CyberCom Technical Report

UHF Radiowave Propagation Through Forests

Prepared by

R.H. Lang, A. Schneider and F.J. Altman

For

US Army Research Office
Research Triangle Park, North Carolina

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   During the US Army's Wideband Propagation Measurement System, radiowave propagation experiments were twice conducted in Coventry, Connecticut - first in August 1987 and again in November 1987 after the autumnal leaf fall. A selected subset of these data, representing nearly one-hundred experiments conducted over different distances with different frequencies, polarizations and antenna heights, has been analyzed and trends established which relate delay spread to the environmental and radiophysical parameters characterizing the propagation path.

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1.0 Introduction

The United States Army has recognized, especially as a result of tactical communications experience in Vietnam, the need for a realistic model for wideband UHF radiowave propagation within different types of forest [1]. Although the early dielectric slab models [2,3,4] correctly explain the up-over-and-down lateral waves propagating at the air-forest interface over long VHF paths, they characterize the forest only in terms of an effective dielectric constant which is postulated rather than derived from the biophysical characteristics of the vegetation. Further, the dielectric slab models are not applicable at UHF and above where incoherent scatter dominates and wideband signals suffer appreciable delay spread.

More recently, CyberCom, with the support of US Army CECOM and the cooperation of SRI International, has undertaken the development of a realistic stochastic propagation model for characterizing the wideband forest channel. This program, both theoretical and experimental, addresses several interrelated study areas: the biophysical characterization of the forest; electromagnetic interaction of the propagating radiowave with the scatterers using theories of discrete multiple scattering and/or transport theory; and communications channel characterization in terms of transmission loss and delay-Doppler spread. The early CyberCom studies were restricted to trunk-dominant coniferous forests [5,6,7]; more recently, canopy-dominant deciduous forests have been considered [8].

The acquisition of experimental data supporting the development of a propagation model for canopy-dominant deciduous forests began in August, 1987 within an experimental red maple forest located near Coventry, Connecticut. Anticipating that model development and validation might require a detailed biophysical description of the forest, this site was selected because it had been the subject of a recent, detailed, quantitative, biophysical study conducted by its owner and manager, the University of Connecticut.

The experiments at Coventry were first conducted during the summer’s end of 1987 (24 August to 4 September), and then repeated in November after the autumnal fall of the leaves in order to assess the seasonal effect of the foliage. Although data from the first set of measurements had been processed and analyzed [9], data from the second set had not. A selected sub-set of these data is analyzed in this report to assess the effects of foliage, rain, and snow on delay-spread in canopy-dominated deciduous forests.
2.0 Background

From the communications viewpoint, radiowave transmission through forests may be modeled by a randomly time-variant linear channel whose input and output signals are related by the integral transform [10]

\[ y(t) = \int x(t-\xi)g(t,\xi)d\xi \]  

(2-1)

where \( x(t) \) is the transmitted (input) signal, \( y(t) \) is the received (output) signal, and \( g(t,\xi) \) is the response of the channel at time \( t \) to a unit impulse applied at time \( t-\xi \). Thus, the stochastic behavior of the channel is manifested through \( g(t,\xi) \) in two dimensions via the propagation delay variable \( \xi \) which characterizes the spatial configuration of the forest scatterers and via the time variable \( t \) which characterizes their (possibly) time-variant configuration. Since \( x(t) \) and \( y(t) \) are scalars, the vector coupling of the forest-scattered electromagnetic fields to the transmitting and receiving antennas is assumed to be implicitly embedded within \( g(t,\xi) \).

In order to characterize the stochastic behavior of the forest channel completely, multi-dimensional probability density functions of \( g(t,\xi) \) are required. However, because of multiple scattering within the forest, the received signal may be considered to arise from the superposition of a large number of independent contributions having the same relative delay \( \xi \). As a consequence of the central limit theorem it may be concluded that \( y(t) \) is a gaussian random process and, in view of Equation (2-1), so too is \( g(t,\xi) \). The principal utility of this hypothesis lies in the consequence that all orders of the multi-dimensional probability density function describing \( g(t,\xi) \) can be expressed in terms of the correlation function

\[ R_g(t_1,t_2;\xi_1,\xi_2) = \langle g(t_1,\xi_1)g^*(t_2,\xi_2) \rangle \]  

(2-2)

If the channel transfer function \( g(t,\xi) \) can be considered wide-sense stationary in the time variable \( t \) and the scattered signals corresponding to different delays \( \xi \) uncorrelated, then the channel correlation function simplifies to

\[ \langle g(t,\xi)g^*(t+r,\eta) \rangle = Q(r,\xi)\delta(\xi-\eta) \]  

(2-3)

where \( \delta(*) \) is the Dirac delta function and \( Q(r,\xi) \) is the co-variance function of those channel fluctuations having propagation delays in the interval \( (\xi,\xi+3\xi) \). The function \( Q(0,\xi) \) is variously called delay power spectrum or the delay-spread function.
In the absence of relative forest motion due to wind and/or terminal movement, the forest channel \( g(t, \xi) \) may be considered time-invariant. The ensemble-averaged channel correlation function then simplifies to

\[
< g(t, \xi) g^*(t, \eta) > = Q(\xi) \delta(\xi - \eta) \tag{2-4}
\]

where

\[
Q(\xi) = Q(0, \xi) \tag{2-5}
\]

is the delay-spread function.

A physically appealing interpretation of the delay-spread function can be derived by considering the received power when an unmodulated sinusoid is transmitted. In this case, the transmitted signal is

\[
x(t) = \exp(j2\pi f_o t) \tag{2-6}
\]

so that, according to Equation (2-1), the received signal is

\[
y(t) = \int \exp(j2\pi f_o (t-\xi)) g(t, \xi) d\xi \tag{2-7}
\]

and the received power is

\[
<P> = \langle y^2(t) \rangle = \int \int \exp(j2\pi f_o (t-\xi_1)) \exp(-j2\pi f_o (t-\xi_2)) < g(t, \xi_1) g^*(t, \xi_2) > d\xi_1 d\xi_2 \tag{2-8}
\]

\[
= \int \int \exp(-j2\pi f_o (\xi_1 - \xi_2)) Q(\xi_1) \delta(\xi_1 - \xi_2) d\xi_1 d\xi_2 - \int Q(\xi) d\xi \tag{2-9}
\]

Since \( \xi \) denotes the propagation delay, it is apparent from Equation (2-10) that \( Q(\xi) \) describes the ensemble-averaged distribution of the incremental power received within a delay interval \( d\xi \). According to the forest propagation model developed in reference [7], the theoretical ensemble-averaged delay-spread of a homogeneous, trunk-dominant forest is of the form

\[
Q(\xi) = \xi_0^{1/\beta} \exp(\xi/\xi_0) \tag{2-11}
\]

where \( \xi_0 \) is the delay constant, a parameter related to the spread. This function is plotted in Figure 2-1.

