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Practical Measurement of Effective Antenna Noise Factor and Noise Equivalent Bandwidth

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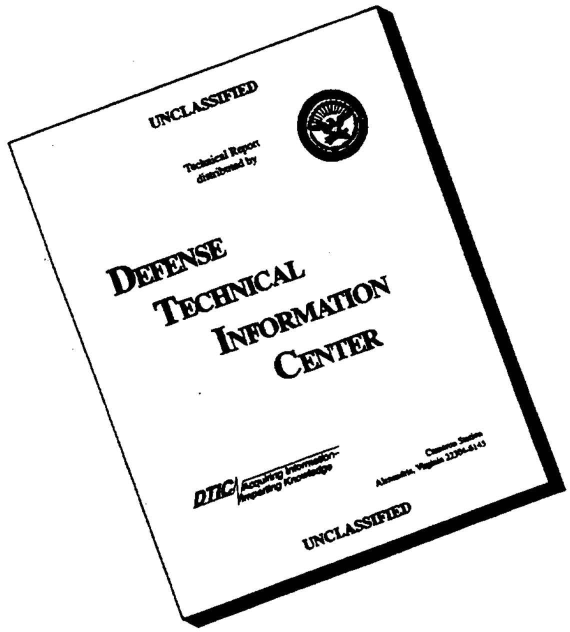

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Practical Measurement of Effective Antenna Noise Factor and Noise Equivalent Bandwidth

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ABSTRACT

Effective Antenna Noise Factor is a measure of external radio noise widely used in the prediction of link performance and in surveys of the noise environment. The practicalities of accurately estimating this quantity and a novel technique for measuring the Noise Equivalent Bandwidth of a complete receiving system are described.

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EXECUTIVE SUMMARY

A standard measure of external radio noise used in the prediction of radio link performance is the noise power spectral density expressed in terms of the Effective Antenna Noise Factor. The Effective Antenna Noise Factor is also commonly used in surveys of environmental radio noise at specific global locations. In this report an expression for the Effective Antenna Noise Factor is mathematically derived in a form suitable for link performance estimation from directly measurable quantities. It has been used in the analysis of recent DSTO radio noise trials. A novel and superior technique is also presented for the digital measurement of the Noise Equivalent Bandwidth of the receiver, recording and replay system, a parameter used in the estimation of the Effective Antenna Noise Factor.

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Contents

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1 Introduction

A standard measure of external radio noise used in the prediction of radio link performance is the noise power spectral density expressed in terms of the *Effective Antenna Noise Factor*, F_a. This measure, defined in [1], is also commonly used in surveys of environmental noise at specific global locations, e.g., [2]. The aim of this paper is to concisely relate the mathematical derivation of the Effective Antenna Noise Factor and to describe the practical issues associated with the accurate estimation of this quantity in DSTO radio noise trials. A novel and superior technique is also presented for the digital measurement of the *Noise Equivalent Bandwidth* of the receiver and recording and replay system, a parameter used in the estimation of F_a.

2 Derivation of Effective Antenna Noise Factor

The Effective Antenna Noise Factor, F_a, is defined by:

$$\begin{aligned} F_a &= 10\log_{10} f_a, \\ \text{where } f_a &= \frac{w}{kT_0 b}, \end{aligned}$$

and w is the *average*[1] external noise power (in W) in bandwidth b (in Hz) available from an equivalent lossless antenna. $k = 1.38 \times 10^{-23}$ JK^{-1} is Boltzmann's constant and T_0=288 K is the reference temperature.

Note that f_a is a dimensionless quantity, being the ratio of two powers. However, it is a measure of the available power spectral density in terms of kT_0b. For this reason, F_a is commonly seen with units attached (eg., dB relative to kT_0 or kT_0b).

The power available from the antenna is dissipated in the antenna resistance, antenna coupler and receiver input resistance. *Provided the coupler is adjusted for maximal transfer of power into the receiver input resistance*, it may be expressed in a simple manner, in terms of the *rms* voltage, v (in V), at the receiver terminals, the antenna coupler power gain, g_c, and the receiver input resistance, r (in Ω), as follows:

$$w = \frac{v^2}{r g_c}$$

Hence, F_a is related to the *rms* receiver input voltage by:

$$F_a = 10\log_{10}\{\frac{v^2}{r} \times \frac{1}{kT_0 b} \times \frac{1}{g_c}\}$$

[1] For skywave reception, median instead of average power is sometimes used and an allowance must be made for fading: see p.251 of [4]. Assuming Rayleigh fading, F_a will be 1.6 dB higher using median values.

