*Radio Science*, Volume 36, Number 6, Pages 1385–1391, November–December 2001

# Wideband model of HF atmospheric radio noise

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**Abstract.** A model of the waveform generated by high-frequency atmospheric radio noise is presented. Cumulative probability distributions of the noise envelope are derived and shown to be in good agreement with a large database collected from a wide range of noise environments. The model includes correlations in the waveforms that simulate the burst structure of measured atmospheric noise. The bandwidth dependence of the voltage deviation parameter, which parameterizes the impulsiveness of the noise, shows behavior that is qualitatively similar to a limited amount of measured data.

## 1. Introduction

Motivated by the application of spread spectrum technology and digital signal processing techniques to high-frequency (HF) communication systems, advanced HF systems that operate over wide bandwidths (on the order of 1 MHz or more) are being developed. Since many uncertainties exist concerning the performance of such systems, it is important to have channel models for theoretical predictions of system performance and for laboratory measurements of system performance using channel simulators.

New HF channel models have been developed that (1) are accurate over bandwidths on the order of 1 MHz, (2) can be validated with measured data, and (3) are suitable for implementation in a channel simulator. These new models have been developed because the HF channel simulators currently in widespread use implement a model of the HF channel that has only been verified for narrowband (less than 12 kHz) stable channels [*Watterson et al.*, 1970].

The new wideband models of HF sky wave propagation and of man-made noise and interference have been discussed by *Vogler and Hoffmeyer* [1993] and by *Lemmon* [1997], respectively. These papers pointed out that the model development has been motivated by the need for models that can be implemented in a channel simulator. The noise and interference models are therefore models of the noise and interference waveforms that are combined with the desired signal in a channel simulator.

This paper describes a wideband waveform model of received atmospheric noise in the HF band (3–30 MHz). Here the term "wideband" is used in the sense that one is observing the noise over a bandwidth on the order of 1 MHz. However, it is assumed that the center frequency is sufficiently large relative to the bandwidth to allow the noise process to be characterized by a well-defined envelope and phase. Thus the received noise voltage can be written as

$$V(t)\cos\left[\omega_0 t + \phi(t)\right],$$

where $\omega_0$ is the RF center frequency. Atmospheric noise bursts arise from numerous distinct processes in lightning discharges and can exhibit a wide variety of extremely complex structures [*Uman*, 1987]. The voltage envelope $V(t)$ and phase $\phi(t)$ are therefore treated as random variables.

The development of the man-made noise and interference waveform model was based on examining statistical characteristics obtained from analyses of measured waveforms and developing a model of the waveform that exhibited those same characteristics. However, none of the measured waveforms that were examined revealed the presence of atmospheric noise bursts in the raw data; the pulse width and spacing distributions of the burst noise that were observed were not consistent with those of atmospheric noise [*Lemmon and Behm*, 1993]. Presumably, this was because any atmospheric noise that was present was dominated by the narrowband interference, which was not excised from the data. Therefore the validity of the atmospheric (as opposed to the man-made) noise model has been investigated by comparing the statistical characteristics of simulated waveforms with the characteristics of measured atmospheric noise that have been reported in the literature.



Paper number 2000RS002364.

