AN UPDATED NOISE MODEL FOR USE IN IONCAP

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This report presents an updated and improved noise model designed for use in the HF propagation prediction program, IONCAP. The model has, however, much more general applicability, since the frequency range 10 kHz to 30 MHz is covered. The report gives the history, as near as can be determined, of the existing noise routines, and then develops the updated model based on current information. The three noise sources - atmospheric, man-made, and galactic are treated and a more appropriate means of combining these three sources is developed. Examples of the use of the improved model in IONCAP are included and comparisons made with the existing model.

Key Words: Atmospheric noise, galactic noise, IONCAP, man-made noise, noise model, overall operating noise threshold

1. INTRODUCTION and BACKGROUND

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. In general, 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. Often, the signal-to-noise ratio (and its variation with time and location) is the only parameter considered. In general, we have a number of noise processes to consider: the noise internally generated by the receiving system; natural noise, i.e., atmospheric and galactic; unintentionally radiated man-made noise; and intentionally radiated noise, e.g., undesired (by us) signals. While, depending on frequency, time, and location, one of these noises may dominate, all (or various combinations) may need to be considered. This is especially true at HF frequencies. The various ionospheric propagation prediction programs such as IONCAP (Ionospheric Communication Analysis and Prediction Program) use algorithms to predict the appropriate (atmospheric, galactic, and man-made) noise levels and combine them to obtain an estimate of the overall interfering noise level and its statistical variation. In the current version of IONCAP (Teters et al., 1983), this is accomplished by

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various subroutines, the main one being termed GENOIS. The noise subroutines have evolved over approximately the past 20 years and are in need of updating, both in terms of the noise levels used and how they are combined. It is the purpose of this report to attempt to explain the development of the current noise routines, especially with regard to man-made noise, to point out the areas where they are no longer valid, and to develop an updated and improved version. The improved version is changed only internally, so that it can be used directly in the existing programs. Modernizations which would require changes in the entire program (e.g., IONCAP) are not made, but left for an overall updating. The existing noise models which are used in the update are the new CCIR Report 322-3 (1986) for atmospheric noise and CCIR Report 258-4 (1982) for man-made noise. The particulars that resulted in Report 322-3 are given by Spaulding and Washburn (1985) and for Report 258-4 by Spaulding and Disney (1974).

We start with some basic definitions for review and to point out how the receiving system's internal noise is combined with the external noise to obtain an overall noise operating threshold. While this is, by now, well known material, it will provide the basic definitions we will use later, treat one of the noises (internal) listed above, and show how a receiving system's sensitivity enters into the picture. Basically we need a receiving system with a sensitivity no greater than that governed by the external noise. Worldwide minimum noise levels have been estimated for this purpose (CCIR Report 670, 1978).

