, the upper and lower decile values; i.e., the values exceeded 10% and 90% 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 fall (September, October, November) and six 4hr time blocks (0000-0400, etc.).

A method was developed to obtain the APD from the measured statistical moments V_d and L_d (Crichlow et al., 1960a,b). Later it was shown that for atmospheric noise there is strong correlation between V_d and L_d, and a good approximation of the APD could be obtained from V_d alone (Spaulding et al., 1962). Also, a means of converting the APD from one bandwidth to another was developed (Spaulding et al., 1962). It has since been shown, based on numerous measurements, that this bandwidth conversion method is strictly valid for only small changes in bandwidth (5 to 1, say).

In 1963, CCIR Report 322, World Distribution and Characteristics of Atmospheric Radio Noise, was published by the International Telecommunications Union 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 14. The expected APD for various values of V_d (1.05 dB for Rayleigh to 30 dB) are also given along with the expected variation in the APD.

Figure 15 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 16 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 16 here). The expected APD for a given V_d is given in Figure 17 (which is Figure 27 of Report 322). 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 reproduce all of Report 322. This numerical representation is also contained in the ITU HF propagation prediction programs. A numerical representation (computer program) of the APD as a function of V_d is also available (Akima, 1972).

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 via an example. Suppose we want F_a and its variation for the summer season, 2000-2400 time block for Boulder, Colorado, at 500 kHz. [As mentioned in Section II, F_a is independent of bandwidth.] From Figure 15, the 1 MHz F_{am} value is 90 dB. From Figure 16 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 18 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 18, all the measured values of F_a measured at Boulder at 500 kHz

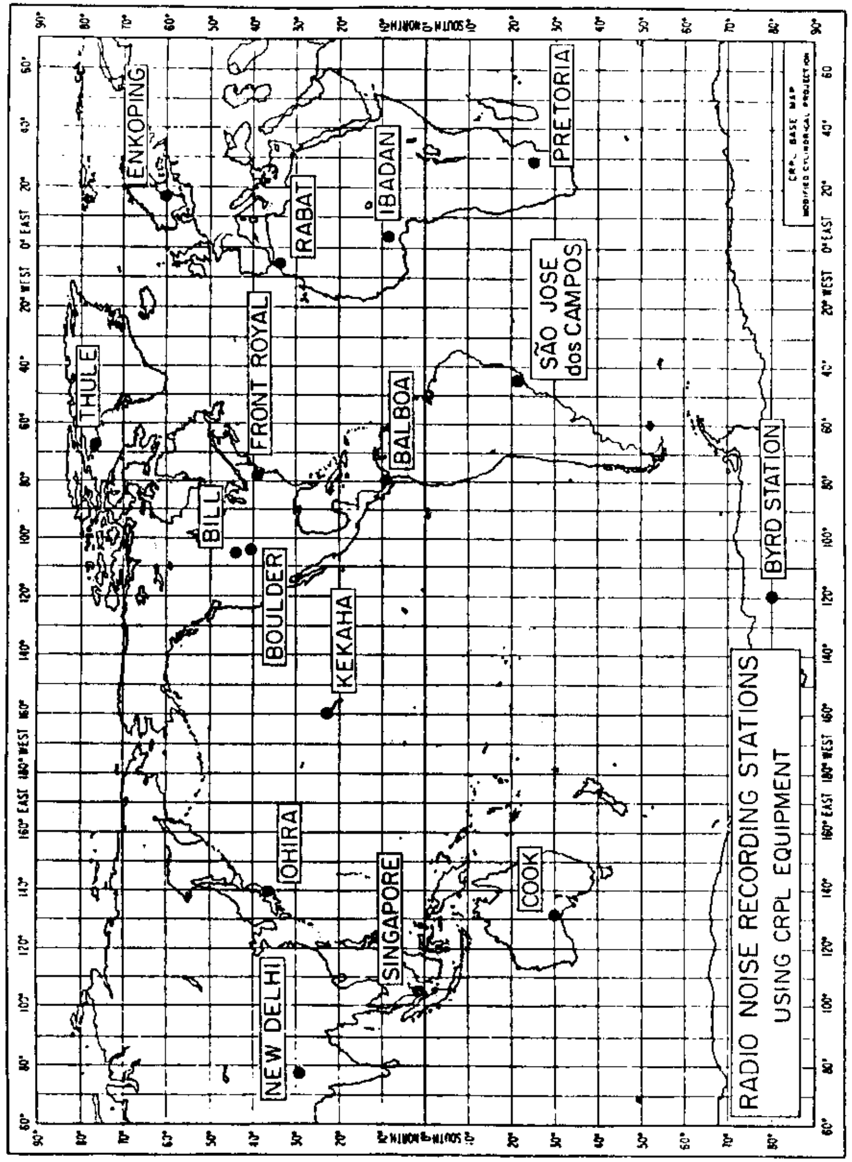


Figure 14. Radio noise recording stations used to obtain most of the data used for CCIR Report 322.

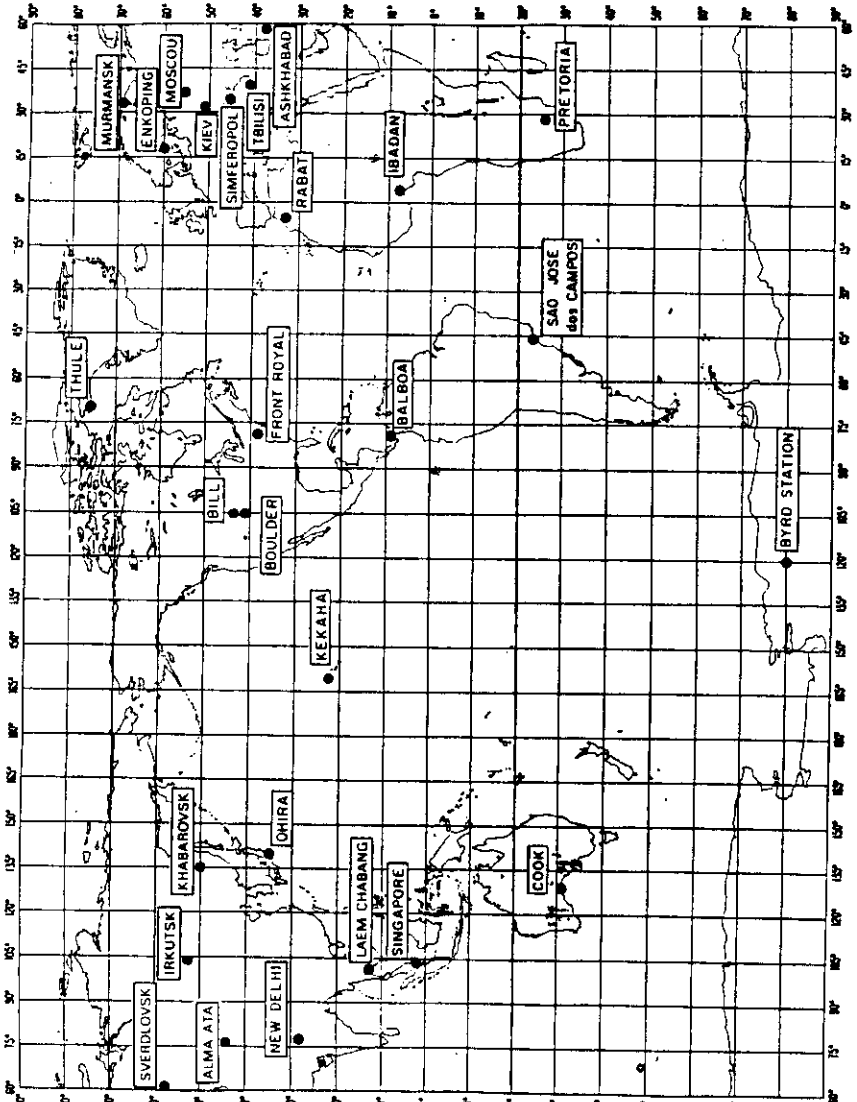


FIGURE 1 – *Stations qui ont fourni des données de bruit radioélectrique*
FIGURE 1 – *Stations which provided radio noise data*
FIGURA 1 – *Estaciones de medida que han suministrado datos del ruido radioeléctrico*