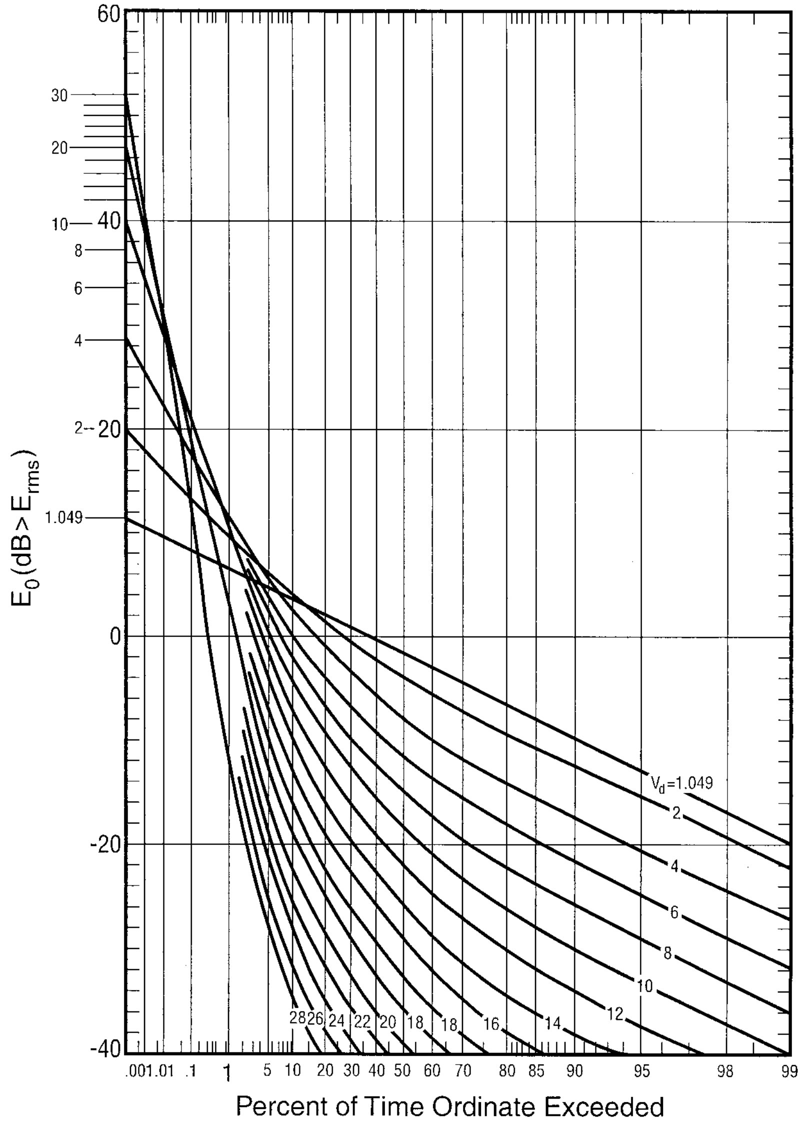


**Figure 1.** Set of amplitude probability distributions of atmospheric radio noise for various $V_d$ values from *ITU-R* [1986].

## 2. First-Order Statistics

The first-order statistics of a random process describe the time-averaged behavior of the process. These statistics have been described for atmospheric noise by a model developed by *Spaulding and Washburn* [1985] and approved by the *International Telecommunications Union, Radiocommunications Assembly* [*ITU-R*, 1986]. This model specifies cumulative probability distributions of the received noise voltage envelope and assumes uniformly distributed phase. The model is shown in Figure 1, in which the probability distributions are parameterized by the voltage deviation parameter $V_d$ (the dB difference between the rms and mean values of the noise voltage envelope).

Unlike Gaussian noise, the characteristics of atmospheric noise are a function of receiver bandwidth. *Herman and DeAngelis* [1987] have given results on the effect of bandwidth on $V_d$, shown in Figure 2. These results are based on medium-frequency data (450-kHz center frequency). However, it was pointed out by the authors that preliminary analysis of some limited HF data indicated similar behavior, so that