The measurement of the wideband transfer function \( g(t, \xi) \) (and its corresponding delay-spread function \( Q(\xi) \)) requires a wideband channel probe. If the transmitted waveform is bi-phase modulated with a pseudo-random maximal-length sequence, the autocorrelation function of the transmitted
signal is impulsive, i.e.

\[ R_x(\tau) = \langle x(t)x(t-\tau) \rangle \equiv \delta(\tau) \quad (2-12) \]

Cross-correlation of the received signal with \( x(t-\tau) \) yields

\[ \langle x(t-\tau)y(t) \rangle = \int \langle x(t-\tau)x(t-\xi) \rangle g(t,\xi) d\xi = \int R_x(\tau-\xi) g(t,\xi) d\xi = \tilde{g}(t,\tau) \quad (2-13) \]

so that to the extent that \( R_x(\tau) \) is approximated by a Dirac delta function, the cross-correlated output \( \tilde{g}(t,\tau) \) approximates the input delay-spread function. The delay-spread function \( Q(\tau) \) is approximated by

\[ P(\tau) = |\tilde{g}(t,\tau)|^2 \quad (2-14) \]

This measured counterpart, distinguished here by the name Power Time-Variant Impulse Response [PTVIR], is shown in Figure 2-2. Its ragged, stochastic structure can be attributed to phase interference between forest-scattered radiowaves having the same propagation delay \( \tau \) and so suggests that the power \( P(\tau) \) is an exponentially-distributed random variable.

For time-variant ergodic media, time-averaging can be used to smooth successive PTVIR measurements for comparison with their theoretical ensemble-averaged counterparts. However, except for terminal and/or wind-induced canopy motion, the forest channel is essentially time-invariant so that time-averaging plays no role. Although the PTVIR might still be smoothed by curve-fitting, the performance of digital radio communication systems performance is not particularly sensitive to the shape of the PTVIR [17] but rather only to its width or "delay spread". Therefore, a sufficient (and certainly simpler) comparison between theory and experiment can be effected in terms of the delay spread.
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3.0 Experiment

3.1 Forest Site Description

The Coventry site, a flat floodplain with a 30-year old stand of red maple [Acer rubrum] with occasional white pine [Pinus strobus] and trembling aspen [Populus tremuloides] at the edges, is part of the University of Connecticut's forest research station. A photograph and plan of the Coventry site can be found in Figures 3-1 and 3-2. The measured propagation paths are identified on the site plan.

A regular grid of 20 circular plots of 20-foot radius was laid out with 100-foot separations. The number of trees and their diameters within each plot were recorded and used to calculate the tree-trunk number density and mean tree-trunk diameter which were then used to construct the contour plots shown in Figures 3-3 and 3-4 and the trunk-diameter histogram of Figure 3-5. The stem density path profiles shown in Figure 3-6 were derived from the tree-trunk number density contour plots. Using a platform elevator provided by the University of Connecticut, the mean tree height was estimated to be 47 feet (14.3 m) with no more than about 5 percent of the trees exceeding 61 feet (18.6 m); the live canopy began at a mean height above ground of about 35 feet (10.7 m).

The deciduous canopy characteristics, recently measured by Professor David Miller and his students [13,14,15], are summarized in Figures 3-7, 3-8 and 3-9 which show, respectively, leaf-area-index (LAI) and histograms of leaf inclination angle and leaf azimuth angle. The leaf number density $\rho_1$ and the fractional volume occupied by the foliage $f_v$ can be estimated from the relations

$$\rho_1 = \frac{\text{LAI}}{A\cdot h}$$  \hspace{1cm} (3-1)

$$f_v = \rho_1 \cdot \frac{V_1}{h} = \frac{\text{LAI} \cdot t}{h}$$  \hspace{1cm} (3-2)

where LAI denotes the leaf-area-index, $A$ is the average area per leaf, $t$ is the average leaf thickness, and $h$ is the canopy thickness. Typically, for red maple, $A$ is 25 cm$^2$ and $t$ is 0.2 mm. Thus, for a measured LAI of 4.5 (refer to Figure 3-7) and canopy thickness of 3.6 m (see above), the corresponding leaf number density is 500 leaves per cubic meter and the leaf fractional volume is 0.025 percent.
Figure 3-1: Coventry Sire Photo
Figure 3-4: Coventry Average Trunk Diameter Contours (1987)
Figure 2-5: Coventry Trunk Diameter Histogram (1987)

DBH Class in Inches

Number of Trunks

Mean Basal Area = 49
Coef. Var. = 0.48
Std. Dev. = 2.25
Mean = 4.5
N = 317

Trunk Diameter Histogram (November 1987)

UConn Forest (1720 ft. Radius Plots)
Figure 3-6: Stem Density Path Profiles (Coventry, 1987)
Figure 3-7: Coventry Leaf Area Index
Figure 3-8: Coventry Leaf Inclination Angle Histogram
Figure 3-9: Coventry Leaf Azimuthal Angle Histogram
3.2 Channel Probe

The experimental radiowave propagation data were acquired using the US Army's Wideband Propagation Measurement System (WPMS). The WPMS, designed and built for the US army by SRI International [16,17], was developed especially for measuring ground-to-ground communication channel characteristics (transmission loss and delay-Doppler spread) in the 200-2000 MHz band. This computer-controlled, mobile, radio-channel probe uses a direct-sequence, pseudo-randomly modulated, wideband waveform and sliding correlator architecture. Its capabilities are summarized in Table 3-1.

The essential elements of WPMS operation can be described with the aid of the diagram shown in Figure 3-10. The transmitter sends out a repetitive pseudo-random waveform, $X_T(t)$, with a "chip" interval, $\Delta t$, and a code period, $T$. The in-phase (I) and quadrature-phase (Q) components of the received signal are then cross-correlated against a replica of the transmitted pseudo-random waveform in each of four parallel sub-channels successively offset from each other by one-quarter chip (to improve TVIR resolution). The output of each correlator is integrated for $T$ seconds and then sampled. The receiver pseudo-random code generator is then delayed (slipped) one chip and the integrate-and-sample operation repeated. The complete cycle is repeated $N$ times, where $N$ is the number of chips in the pseudo-random code period. Thus, each complex receiver sub-channel produces one output every $T + \Delta t$ seconds. To obtain a valid measurement of the entire delay-spread function, the channel must remain essentially time-invariant for $N(T+\Delta t)$ seconds. The resulting output is stored and displayed as a time-varying impulse response (TVIR) of length $N\Delta t$ and resolution $\Delta t$.

For any given episode (a prescribed configuration of radio/antenna parameters), the TVIR is measured repeatedly until the data buffer overflows (approximately 2 Megabytes of raw TVIR data). These data are then stored in the binary data (BDAT) format of the HP-1000 computer on half-inch wide, 9-track magnetic tape (10.5-inch diameter reels). Each tape stores up to 8 episodes (files). The file structure is shown in Figure 3-11. These data are archived at SRI International in Menlo Park, California.
<table>
<thead>
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<tr>
<td>Carrier frequency range</td>
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</tr>
<tr>
<td>Delay-spread range</td>
<td>1-20 μ-sec</td>
</tr>
<tr>
<td>Delay-spread resolution</td>
<td>1 nanosec</td>
</tr>
<tr>
<td>Doppler-spread range</td>
<td>15-240 Hz</td>
</tr>
<tr>
<td>Doppler-spread resolution</td>
<td>2 Hz (max)</td>
</tr>
<tr>
<td>TVIR amplitude resolution</td>
<td>0.1 dB</td>
</tr>
<tr>
<td>TVIR multipath amplitude resolution</td>
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<tr>
<td>Measurable path loss</td>
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</tr>
<tr>
<td>Directional</td>
<td>Log-Periodic Dipole</td>
</tr>
<tr>
<td>Transmitter polarization</td>
<td>V, H, RCP</td>
</tr>
<tr>
<td>Receiver polarization</td>
<td>V, H, RCP, LCP</td>
</tr>
<tr>
<td>Azimuthal range</td>
<td>360 degrees</td>
</tr>
<tr>
<td>Height range</td>
<td>5-65 feet</td>
</tr>
</tbody>
</table>