Figure 14A

R 322-3 / Rep. 322-3 / I. 322-3

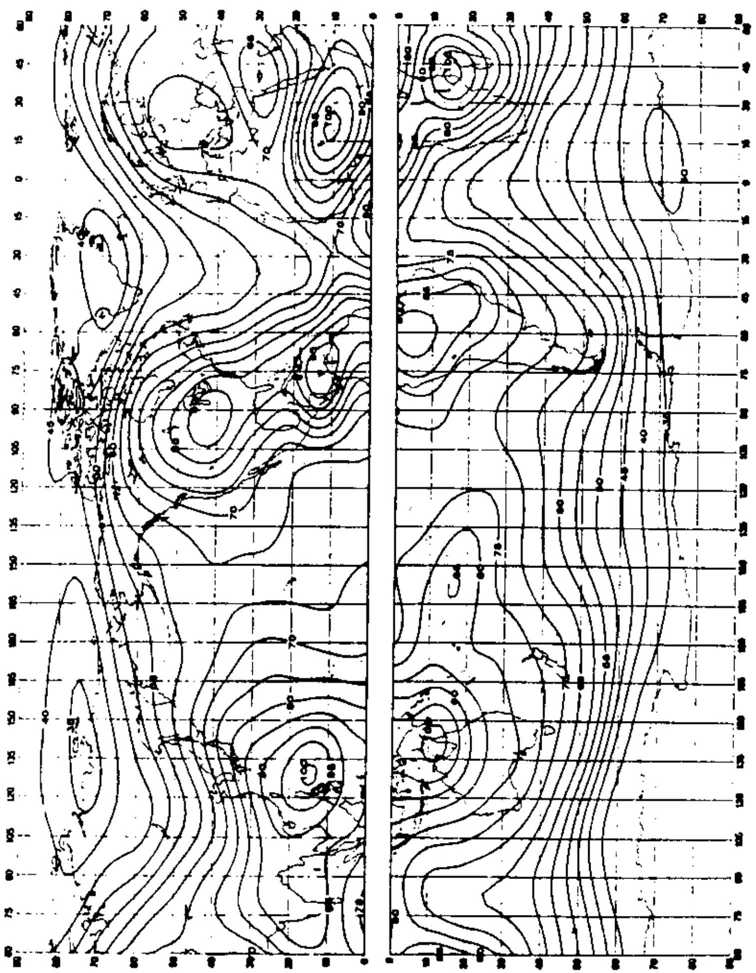


FIGURE 19a – *Valeurs attendues du bruit atmosphérique radioélectrique, F_{am}, en dB au-dessus de kT_0b à 1 MHz (Eté; 2000-2400 heure locale)*
FIGURE 19a – *Expected values of atmospheric radio noise, F_{am} (dB above kT_0b at 1 MHz) (Summer; 2000-2400 LT)*
FIGURA 19a – *Valores probables del ruido atmosférico, F_{am}, en dB por encima de kT_0b en 1 MHz (Verano; 2000-2400 hora local)*

Figure 15. Figure 19A from CCIR Report 322-3

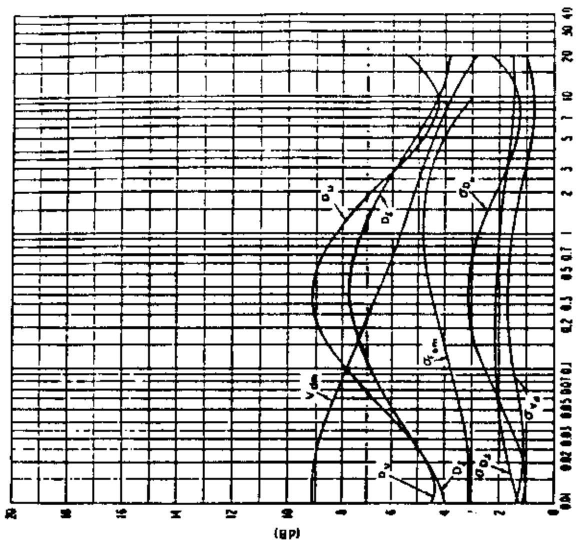


FIGURE 19c – *Données sur la variabilité et le caractère du bruit (Été; 2000-2400 heure locale)*
FIGURE 19c – *Data on noise variability and character (Summer; 2000-2400 LT)*
FIGURA 19c – *Datos sobre la variabilidad y el carácter del ruido (Verano; 2000-2400 hora local)*

Voir la légende de la Fig. 2c/See legend of Fig. 2c/Véase la leyenda de la fig. 2c

Figure 16, Figure 19b from CCIR Report 322-3

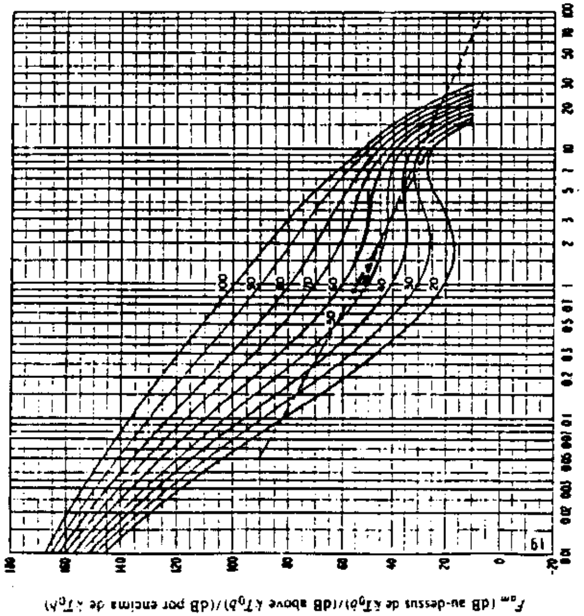


FIGURE 19b – *Variation du bruit radioélectrique en fonction de la fréquence (Été; 2000-2400 heure locale)*
FIGURE 19b – *Variation of radio noise with frequency (Summer; 2000-2400 LT)*
FIGURA 19b – *Variaciones del ruido radioeléctrico con la frecuencia (Verano; 2000-2400 hora local)*

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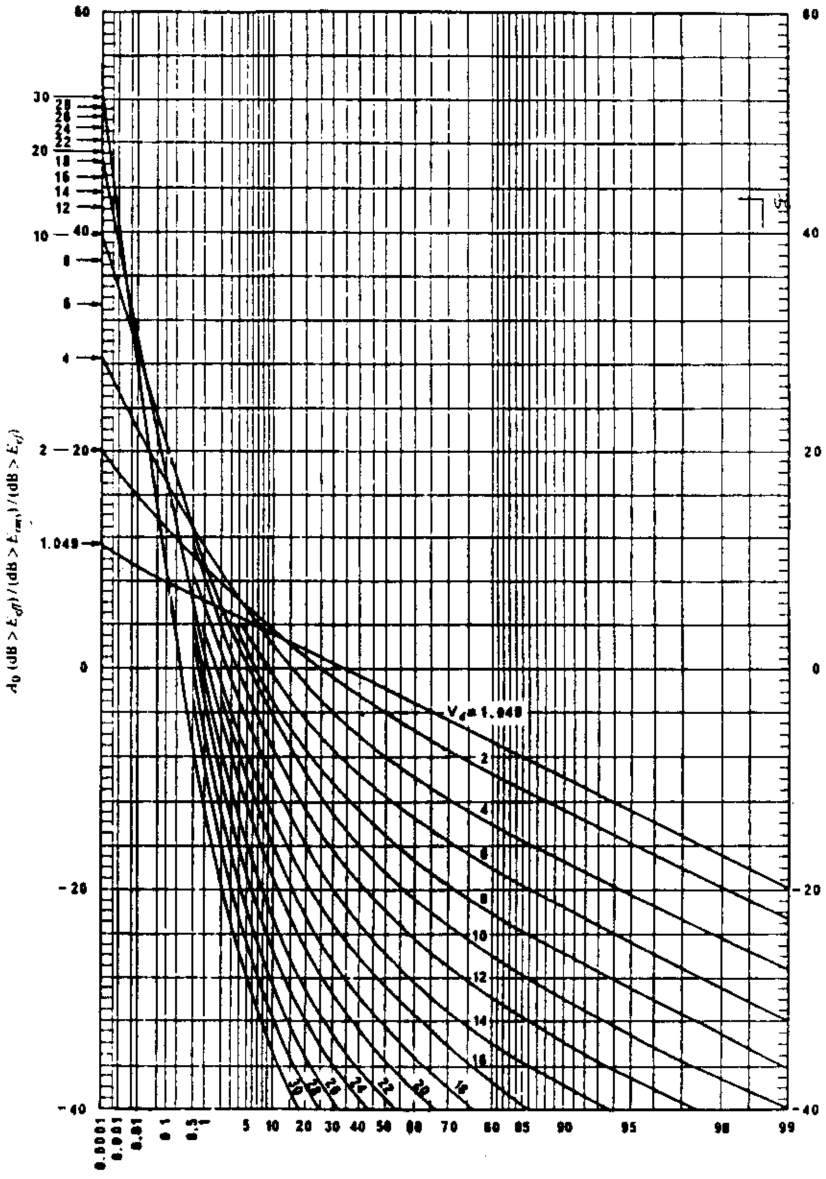