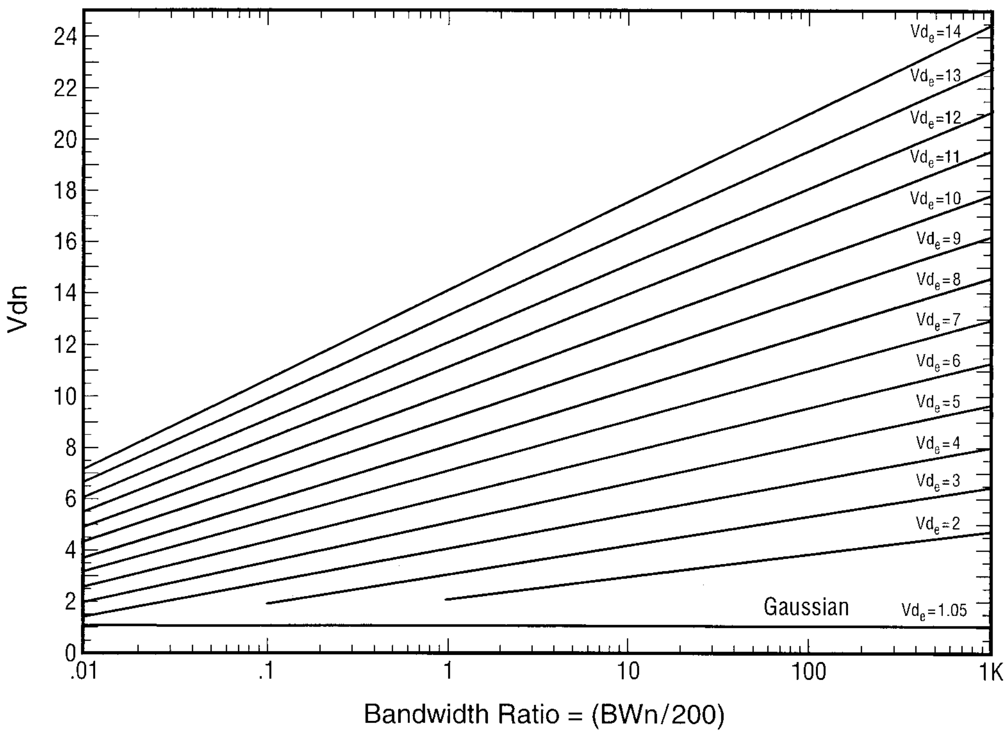


**Figure 2.** Translation of $V_d$ from a 200-Hz bandwidth to other bandwidths, based on measured medium frequency data [*Herman and DeAngelis*, 1987].

the results were assumed, with caution, to be applicable to the HF band.

In this paper the first-order statistics of the atmospheric noise waveform are characterized by the *Hall* [1966] model. This model was developed to describe atmospheric radio noise and was shown to be in good agreement with the first-order envelope statistics of measured atmospheric noise in the VLF, LF, and HF bands observed over bandwidths on the order of 1 kHz. It will be shown in the present paper that this model is also in good agreement with the measured first-order envelope statistics of atmospheric noise over much wider bandwidths.

In accordance with the Hall model it is assumed that the phase $\phi(t)$ is uniformly distributed and the probability density function $p_V(V)$ of the voltage envelope $V(t)$ is given by

$$p_V(V) = \frac{(\theta - 1)\gamma^{\theta-1}V}{(V^2 + \gamma^2)^{(\theta+1)/2}}, \qquad (1)$$

where $\theta$ and $\gamma$ are free parameters (with the constraint that $\theta > 1$, so that $p_V(V)$ is normalizable). A set of amplitudes distributed according to (1) can be generated by integrating (1) to obtain the cumulative probability $P(V)$,

$$P(V) = 1 - \frac{\gamma^{\theta-1}}{(V^2 + \gamma^2)^{(\theta-1)/2}}, \qquad (2)$$

inverting the result to obtain $V(P)$,

$$V(P) = \gamma\left(\frac{1}{(1 - P)^{2/(\theta-1)}} - 1\right)^{1/2}, \qquad (3)$$

and treating the cumulative probability $P$ as a random variable uniformly distributed between 0 and 1.

Values of $\theta$ and $\gamma$ can be determined by relating them to values of $V_d$ and the mean noise power measured at the terminals of a lossless, short monopole antenna, which have been specified for various geographical locations, times of day, seasons, and frequencies [*Spaulding and Washburn*, 1985; *ITU-R*, 1986]. From (3) it can be seen that values of a random variable $V(t)$ distributed according to (1) are proportional to $\gamma$; therefore $V_d$, which is proportional to the logarithm of a voltage ratio, is independent of $\gamma$ and depends only upon $\theta$.

