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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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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.

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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]

$$y(t) = \int x(t-\xi)g(t,\xi)d\xi \quad (2-1)$$

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 ξ 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 ξ . 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

$$R_g(t_1, t_2; \xi_1, \xi_2) = \langle g(t_1, \xi_1) g^*(t_2, \xi_2) \rangle \quad (2-2)$$

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 ξ uncorrelated, then the channel correlation function simplifies to

$$\langle g(t, \xi) g^*(t+\tau, \eta) \rangle = Q(\tau, \xi) \delta(\xi - \eta) \quad (2-3)$$

where $\delta(\cdot)$ is the Dirac delta function and $Q(\tau, \xi)$ is the co-variance function of those channel fluctuations having propagation delays in the interval $(\xi, \xi+d\xi)$. 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 [and $g(t, \xi)$] may be considered time-invariant. The ensemble-averaged channel correlation function then simplifies to

$$\langle g(t, \xi) g^*(t, \eta) \rangle = Q(\xi) \delta(\xi - \eta) \quad (2-4)$$

where

$$Q(\xi) = Q(0, \xi) \quad (2-5)$$

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

$$x(t) = \exp(j2\pi f_0 t) \quad (2-6)$$

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

$$y(t) = \int \exp(j2\pi f_0 (t - \xi)) g(t, \xi) d\xi \quad (2-7)$$

and the received power is

$$\begin{aligned} \langle P_r \rangle = \langle y^2(t) \rangle &= \iint \exp(j2\pi f_0 (t - \xi_1)) \exp(-j2\pi f_0 (t - \xi_2)) \\ &\quad \langle g(t, \xi_1) g^*(t, \xi_2) \rangle d\xi_1 d\xi_2 \end{aligned} \quad (2-8)$$

$$= \iint \exp(-j2\pi f_0 (\xi_1 - \xi_2)) Q(\xi_1) \delta(\xi_1 - \xi_2) d\xi_1 d\xi_2 \quad (2-9)$$

$$= \int Q(\xi) d\xi \quad (2-10)$$

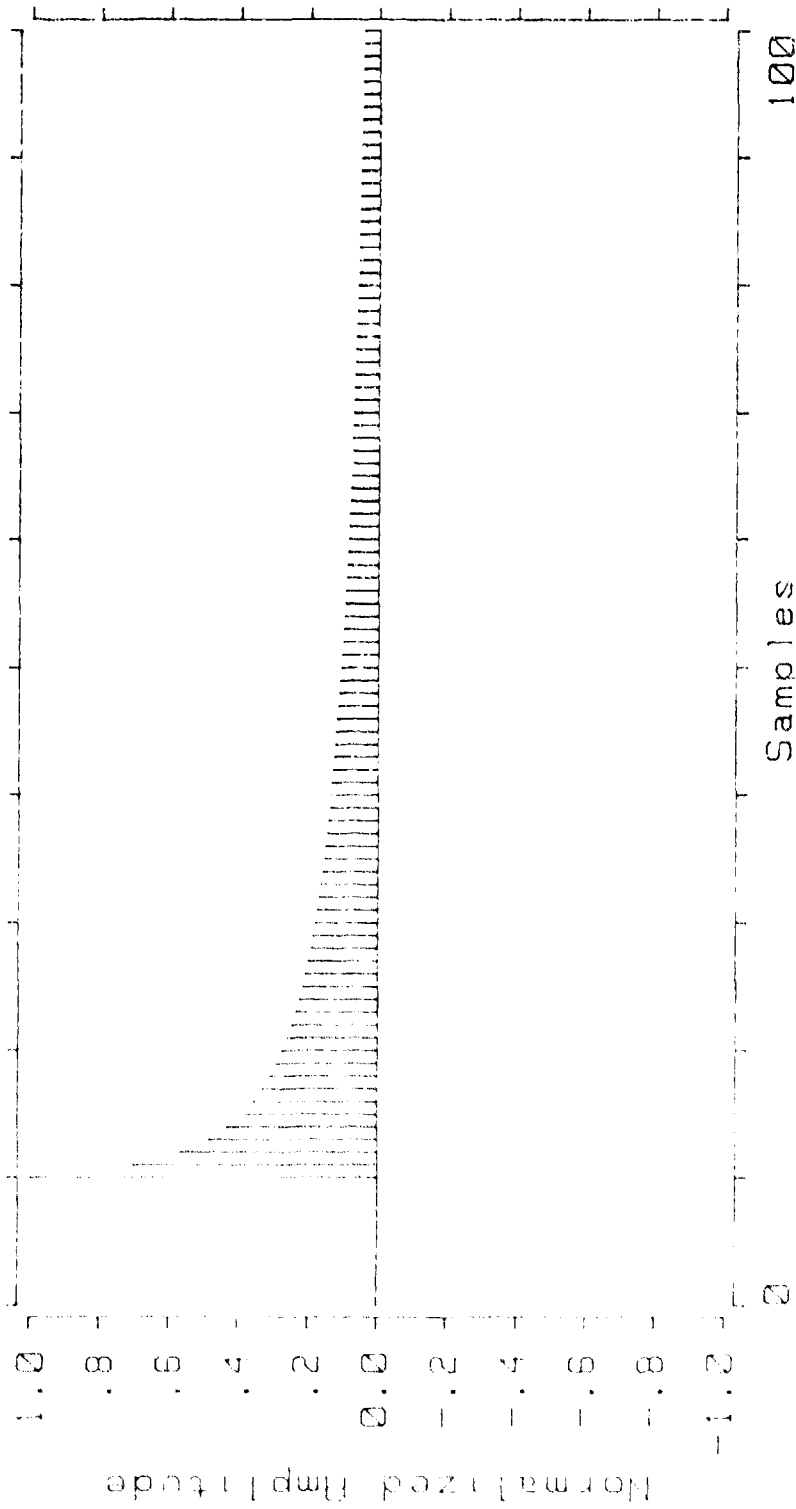
Since ξ denotes the propagation delay, it is apparent from Equation (2-10) that $Q(\xi)$ describes the ensemble-averaged distribution of the incremental power received within a delay interval $d\xi$. According to the forest propagation model developed in reference [1], the theoretical ensemble-averaged delay-spread of a homogeneous, trunk-dominant forest is of the form