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

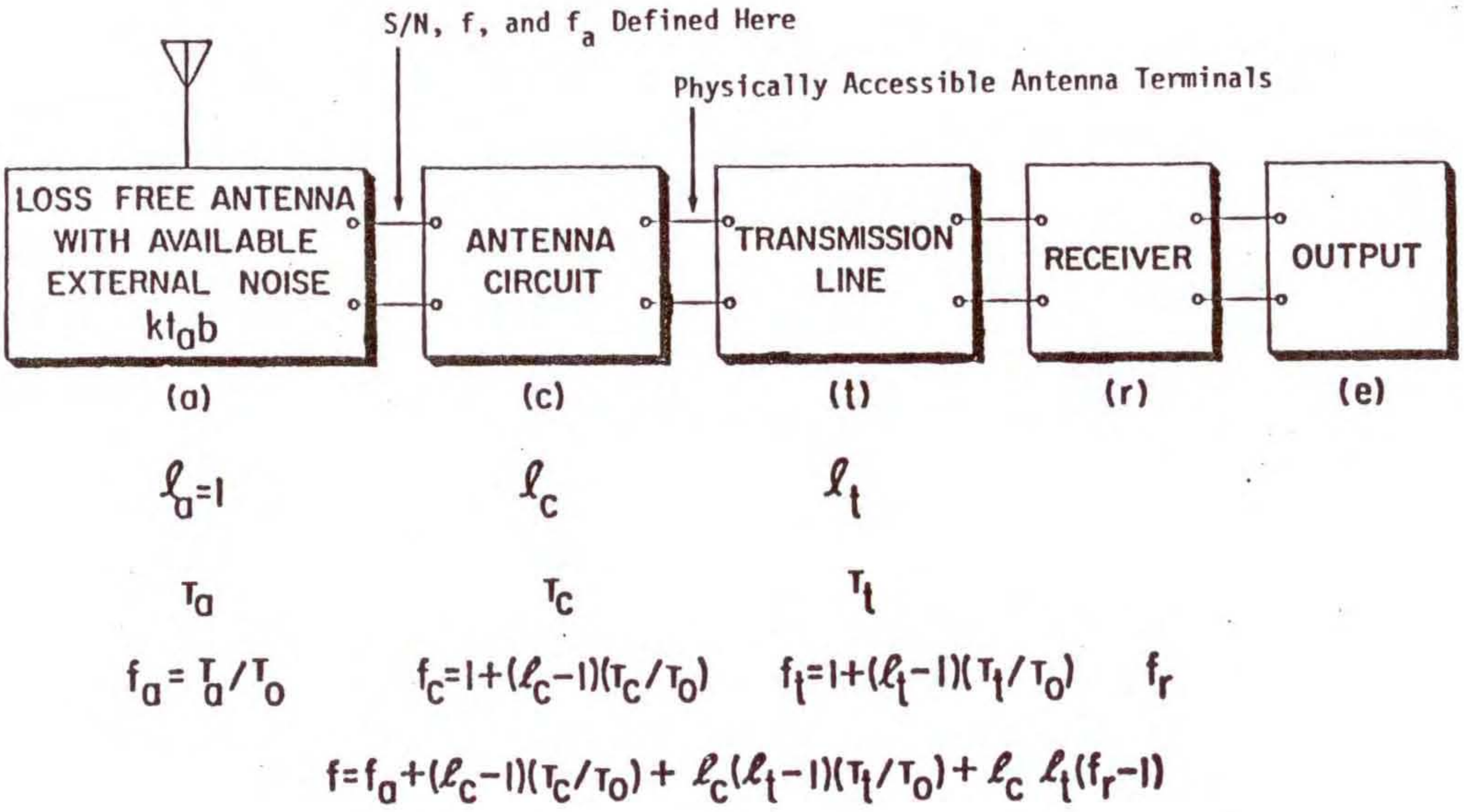

Figure 1. The receiving system and its operating noise factor, f.

define a receiving system overall operating noise factor, f, such that $n = fkT_ob$, where k = Boltzmann's constant = 1.38×10^{-23}J/K, T_o = the reference temperature in K taken as 288 K, 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:

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

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

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

where

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

$$f_a = \frac{P_n}{kT_ob};$$

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;
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,

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

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

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

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

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

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

Relation (3) can be written

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

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

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

where E_n is the field strength [dB(1μV/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,

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

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.

We express all our external noises in terms of f_a. The next section of this report covers the new atmospheric noise estimates. Section 3 covers man-made and galactic noise and Section 4 details the combining of the three f_a's (atmospheric, man-made, and galactic) to obtain the overall f_a and its statistical variation. All of the techniques used are different from those in the current routines. Section 5 then presents various comparisons between the results (outputs) of the new routines developed here and the current ones.

2. ATMOSPHERIC NOISE

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. The frequency range 13 kHz to 20 MHz was covered, and measurements of f_a were made using a bandwidth of 200 Hz. Other statistical parameters of the noise process were also measured but are not of concern to us here.

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. In addition, the corresponding season-time block values were given for the four seasons, winter (December, January, and February), spring (March, April, and May); summer (June, July and August); and fall (September, October, and November); (reversed in the Southern Hemisphere), 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, and its statistical variations for each season-time block and is based on all the available measurements to that date. 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. Report 322 gives worldwide maps of the time block median value of F_a, F_{am}, at 1 MHz. The F_{am} for other frequencies, 10 MHz to 30 MHz, is given by "frequency law" curves. The statistical variations of F_a are given as a function of frequency, by D_μ, D_ℓ, σ_{D_μ}, σ_{D_ℓ}, and $\sigma_{F_{am}}$. Other atmospheric noise parameters are also given.