The relationship between $V_d$ and $\theta$ was determined numerically by simulating waveforms using (3) with various values of $\theta$ and calculating $V_d$ for each waveform. The results are shown in Figure 3, in which $V_d$ is plotted versus $\theta$. For each value of $\theta$, 100 waveforms (each consisting of 32,000 samples) were simulated. The three values of $V_d$ that are plotted for each value of $\theta$ are the mean value and the mean value $\pm 1$ standard deviation for the 100 waveforms.

Having determined $\theta$ from $V_d$, $\gamma$ can be determined from $\theta$ and the mean noise power as follows. If $P$ is the noise power at the antenna terminals and $V$ is the received noise voltage envelope, then $P = V^2/R$, where $R$ is the receiver load. Transforming variables from voltage $V$ to power $P$, the probability density function of power $p_P(P)$ corresponding to the probability density function of voltage in (1) is

$$p_P(P) = \frac{(\theta - 1)(\gamma^2/R)^{(\theta-1)/2}}{2(P + \gamma^2/R)^{(\theta+1)/2}}. \tag{4}$$

Denoting the mean power by $P_m$, it follows that

$$\int_0^\infty P p_P(P)\, dP = P_m. \tag{5}$$

Substituting (4) into (5), carrying out the integration, and solving for $\gamma$ results in

$$\gamma = \left\{ \frac{R}{2} \left[ -P_m + \left( P_m^2 + 4 \frac{\theta - 1}{\theta + 1} \right)^{1/2} \right] \right\}^{1/2}. \tag{6}$$