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<td>Frequency range XMTR no. 1</td>
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</tr>
<tr>
<td>Frequency range XMTR no. 2</td>
<td>700-2000 MHz</td>
</tr>
<tr>
<td>Power output</td>
<td>100 W (max)</td>
</tr>
<tr>
<td>Modulation Direct-Sequence BPSK</td>
<td>Coherent</td>
</tr>
<tr>
<td>Continuous Wave (CW)</td>
<td></td>
</tr>
<tr>
<td>DS code length (chips)</td>
<td>255, 511, 1023 or 2047</td>
</tr>
<tr>
<td>DS code rate</td>
<td>50, 125 or 250 MHz</td>
</tr>
<tr>
<td>Bandwidth (null-to-null)</td>
<td>100, 250 or 500 MHz</td>
</tr>
<tr>
<td>Control</td>
<td>Local or Remote (RCVR)</td>
</tr>
</tbody>
</table>

<table>
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<th><strong>Receivers</strong></th>
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</tr>
</thead>
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<tr>
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<td>Continuous Wave (CW)</td>
<td>Coherent</td>
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<tr>
<td>DS code length (chips)</td>
<td>255, 511, 1023 or 2047</td>
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<tr>
<td>DS code rate</td>
<td>50, 125 or 250 MHz</td>
</tr>
<tr>
<td>Bandwidth (null-to-null)</td>
<td>100, 250 or 500 MHz</td>
</tr>
<tr>
<td>Control</td>
<td>Local computer</td>
</tr>
<tr>
<td>Input signal range</td>
<td>-95 - 0 dBm</td>
</tr>
<tr>
<td>Instantaneous dynamic range</td>
<td>50 dB</td>
</tr>
<tr>
<td>AGC (computer controlled)</td>
<td>1 dB increments</td>
</tr>
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Figure 3-10: WPITS Block Diagram
### WPMS Raw Data Format

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<td>1 q</td>
<td>1 q</td>
<td>1 q</td>
<td>1 q</td>
<td>1 q</td>
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</tr>
<tr>
<td></td>
<td>Channel 1</td>
<td>Channel 2</td>
<td>Channel 3</td>
<td>Channel 4</td>
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<td></td>
</tr>
<tr>
<td>No.</td>
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<td></td>
<td></td>
<td></td>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**RCVR #1**

Set 16: i q i q i q i q 8

---

**RCVR #2**

Set 16: i q i q i q i q 8

---

One Episode - 256 Records - 1 File - 32 Data Sets

---

*Figure 3-11: WPMS Raw Data File Format*
3.3 Data Transfer

Unfortunately, the HP-1000 computer is now obsolete and the computer facilities available to CyberCom [IBM 370 and HP-9000] were unable to read the binary data tapes. Although a number-builder might have been constructed, CyberCom elected to use an HP-1000 still available at CECOM in Fort Monmouth, New Jersey to read the tapes and to translate the data into ASCII format for compatibility with the IBM 370 [and most other computers]. Although the HP-1000 software used by SRI International for reading the binary tapes was made available to CyberCom, these programs proved unwieldy to use and provided superfluous data detail. A simpler program, developed by the National Bureau of Standards and acquired from them, was used instead [see Appendix A].

Earlier, CyberCom had developed some of the software that would be used for propagation data analysis. These programs, however, ran only under HP-BASIC on CyberCom's HP-9816 computer. Unfortunately, this computer does not interface with the nine-track tape drives required to read the HP-1000 ASCII data tapes. However these tape drives were available locally at the George Washington University in Washington, D.C. where CyberCom maintains a computer account. It was decided then to transfer the ASCII data from tape to disk using GWU's IBM 370 computer and then to download the files to CyberCom's HP-9816 using telephone lines.

Using IBM's Job Control Language (JCL) the automated utility program TRNSFR [see Appendix B] was developed for GWU's IBM 370 to read the HP-1000's ASCII data tapes and re-write a reduced data set [16 PTVIRs from the first sub-channel for each of two receivers] on disk according to the format shown in Figure 3-12. The reduced data sets are then down-loaded to CyberCom using our HP-9816 computer and HP-supplied ASCII Terminal Emulator.

At CyberCom the down-loaded ASCII data are temporarily stored on 3.5-inch floppy disks. The limited capacity of these media (266 kilobytes) led CyberCom to develop the software utility BCKUP [see Appendix C] for re-storing the ASCII data on 150-foot, 1/4-inch wide, 16-track magnetic tape, HP-88140SC data cartridges (16.7 megabytes/cartridge). Headers identifying salient experimental parameters are prefixed to each file and summarized for convenient access in a Measurement File Catalog. Another program, KELVIN [see Appendix D], was developed to read the ASCII data from the tape cartridges, re-format it for consistency with previously developed analysis software, and re-store it in binary (BDAT) format. The temporary BDAT files are used in data analysis because they have much higher transfer rates than the ASCII files.
**Figure 3-12: GWU Reduced Data Set File Format**

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<th>Column</th>
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<th>1</th>
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- **Tape xxx File y**
- **Column Length**: 16
- **Code Length**: L

**Notes**:
- "TxxxFyHDRA"
- "TxxxFyAA"
- "TxxxFyBA"
- "TxxxFyCA"
- "TxxxFyDA"
- "Trailer"
The time to transfer the data of a single episode from an archived file (HP-1000 BDAT on 9-track tape) to a reduced data set (ASCII data on 1/4-inch tape cartridge) is not negligible — approximately 75 minutes per episode. 40 minutes are required by the HP-1000 to convert the data from PDAT to ASCII, 5 minutes are required by the IBM-370 to read the ASCII data and re-write the reduced data set on disk, 25 minutes are required to transfer the reduced data set to CyberCom, and 5 minutes are required to re-store the data on tape cartridge.

3.4 Data Selection

A summary overview of the forest experiments can be found in SRI's Final Report [9]. CyberCom reviewed these data and selected a subset of ten (10) computer tapes representing nearly one-hundred experiments conducted over different distances with different frequencies, polarizations and antenna heights.

3.5 Data Analysis

The quantitative characterization of the measured PTWIR $P(r_k)$ is complicated by the stochastic character of the multipath and by the contaminating noise (both thermal and code) contributed by the radio equipment. The problem is illustrated in the profile of Figure 3-13: region A is the noise-dominated "precursor" region attributable primarily to thermal noise in the receiver front-end, and code noise due to imbalance in the correlators; region B is the multipath-dominated signal region where noise is negligible; and region C is the noise-dominated "tail" region where the multipath signal disappears into the noise.

Because the received signal power associated with any particular multipath delay is contributed by scattering from a large number of trees, $P(r_k)$ is an exponentially-distributed random variable (the received voltage then being Rayleigh-distributed). Fluctuations in $P(r_k)$ can, for wide-sense stationary, time-variant media, be reduced by profile averaging; for the time-invariant forest channel measured on a single path, profile averaging serves only to smooth the noise-dominated regions A and C which are of little intrinsic interest, and does not provide an ensemble average.