Pourcentage du temps pendant lequel la valeur de l'ordonnée est dépassée/Percentage of time ordinate exceeded/Porcentaje de tiempo durante el cual se rebasa el valor de ordenadas

Figure 17, Amplitude probability distributions for atmospheric radio noise for various V_d values

Figure 17a. Translation of a 200 Hz bandwidth V_{dm} to other bandwidths, b

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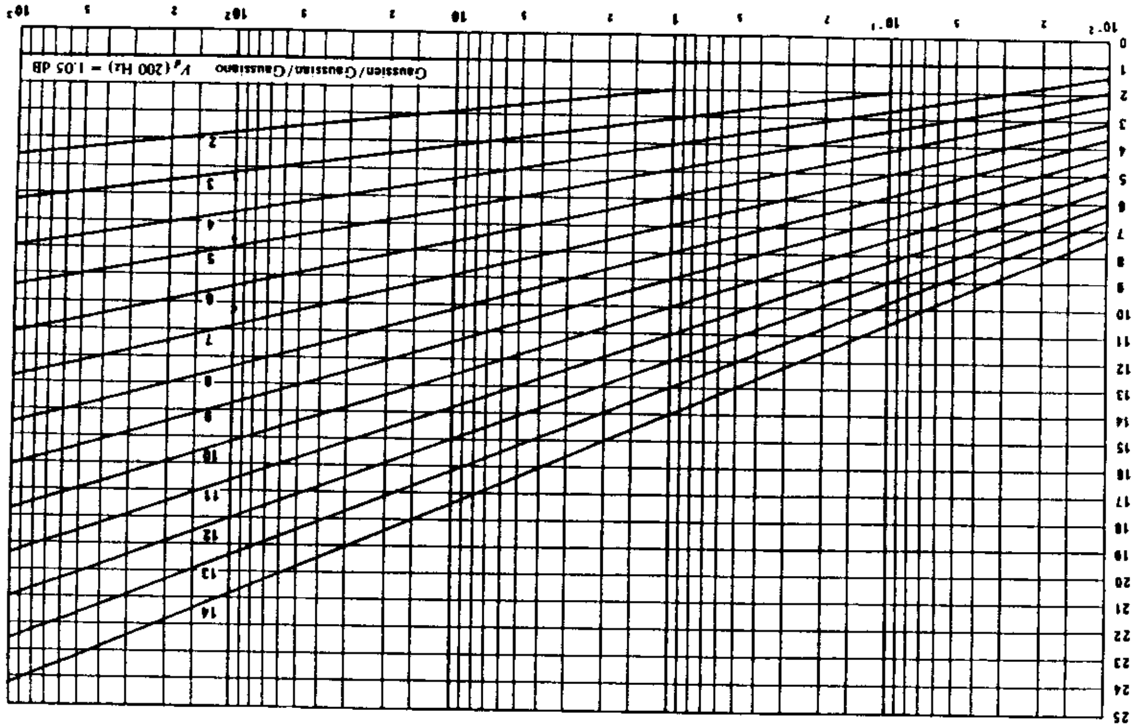

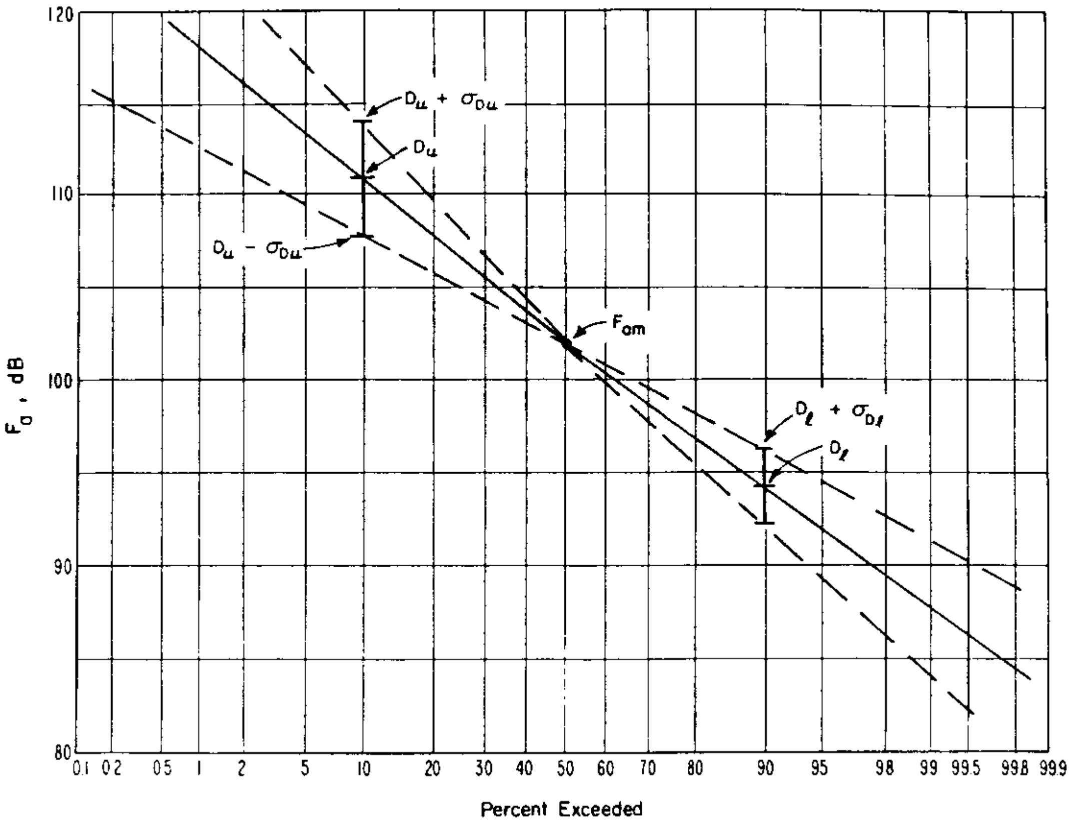

Figure 18. The distribution of F_a values expected at Boulder, Colorado, 500 kHz, for the summer season, 2000-2400 hrs.

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 gives examples of using the noise data to determine the required signal strength in order for various communications systems to operate according to some given specifications. What these specifications usually are in order to take into account the noise (and signal) variability with time and location are covered in Section 4 of this chapter.

D. Summary of Mathematical Models for Atmospheric Radio Noise Processes

In order to be able to determine the optimum receiving system for a given class of signals and analyze its performance, a mathematical model for the random interference process is required. That is, for optimal system studies and also for determining the performance of some of the existing suboptimum systems, more information about the interference process is required than can generally be obtained by measurement alone. The problem is to develop a model for the interference that fits all the available measurements; is physically meaningful when the nature of the noise sources, their distributions in time and space, propagation, etc. are considered; is directly relatable to the physical mechanisms giving rise to the interference; and is still simple enough so that the required statistics can be obtained for solving signal detection problems. While various models have been proposed in the past (to be summarized later) that meet these requirements in particular instances, the only general (canonical) model proposed to date that meets all the above requirements is that proposed by Middleton (1977, 1979).

Models that have been developed to date can be categorized into two basic types. The first type (and earliest models) are empirical models which do not represent the interference process itself but which propose various mathematical expressions designed only to fit the measured statistics of the interference. The second type of model is that which is designed to represent the entire random interference process itself. The majority of these models represents the received interference waveform as a summation of filtered impulses.

Most of the empirical models have concentrated on the amplitude probability distribution (APD) of the noise envelope, $P(V > V_o)$. This distribution has been measured extensively for atmospheric noise (see the bibliography by Spaulding et al. 1975, which deals with man-made noise but also contains an extensive section on atmospheric noise).

The first "model" for the noise envelope was the Rayleigh distribution

$$P(V > V_o) = e^{-aV_o^2} \quad .$$

This simply assumes that the interference is Gaussian and was quickly recognized to be quite inappropriate, since the envelope distribution of atmospheric and man-made noise exhibits large impulsive tails (e.g., Figure 10).

In 1954, Hesperper, Kessler, Sullivan, and Wells independently proposed the log normal distribution for atmospheric noise (see Furutsu and Ishida, 1960),

$$P(V) = \frac{1}{\sigma\sqrt{2\mu}}\, e^{-\frac{1}{2}\left(\frac{\log V - \log \mu}{\sigma}\right)^2} \quad .$$

This approach gave reasonable approximations to the impulsive tail of the distribution but did not match the Rayleigh (Gaussian) character of the interference at the lower amplitude levels.