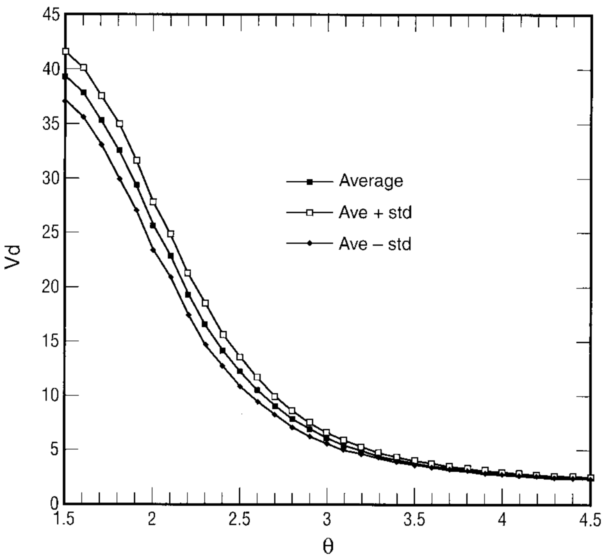


**Figure 3.** Relationship between $V_d$ and $\theta$ for the atmospheric radio noise simulation model.

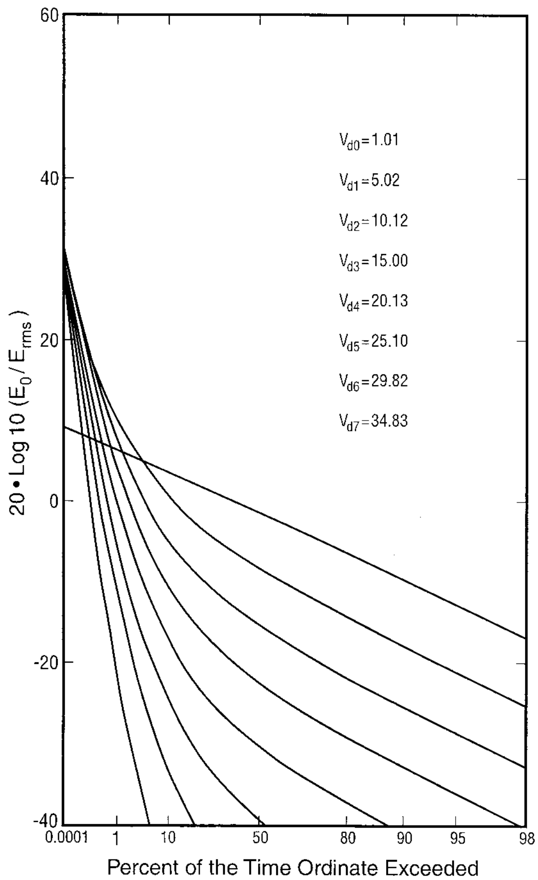


**Figure 4.** Set of amplitude probability distributions of simulated atmospheric radio noise for various $V_d$ values.

As indicated above, it has been shown that the probability distribution function of the noise envelope given by the Hall model is in general agreement with a limited amount of narrowband HF atmospheric noise data [*Hall*, 1966]. However, it is of interest to compare the Hall model with the ITU-R model, which is based on a wide range of measured data and which relates various environments to specific values of $V_d$ and $P_m$.

Using the relationship between $\theta$ and $V_d$ shown in Figure 3, noise waveforms (4 million samples) with various values of $V_d$ were simulated. The cumulative distribution functions of their voltage envelopes are plotted in Figure 4. Comparison of Figures 1 and 4 indicates that the probabilities of the simulated noise envelopes generally agree with those given by the ITU-R for exceedance probabilities greater than $10^{-4}$ (0.01%). Thus the first-order statistics of the model are consistent with those of measured data over a large range of values of the noise envelope. Moreover, the relationships between the model parameters $\theta$ and $\gamma$ and the parameters $V_d$ and $P_m$ enable one to determine specific values of the model parameters for various environments.

## 3. Higher-Order Statistics

Atmospheric noise bursts are well known to be clustered in time, because of the presence of numerous individual lightning strokes within a single flash [*Uman*, 1987]. These correlations have been studied by *Fishman et al.* [1991], who have developed a model for burst duration and time between bursts based on measured data. The data were collected by the Mitre Corporation in Bedford, Massachusetts, and consist of successive 1-ms averages of noise power over a wideband (1 MHz) channel with center frequencies in the 13- to 16-MHz range. The noise power was recorded after suppression of narrowband interference via a block fast-Fourier-transform- (FFT)-based operation which sets to zero all spectral components exceeding a threshold.

A three-parameter renewal process model was found to provide a good description of both burst duration and time between bursts. A burst event is defined to start (end) when the average noise power becomes greater (less) than a specified threshold. The probability density functions $p_T(T)$ of burst duration and time between bursts are of the form

$$p_T(T) = (C_1 e^{-C_2 T} + C_3) \cdot \exp\left[-\frac{C_1}{C_2}(1 - e^{-C_2 T}) - C_3 T\right], \quad (7)$$

where $C_1$, $C_2$, and $C_3$ are free parameters and $T$ is the burst duration or time between bursts in seconds.

Accordingly, it is proposed that the burst structure of atmospheric noise be simulated by the following procedure. First, independent samples of the voltage envelope with a probability density function given by (1) are generated. The samples are then separated into two sets: a "quiet" set consisting of sample values less than a given threshold and a "burst" set consisting of sample values greater than that threshold. Independent samples of burst duration and time between bursts with probability density functions of the form (7) are generated and alternatively concatenated, so that time is partitioned into intervals that alternate between quiet and burst states. The waveform is simulated by selecting independent samples of the voltage envelope exclusively from the quiet (or burst) set during the quiet (or burst) time intervals.

Samples of time durations distributed according to (7) were generated by integrating (7) to obtain the cumulative distribution $P(T)$,

$$P(T) = 1 - \exp\left[-\frac{C_1}{C_2}(1 - e^{-C_2 T}) - C_3 T\right], \quad (8)$$

inverting (8) to obtain $T(P)$, and treating $P$ as a uniformly distributed random variable between 0 and 1. The inversion of (8) was performed numerically by constructing a lookup table for $T(P)$.