Although time-invariance simplifies data acquisition, it complicates data analysis because the ergodic hypothesis can not be invoked to smooth measurements by time-averaging. Fortunately, however, radio communication system performance is not particularly sensitive to the shape of the PTWIR
Figure 3-13: PIVIR Precursors and Tails

Normalized Amplitude

Samples

A: Noise-dominated precursor region
B: Multi-path dominated signal region
C: Noise-dominated "tail" region

Date: 08/24/87  Time: 24:00
[12] but rather only to its width or "spread." Perhaps the most universally accepted and tractable measure of delay spread is the radius-of-gyration (square-root of the second-central-moment) defined by

$$T_{\text{reg}} = \sqrt{m_2/m_0 - m_1^2/m_0}$$  \hspace{1cm} (3-3)

where the moments $m_k$ are defined by

$$m_0 = \int_0^T Q(\xi) d\xi = \sum_{k=0}^K r_k P(r_k)$$  \hspace{1cm} (3-4)

$$m_1 = \int_0^T \xi Q(\xi) d\xi = \sum_{k=0}^K r_k^2 P(r_k)$$  \hspace{1cm} (3-5)

$$m_2 = \int_0^T \xi^2 Q(\xi) d\xi = \sum_{k=0}^K r_k^4 P(r_k)$$  \hspace{1cm} (3-6)

with the integrals being used with continuous analytic expressions for the delay-spread function $Q(\xi)$ and the summations with sampled-data representations for the PTVIR $P(r_k)$. The mean delay (center-of-gravity) of the PTVIR is given by

$$T_{\text{avg}} = m_1/m_0$$  \hspace{1cm} (3-7)

The "leading edge" of the PTVIR where the received power first becomes distinguishable from the background noise of the receiver will be denoted by $T_{\text{min}}$. Excess delay, the difference between $T_{\text{avg}}$ and $T_{\text{min}}$, is

$$T_{\text{exc}} = T_{\text{avg}} - T_{\text{min}}$$  \hspace{1cm} (3-8)

Still another measure of delay spread and better suited to the non-symmetric delay-spread functions measured in forests is

$$T_{\text{spr}} = T_{\text{exc}} + T_{\text{reg}}$$  \hspace{1cm} (3-9)

Computer program MELVIN, developed to calculate the moments $m_k$, is listed in Appendix E. The algorithm upon which MELVIN is based consists of two parts:

**Threshold Determination:** Divide the measured PTVIR into four equal-duration intervals. For each of the four intervals calculate the average power using the first 15 consecutive samples. Select the lowest average power of the four and set a threshold level five times (7 dB above) this noise-power average.
Delay Spread Calculation:—Determine the peak signal power of the measured PTVIR. Begin the calculation of the moments \( m_k \) when a PTVIR sample reaches one-quarter of that peak for first time. When the PTVIR drops below half threshold for the first time, begin calculation of the 10-sample average power, but re-initializing the calculation if the signal rises above twice threshold. Continue calculating the moments until two successive 10-sample averages are less than half threshold.

The highly complex and stochastic character of the experimental PTVIRs has led to several algorithms in the search for consistent measures of delay spread. For example, Cox [18] also used the radius-of-gyration measure but rejected all responses 30 dB or more below the peak. The SRI [9] delay-spread measure is based on the time interval between the first and last crossing of a threshold four (4) times above the average.

The delay-spread calculations are summarized in Tables 3-3 (Vertical Polarization) and 3-4 (Horizontal Polarization) and grouped according to antenna height (trunk or canopy), season (summer or autumn), path length (927, 471, and 361 feet), and frequency (451, 751, 1251 and 1751 MHz). Column headings, abbreviated for compactness, are as follows:

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<td></td>
<td>( O ) - Omni-directional</td>
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<td></td>
<td>Upper case = vertical polarization</td>
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<td></td>
<td>Lower case = horizontal polarization</td>
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<td>Channel Noise</td>
<td>Estimated noise power floor of the PTVIR</td>
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<td>Nmin, ( \bar{n} ) sig</td>
<td>(relative to peak power) and its standard deviation (relative to noise floor)</td>
</tr>
<tr>
<td>Delay Spread</td>
<td>Delay Spread Moments (Episode Average)</td>
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<td>Excess Delay [Eq. (3-8)]</td>
</tr>
<tr>
<td>( T_{\text{rg}} )</td>
<td>Radius-of-Gyration [Eq. (3-1)]</td>
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<tr>
<td>( T_{\text{spr}} )</td>
<td>Delay Spread [Eq. (3-9)]</td>
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<tr>
<td>( \sigma_{\text{spr}} )</td>
<td>Standard Deviation of ( T_{\text{spr}} )</td>
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</table>

Episode averages and standard deviations are based on seven (7) PTVIRs taken from successive data sets (refer to Figure 3-12) and separated in time by 16.7 milliseconds.

5 - 20
## Table 3-2: Delay-Spread Calculations (Vertical Polarization)

[Coventry, Connecticut - 1987]

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### Table 3-3: Delay-Spread Calculations (Horizontal Polarization)

[Coventry, Connecticut - 1987]

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<td>11/11</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>451</td>
<td>-37.9</td>
<td>0.1</td>
</tr>
<tr>
<td>T264F2</td>
<td>11/09</td>
<td>&quot;</td>
<td>42</td>
<td>&quot;</td>
<td>699</td>
<td>-41.9</td>
<td>0.1</td>
</tr>
<tr>
<td>T263F3</td>
<td>&quot;</td>
<td>&quot;</td>
<td>38</td>
<td>&quot;</td>
<td>699</td>
<td>-41.5</td>
<td>0.0</td>
</tr>
<tr>
<td>T273F4</td>
<td>11/10</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>699</td>
<td>-38.8</td>
<td>0.4</td>
</tr>
<tr>
<td>T265F7</td>
<td>11/11</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>699</td>
<td>-40.5</td>
<td>-0.6</td>
</tr>
<tr>
<td>T264F3</td>
<td>11/09</td>
<td>&quot;</td>
<td>42</td>
<td>&quot;</td>
<td>1251</td>
<td>-40.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>T265F4</td>
<td>&quot;</td>
<td>&quot;</td>
<td>38</td>
<td>&quot;</td>
<td>1251</td>
<td>-39.3</td>
<td>0.3</td>
</tr>
<tr>
<td>T86F3</td>
<td>11/11</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1251</td>
<td>-38.7</td>
<td>0.1</td>
</tr>
<tr>
<td>T264F4</td>
<td>11/09</td>
<td>&quot;</td>
<td>42</td>
<td>&quot;</td>
<td>1751</td>
<td>-33.9</td>
<td>-0.4</td>
</tr>
<tr>
<td>T265F5</td>
<td>&quot;</td>
<td>&quot;</td>
<td>38</td>
<td>&quot;</td>
<td>1751</td>
<td>-25.9</td>
<td>-0.2</td>
</tr>
<tr>
<td>T86F4</td>
<td>11/11</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1751</td>
<td>-36.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>
4.0 Conclusions

Before attempting to draw any meaningful conclusions from the delay spread calculations of Tables 3-2 and 3-3, it seems prudent to consider first the quality (or significance) of the data. Two measures of data quality are provided in the Tables by: the estimated channel (background) noise power \( N_{\text{min}} \) and the standard deviation of the delay spread \( \sigma_{\text{spr}} \). A cursory review of the Tables quickly reveals the strong correlation between these two calculated variables: the higher the channel noise, the larger the standard deviation. It is also apparent that the least reliable data are associated with vertical polarization, high frequencies and long ranges, and correlate directly with greater transmission losses and smaller received signals associated with these propagation conditions.