In 1965 (Lucas and Harper), numerical representation of CCIR Report 322-1 became available. It is this numerical representation that is contained in the current noise subroutines used in IONCAP (for example). 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 numerical mapping of the original data points (84 longitude, 100 latitude grid points) which produced the CCIR 322 maps. This procedure gave differences of over 10 dB occasionally being noted between the CCIR 322 maps and the Lucas and Harper numerical representation. The numerical representation of the frequency variation of F_{am} and D_{μ} and D_{ℓ} variation given by Lucas and Harper are "precise" being the same numerical routine used to produce these parts of CCIR 322. In 1970, Zacharisen and Jones developed 1 MHz noise maps in universal time (rather than local time as in CCIR 322) using the "original" Report 322 data; i.e., the 84 x 100 grid points. Mapping in universal time produces quite high gradients, and the Zacharisen and Jones maps are also substantially different than the CCIR 322 maps for some times and locations. Also using the original data used 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. This model is a simplified (fewer coefficients) version of the Zacharisen and Jones maps, and therefore even less accurate.

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 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. All these data have been analyzed and an updated set of atmospheric radio noise estimates produced, essentially in the CCIR Report 322 format. The details of this analysis, new 1 MHz noise maps, etc. are given by Spaulding and Washburn (1985). These new and greatly improved atmospheric noise estimates are also contained in CCIR Report 322-3, an output document of the CCIR XVI Plenary Assembly, Dubrovnik, Yugoslavia, 1986; currently being printed by the ITU. Figures 2 and 3 are Figures 2a, 2b, and 2c from CCIR Report 322-3. (Actually, since 322-3 is currently being printed, Figures 2 and 3 are from the Dubrovnik documents.) Note that as in earlier versions of Report 322, the 1 MHz maps are split at the equator, so that the maps are for a given season, rather than a given three month period, as in Spaulding and Washburn. All the data is identical, however. All of Report 322-3 is available in numerical form, and unlike the earlier versions of 322 and its numerical representation, the numerical version of 322-3 is exact. That is, the numerical version and the graphical version give precisely identical values for all the parameters, including the 1 MHz F_{am} value.