Likhter (1956) used a combination of two Rayleigh distributions for atmospheric noise:

$$P(V > V_o) = (1 - c)\, e^{-aV_o^2} + c\, e^{-bV_o^2} \quad .$$

This distribution gave poor agreement with actual data.

Also in 1956 Watt proposed a variation on the Rayleigh distribution (see Furutsu and Ishida, 1960),

$$P(V > V_o) = e^{-x^2} ,$$

where

$$x = a_1 V_o + a_2 V_o^{(b+1)/2} + a_3 V_o^{b} ,$$

$$b = 0.6[20 \log(V_{rms}/V_{ave})] .$$

This distribution was designed for atmospheric noise and was claimed to give better results at high and low probabilities than the previously proposed distributions.

Ishida (1956) proposed a combination for atmospheric noise,

$$P(V > V_o) = (1 - c)\, e^{-aV_o} + c(\text{log normal distribution}) .$$

Nakai (1960) recommended this same combination. Ibukun (1966) found good agreement with some measured data for this log normal, Rayleigh combination.

In 1956 Horner and Harwood (see Ishida, 1969) used

$$P(V > V_o) = \frac{\gamma^2}{(V_o^{q} + \gamma^2)}$$

to represent the APD of atmospheric noise, and also in 1956 the Department of Scientific and Industrial Research of Great Britain proposed the following distribution (see Ibukun, 1966):

$$P(V > V_o) = \frac{1}{[1 + (\frac{\alpha V_o}{V_o})^r]^{-1}} ,$$

obtaining experimental values for α and r of 2.7 and 1.4 respectively, using atmospheric noise data from Nakai (1960).

Crichlow et al. (1960) represented the APD of atmospheric noise by a Rayleigh distribution at the lower amplitude levels and a "power" Rayleigh distribution at the higher levels

$$P(V > V_o) = e^{-(a\, V_o^{2})^{1/s}} , \quad y > B ,$$

with these two distributions being joined by a third expression for the middle range of amplitudes. These APD's were found to fit data very well over a wide range of bandwidths and are still the "standard" representation for atmospheric radio noise (CCIR Report 322). Means of obtaining the distribution for bandwidths other than the measurement bandwidth was also obtained (Spaulding et al., 1962). It has been this empirical representation that has generally been used in determining the performance of digital systems in atmospheric noise (see Akima, 1972, and the bibliography by Spaulding et al., 1975).

Galejs (1966) used a variation of the Rayleigh distribution

$$P(V > V_o) = (1 - \delta)\, e^{-\alpha_1 V_o} + \delta e^{-\alpha_2 V_o} .$$

He reported satisfactory agreement with atmospheric noise data using appropriate values of the parameters δ, α_1, and α_2. Galejs (1967) also used a more complicated version for atmospherics

$$P(V > V_o) = [1 - (\tfrac{b}{a})^2 - (\tfrac{d}{a})^2]\, e^{-(\frac{V_o}{\sigma})^2} + \frac{b^2}{(V_o^{2}+a^2) + V_o(V_o^{2}+a^2)^{\frac{1}{2}}} + (\tfrac{d}{a})^2\, e^{-sV_o} .$$

Finally, Ponhratov and Antonov (1967) used a variation of the normal distribution with mean μ to represent the instantaneous amplitude

$$p(x) = \frac{\nu}{2\sqrt{2}\,\Gamma(\frac{1}{2})\mu} \exp(-\frac{|x|^{\nu}}{2^{\nu/2}\mu^{\nu}}) , \quad -\infty < x < \infty ,$$

with $1/2 < \nu < 1$. They found this to be a good approximation for the probability density of atmospheric noise.

Almost all of the above empirical models concentrated on the envelope of the received noise process. Such models, while useful in determining the performance of "idealized" digital systems using matched filter or correlation receivers (i.e., those optimum for white Gaussian noise), give no insight into the physical processes that cause the interference. Neither can they be used to determine performance of "real" systems which employ various kinds of nonlinear processing nor can they be used in optimum signal detection problems. Various investigators have developed models for the entire interference process. The most significant of these models are as follows:

Furutsu and Ishida (1960) represented atmospheric noise as a summation of filtered impulses and considered two cases: (1) Poisson noise, consisting of the superposition of independent, randomly occurring impulses and (2) Poisson-Poisson noise, consisting of the superposition of independent, randomly occurring Poisson noise--each Poisson noise forming a wave packet of some duration. They represent the response of the receiver for an elementary pulse to be

$$r = r(t,a) \cos(\omega t + \psi) \quad ,$$

express this response as a vector and take the summation of n(n random) such vectors. They obtain, for the envelope amplitude for Poisson noise,

$$P(V) = \int_0^\infty \lambda V J_0(\lambda V)\, f(\lambda,T)\, d\lambda \quad ,$$

where the characteristic function $f(\lambda,T)$ is given by

$$f(\lambda,T) = \exp[\nu \int_0^T dt \int da\, p(a)\{J_0(\lambda r) - 1\}] \quad ,$$

and ν is the mean rate of occurrence of pulses in the Poisson distribution, T is the total time period of interest, and p(a) is the pdf of a. They also obtain

$$P(V < V_0) = V_0 \int_0^\infty J_1(\lambda V_0)\, f(\lambda,T)\, d\lambda \quad .$$

Corresponding results are obtained for Poisson-Poisson noise (ν becomes Poisson distributed) and for second-order distributions, i.e., $p(V_1, V_2)$ and $f(\lambda_1, \lambda_2, T)$.

Furutsu and Ishida (1960) proceeded to evaluate $P(V < V_0)$ for two "typical" cases of discrete and continuous spatial distributions of sources [using $f(\lambda,\infty)$]. Their results showed good agreement with measurements.

Beckmann (1962, 1964) developed a theoretical model for the received envelope of atmospheric noise and related his results to the number of sources (atmospheric discharges) and the properties of the propagation paths from these sources to the receiver. He assumed that the shape of the envelope of an individual atmospheric (attaining its peak value E_p at time t_0) was of the form

$$u_0(t) = \begin{cases} E_p \exp(-\frac{t-t_0}{a}) & \text{for } t > t_0 \\ E_p \exp(\frac{t-t_0}{b}) & \text{for } t < t_0 \end{cases} \quad .$$

The total signal at time t_0 is given as

$$\hat{U} = \hat{u}_0 + \sum_{k=1}^{\infty} \hat{u}_k + \sum_{k=1}^{\infty} \hat{s}_k \quad ,$$

where the circumflex accents denote uniformly distributed phase vectors, the u_k are atmospherics that have reached their peak values at times previous to t_0, and the s_k are atmospherics that have not yet reached their peak values. For any arbitrary time, t (between two successive peaks), the amplitude is

$$V = U\, e^{-t/a} \quad .$$

A Poisson distribution is assumed for the occurrence times of the atmospherics and a log-normal distribution is postulated for the peak amplitude, E_p; i.e.,

$$E_p = e^{\Delta} \quad ,$$

where Δ is normally distributed with mean μ and variance σ^2. Beckmann's results from the above are

$$V_{rms} \approx \sqrt{Nc\, \ln(1/Nc)}\; e^{\sigma^2+\mu} \quad ,$$

where N is the number of discharges per unit time and c = (a+b)/2, and

$$P(\frac{V}{V_{rms}} > V_0) = \frac{2}{Nc\sigma\sqrt{2\pi}} \int_{V_0}^{\infty} dx \int_0^{\infty} dy \frac{x}{y} \exp[-\frac{x^2+v^2}{Nc} - \frac{(\ln y+\sigma^2)}{2\sigma^2}] I_0(\frac{2xy}{Nc}) \quad ,$$

which reduces for large and small values of V_0 to

$$P(\frac{V}{V_{rms}} > V_0) \approx \frac{1}{2} [1 - \mathrm{erf}(\frac{\ln V_0+\sigma^2}{\sigma\sqrt{2}})] \quad ,$$

for large V_0, and

$$P(\frac{V}{V_{rms}} > V_0) \approx e^{-V_0^2/Nc} \quad ,$$

for small V_0 respectively.

These results showed good agreement with measurements and were the first results which related measurements to the physical properties giving rise to the noise. The parameter Nc depends on the properties of atmospheric discharges, and μ and σ^2 are the mean and variance of the total attenuation, which is determined by the properties of the propagation path. Beckmann's analysis, however, gave no consideration to the characteristics of the receiver.

