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

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ABSTRACT

It is desirable to design receiving systems so that the receiver will be close to being limited by external noise. Indeed, it is cost ineffective to design radio receiving systems with noise figures significantly less than the minimum values of the environmental radio noise. The best available estimates of the minimum values of the environmental radio noise for vertically polarized antennas expected worldwide (0.1 Hz to 100 GHz) presented in this paper should facilitate cost-effective future receiver design.

PRE-DETECTION SIGNAL-TO-NOISE RATIO AND RECEIVING SYSTEM OPERATING NOISE FACTOR

The pre-detection signal-to-noise ratio (S/N) **is an important telecommunications system design** parameter. 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 Fig. 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 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 288K,
- b = the noise power bandwidth of the receiving system in Hz.

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

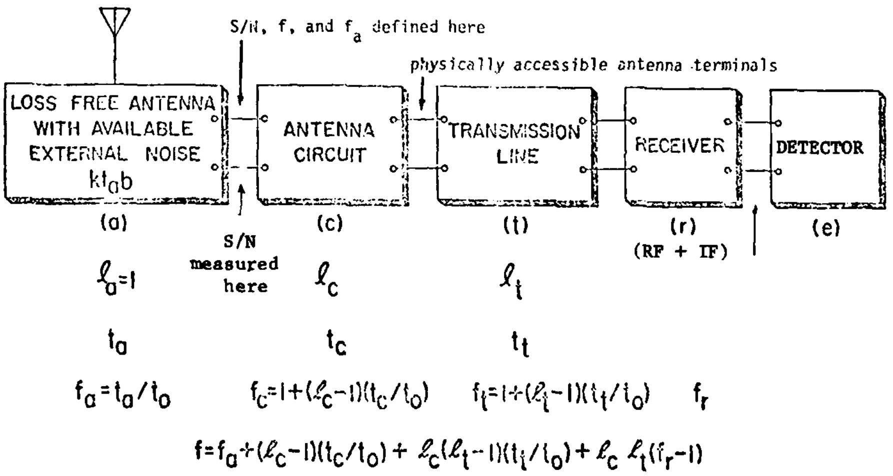

Figure 1. The receiving system and its operating noise factor, f.

$$10 \log_{10}(s/n) = S - N \quad (1)$$

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

$$f = f_a + (\ell_c - 1)\left(\frac{t_c}{t_o}\right) + \ell_c\,(\ell_t - 1)\left(\frac{t_t}{t_o}\right) + \ell_c \ell_t\,(f_r - 1) \quad (2)$$

where,

f_a = the external noise factor defined as

$$f_a = \frac{p_n}{k t_o b}, \quad (3)$$

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 Fig. 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

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,

$$f_c = 1 + (\ell_c - 1)\left(\frac{t_c}{t_o}\right), \quad (4)$$

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

$$f_t = 1 + (\ell_t - 1)\left(\frac{t_t}{t_o}\right). \quad (5)$$

If $t_c = t_t = t_o$, (2) becomes*

$$f = f_a - 1 + f_c f_t f_r . \quad (6)$$

*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

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

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

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

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 half-wave dipole in free space,

$$E_n = F_a + 20 \log f_{MHz} + B - 89.9 \text{ dB}(1\mu V/m). \quad (9)$$

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

$$f_a = \frac{t_a}{t_o}, \quad (10)$$

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), and supplementary discussions on natural and man-made noise are provided in CCIR Reports 322 (1963) and 258 (1976) respectively.

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 the noise power bandwidth, b, are summarized in Fig. 2 (from Spaulding, 1976 and Hagn, 1978). 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 $P_n = -164$ dB(1W). If $\ell_t = 3$, then the noise power available from the receiving antenna transmission line is -172 dB(1W).

ESTIMATES OF MINIMUM 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. Fig. 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