The coupler gain may be determined by using a transmitter, radiating a constant power at a frequency within the bandpass of the system, and measuring the *rms* value of the vertical component of the field strength e (in Vm^{-1}) with a calibrated field strength meter and the corresponding *rms* receiver input voltage with the coupler tuned to deliver maximum power (viz voltage) at the receiver input terminals.

The field strength is related to the power density, p (in Wm^{-2}), of the incident electromagnetic wave by:

$$e = \sqrt{120\pi p}$$

and p is simply

$$p = \frac{w}{a}$$

where a is the "effective" area of the antenna (in m^2),

$$a = \frac{\lambda^2 g_a}{4\pi}.$$

λ is the wavelength (in m) and g_a is the antenna power gain[2].

Expressed in terms of frequency, f (in Hz),

$$\begin{aligned} p &= \frac{4\pi f^2}{c^2} \times \frac{w}{g_a} \\ &= \frac{4\pi f^2}{c^2} \times \frac{v^2}{r g_a g_c} \end{aligned}$$

where c is the speed of light ($3.0 \times 10^8\ \mathrm{ms}^{-1}$). Hence,

$$e = \frac{\sqrt{480\pi}}{c} \times \frac{fv}{\sqrt{r g_a g_c}}$$

Defining the *Antenna Factor*,

$$A_f = 20\ \log_{10}\{\frac{v}{e}\},$$

to be the logarithm of the ratio of the receiver voltage *in a system with a matched coupler* and corresponding field strength measured at frequency f with a field strength meter, then

$$A_f = 10\ \log_{10}\{\frac{c^2}{480\pi^2} \times \frac{1}{f^2}\} + 10\ \log_{10}\{r g_a g_c\}$$

Rearranging, we obtain the coupler gain:

$$g_c = \frac{480\pi^2 f^2}{c^2 g_a r} \times\ \mathrm{antilog}_{10}\{\frac{A_f}{10}\}$$

[2]Eg., for a grounded, lossless isotropic antenna g_a=1 and for a short (height $\ll \lambda$) grounded, lossless vertical monopole $g_a \simeq 3.6$

Substituting this into the formula for F_a we get,

$$F_a = 10\ \log_{10}\{v^2 \times \frac{1}{kT_0b} \times g_a\} + 10\ \log_{10}\{\frac{c^2}{480\pi^2} \times \frac{1}{f^2}\} - A_f$$

Thus, F_a is a function only of receiver *rms* input voltage, frequency, receiver system bandwidth, antenna factor and antenna power gain.

$$\begin{aligned} F_a &= 10\ \log_{10}\{\frac{v^2}{f^2} \times g_a\} + 10\ \log_{10}\{\frac{c^2}{480\pi^2} \times \frac{1}{kT_0b}\} - A_f \\ &= 10\ \log_{10}\{\frac{v^2}{bf^2} \times g_a\} - A_f + 336.79\ (\text{dB}) \end{aligned}$$

Alternatively, letting G_{co} be the coupler gain (in dB) with an *isotropic* antenna, viz

$$\begin{aligned} G_{co} &= 10\ \log_{10}\{g_c(g_a = 1)\} \\ &= A_f + 10\ \log_{10}\{\frac{480\pi^2 f^2}{c^2 r}\} \end{aligned}$$

$$\text{then, } F_a = 10\ \log_{10}\{\frac{v^2}{kT_0br}\} - G_{co} + 10\ \log_{10}\{g_a\} = P_n - G_{co} + G_a$$

where P_n is the *average* noise power (in dB relative to kT_0b) dissipated in the receiver input resistance and G_a is the antenna gain in dB.

3 Measurement Issues

The accurate estimation of F_a involves the accurate measurement of the following antenna and receiver system constants.

3.1 Receiver System Voltage Gain

When the output of the analogue receiver is digitised, the *system voltage gain factor*, γ, can be determined by dividing the digitised output voltage (an integer $\hat{v}$) by the *rms* input voltage, v, viz.,

$$\gamma = \frac{\hat{v}}{v}.$$

γ is measured with a sinewave generator at a frequency within the receiver system passband where there is maximum power response; this overcomes the problem of frequency selection when there are ripples in the passband. The receiver *system* for these purposes includes the receiver itself plus analogue recording system (eg digital-audio tape drive), analogue to digital converter (ADC) and digital processing system (eg Hilbert filter) that may scale the amplitude or modify the spectrum of the received signal. The units of γ are ADC counts per volt. Accurate system gain measurement is contingent on using an accurately calibrated signal generator.