4.1 Trunk-Dominant Measurements

Tables 3-2 and 3-3 clearly reveal that for the trunk-dominant propagation the delay spread is greater for vertical polarization than for horizontal polarization, although the difference appears to decrease with increasing frequency. The frequency dependence of the delay spread depends upon the polarization: decreasing with increasing frequency for vertical polarization, and increasing with increasing frequency for horizontal polarization. For both vertical and horizontal polarization, the delay spread increases with increasing path length. This is also apparent from Figure 4-1 which provides a comparison with South Perry data acquired previously [8 Figure 4-45]. The differences in delay spread (greatest between 400 and 651 MHz) can be attributed to the different biophysical parameters characterizing the sites [137 stems/acre at South Perry versus 769 stems/acre at Coventry; 9.6 inches average tree-trunk diameter at South Perry versus 4.6 inches at Coventry]. The nearly-equal first and second moments of the delay spread \( \bar{t}_{\text{spr}} \) and \( \text{var}_{\text{spr}} \), respectively] revealed by Figures 4-2 and 4-3 confirms the near-exponential dependence predicted by theory [Equation (2.11)].

4.2 Canopy-Dominant Measurements

As with trunk-dominant propagation, the delay spread is greater for vertical polarization than for horizontal polarization. However, although the delay spread of canopy-dominant propagation is about the same as that of trunk-dominant propagation for horizontal polarization, for vertical polarization it becomes significantly smaller with increasing range. For canopy-dominant propagation, the delay spread appears to be only weakly
Figure 4-1: Delay Spread Path Length Determination
Figure 4-2: Delay Spread Plots
Figure 4-3: Delay Spread Plots
dependent on frequency, if at all. Distance dependence cannot be inferred from the limited data of the Tables. Figure 4-4 clearly reveals the delay-spread function to be non-exponential since the second-central-moment $T_{\text{rog}}$ is several times larger than the first-moment $T_{\text{e}}$. Especially surprising is the observation that for canopy-dominant propagation, delay spread seems to be greater in winter when the trees are bare (no foliage) than in summer. Rain, snow and sleet seem to have no effect on delay spread.
Figure 4-4: Delay Spread Plots
5.0 References


APPENDIX A:

Program TP-6
program tp6(,95)
ema buf1,bufq,power
tnteger trimlen
character*1600 string
integer b1(8192),b2(8192)
integer bufi(8192),bufq(8192),bufd,sorti(511),sortq(511)
real power(511,16)
tnteger ihard(28)

C EPISODE SECTION
C INDEX IS CHANNEL
INTEGER*2
- LCODE(2), ! CODE LENGTH 255,511,1023,2047=0,1,2,3
- LBAND(2), ! BAND WIDTH H,M,L,CW=0,1,2,3
- LCYCL(2), ! CYCLES/SAMPLE 1,2,4,8=0,1,2,3
- IPA(2), ! POWER AMP ASSIGNMENTS
REAL*4
- IFREQ(2), ! RCVR FREQ MHz
- JFREQ(2) ! TX FREQ MHz

INDEX=1 FOR RECEIVER, =2 FOR TRANSMITTER

INTEGER*2
- IATYP(2), ! ANTENNA CODE: 1=OMNI 2=VERTICAL
- 3=HORIZONTAL 4=RH
- 5=LH (RCVR ONLY)

REAL*4
- ADIR(2), ! ANTENNA DIRECTION
- AHGT(2) ! ANTENNA HEIGHT

EQUIVALENCE(IHARD(1), LCODE)
EQUIVALENCE(IHARD(3), LBAND)
EQUIVALENCE(IHARD(5), IFREQ)
EQUIVALENCE(IHARD(9), IPA)
EQUIVALENCE(IHARD(11), JFREQ)
EQUIVALENCE(IHARD(15), IATYP)
EQUIVALENCE(IHARD(17), ADIR)
EQUIVALENCE(IHARD(21), AHCT)
EQUIVALENCE(IHARD(25), LCYCL)
EQUIVALENCE(IHARD(27), IALOC)

C THE REMAINING 4 WORDS ARE SPARES

equivalence (string,b2)
equivalence (IHARD,B2(7169))

call igbuf(b1,8192)
call chpar

READ(7,iosstat - iostat, err=900, end=950) b2
length = trimlen(string)

OPEN(10, FILE='TVIR.DAT')

WRITE(10,'("RECEIVER FREQ1 =","F7.2," RECEIVER FREQ2 =","F7.2"
&,"TRANSMITTER FREQ1 =","F7.2," TRANSMITTER FREQ2 =","F7.2")')
& IFREQ(1), IFREQ(2), JFREQ(1), JFREQ(2)

WRITE(1O,'("RX ANTENNA HEIGHT-",F7.2," RX ANTENNA DIRECTION-",F7.2,
&/"TX ANTENNA HEIGHT-",F7.2," TX ANTENNA DIRECTION-",F7.2")')
& AHGT(1), ADIR(1), ADIR(2), AHGT(2)

IF (IHARD(1) .eq. 0) Write(10,'("Code length = 255")')
IF (IHARD(1) .eq. 1) Write(10,'("Code length = 511")')
IF (IHARD(1) .eq. 2) Write(10,'("Code length = 1023")')
IF (IHARD(1) .eq. 3) Write(10,'("Code length = 2047")')

if (ihard(3) .eq. 0) write(10,'("Bandwidth = 250 MHz")')
if (ihard(3) .eq. 1) write(10,'("Bandwidth = 125 MHz")')
if (ihard(3) .eq. 2) write(10,'("Bandwidth = 50 MHz")')
if (ihard(3) .eq. 3) write(10,'("Bandwidth = 0 MHz")')
DO III = 1, 2
if (iii .eq. 1) then
  if (ihard(14+iii) .eq. 1) then
    write (10,'("RX antenna type = Omni")')
  else
    if (ihard(14+iii) .eq. 2) then
      write (10,'("RX antenna type = Vertical")')
    else
      if (ihard(14+iii) .eq. 3) then
        write (10,'("RX antenna type = Horizontal")')
      else
        if (ihard(14+iii) .eq. 4) then
          write (10,'("RX antenna type = RHC")')
        else
          if (ihard(14+iii) .eq. 5) then
            write (10,'("RX antenna type = LHC")')
          end if
        end if
      end if
    end if
  end if
else
  if (ihard(14+iii) .eq. 1) then
    write (10,'("TX antenna type = Omni")')
  else
    if (ihard(14+iii) .eq. 2) then
      write (10,'("TX antenna type = Vertical")')
    else
      if (ihard(14+iii) .eq. 3) then
        write (10,'("TX antenna type = Horizontal")')
      else
        if (ihard(14+iii) .eq. 4) then
          write (10,'("TX antenna type = RHC")')
        else
          if (ihard(14+iii) .eq. 5) then
            write (10,'("TX antenna type = LHC")')
          end if
        end if
      end if
    end if
  end if
END IF
END DO

DO ircvr = 1, 2 ! Do for both receivers
do iset = 1, 16 ! each set has 8 sweeps that will be averaged
  DO 10 J=1, 4 ! j = channel no.
if (j .eq. 1) then
  READ(7, iostat=ios, err=900, end=950) (bufi(k), k=1, 8192)
  READ(7, iostat=ios, err=900, end=950) (bufq(k), k=1, 8192)
  iloc = 6 * 1024
  DO it = 1, 511
    sorti(it) = bufi(it + iloc)
    sortq(it) = bufq(it + iloc)
  End do ! end it
  call shell_sort(sorti, 511)
  call shell_sort(sortq, 511)
  iav'i = sort'i(256)
  iavq = sortq(256)
end if