Hall (1966) applied work on the applicability of a class of "self similar" random processes as a model for certain intermittent phenomena to signal detection problems considering LF atmospheric noise. The concept introduced is that of a random process that is controlled by one "regime" for the duration of observation, while this regime is itself a random process. The model that Hall proposed for received impulsive noise is one that takes the received noise to be a narrowband Gaussian process multiplied by a weighting factor that varies with time. Thus, the received atmospheric noise x(t) is assumed to have the form

$$x(t) = a(t)\, n(t) \quad ,$$

where n(t) is a zero-mean narrowband Gaussian process with covariance function $R_n(\tau)$, and a(t), the regime process, is a stationary random process, independent of n(t), whose statistics are to be chosen so that x(t) is an accurate description of the received atmospheric noise. For a(t), Hall chose the "two sided" chi distribution, $\chi_2(m,\sigma)$, for the reciprocal of a(t), resulting in

$$p(a) = \frac{(m/2)^{m/2}}{\sigma^m \Gamma(m/2)} \frac{1}{|a|^{m+1}} \exp[-\frac{m}{2a^2\sigma^2}] \quad ,$$

and

$$p(n) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp[-\frac{n^2}{2\sigma_1^2}] \quad .$$

Using the two equations above, Hall found the pdf of the noise to be given by

$$p(x) = \frac{\Gamma(\frac{\theta}{2})}{\Gamma(\frac{\theta-1}{2})} \frac{\gamma^{\theta-1}}{\sqrt{\pi}} \frac{1}{[x^2+\gamma^2]^{\theta/2}} \quad ,$$

where $\gamma = m^{\frac{1}{2}}\sigma_1/\sigma$ and $\theta \equiv m+1 > 1$. For the special case $\sigma_1 = \sigma$, p(x) is Student's "t"-distribution. Hall terms the above the generalized "t"-distribution with parameters θ and γ. Hall shows that θ in the range $2 < \theta \leq 4$ is appropriate to fit measured data of atmospheric noise and that $\theta \approx 3$ is appropriate to fit a large body of data at VLF and LF. [Unfortunately, for θ in the range $2 < \theta \leq 3$, x(t) has infinite variance and therefore cannot be a model for physical noise, although it fits the data very closely.]

Hall then considers the envelope and phase of the received noise; i.e.,

$$x(t) = V(t) \cos[\omega_0 t + \phi(t)] \quad .$$

Using

$$p_{V,\phi}(V,\phi) = V\, p_{y,\tilde{y}}(V \cos\phi,\, V \sin\phi) \quad ,$$

where $V = (y^2 + \tilde{y}^2)^{1/2}$, $\phi = \tan^{-1}(\tilde{y}/y)$, and $\tilde{y}(t)$ is the Hilbert transform of $y(t)$, Hall showed that the phase is uniformly distributed and that the envelope distribution is given by

$$P(V) = (\theta-1)\ \gamma^{\theta-1} \frac{V}{[V^2+\gamma^2]^{(\theta+1)/2}} \quad .$$

For his model, Hall also obtains expressions for the average rate of envelope level crossings and the distribution of pulse widths and pulse spacings. The envelope distributions and level crossing rates show good agreement with measurements but poor agreement with measurements of pulse width and pulse spacing distributions (Hall, 1966; Spaulding et al., 1969).

Hall uses his model to determine the optimum receiver for coherent ON-OFF signaling and analyzes its performance. While the Hall model results in expressions that are mathematically simple enough for solving detection problems, the parameters of the model, θ and γ, have no relation to the physical processes causing the interference.

Omura (1969) presented a noise process similar to that of Hall (1966). He defined

$$x(t) = A\ X(t)\ \sin(\omega_0 t + \phi(t)) \quad ,$$

where

$$X(t) = \text{a log normal process} = e^{b(t)} \quad ,$$

where $b(t)$ is a stationary Gaussian process with zero mean and autocorrelation $R_b(\tau)$ and A is a constant to be determined from noise power estimates. This results in the phase being uniformly distributed, and

$$p(AX) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left[\frac{\log(\frac{X}{A})}{\sigma}\right]^2\right\} ,$$

where $\sigma \equiv \sigma_{\log X}$. Omura also obtained expressions for the average rate of envelope level crossings and pulse width and pulse spacing distributions. The model showed agreement with measurements only at the higher envelope levels. Omura used his model to calculate the performance of various LF and VLF digital modems.

Giordano (1970, 1972) used a filtered impulse model to obtain results similar to Furutsu and Ishida (1960) for the envelope distribution of atmospheric noise. He obtained

$$p(V) = V \int_0^\infty d\lambda\ H(\lambda)\ J_1(\lambda V) \quad ,$$

where $H(\lambda)$ is a characteristic function obtained along the lines of Furutsu and Ishida's (1960) development. Giordano evaluates $p(V)$ for various spacial distributions and propagation situations. Each such assumption results in a different "model." One case of interest that Giordano treats is:

(1) uniform spatial distribution of sources,

(2) field strength that varies inversely with distance, and

(3) arbitrary receiver envelope response.

The result is a distribution of the Hall (1966) form, and so Giordano gave a physical rationale to the Hall model.

Giordano considered numerous other cases of propagation and source distributions and also developed expressions for the average rate of envelope crossings and pulse spacing distributions.

Recent work by Middleton (1977, 1979) has led to the development of a physical-statistical model for radio noise. The Middleton model is the only general one proposed to date in which the parameters of the model are determined explicitly by the underlying physical mechanisms (e.g., source density, beam-patterns, propagation conditions, emission waveforms, etc.). The model is also canonical in nature in that the mathematical forms do not change with changing physical conditions.

As in past models, Middleton's model postulates the familiar Poisson mechanism for the initiation of the interfering signals that comprise the received waveform X(t). The received interfering process is

$$X(t) = \sum_j U_j(t,\underline{\theta}) \quad ,$$

where U_j denotes the jth received waveform from an interfering source and $\underline{\theta}$ represents the random parameters that describe the waveform scale and structure. It is next assumed that only one type of waveform, U, is generated with variations in the individual waveforms taken care of by appropriate statistical treatment of the parameters $\underline{\theta}$.

With the assumption that the sources are Poisson distributed in space and emit their waveforms independently according to the Poisson distribution in time, the first-order characteristic function of X(t) is obtained in a manner similar to the analyses of Furutsu and Ishida (1960) and Girodano (1970, 1972). These investigators have made various assumptions for the distributions required to perform averages needed to obtain a characteristic function that could be transformed to obtain the corresponding probability density function. Each different assumption, of course, leads to a different model (mathematical form). A unique approach of Middleton's model is to develop expressions for the transform of the characteristic function without performing these averages explicitly, thereby obtaining a canonical model.

For atmospheric noise, the results are for the instantaneous amplitude

$$p(x) = \frac{e^{-x^2}}{\pi} \sum_{m=0}^{\infty} \frac{(-1)^m}{m!} A_\alpha^m \, \Gamma\left(\frac{m\alpha+1}{2}\right) \, {}_1F_1\left(-\frac{m\alpha}{2};\frac{1}{2};x^2\right) \quad ,$$

where ${}_1F_1$ is a confluent hypergeometric function. The model has the two parameters α and A_α. Both these parameters are intimately involved in the physical processes causing the interference. That is, the model is sensitive to sourse distributions and the propagation law. Specifically,

$$\alpha = \frac{2-\mu}{\gamma}, \quad 0 \leq \alpha < 2 \quad ,$$

where

$$\text{source density} \sim 1/\lambda^{\mu} \quad ,$$

and

$$\text{propagation law} \sim 1/\lambda^{\gamma} \quad ,$$

where λ denotes distance. The parameter A_α includes the parameter α and other terms depending on the physical mechanisms. The normalization in the above is to the power in the Gaussian portion of the distribution, since as with the Hall (1966) model or the Furutsu and Ishida (1960) model, we obtain infinite variance for some values of the parameters α and A_α. For the case $\alpha = 1$, p(x) reduces to a distribution of the Hall form. [A more complete model (Middleton, 1977, 1979) exists which does not have this infinite variance problem, i.e., a model for which all moments exist.]

The corresponding results for the envelope APD are

$$P(V > V_0) = e^{-V_0^2} \left[1 - V_0^2 \sum_{m=1}^{\infty} \frac{(-1)^m}{m!} A_\alpha^m \times \Gamma\left(1 + \frac{m\alpha}{2}\right) \, {}_1F_1\left(1 - \frac{m\alpha}{2};2;V_0^2\right)\right] \quad .$$

While the Middleton model is somewhat more mathematically complex than others, it still can be (and has been) used with good success to develop optimum receiving systems and analyze the performance of existing systems (e.g., see Spaulding, 1979).

IV. EFFECT OF ATMOSPHERIC NOISE ON SYSTEM PERFORMANCE

A. Introduction

Here we want to briefly discuss the wide variety of interference effects atmospheric noise (or similar forms of impulsive noise) has on system performance. In the next section (B), we give a broad overview or summary of known effects of atmospheric noise on communication systems, primarily digital, but with some measured results for analog voice systems included. After that (Section C) various means of improving system performance in impulsive noise are covered.