As with the Lucas and Harper maps, the new 1 MHz F_{am} maps are given by a

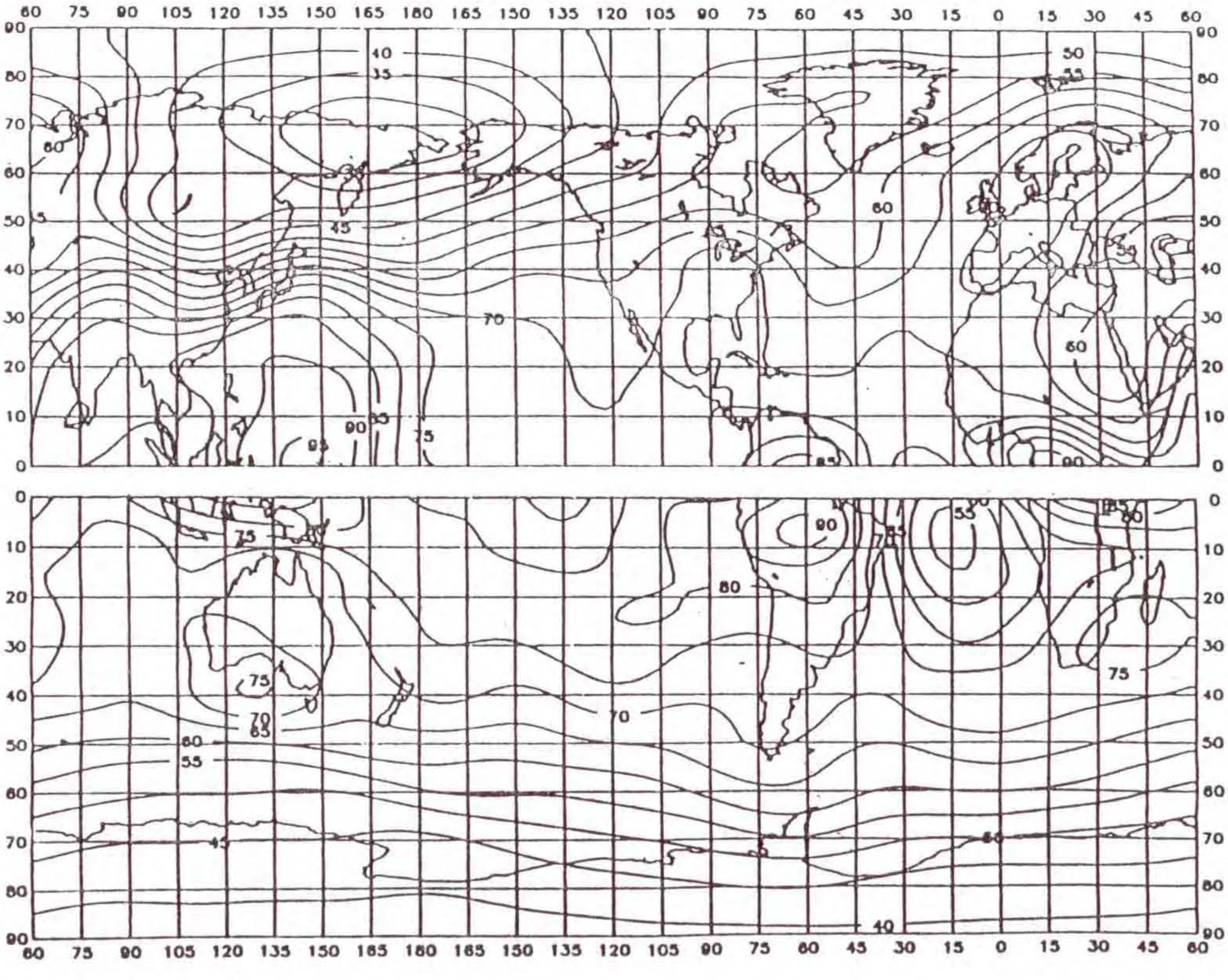

FIGURE 2a – *Expected values of atmospheric radio noise,* F_{am} *(dB above* kT_0b *at 1 MHz)*
(Winter; 0000-0400 LT)

Figure 2. Figure 2a from CCIR Report 322-3.

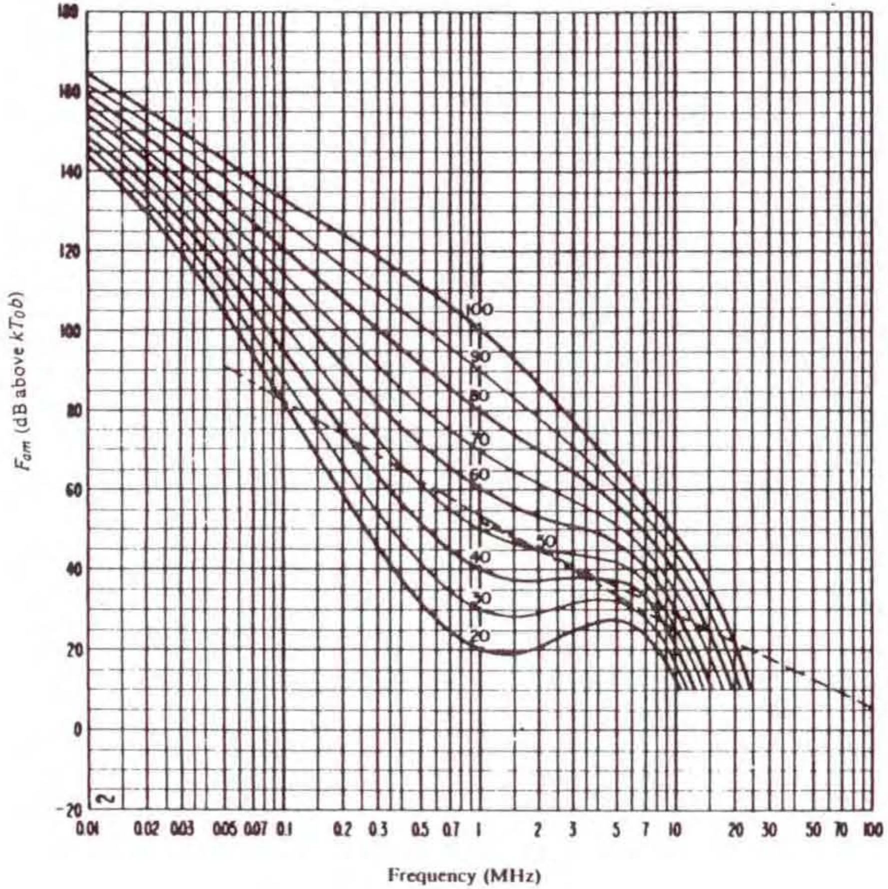

FIGURE 2b – *Variation of radio noise with frequency (Winter; 0000-0400* LT)