  ! end DC Bias determination

do m = 1, 511
  x = 1.0
  x = ((float(bufi(m + iloc)) - float(iav'i)))**2.0 +
  2.0
  if (x .gt. 0.0) then
    power(m, iset) = 10.0*Aalog10(x)
  else
    power(m, iset) = -99.0
  end if
  end do ! end m

else
  read(7) bufd
  read(7) bufd
end if
10 continue

END DO ! iset do loop

do 20 i=1, 511
  write(10, '((15,16f7.2))') i, (power(i, iset), iset=1, 16)
20
END DC ! ircvr do loop

ISTOP = LENGTH/80
DO IS = 1, ISTOP
  write(10, '((a80/))') string((IS-1)*80+1:IS*80)
END DO
IF(ISTOP*80 .LT. LENGTH) write(10, '((a80/))')
& string(istop*80+1:length)

close(10)
stop
900 write(i, '("Error on read no. =",i4)') ios
stop
950 write(1, '("EOF on read")' )
end
APPENDIX D:

PROGRAM TRNSFR
C234567

C PROGRAM TRNSFR
C THIS PROGRAM READS CECOM ASCII FILES FROM TAPE, PARTITIONS THEM,
C AND RE-WRITES THEM ON DISK
C
CHARACTER*109 TXT
DIMENSION PWR(511,16)
C
5 FORMAT(109A)
 10 FORMAT(5X,16F7.2)
 11 FORMAT(8F7.2)
C
DO 100 I=1 TO 48
   READ(10,5) TXT
   WRITE(6,5) TXT [Display Header on Screen]
100
C
DO 300 J=1,511
300   READ(10,10) (PWR(J,K), K=1,16)
C
DO 400 J=1,511
400   WRITE(12,11) (PWR(J,K), K=1,8) [TVIRs 1-8, RCVR 1]
   DO 401 J=1,511
401   WRITE(14,11) (PWR(J,K), K=1,8) [TVIRs 1-8, RCVR 2]
C
STOP
END

/* TRNSFR EXEC */
DO I = 1 TO 8
   J = 2*I-1
   'FILEDEF KEVIN1 TAPE NL' J
   'FILEDEF SEVIN1 DISK TEST FILE B'
   'MOVEFILE KEVIN1 SEVIN1'
   'ASCTOEBG TEST FILE B TEST EBC B'
   'FILEDEF 10 DISK TEST EBC B'
   'FILEDEF 11 DISK' 'F'||1'||1'||'HDR' 'DATA B (LRECL 109)' [File Header]
   'FILEDEF 12 DISK' 'F'||1'||1'||'A' 'DATA B'
   'FILEDEF 13 DISK' 'F'||1'||1'||'B' 'DATA B'
   'FILEDEF 14 DISK' 'F'||1'||1'||'C' 'DATA B'
   'FILEDEF 15 DISK' 'F'||1'||1'||'D' 'DATA B'
   'FORTGO TRNSFR'
   'TAPE KEW'
END
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APPENDIX C:

PROGRAM PCKUP
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! BCKUP - On Blue? - 3/15/90

! OPTION BASE 1
40 DIM Suf$(3)[8]
50 DATA "HDRA       ","AA       ","CA       
60 READ Suf$(*)
70 FOR I=1 TO 4
80    FOR J=1 TO 3
90        Sor$="F"&VAL$(I)&Suf$(J)
100       Des$="T226F"&VAL$(I MOD 9)&Suf$(J)
110       Des$=Des$[1,7]&"A"
120       PRINT Sor$,"",Des$
130       COP$ Sor$&":HP8290X,700,0" TO Des$&":CS80,705"
150     NEXT J
160  NEXT I
180 END
APPENDIX D:

Program KELVIN
This Program Reads an ITS ASCII Data File From Disc, Rewrites It as a STAT Package-Compatible BDAT Data File on disc, and produces Summary Data Sheets. [Delay Spread is not calculated.]

OPTION BASE 1

REAL Sc(20)

DIM T$(80),Vn$(50),Sn$(20)

DIM A$(50),B$(513),Y(8,511),Tp$(6),Rc$(4)

DATA "T247","T226","T225","T273","T264","T285"

DATA "R1","R3","R2","R4"

READ Tp$(A),Rc$(*)

C=1

INPUT "ENTER the number of the file to be copied",C

Cc=C MOD 8

Tc=C DIV 8+1

PRINT CHR$(12)

PRINT

PRINT

MASS STORAGE IS ":HP82901,700,0"

! Reading the Header

C$="F"&VAL$(C)&"HDRA_

ASSIGN @Inpath TO C$

ENTER @Inpath;A$(*)

GOSUB 610

ASSIGN @Inpath TO *

INPUT "Do you want to store this data on disc? [Yes=1 No=0]",Yn

IF Yn=0 THEN 1410

PRINT CHR$(12)

FOR L=1 TO 4 STEP 2

C$="F"&VAL$(C)&CHR$(64+L)&"A_

C$=C$[1,10]

F$=Tp$(Tc)&"F"&VAL$(Cc)&Rc$(L)

DISP "Reading ASCII Data File ","&C$

ASSIGN @Inpath TO C$

ENTER @Inpath;B$(*)

DISP "Processing ASCII Data from File ","&C$

FOR J=3 TO 513

FOR K=1 TO Nv

Y(K,J-2)=10.0*(VAL(B$(J)[7*K-4,7*K+2])/10)

NEXT K

NEXT J

ASSIGN @Inpath TO *

! Write First Record to Disc

DISP "Writing Header on Disc"

MASS STORAGE IS ":HP8290X,700,1"

CREATE BDAT F$,INT((8*Nv*No)/1280)+3,1280

ASSIGN @File1 TO F$

OUTPUT @File1;T$,No,aIv,Vn$(*) ,Nn,Sn$(*) ,Sc(*)

! Write TVIRs (1-8) on Disc

DISP "Writing PTIRs to Disc ","&F$

OUTPUT @File1,2

OUTPUT @File1;Y(*)

ASSIGN @File1 TO *

MASS STORAGE IS ":HP8290X,700,0"

DISP ""

NEXT L

GOTO 1410
! Constructing the Header
DATA "PTVIR1", "PTVIR2", "PTVIR3", "PTVIR4", "PTVIR5", "PTVIR6"
1200 PRINT TAB(18),"Derived from PTVIR: &Vn$(31)& dBm"
1210 PRINT
1220 PRINT TAB(10),"Received Power:"
1230 PRINT
1240 PRINT TAB(18),"Wideband: &Vn$(32)& dBm"
1250 PRINT TAB(18),"Narrowband: &Vn$(33)& dBm"
1260 PRINT TAB(18),"PTVIR: &Vn$(34)& dBm"
1270 PRINT
1280 PRINT TAB(10),"Transmitted Power (EIRP): &Vn$(35)& dBm"
1290 PRINT
1300 IF (Printo=1) THEN GOTO Final
1310 INPUT "Do You Want This Information on Hard Copy? [Yes=1 No=0]",Pyn
1320 IF (Pyn=0) THEN GOTO Final
1330 PRINTER IS 9
1340 PRINT CHR$(9)
1350 Printo=1
1360 GOTO 890
1370 Final:IF (Printo=0) THEN GOTO 1400
1380 PRINT CHR$(12)
1390 PRINTER IS 1
1400 RETURN
1410 END
APPENDIX E:

PROGRAM MELVIN
This Program Reads SRI BDAT Data Files from Disc, Calculates the Delay Spreads (second central moments) using the Altman Algorithm (CyberCom Technical Report CTR-117-01, Section 4.3.3), and produces Summary Data Sheets (op. cit., Table 4-4).