3.2 Receiver System Bandwidth

The bandwidth in the F_a calculation is the overall receiver system *Noise Equivalent Bandwidth* (NEB), which is the bandwidth of an ideal bandpass filter having a rectangular spectral power response and identical power output to that of the receiver system with white noise input[3]. Traditionally [3], NEB measurements are achieved by feeding a signal of known power (w_{ref}) and bandwidth (b_{ref}) from a calibrated wideband white noise generator into a receiver whose *peak* voltage gain, γ, has been determined, and computing the equivalent input signal power, w, from measurements of the *rms* output voltage, v_o. In the case of a digital system, the *rms* output voltage, v_o, is obtained from N envelope voltage samples $\{\hat{v}_k\}$ as follows:

$$v_o = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\hat{v}_k^2}$$

Hence,

$$w = \frac{v_o^2}{\gamma}$$

and the NEB is obtained from:

$$b = \frac{b_{ref}}{w_{ref}} \times w.$$

An alternative, simpler, and more accurate[4] method of measuring system NEB has been devised by the author. It is based on the mean of the statistical distribution of the the number of *runs* in the digitised instantaneous envelope voltage samples. A run is simply a sequence of consecutively increasing (or decreasing) sample voltages. Assuming that the samples are statistically independent, the total number of runs in N samples may be regarded as normally distributed (for N >20) with mean and variance given by [5]:

$$\begin{aligned} \mu_R &= \frac{1}{3}(2N-1) \\ \sigma_R^2 &= \frac{1}{90}(16N-29) = \frac{8\mu_R - 7}{30} \end{aligned}$$

respectively[5]. Several recordings of white noise can be played through the system to estimate the mean number of runs. The Maximum Likelihood Estimator (MLE) for the mean number of runs, $\tilde{\mu}_R$, for this particular distribution is found by solving for the positive root of the quadratic equation:

$$\tilde{\mu}_R^2 - \frac{89}{60}\tilde{\mu}_R + (\frac{7}{4}\bar{R} - \frac{\overline{R^2}}{2} - \frac{7}{30}) = 0$$

where $\bar{R}$ and $\overline{R^2}$ are the average number of runs and the average of the squares of the number of runs over the recordings respectively.

[3]NEB usually cannot be accurately determined from the -3 dB points of the frequency response.

[4]Because neither a calibrated white noise generator is required nor knowledge of the system gain.

[5]The mean number of runs per unit time is equivalent to the number of zero crossings per unit time of the time derivative of the voltage in the limit as the sampling frequency tends to infinity.

Bandpass filtered white noise samples are independent (hence uncorrelated) for an ideal filter *provided* the sampling frequency, f_S, is equal to an integer multiple of the *Nyquist Rate* [7], $f_N = 2b$, and the expectation of the estimate of the mean number of runs in the noise recordings is given by[6]

$$E[\tilde{\mu}_R] \simeq \frac{f_N}{f_S} \times \mu_R$$

Hence the noise equivalent bandwidth may be estimated from

$$\tilde{b} = \frac{f_S}{2} \times \frac{\mu_R}{\tilde{\mu}_R}.$$

By way of illustration, in our laboratory we used nine white noise recordings, each of one minute duration, and each was subdivided into sixty serial sub-records, each comprising $N = 8000$ envelope voltage samples. The sampling frequency was $f_S = 8$ kHz. For each recording we obtained sixty $\bar{R}$ and $\overline{R^2}$ values which were then averaged and used in the computation of $\tilde{b}$. A 95% confidence interval for b was obtained[7] from

$$b = \bar{\tilde{b}} \pm \Upsilon_{8,0.975} \times \sqrt{\frac{s_{\tilde{b}^2}}{9}}$$

where $\bar{\tilde{b}}$ is the average of the $\tilde{b}$, $s^2_{\tilde{b}}$ is the variance of the nine estimates, and $\Upsilon_{n,\alpha}$ is the α critical point for the Student t distribution with n degrees of freedom. The final result[8] was $b = 2517.6 \pm 2.3$ Hz.