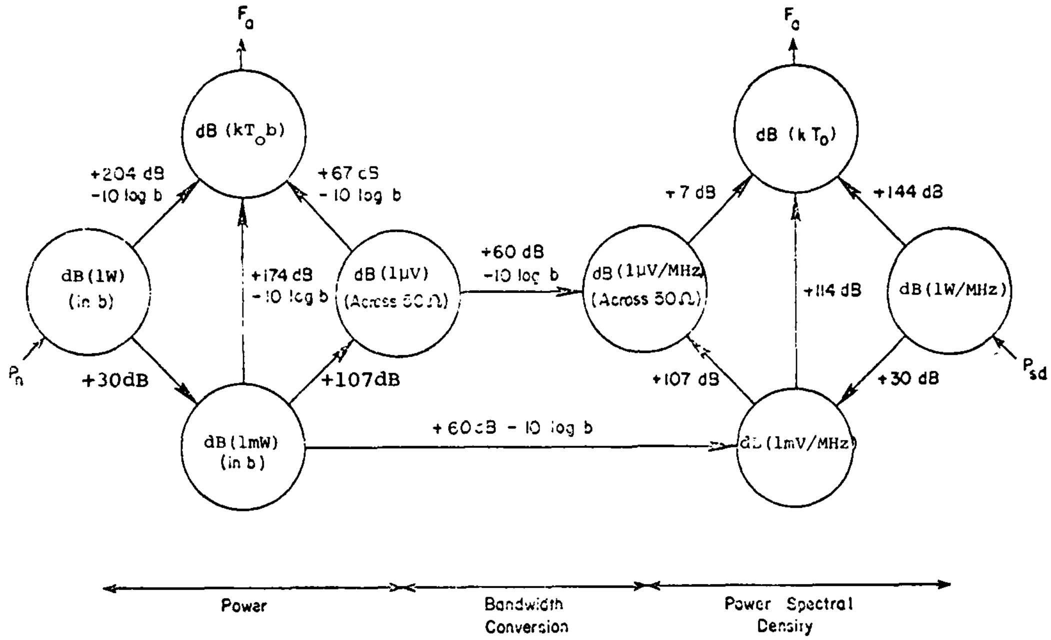

Figure 2. Relationships between power, power spectral density, and bandwidth (rsms detector).

(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.

Fig. 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 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). 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 CCIR Report 258 (1976), Spaulding and Disney (1974) and references therein, and Hagn and Shepherd (1974).

On Fig. 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 are 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 narrow-beam antennas.

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

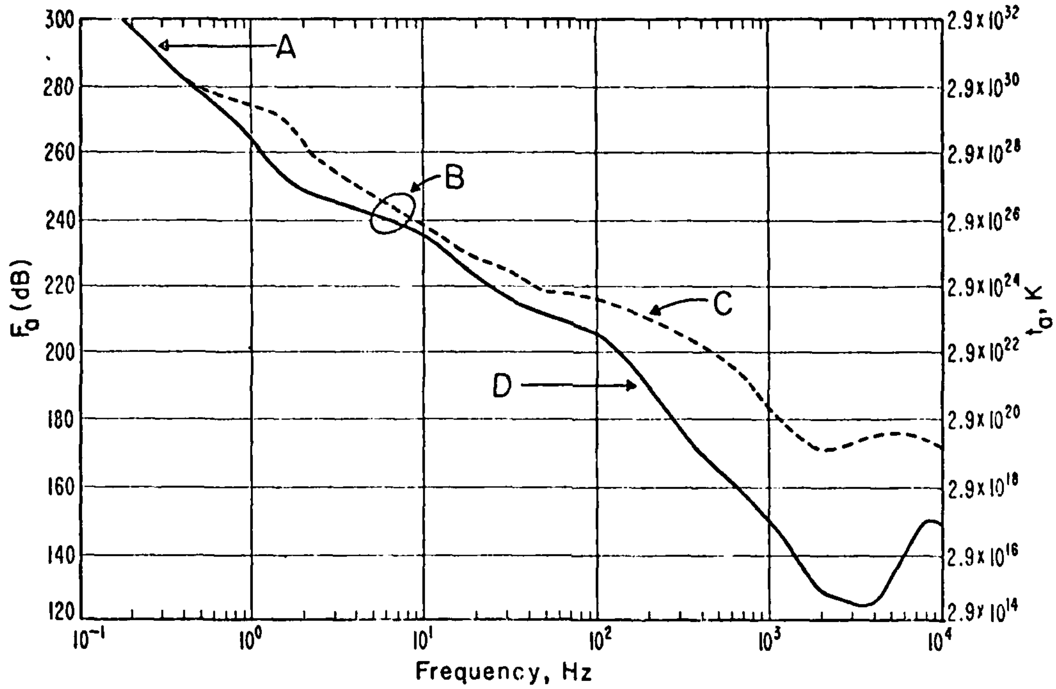

Figure 3. F_a, minimum and maximum, versus frequency (0.1 to 10^4 Hz).

A: Micropulsations
B: Atmospheric noise from lightning
C: Maximum expected
D: Minimum expected

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 Fig. 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

$$f = f_a - 1 + f_r . \qquad (11)$$

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,

$$f = f_a - 1 + 10000\, f_r . \qquad (12)$$

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>.

CONCLUDING REMARKS

Throughout this paper we have considered noise as a source of system degradation and interference as the degradation produced (see Hagn, 1977 for a discussion of the basic definitions and rationale). This is consistent with current internationally accepted usage (CCIR, 1974). Finally, it should be noted that many of the external noises (e.g., many forms of atmospheric and man-made noise) are impulsive in nature. This means that the external noise can still limit performance of a communications system, even though the receiver noise is made as high as possible so as not to increase the overall operating noise factor f. That is, system performance depends not only on the level of the interfering noise power (signal-to-noise ratio), but also on the detailed statistical characteristics of the noise.