OPTION BASE 1
INTEGER Pl, Pp(4), Dp, P, Q, Rf
REAL Sc(20)
DIM T$(80), Vn$(50)[10], Sn$(20)[10], Nn(20), Title1$[80], Title2$[80]
FS$="T225F6R1"
ASSIGN @Path TO FS$
ENTER @Path; T$, No, Nv, Vn$(*) , Ns, S n$(*) , Sc(*)
CF=1000/VAL(Vn$(13)) ! Sample interval in nanoseconds
NC=C
!
Noise Window Definition
DATA 12, 40, 5
READ Pl, Dp, Fac
INPUT "Noise-Window Start and Width (in Samples)?", Pl, Dp
INPUT "Threshold/Noise = ? [Default = 5]", Fac
Pp(1)=Pl ! Location of first noise window
FOR J=2 TO 4
Pp(J)=Pp(J-1)+INT(No/4) ! Location of subsequent noise windows
NEXT J
!
ENTER @Path, 2
ALLOCATE Z(No)
ALLOCATE Pkl(Nv), Av4(Nv), Sig(Nv), Sprd(Nv)
PRINT TAB(11), "PTVIR Nmin Nsig Start Mean Sigma Spread"
!
FOR Typ=1 TO Nv ! PTVIR loop
READ PTVIRs from Disc
ENTER @Path; Z(*)
MAT SEARCH Z(*) , LOC MAX; Pk
Zpk=Z(Pk)
Inc=INT((No+1)/8)
RF=Pk-Pk MOD Inc+1-Inc
IF RF=1 THEN 440
ALLOCATE Zt(No) ! Shifts PTVIR
MAT Zt=Z
MAT Zt(1:No-Rf+1)=Zt(Rf:No)
MAT Zt(No-Rf+2:No)=Zt(1:RF-1)
DEALLOCATE Zt(*)
!
Finding rms noise within the windows
DATA 0, 5, 0,1, 1, 100000
RESTORE <50
READ S0, S1, S2, Pk, Flag, Nmin
!
FOR P=1 TO No
IF Z(Pk)<Z(P) THEN Pk=P ! Locates location of PTVIR max.
IF Flag=5 THEN 670 ! ReJECTS non-window noise samples
IF P>Pp(Flag)+Dp THEN
N(Flag)=INT(S1/S0)
Mm=S0*S2-S1*S1
IF N(Flag)<Nmin THEN
Ni=Flag
E - 3
Nmin=N(Flag)

Nsig=INT(SQR(Mm)/S0)

END IF

RESTORE 450

READ S0,S1,S2

Flag=Flag+1

END IF

NEXT P

GOSUB 2030

GOTO 720

INPUT "Retain for Delay-Spread Calculation? [Yes=1 No=0]",Yn

IF Yn=0 THEN 1330

Nc=Nc+1

Calculation of Delay Spread

RESTORE 450

READ S1,S2,S3

RESTORE 450

READ Flg,Fig,Fcq

S4=0

Jj=1

P2=1

Ct=10

Th=Fac*Nmin

FOR I=1 TO 10

Nn(I)=0

NEXT I

FOR Q=1 TO Nc

P=0

IF Flg=1 THEN 1250

IF Fig=1 THEN 960

IF Z(P)>2Pk/4 THEN

Flg=1

Pki(Typ)=P

ELSE

GOTO 1260

END IF

END IF

IF Fig=1 THEN 990

IF Z(P)<.5*Th THEN

Fig=1

IF Z(P)>2*Th THEN

Jj=1

Flg=0

Su=0

P2=0

GOTO 1200

END IF

P2=P2+1

Su=Su+Z(P)

IF P2>Ct THEN

Nn(Jj)=Su/Ct

IF Jj=1 THEN 1160

IF Nn(Jj)<.5*Th AND Nn(Jj-1)<.5*Th THEN

Pend=P

Fog=1

GOTO 1240

END IF

Jj=Jj+1

Su=0

P2=0

END IF
END I

1210 $1 = $1 + T(P)
1220 $2 = $2 + $P * Q
1230 $3 = $3 + Z(P) * Q * Q
1240 IF $Z(P) < Fac * Th AND Fog = 1 THEN 1260
1250 $4 = $4 + $Z(P)

1260 NEXT Q
1270 Avg(Typ) = $2 / $1
1280 IF Pk < Mid THEN 1300
1290 Avg(Typ) = Avg(Typ) + Mid
1300 Sig(Typ) = SQRT($3 * $1 - $2 * $2) / $1
1310 Sprd(Typ) = INT(Avg(Typ) - Pkl(Typ) + Sig(Typ))
1320 PRINT USING Frm1; Typ, Nmnin, Nsig, Pkl(Typ), Avg(Typ), Sig(Typ), Sprd(Typ)
1330 NEXT Typ
1340 Frmt1: IMAGE 11X, DD, 2(4X, DDDDD), 4(5X, DDDDD)
1350 Strt = SUM(Pkl) / Nc
1360 Dspr = SUM(Sprd) / Nc
1370 PRINT USING Frmt2; Strt, Dspr
1380 Frmt2: IMAGE 8X, "Averages", 20X, DDDDD, 23X, DDDDD
1390 WAIT 2.5
1400 ! Next PTVIR
1410 ASSIGN @Path TO *
1420 DISP ""
1430 GRAPHCICS OFF
1440 GOSUB 1540
1450 INPUT "Do you want a hard copy? [Yes=1 or No=0]", Yn
1460 PRINT CHR$(12)
1470 GRAPHICS ON
1480 IF Yn = 0 THEN 2220
1490 PRINTER IS 9
1500 GOSUB 1540
1510 PRINT CHR$(12)
1520 PRINTER IS 1
1530 GOTO 2220
1540 ! Print File Description
1550 PRINT TAB(31), "WPMS File Description"
1560 PRINT
1570 PRINT TAB(10), Title2$
1580 PRINT
1590 PRINT TAB(10), "Channel: " & FS[8, 8]
1600 PRINT
1610 PRINT TAB(10), "Code Length: " & Vn$[17] & " Chips"
1620 PRINT
1630 PRINT TAB(10), "Bandwidth: " & Vn$[18] & " MHz"
1640 PRINT
1650 PRINT TAB(10), "Carrier Frequency: " & Vn$(19) & " MHz"
1660 PRINT
1670 PRINT TAB(10), "Transmitting Antenna:"
1680 PRINT
1690 PRINT TAB(18), "Type: " & Vn$(20)
1700 PRINT TAB(18), "Location: " & Vn$(21)
1710 PRINT TAB(18), "Direction: " & Vn$(22) & " Degrees"
1720 PRINT TAB(18), "Height: " & Vn$(23) & " ft"
1730 PRINT
1740 PRINT TAB(10), "Receiving Antenna:"
1750 PRINT
1760 PRINT TAB(18), "Type: " & Vn$(24)
1770 PRINT TAB(18), "Location: " & Vn$(25)
1780 PRINT TAB(18), "Direction: " & Vn$(26) & " Degrees"
1790 PRINT TAB(18), "Height: " & Vn$(27) & " ft"
1800 PRINT
1810 PRINT TAB(10), "Path Loss:", 2.820
1820 PRINT
1830 PRINT TAB(18), "Derived from KSL: &Vn$(30) dBm"
1840 PRINT TAB(18), "Derived from PTVIP: &Vn$(31) dBm"
1850 PRINT
1860 PRINT TAB(10), "Received Power:
1870 PRINT
1880 PRINT TAB(18), "Wideband: &Vn$(32) dBm"
1890 PRINT TAB(18), "Narrowband: &Vn$(33) dBm"
1900 PRINT TAB(18), "PTVIR: &Vn$(34) dBm"
1910 PRINT
1920 PRINT TAB(10), "Transmitted Power (EIRP): &Vn$(35) dBm"
1930 PRINT
1940 PRINT TAB(10), "Delay-Spread Calculations:
1950 PRINT
1960 Cf=1
1970 PRINT USING Frmt4: Avg*Cf, Dspr*Cf
1980 PRINT USING Frmt5: Strt*Cf, Dspr*Cf
1990 Frmt4: IMAGE 17X, "Delay: Average = ", 4D, " Std.Dev. = ", 4D, " ns"
2010 PRINT
2020 RETURN
2030 ! Plotting of Delay Spread Function
2040 Frst=1
2050 Lst=No+1
2060 Title1$=" " ! "Delay-Spread Function"
2070 Title2$=T$[1, POS(T$, "Date") +14]
2080 Crt=0
2090 CALL Plot_pnts(Z(*), Frst, Lst, Title1$, Title2$, Cf, Crt)
2100 GOTO 2210
2110 ! GRAPHICS OFF
2120 INPUT "Do you want to use the plotter? [Yes=1, No=0]", Ans
2130 IF Ans=0 THEN 2170
2140 Crt=1
2150 INPUT "When the plotter is ready press ENTER", Ans
2160 GOTO 2200
2170 ! INPUT "Do you want to plot a sub-set or quit? [Sub-set=1, Quit=0]", Ans
2180 IF Ans=0 THEN 1530
2190 ! INPUT "Enter the first and last points to be plotted: ", Frst, Lst
2200 ! GOTO 2980
2210 RETURN
2220 END
2230
2240 SUB Plot pnts(Array(*), First_pnt, Last_pnt, Main_title$, Ref_title$, Samp_int, Crt, OPTIONAL 0)
2250 :
2260 : Array(*) CONTAINS THE POINTS TO BE PLOTTED
2270 :
2280 DIM Dummy$(80)
2290 ! DISP "Graph Title: [80 Char Max, DEFAULT="&Main_title$&" ":
2300 ! INPUT Dummy$
2310 ! IF Dummy$<>"" THEN Main_title$=Dummy$
2320 Lab1l: Answer$="B"
2330 ! INPUT "Bar (B) or Line (L) Graph (DEFAULT=B) ?", Answer$
2340 ! IF Answer$<>"B" AND Answer$<>"L" THEN Lab1l
2350 Smin=First_pnt
2360 Smax=Last_pnt
2370 ! DISP "Plot samples between Smin, Smax [DEFAULTS=(";First_pnt:";";Last_pnt;"):GCLear