———————	Expected values of atmospheric noise
— · — · — · —	Expected values of man-made noise at a quiet receiving location
— — — — —	Expected values of galactic noise

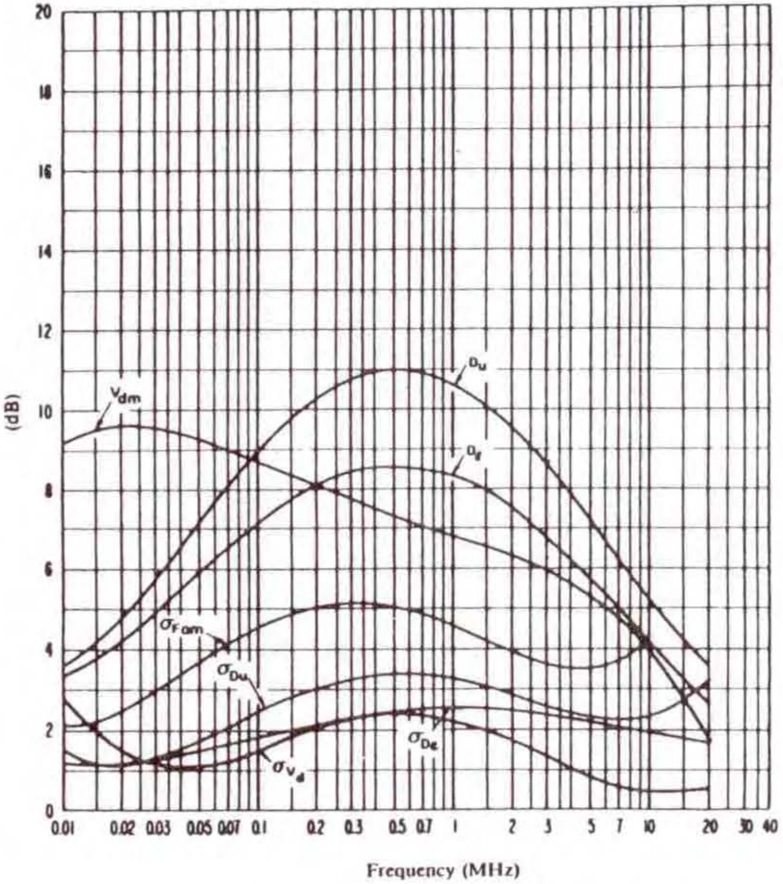

FIGURE 2c – *Data on noise variability and character (Winter; 0000-0400* LT)

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

σ_{V_d}: standard deviation of V_d

Figure 3. Figures 2b and 2c from CCIR Report 322-3.

two-dimensional Fourier sine series,

$$F_{am}(x,y) = \sum_{k=1}^{29} \left(\sum_{j=1}^{15} b_{j,k} \sin jy + \chi_k \right) \sin kx + \alpha + \beta x, \quad (11)$$

where

x = latitude in radians ($0 \rightarrow \pi$) or degrees North of South pole x $\pi/180$

y = longitude in radians ($0 \rightarrow \pi$) or degrees East of Greenwich x $\pi/360$,

χ_k = longitude coefficient such that $F_{am}(x,o) = F_{am}(x,\pi)$,

and α and β are coefficient such that there is only one value at the North and South poles for every longitude. The details of the mapping are contained in Spaulding and Washburn (1985).

The frequency variation of F_{am} (Figure 3) is given by

$$F_{am}(x,z) = A_1(z) + A_2(z)x + A_3(z)x^2 + \ldots + A_7(z)x^6. \quad (12)$$

where

$$A_i(z) = B_{i,1} + B_{i,2}z, \quad i = 1,7. \quad (13)$$

z = the 1 MHz F_{am}(from the contour maps), and

$$\chi = \frac{8 \times 2^{\log_{10} f} - 11}{4}, \quad (14)$$

where f is the frequency in MHz. Also $F_{am}(-0.75,z) = z$ (i.e., the 1 MHz value must equal z). So 14 coefficients represent each of the 24 sets of frequency variations (each season and 4-hour time block).