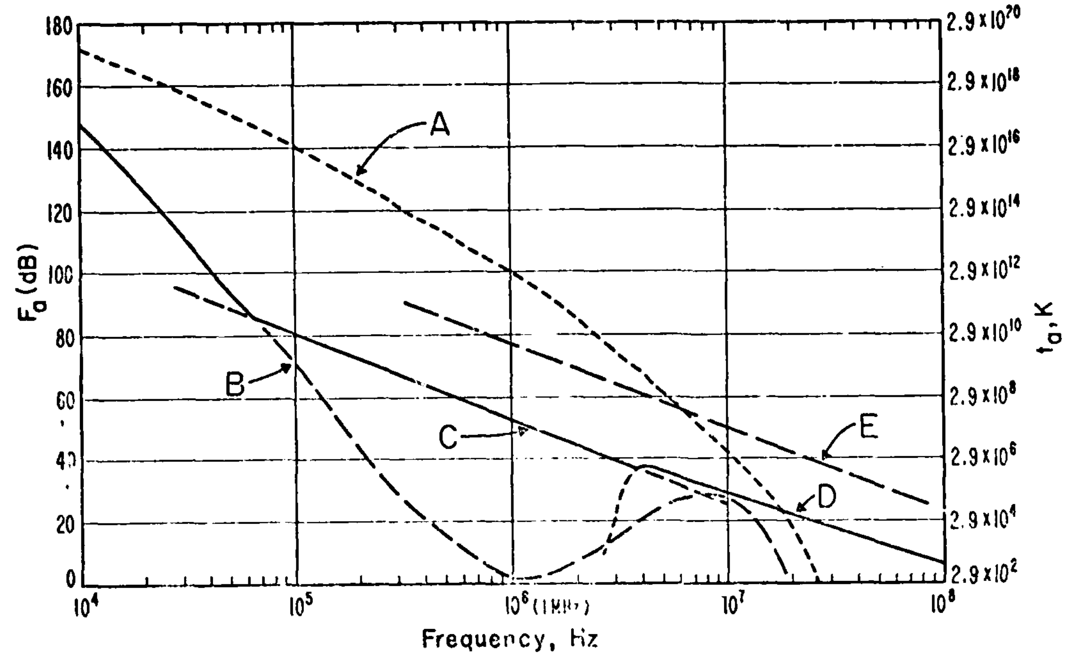

Figure 4. F_a versus frequency (10^4 to 10^8 Hz)

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

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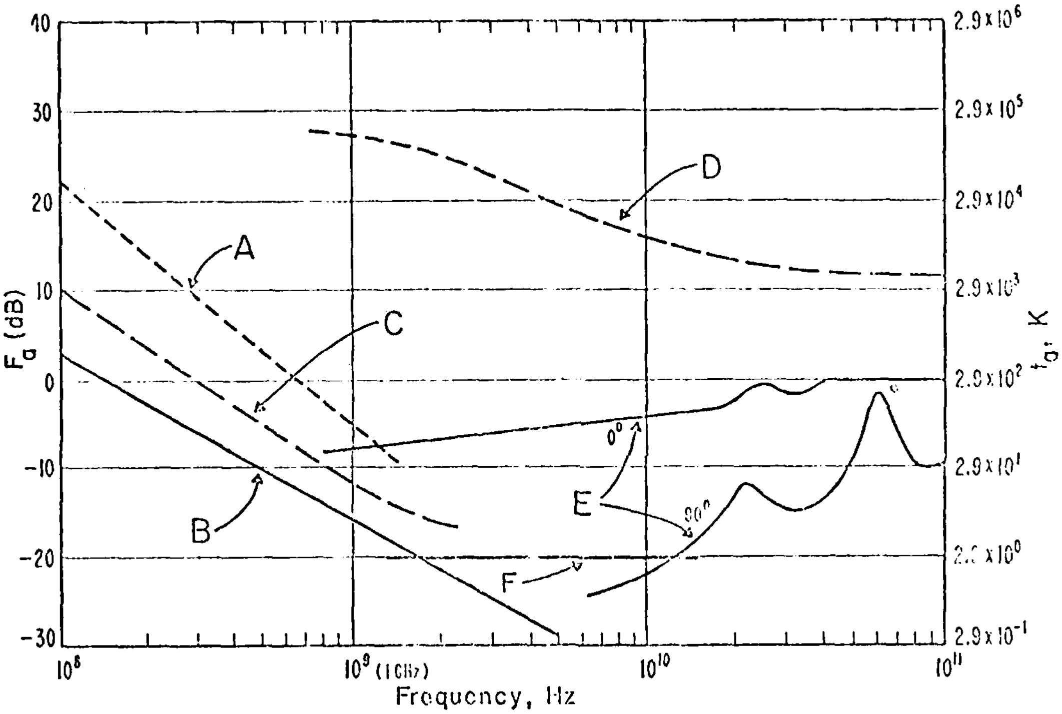

Figure 5. F_a versus frequency (10^8 to 10^{11} Hz).

A: Estimated median business-area man-made noise
B: Galactic noise
C: Galactic noise (toward galactic center with infinitely narrow beamwidth)
D: Quiet sun (½ 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