B. General Effects of Atmospheric Noise on System Performance

Until recently, most analyses of communication systems have been based on the additive, Gaussian noise channel. It has long been recognized that in most communications situations the additive noise is not Gaussian in character, but rather it is impulsive in nature. Many investigators have studied the effects of impulsive broadband noise on digital communication systems [see the bibliography by Spaulding et al. (1975) which lists some 315 references pertaining to system performance in impulsive noise].

For digital signaling, the receivers in general use are those designed to be optimum (minimum probability of error) in white Gaussian noise (usually termed matched filter or correlation receivers). The early work analyzed these receivers in impulsive atmospheric noise by following the steps of the Gaussian analysis but using the appropriate distributions of the atmospheric noise.

Following Montgomery (1954), we have the following results for any arbitrary additive noise which is independent from one integration period (bit length) to the next and which has uniformly distributed phase. For the symmetric binary NCFSK (noncoherent frequency shift keying) system, the probability of a bit being in error is given by one half the probability that the noise envelope exceeds the signal envelope, and for symmetric binary CPSK (coherent phase shift keying), the probability of an error is given by one half the probability that the quadrature

component of the noise envelope exceeds the signal. While Montgomery's result for FSK is in terms of the noise and signal envelopes at the input to an ideal discriminator, it has been shown (White, 1966) that the result is also directly applicable to most common FSK receivers (bandpass-filter, discriminator receivers and matched-filter, envelope detection receivers). Using the above, Conda (1965) has given results for NCFSK for the entire range of atmospheric noise conditions likely to occur and for a wide range of flat fading signal conditions. Shepelavey (1963) and Spaulding (1964) have given results for impulsive noise for the CPSK binary system. The CFSK binary system has the same error characteristic as CPSK with a 3 dB shift in signal-to-noise ratio (SNR); that is, a given error rate requires a 3 dB greater SNR for CFSK than for CPSK. Here SNR is the ratio of the energy per received signal to the noise power density. In the bi-phase DCPSK (differentially coherent phase shift keying) system, the receiver compares the phase ϕ of a noisy signal with a reference phase $\overline{\phi}$ to decide whether the corresponding pure-signal relative phase ψ was 0 or π ($\psi = 0$ is selected if $|\phi - \overline{\phi}| < \pi/2$, and $\psi = \pi$ otherwise). The reference phase is obtained from the previously received signals; usually it is just the phase of the previous signal. Thus the analysis of this system is complicated by the fact that both ϕ and $\overline{\phi}$ are affected by noise. This system also has adjacent symbol dependency, and, therefore, the occurrence of paired errors and other error groupings cannot be obtained easily, even with independent noise. Halton and Spaulding (1966) have given results for this system, including the occurrence of various groupings or errors.

In general, the results of such analyses for suboptimum receivers (i.e., those designed to be optimum in Gaussian noise) correspond to experimental observations and can be summarized as follows:

(1) For digital systems and constant signal, white impulsive noise is much more harmful (causes more errors) than Gaussian noise of the same energy at the higher SNR's, while Gaussian noise is more

harmful for the lower SNR's. This is illustrated by Figure 19 which shows the APD for a sample of atmospheric noise (see Figure 10) along with the probability of binary bit error for a CPSK system with constant signal. Since the noise distribution is given relative to its rms level, the ordinate scale can also serve as a signal-to-noise ratio scale. Gaussian noise is also shown for contrast. By presenting the error rate characteristic jointly with the APD, it is easy to see how the impulsive nature of atmospheric noise effects system performance. Figure 20 shows the probability of character error for a four-phase DCPSK system for various atmospheric noise conditions (given by V_d).

(2) When the signal is Rayleigh fading, Gaussian noise is more harmful at all SNR's. For diversity reception, however, impulsive noise is again more harmful at higher SNR's. For diversity reception, impulse noise, and Rayleigh fading signal, the degree of statistical dependence between the noise on the different diversity branches has a relatively minor effect on system performance for low order of diversity. For nondiversity operation of a binary system with Rayleigh fading signal, the error probability for a large SNR is essentially independent of the additive noise statistics. Other flat fading situations (e.g., log-normal fading) do arise for which impulsive noise will cause more errors than Gaussian noise at some SNR's. Figure 21 illustrated some of these results using a binary NCFSK system for example.

(3) For analog voice systems, impulsive noise is less harmful than Gaussian noise in the sense that understandability can be maintained at much lower SNR's, although the impulse interference is quite bothersome. Figure 22 (from Systems Development Corporation, 1968) shows an example for AM voice in atmospheric noise.

(4) In addition to the above additive noise and flat fading signal effects, systems are also subject to multiplicative noise. This form of signal distortion is sometimes termed frequency selective fading. In digital systems, the effect of multiplicative noise is generally to produce a P_e threshold; that is, a value of P_e which cannot be lowered by increasing signal power. For examples of this phenomena, see Watterson and Minister (1975).

In general, the studies and example results above obtain a single number (e.g., error rate) to describe the system performance. A long-term average, such as error rate, gives a good measure of the performance of a system only if we are dealing with stationary noise and signal processes (Gaussian noise and constant signal, for example). Since atmospheric noise is a nonstationary random process and the signal processes are also, in general, nonstationary, information in addition to the error rate (or a similar measure for analog systems) is required to specify the performance of a given system.

It has become common to give two additional measures: the percentage of time a given error rate or better will be achieved (termed time availability) and the probability that a given system will achieve a specified time availability and error rate (termed service probability). The service probability is designed to account for the probable errors in the prediction of noise and signal distributions, antenna gains, and the like. These concepts are illustrated in the following quantitative definition of detrimental interference: Detrimental interference will exist for a particular receiving system whenever the available power of the wanted signal at the receiving antenna terminals is less than the operating threshold of this receiving system, corresponding to a specified required grade of service, g_r, for the specified required fraction, q_r, of some specified period of time, T (see CCIR Report 413). This quantitative definition of detrimental interference depends on the quantitative specification of g_r, q_r, and T. The determination of the grade of service, g, depends on the detailed statistical characteristics of the desired signal and the noise environment. An example of grade of service is given by a P_e versus SNR characteristic. The determination of the fraction of time, q, depends on the long-term changes in the desired signal and the noise, since in general both of these random processes are nonstationary.

Note further that both the available power of the wanted signal and the operating threshold power of the receiving system are predicted values and, as such, are subject to error.

Assuming that the errors of prediction are known (statistically), it is possible to determine a Service Probability, $Q(g_r, q_r, T)$ (statistical confidence factor), that service of a specified required grade, g_r, or better, will be available for a specified required fraction, q_r, of the specified period of time, T; i.e., will have a "time availability" of qT equal or greater than its required value, q_rT. It is also possible to define an Interference Probability $P(g_r, q_r, T) = 1 - Q(g_r, q_r, T)$. Note that the Service Probability and Interference Probability are simply numbers between 0 and 1. Finally, detrimental interference may be said to exist at the antenna terminals of a particular receiving system if the Service Probability $Q(g_r, q_r, T)$ is less than some specified value (e.g., 0.95). Once an error rate or like measure has been obtained, examples of obtaining the Time Availability and Service Probability are given in the references (e.g., CCIR Reports 322 and 413).