The threshold separating the burst and quiet samples was determined by requiring the fraction of samples in the quiet set to equal the fraction of time in the quiet state. The quiet and burst time durations are random variables. However, the expected value of the fraction of quiet time for a record of infinite length is $T_Q/(T_Q + T_B)$, where $T_Q$ and $T_B$ are the mean values of the time between bursts and the burst duration, respectively. These values were determined from (7) by evaluating

$$\int_0^\infty T p_T(T)\, dT$$

numerically. Thus, if $P_0$ is the power threshold,

$$\int_0^{P_0} p_P(P)\, dP = \frac{T_Q}{T_Q + T_B}, \quad (9)$$

where $p_P(P)$ is the power probability density function in (4). Substituting (4) into (9), carrying out the integration, and solving for $P_0$ gives

$$P_0 = \frac{\gamma^2}{R}\left[\left(1 + \frac{T_Q}{T_B}\right)^{2/(\theta-1)} - 1\right]. \quad (10)$$

The threshold in (10) does not precisely correspond to the thresholds used by *Fishman et al.* [1991] to model the distributions of burst duration and time between bursts. However, this procedure does provide a means of correlating the noise bursts in time in a way that is approximately consistent with measured data. Note that the procedure in no way depends upon the particular forms of the probability density functions in (7). Also note that this procedure, which amounts to generating correlations in a set of independent samples of the voltage envelope, in no way affects the first-order statistics. Thus the agreement between the probability distributions of the model and measured data remains intact.

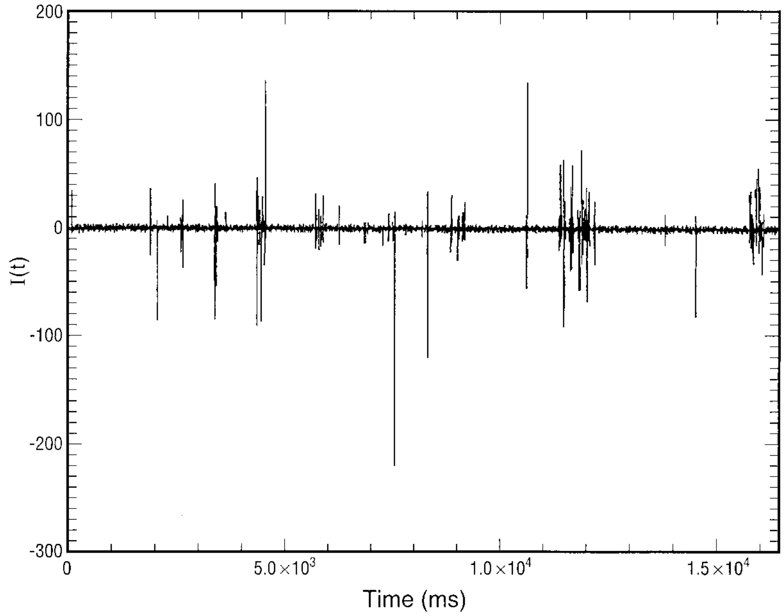


**Figure 5.** Sixteen seconds of the in-phase component of a simulated atmospheric noise waveform.

An example waveform that was simulated with the model is shown in Figure 5. Plotted is the in-phase component of the baseband voltage, $V(t)\cos\phi(t)$, sampled once per millisecond over a time interval of 16 s. The values of the parameters in the voltage envelope distribution are $\gamma = 1.0$ and $\theta = 2.5$ ($V_d$ = 8.9 dB). The parameter values used in the distributions of burst duration and time between bursts were taken from an example discussed by *Fishman et al.* [1991]: For the burst durations, $C_1 = 57.43$, $C_2 = 32.23$, and $C_3 = 12.68$ ($T_B$ = 26 ms); for the time between bursts, $C_1 = 18.62$, $C_2 = 16.62$, and $C_3 = 1.49$ ($T_Q$ = 247 ms). These parameter values provide a good fit to the distributions obtained from measured wideband (1 MHz) atmospheric noise at a center frequency of 13.666 MHz.