3.3 Antenna Power Gain

The power gain, g_a, of an antenna[9] is commonly defined [6] as the ratio of the maximum radiation intensity in a given direction to the maximum radiation intensity produced in the same direction from a reference antenna, usually a lossless isotropic radiator, with the same input power:

$$g_a = \frac{4\pi\eta e^2_{max}}{\int_0^{2\pi}\int_0^{\pi} e^2(\theta,\phi) sin(\theta) d\theta d\phi}$$

$e(\theta, \phi)$ is the value of the field strength at elevation angle θ and azimuth ϕ which corresponds to the isotropic reference value of e_{max}. The antenna efficiency factor, η, depends upon copper, dielectric and mismatch losses and is normally assumed to be very close to one. The same antenna used for receiving has identical properties (viz radiation pattern, impedance and power gain) as a consequence of the reciprocity theorem. When complete field strength measurements are unavailable, the use of zero elevation polar plots and the approximation

$$g_a \simeq \frac{2\pi e^2_{max}}{\int_0^{2\pi} e^2(0,\phi) d\phi}$$

[6]An approximation which is only *exact* for an ideal filter.

[7]Assuming the bandwidth estimates are normally distributed.

[8]The first method using an uncalibrated white noise generator yielded a 5% lower NEB of 2382.1 Hz.

[9]Described in [6] as "probably the most difficult antenna measurement to be made".

which assumes the field strength is the same for all elevation angles at a given azimuth, may lead to the underestimation of F_a. For example, consider a short grounded vertical monopole antenna, a type frequently encountered on ships, which has a vertical half-power beamwidth of approximately 39 deg and the received power is about 1 dB down at 22 deg elevation[10]. For this type of antenna, only over-the-horizon surface sources located further away than approximately 300km[11] would contribute significantly to F_a. When F2-Layer propagation predominates, the noise contribution from weak sources located further distant than 900 km may exceed that from strong sources at much closer distances simply due to angular effects.

Much the same is true for antennas on low speed aircraft which employ wire supported between the vertical fin and the fuselage. According to [6, p.27–12], most aircraft antennas of this type are designed to maximise the electromagnetic coupling to the airframe (a good conductor in the 2 to 25 MHz frequency range) and provide high average power gain in the angular sectors bounded by cones 30 deg above and below the horizon. The efficiency of long wire aircraft antennas used for reception is usually not high because of wire resistance. Incidentally, direct line-of-sight surface sources[12] may also contribute to aircraft F_a measurements.

Moreover, in the case of mobile receiving platforms, antennas with high directivity will exacerbate noise fading due to platform pitch and roll. Ideally, the angular orientation of the antenna should be measured with time to enable the correction of instantaneous noise measurements: however, the calculation of F_a will be reasonably accurate provided the input *rms* noise voltage is averaged over a period of time that is long compared with the pitch and roll periods of the platform. In short, the vertical antenna pattern should not be neglected.

3.4 Antenna Factor

One of the most important requirements for accurately determining A_f is that the measurements of the field strength, e, and the *rms* receiver input voltage, v, be undertaken *simultaneously*. This can be difficult to achieve in practice without automatic data logging. However, if the transmitter antenna used in the measurement is within line of sight of the receiver antenna, fading is less problematic and A_f may be accurately determined by simply taking the average of several measurements.

[10]Based on normalised power pattern for a short vertical monopole, see p.311 of [8]:

$$e^2(\theta,\phi)/e^2_{max} = \frac{\cos^2(\frac{1}{2}\pi\sin\theta)}{\cos^2\theta}.$$

[11]The minimum distance, derived from §3, p.241 of [4], assumes E-Layer ionospheric propagation. The distance, d, is the solution of:

$$\theta = \arctan\left(\cot\left[\frac{d}{2R}\right] - \frac{R}{R+h'}\operatorname{cosec}\left[\frac{d}{2R}\right]\right)$$

where $R = 6371$ km is the radius of the Earth and $h' = 110$ km is the mean height of the E-Layer.

[12]Located at distances less than approximately $1.20\sqrt{h}$ km, where h is the aircraft height in m.

4 Conclusion

An expression for the Effective Antenna Noise Factor, F_a, has been mathematically derived in a form suitable for estimation from directly measurable quantities. The practical difficulties involved in the accurate measurement of F_a have been discussed and a novel and accurate method of measuring the Noise Equivalent Bandwidth of a receiver and its associated digital recording and replay system has been proposed.

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