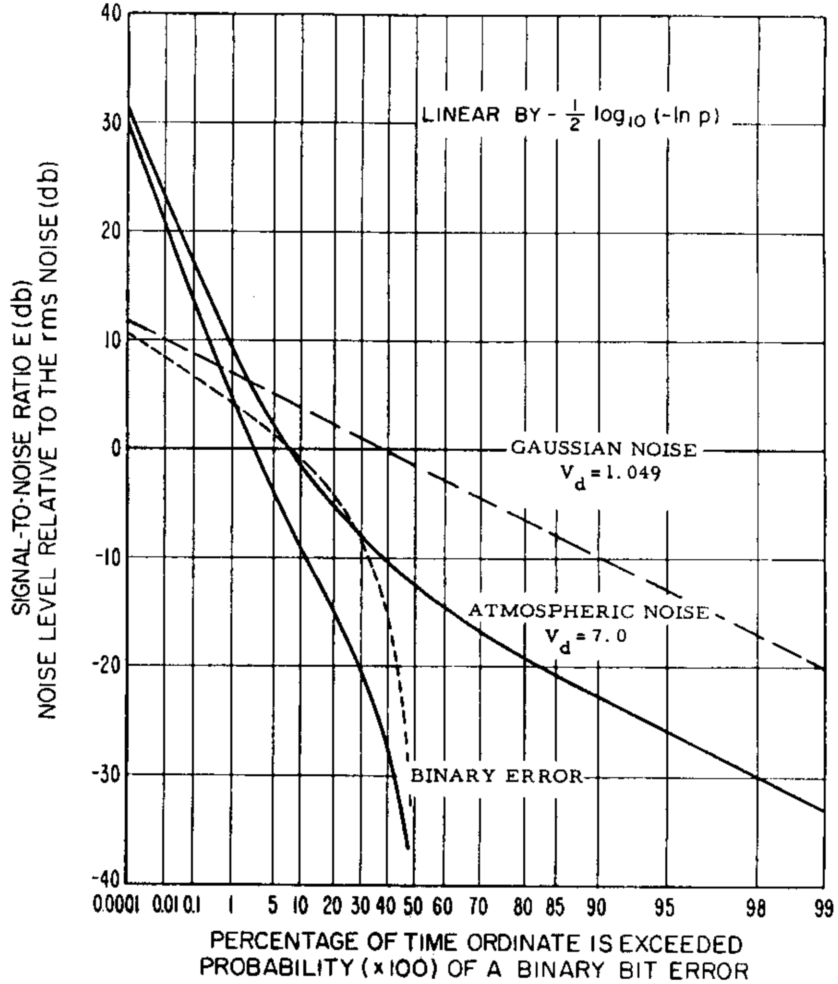

Figure 19. Amplitude probability distributions of the noise envelope for Gaussian noise and a sample of atmospheric-noise shown with the corresponding probabilities of binary bit error for a CPSK system.

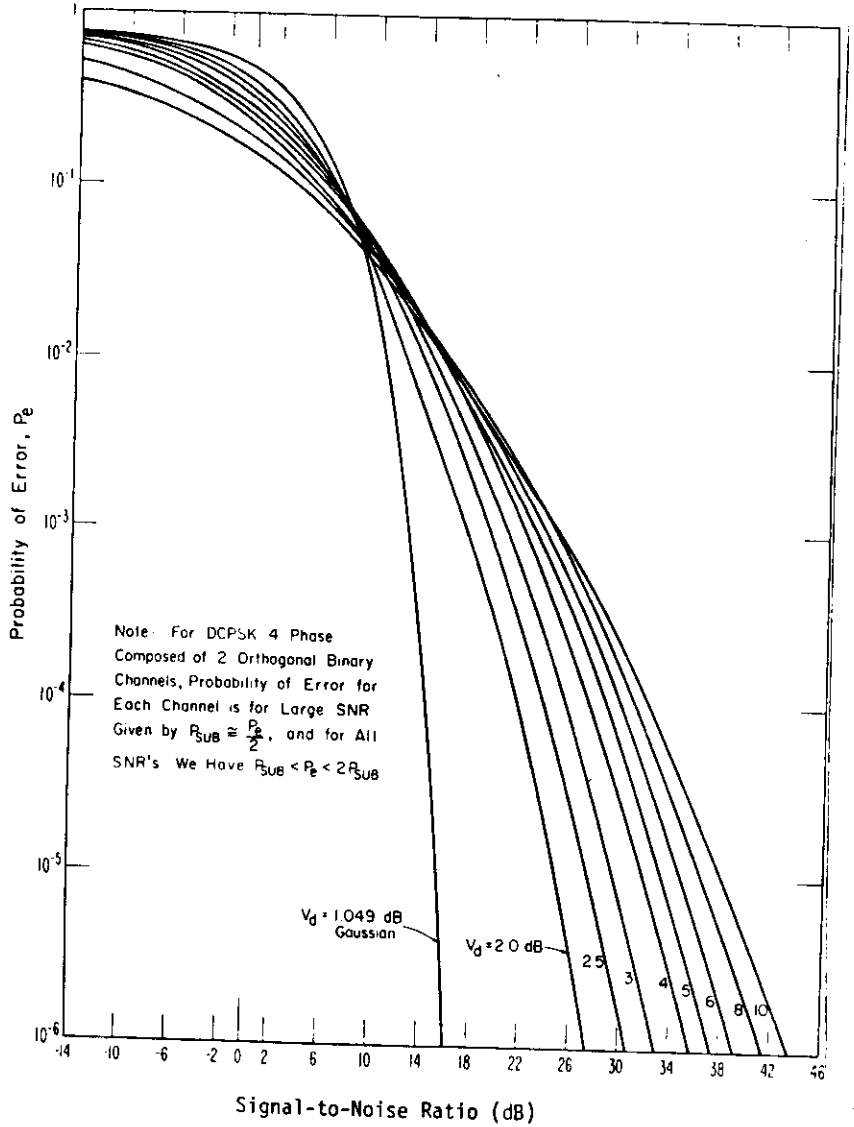

Figure 20. Probability of character error for a range of atmospheric noise conditions (V_d) for constant signal for a 4-phase DCPSK system.

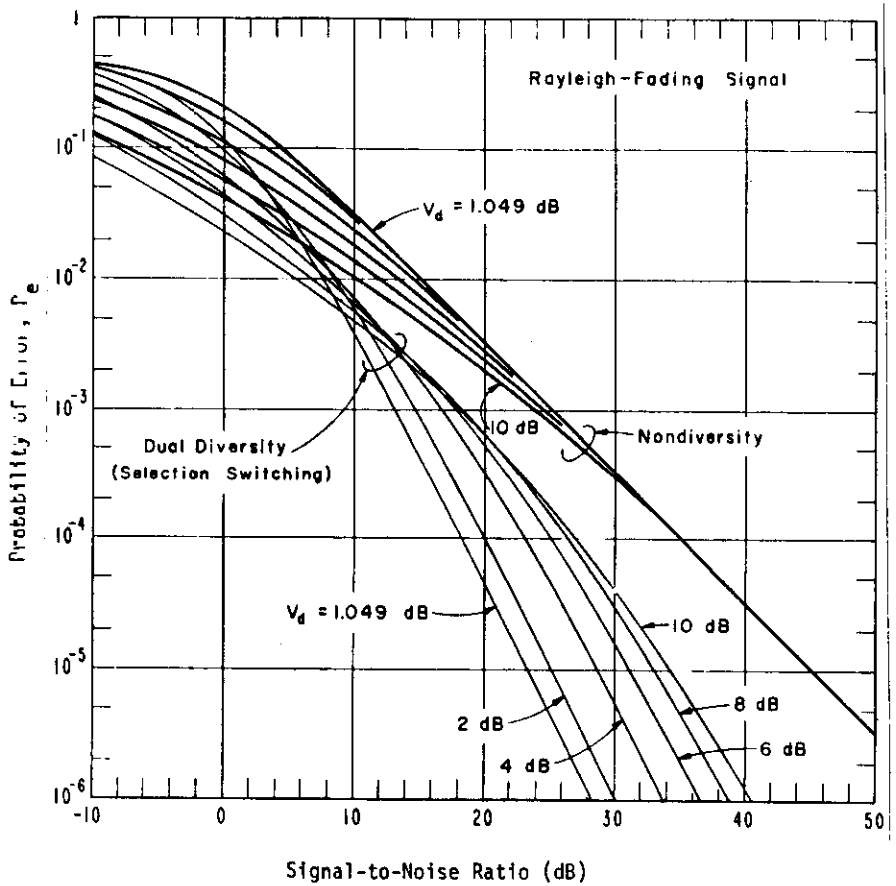

Figure 21. Probability of binary error for a slow flat Rayleigh fading signal for a NCFSK system for both nondiversity and dual diversity reception.

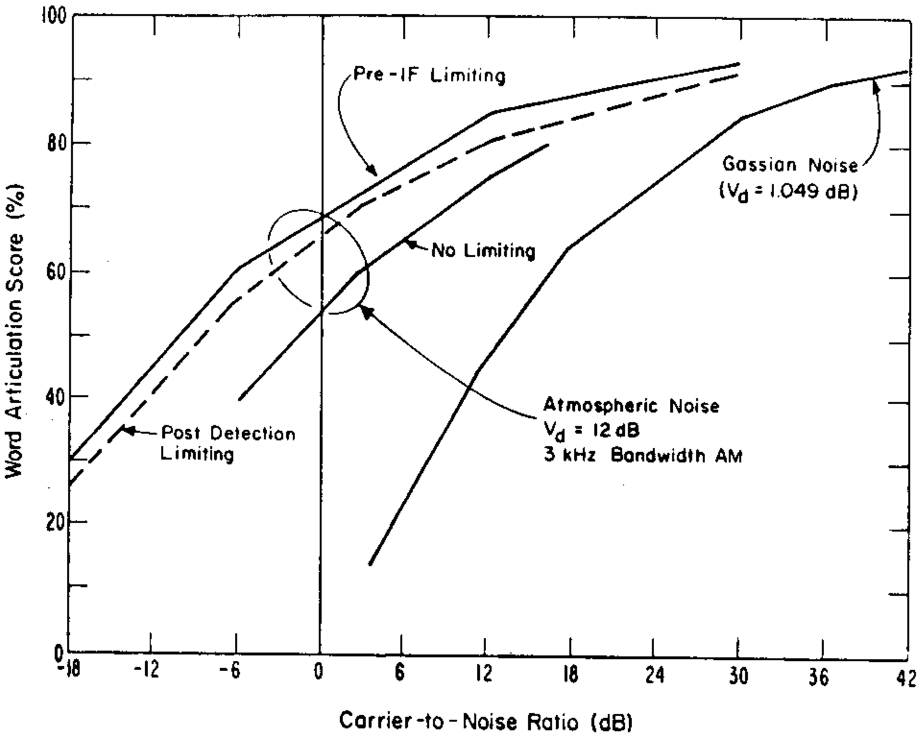

Figure 22. Comparison of performance of AM voice system in Gaussian and atmospheric noise (V_d = 12).