The effects of bandwidth on $V_d$ were investigated by filtering simulated waveforms (4 million samples and a sample rate of 1 MHz) with three-pole low-pass filters and calculating the $V_d$ of the filtered waveforms. The cutoff frequencies of the filters were chosen to be 0.1, 0.01, 0.001, and 0.0001 times the

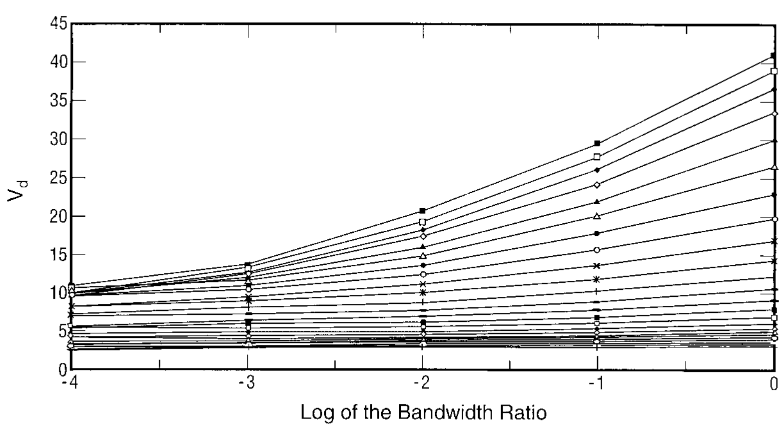


**Figure 6.** Translation of $V_d$ from a 1-MHz bandwidth to other bandwidths for the atmospheric noise simulation model.

bandwidth of the unfiltered waveforms. The parameter values used in the probability density functions of burst duration and time between bursts are the same as in the example above. The results are shown in Figure 6, in which $V_d$ is plotted versus the logarithm of the bandwidth ratio of the filtered and unfiltered waveforms. Comparing Figures 2 and 6 reveals qualitatively similar behavior, although the two sets of curves are not in full quantitative agreement at all values of $V_d$ and bandwidth ratio.

## 4. Summary

A wideband model of HF atmospheric radio noise has been developed. The model enables one to simulate atmospheric noise waveforms over bandwidths of the order of 1 MHz, intended for implementation in a wideband HF channel simulator. Cumulative probability distributions of the voltage envelopes of simulated waveforms are in general agreement with the model approved by the ITU-R, which is based on a large database and range of noise environments. Values of the model parameters that are appropriate for a specific noise environment can be determined a priori, because these parameters have been related to the voltage deviation parameter and the mean noise power, which have been specified for various geographical locations, seasons, times of day, and frequencies.

A procedure has been developed for generating correlations in the waveforms that simulate the observed burst structure of atmospheric noise. This burst structure causes the impulsiveness of the noise, parameterized by the voltage deviation parameter, to be a function of the bandwidth over which the noise is observed. The bandwidth dependence of the voltage deviation parameter of simulated waveforms has been investigated and is in qualitative agreement with a limited amount of HF data analyzed by *Herman and DeAngelis* [1987].

On the other hand, atmospheric noise is notoriously nonstationary, and no attempt has been made to simulate this nonstationarity. As was pointed out in the discussion of the man-made noise and interference model [*Lemmon*, 1997], the purpose of these models is to develop the capability to perform laboratory measurements of radio performance under stationary channel conditions, so that performance and channel conditions can be correlated. Within this context the lack of nonstationarity should not seriously compromise the usefulness of the model.

**Acknowledgments.** The author wishes to thank J. McEvoy and W. Bonser of the U.S. Air Force Rome Laboratory, D. Bodson and G. Rekstad of the National Communications System, and Robert Oldham of the U.S. Army Communication/Electronics Command for their support of the work reported herein. The author also wishes to thank C. J. Behm for his assistance in performing the computer simulations.

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(Received March 31, 2000; revised February 23, 2001; accepted March 22, 2001.)