E - 6
!INPUT Smin,Smax
!IF Smax<Smin THEN 3110
!First_pnt=Smin
!Last_pnt=Smax
GINIT
!IF Crt THEN PLOTER IS 703,"HPGL"
GRAPHICS ON
Xr=.7 ! Reduced from .8
Yr=.5 ! Reduced from .8
Cr=Xr
!IF Xr>1 THEN Cr=1
CSIZE 4*Cr,.6
LORG
5
LDIR 0
PEN 1
ON ERROR GOTO Skip1
VIEWPORT 18*Xr+15,131*Xr+15,91*Yr+10,92*Yr+10! SET UP AXES
WINDOW 0,8,0,1
AXES 1,0,0,0
VIEWPORT 18*Xr+15,131*Xr+15,25*Yr+10,26*Yr+10
WINDOW 0,8,1,0
AXES 1,0,0,0
VIEWPORT 16*Xr+15,17*Xr+15,27*Yr+10,30*Yr+10
WINDOW 1,0,0,1
AXES 0,1,0,0
VIEWPORT 132*Xr+15,133*Xr+15,26*Yr+10,91*Yr+10
WINDOW 0,1,0,1
CLIP OFF
FOR I=1 TO 0 STEP -.2
MOVE .5,I
LABEL USING Image1:I
next I
VIEWPORT 18*Xr+15,131*Xr+15,91*Yr+10,92*Yr+10
WINDOW 0,1,0,1
MOVE 0,.5
LORG 2
LABEL Ref_title$[1,19]
LORG 0
MOVE 1,.5
LABEL Ref_title$[20,34]
VIEWPORT 0*Xr+15,4*Xr+15,26*Yr+10,91*Yr+10
WINDOW 0,1,0,1
CLIP OFF
LDIR PI/2
MOVE .5,.5
LORG 5
LABEL "Normalized Power"
LDIR 0
VIEWPORT 18*Xr+15,131*Xr+15,20*Yr+10,24*Yr+10
WINDOW 0,1,0,1
MOVE 0,.5
LORG 2
LABEL VAL$(First_pnt)
MOVE 1,.5
LORG 8
LABEL VAL$(Last_pnt)
MOVE .5,.5
LORG 5
Image2:IMAGE DDNL$
LORG 2
VIEWPORT 18*Xr+15,131*Xr+15,10*Yr+10,16*Yr+10
WINDOW 0,1,0,1
MOVE 0,.5
Unit$="nsec"
LABEL USING Image4;Sample_int,Unit$
Image4:IMAGE " Sample Interval: ",MD.3DE,1X,K
Ymax=0 ! DETERMINE Ymax
PENUP
FOR I=First_pnt TO Last_pnt-1
   IF ABS(Array(I))>Ymax THEN Ymax=ABS(Array(I))
NEXT I
VIEWPORT 18*Xr+15,131*Xr+15,14*Yr+10,20*Yr+10
WINDOW 0,1,0,1
MOVE 0,.5
LABEL USING Image3;Ymax
Image3:IMAGE " Maximum Power: ",MD.3DESZZ," (=1)"
VIEWPORT 18*Xr+15,131*Xr+15,27*Yr+10,90*Yr-10
IF Ymax<>0 THEN WINDOW First_pnt,Last_pnt,0,Ymax
IF Ymax=0 THEN WINDOW First_pnt,Last_pnt,-1,1
PLOT POINTS
MOVE First_pnt,0
DRAW Last_pnt,0
IF Answer$="B" THEN MOVE Smin,0
IF Answer$="L" THEN MOVE Smin,Array(Smin)
FOR I=Smin TO Smax-1
   IF Answer$="B" THEN
      MOVE I,0
   ELSE
      DRAW I,Array(I)
   END IF
   IF ABS(Array(I)/Ymax)<.01 THEN GOTO 3350
   DRAW I,Array(I)
NEXT I
IF Smin-First_pnt THEN 3400
LINE TYPE 5,2
MOVE Smin,-Ymax
DRAW Smin,+Ymax
IF Smax=Last_pnt THEN 3440
LJNF TYPE 5,2
MOVE Smax,-Ymax
DRAW Smax,+Ymax
LINE TY:1
VIEWPORT 3*Xr+15,146*Xr+15,104*Yr+10,110*Yr+10
WINDOW 0,1,0,1
CSIZE 5*Cr,.6
LORG 5
MOVE .5,.5
LABEL Main_title$
X=LEN(TRIM$(Main_title$))/2
MOVE .5-(6*5*Cr)/(141*Xr)*X,0
DRAW .5+(.6*5*Cr)/(141*Xr)*X,0
Skip1:OFF ERROR
PENUP
PEN 0
ON ERROR GOTO Subend
E - 8
560 01=Ymax
3590 Subend:SUBEND