The other parameters of concern here, D_μ, D_ℓ, σ_{D_μ}, σ_{D_ℓ}, and $\sigma_{F_{am}}$ are all given by

$$p(x) = A_o + A_1x + A_2x^2 + A_3x^3 + A_4x^4, \quad (15)$$

where $x = \log_{10}(f_{MHz})$, and f_{MHz} is the frequency in MHz.

All the coefficients, $b_{j,k}$, χ_k, α, β for the 1 MHz maps, the $B_{i,1}$, $B_{i,2}$, and the 5 sets of A_i, $i = 0, 4$, for each of the 24 season/time blocks are given in Spaulding and Washburn along with computer algorithms for their use. In the program IONCAP, the SUBROUTINE ANOIS1 determines the 1 MHz atmospheric noise value by calling SUBROUTINE NOISY, which uses the $b_{j,k}$, χ_k, α, and β coefficients via (11). In NOISY the $b_{j,k}$ χ_k coefficients and in the array P (29, 16, 8), the α and β coefficients are in ABP (2, 8). The F_{am} at the desired frequency and D_μ, D_ℓ, σ_{D_μ}, σ_{D_ℓ}, and $\sigma_{F_{am}}$ at this frequency are calculated by SUBROUTINE GENFAM. The F_{am} frequency variation coefficients are in array FAM (14, 12) and the coefficients for the other 5 parameters are in array DUD (5, 12, 5). These arrays are only for one season. The 1 MHz maps are in terms of three month periods and P (29, 16, 8) and ABP (2, 8) are for one three-month period, six four-hour time blocks (the sets of coefficients for the "7 and 8" indices are maps of the continental outline and the ratio of F-layer heights to its semi-thickness). The other parameters are given as seasonal variations (not 3 month), so the arrays FAM and DUD have the dimension 12 (rather than 6) so that they include the 6 time-block sets for the Northern Hemisphere and the 6 time-blocks for the Southern Hemisphere. That is, for example, if the month for which IONCAP is being run is say, March, this is Spring in the Northern Hemisphere and Fall in the Southern Hemisphere, so that both the Spring and Fall coefficients are required for the three month period, March, April, and May. In IONCAP when the season is changed, new arrays P, ABP, FAM and DUD (as well as others) must be read in. For modern computers, this is very inefficient. In any case, the new coefficients P (29, 16, 6) and ABP (2, 6) (the "7 and 8" are the same) for the new 1 MHz F_{am} maps have been installed in IONCAP. Except for this change, SUBROUTINES ANOIS1, NOISY AND GENFAM have been altered as explained below, and all the significant improvements are in SUBROUTINE GENOIS, which is the main noise routine.

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, F_a, 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 wanted F_a and its variation for the Winter Season, 0000-0400 time block, for Boulder, Colorado at 3 MHz. From Figure 2 (2a of CCIR 322-2) F_{am} at 1 MHz is 66 dB. From Figure 3 (2b of CCIR 322-3) this translates to 55 dB at 3 MHz. From Figure 3, (2c of CCIR 322-3) the values for the other parameters are

$$D_{\mu} = 8.6 \text{ dB}, D_{\ell} = 6.8 \text{ dB}, \sigma_{D_{\mu}} = 2.6 \text{ dB}, \sigma_{D_{\ell}} = 2.4 \text{ dB, and } \sigma_{F_{am}} = 3.7 \text{ dB}.$$

The sigmas account for the entire Earth's surface being covered by one value of D_{μ}, etc. and represent a location variability and the year-to-year variability. Figure 4 shows the distributions of F_a values estimated via the data above

$$(F_{am}, D_{\mu}, D_{\ell}, \sigma_{D_{\mu}}, \sigma_{D_{\ell}}, \text{ and } \sigma_{F_{am}}).$$

On Figure 4, for the given F_{am}, all the data measured at Boulder 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. In determining the overall variability, however, the $\sigma_{F_{am}}$ must also be considered. This is covered in detail in Section 4, where all the noises are combined and the overall variations determined.

In IONCAP, in the computation of the signal-to-noise ratio, the signal is calculated as a month/hour median with corresponding variations (σ). As we noted above the atmospheric noise values are calculated for season (3 month), 4-hour, time-blocks.