C. Means of Improving System Performance in Impulsive Noise

As shown above, impulsive atmospheric noise can cause serious systems degradation, especially when "normal" communication systems are employed (i.e., those designed for Gaussian noise). In view of this, recent emphasis has been on the application of various ad hoc nonlinear processing, designed to make the additive noise more Gaussian in character so that the existing receivers would be better matched to the interference, thereby improving performance. These techniques take the form of hard limiting, hole punching, and "smear-desmear" filtering. The analysi of the effectiveness of such techniques now requires appropriate mathematical models of the interference process. Bello and Esposito (1969, 1971) use the now-customary model in which the noise takes the form of a summation of filtered impulses, the arrival times of the impulses being Poisson distributed. Bello and Esposito evaluate error rates for PSK and DPSK with and without hard-limiting. In their analyses, the impulses are assumed to be nonoverlapping. Ovchinnikov (1973) and Richter and Smits (1974) present analyses which include the intermediate case where impulses overlap but not so frequently as to approach Gaussian noise. Richter and Smits (1974) also evaluate the case of "smear-desmear" filtering, which is shown to be helpful at high SNR's and harmful at low SNR's. A quite extensive analysis of system performance in atmospheric noise when limiting is employed has been given by Gamble (1974). Signal design techniques to combat impulsive noise have been given by Silver and Kurtz (1972). A useful general analysis has also been given by Fang and Shimbo (1972).

While the various kinds of nonlinear processing mentioned above can be quite helpful in improving system performance, they generally are quite wasteful of spectrum (i.e., time-bandwidth product). Recent studies have also been concerned with developing optimum detection algorithms for impulsive interference--that is, designing receivers that match the interference rather than attempting to change the interference to match some particular type of receiver. In order to obtain improvement using any technique, the time-bandwidth product must be expanded over that normally required by the Gaussian receiver in Gaussian noise. However, the optimum or near optimum detection techniques require a much smaller time-bandwidth product expansion than do the various ad-hoc techniques.

The first such optimum receiver was that proposed by Hall (1966). Hall termed his optimum receiver for broadband impulsive noise a "log correlator" receiver. Figure 23 shows the optimum performance compared to the performance of a "standard" CPSK receiver for a range of atmospheric noise conditions. On Figure 23, the time-bandwidth product is denoted 2TB and is 500, compared to the normal time-bandwidth product of 1 for a binary CPSK system. The atmospheric noise to be combated is received in a bandwidth of 4 kHz (three examples shown), but the effective noise bandwidth is 8 Hz, achieved by using 500 times as much time as "normal" to detect a given binary bit. The performance of the matched-filter receiver for this situation is shown along with the performance of Hall's log-correlator receiver for the same situation (m is a parameter in the Hall model and was defined in Section 3.4). Also shown in the standard performance of a matched-filter receiver in Gaussian noise (for a time-bandwidth product = 1). Note the rather large savings in time-bandwidth product and/or signal energy that can, theoretically, be achieved.

Much recent work has been centered on obtaining optimum threshold receivers; that is, receivers which approach optimality as the signal becomes small. In this situation, it is possible to derive a canonical receiver structure, meaning a structure which is independent of the particular additive noise distribution. The general result which has been obtained by numerous investigations is that the optimum threshold receiver for both coherent and incoherent signals is the same receiver that is optimum for Gaussian noise but preceded by a particular nonlinearity. This nonlinearity is given by the derivative of the logarithm of the probability density function of the instantaneous amplitude of the interference process. (See, for example, Antonov, 1967.) It should be noted that this nonlinearity does not "Gaussianize" the noise. Kushner and Levin (1968) and Ribin (1972) have shown that these

canonical threshold receivers are asymptotically optimum. That is, as the decision time becomes infinite and/or the signal becomes vanishing small, the threshold receiver yields a probability of error no larger than that obtained by any other receiver. Nirenberg (1975) has shown that the threshold results extend to M-ary digital systems, that the receiver is independent of the signal fading characteristics, and that, if the desired signal contains desired amplitude modulation, the threshold receiver takes a more complicated form, requiring additional nonlinear processing. The threshold results have been extended to narrowband non-Gaussian noise by Zachepitsky et al. (1972) and to cases where the observational data represent a sequence of quantized random quantities by Levin and Baronkin (1973). Spaulding and Middleton (1977) have derived and analyzed the performance of threshold receivers for a wide range of system types. In addition, Spaulding (1979) has analyzed optimum threshold detection using both time and spacial sampling.

These optimum receivers are required to be adaptive. They must be able to change themselves to match the changing noise environment. This complicates the receiver structure so that, in addition to the basic receiver, there must also be equipment to estimate the required noise parameters. Nirenberg (1974) has treated this problem for the Hall receiver; and Griffiths (1972), Valeyev (1973), and Valeyev and Gonopol'sky (1973) have attacked the estimation problem for threshold receivers.

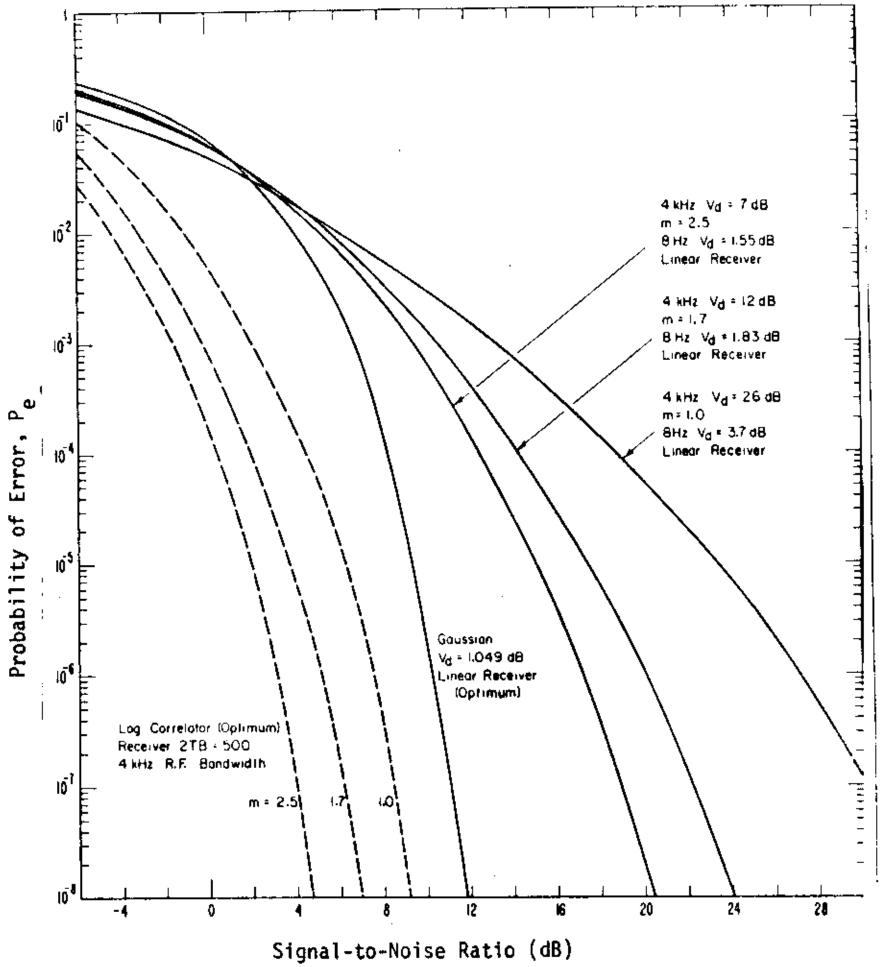

Figure 23. Comparison of the performance of an optimum receiving system for atmospheric noise with the performance of a standard matched filter receiver for constant CPSK binary signals for a range of noise conditions.

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