The routine GENOIS obtains a 3 month/1-hour value for F_{am} and all the variation parameters by linear interpolation between adjacent 4-hour time blocks (for the given season). This is done by calling GENFAM twice, using indices (for the required 4-hour time-blocks) generated in SUBROUTINE ANOIS1. The interpolation gives values at the beginning of the required hour. The F_{am} value, for example, that is obtained from CCIR 322 is placed at the center of the time block (beginning of third hour) and is, therefore, the value returned by the interpolation for the third hour. Some consideration was given to changing the interpolation to obtain values at the midpoint of each hour. This would involve extensive modification to ANOIS1 as to how the required indices are generated. Since the indices that are currently generated in ANOIS1 are used throughout IONCAP and not only in GENOIS, this was not done. Also, as noted below, it would result in no statistical improvement and

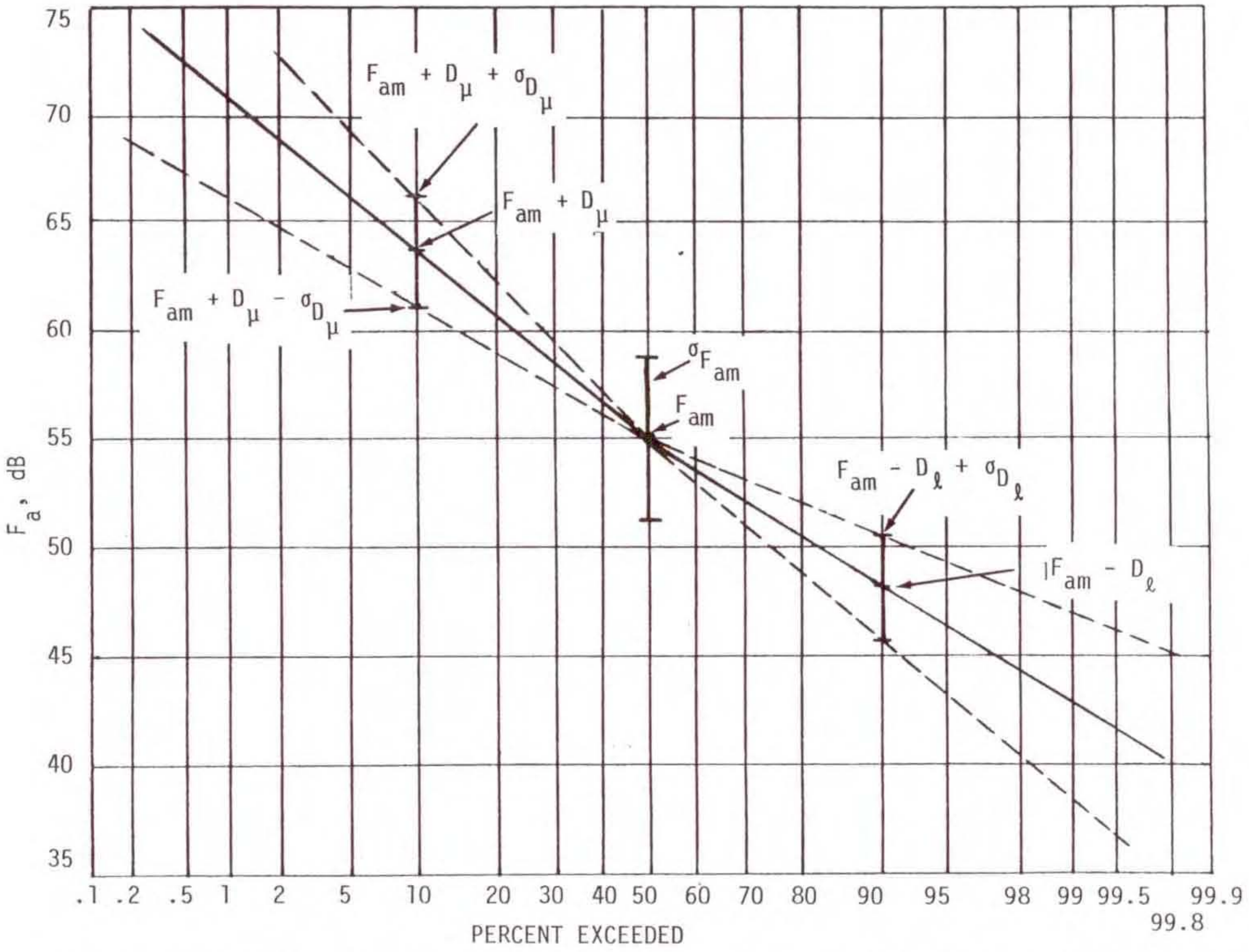

Figure 4. The distribution of F_a values for atmospheric radio noise at Boulder, Colorado 3 MHz, for the Winter Season, 0000-0400 hours.

would only be cosmetic.

The question also arises as to the suitability of using the variation parameters D_μ and D_ℓ which were calculated for a season 4-hour time-block for the season 1-hour time block. If the season 4-hour data is homogeneous, then the statistics estimated from this population should apply to sub-populations. When the original D_μ and D_ℓ estimates were obtained, they were calculated simply by averaging the month-hour values. These are the values given in CCIR Report 322-1 and are as reported in the earlier volumes of the Tech Note 18 series (i.e., before October 1961). The D_μ and D_ℓ's given in the later Tech Note 18's were calculated from the raw data; that is, from all the hourly values for the entire season 4-hour time-block, rather than from averaging the month-hour values. In the analysis of the totality of data (Spaulding and Washburn, 1985) that lead to CCIR Report 322-3, the D_μ and D_ℓ's "correctly" computed were not significantly different from those computed earlier as given in 322-1. Therefore the variation parameters, including the frequency variation of F_{am}, are the same in 322-3 as in 322-1. This gives some indication, at least, that use of the existing season 4-hour values is acceptable for the season 1-hour values. The interpolation on F_{am} to obtain a 1-hour value from the 4-hour value was initiated originally, apparently, to avoid the annoying occasional sharp discontinuity between adjacent time blocks. No increase in statistical significance, however, is gained. The linear interpolation on

$$D_\mu,\ D_\ell,\ \sigma_{D_\mu},\ \sigma_{D_\ell},\ \text{and}\ \sigma_{F_{am}}$$

makes little difference, since these change quite slowly between time blocks (for any given frequency).

Some thought was also given to what would be involved and if anything would be gained if the interpolation was continued (across adjacent seasons) to obtain a month-hour value from 3-month-hour values. From above, it is clear that nothing of any statistical importance would be gained. Also, as noted earlier, going from one season to the next requires the obtaining of completely new sets of coefficients due to how IONCAP is constructed. Doing interpolation between seasons would significantly more than double the running time of the noise value computation. That is, GENOIS would need to call GENFAM four times instead of two and the second two would require obtaining different sets of the coefficient arrays (P, ABP, and DUD). All this would gain nothing. Even so, some preliminary calculations were made to note how the resulting month-hour values of F_{am} might differ from the 3-month-hour values. For the very few examples looked at, no sharp differences were noted.

The above covers the determination of the atmospheric noise F_{am} value and its statistical variation. Man-made noise and galactic noise have f_a values that also are log-normally distributed. The next section covers the estimation of the man-made noise value, its variation, and the galactic noise value and its variation. Then Section 4 covers the addition of the three noises to obtain the overall external f_a and its variation.

3. MAN-MADE AND GALACTIC NOISE

As noted in the introduction, one of the major changes in the SUBROUTINE GENOIS was to replace the current man-made noise estimates with the much more modern ones as given in CCIR Report 258-4 (1982). As will be shown, these estimates are substantially different than the ones currently used, and this, in some situations, will greatly affect the calculated signal-to-noise ratio.

Figure 5 shows the man-made noise levels from CCIR Report 258. These levels and all the associated statistics are directly from Spaulding and Disney (1974), which gives the details of the measurements and analysis giving rise to these estimates. Most of the measurements that went into the estimates were from throughout the continental U.S. The quiet rural curve is from CCIR Report 322 and is based on world-wide measurements. As noted in Report 258, numerous measurements made throughout the world since these estimates were developed generally follow them quite closely for the various areas (i.e., business, residential, etc.) and therefore the Report 258 estimates serve well throughout.

As an additional example of the applicability of the Report 258 estimates, Figure 6 shows recently analyzed noise measurements from Moscow. When the new atmospheric worldwide noise estimates were obtained (Spaulding and Washburn, 1985), some of the "new" data used was from 10 Soviet measurement locations. One of these was Moscow. For Moscow, data are available from March 1958 through December 1964. The frequencies were 12, 25, 35, 60, 100,