$$Q(\xi) = \xi^{-1/2} \exp(-\xi/\xi_0) \quad (2-11)$$

where ξ_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

Tape&File: temp Date: 08/24/87 Time: 24:00



Normalized Amplitude: 2.475E+002 (=1)
Sample Interval: 4.000E-09 sec

Figure 2-1: Ensemble-Averaged Delay-Spread Function

signal is impulsive, i.e.

$$R_x(\tau) = \langle x(t)x(t-\tau) \rangle \cong \delta(\tau) \quad (2-12)$$

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

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

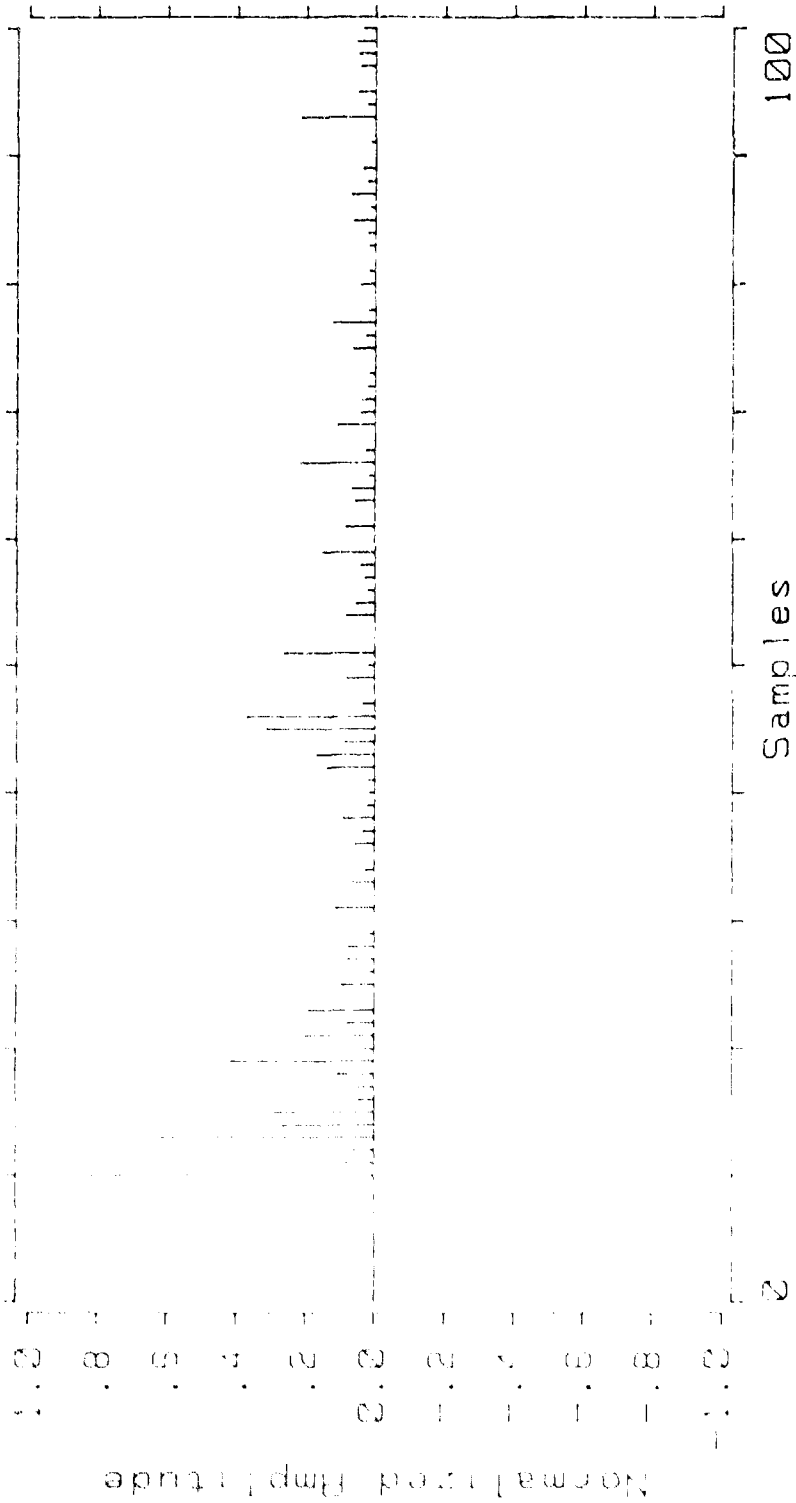
so that to the extent that $R_x(\tau)$ is approximated by a Dirac delta function, the cross-correlated output $\bar{g}(t,\tau)$ approximates the input delay-spread function. The delay-spread function $Q(\cdot)$ is approximated by

$$P(\tau) \cong |\bar{g}(t,\tau)|^2 \quad (2-14)$$

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 τ 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 [12] 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.

Tape&File: temp Date: 08/24/87 Time: 24:00



Normalized Amplitude: 4.410E+002 (=1)

Sample Interval: 4.000E-09 sec

Figure 2-2: Sample Delay-Spread Function

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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 ρ_1 and the fractional volume occupied by the foliage f_v can be estimated from the relations

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

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

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 cm² 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.

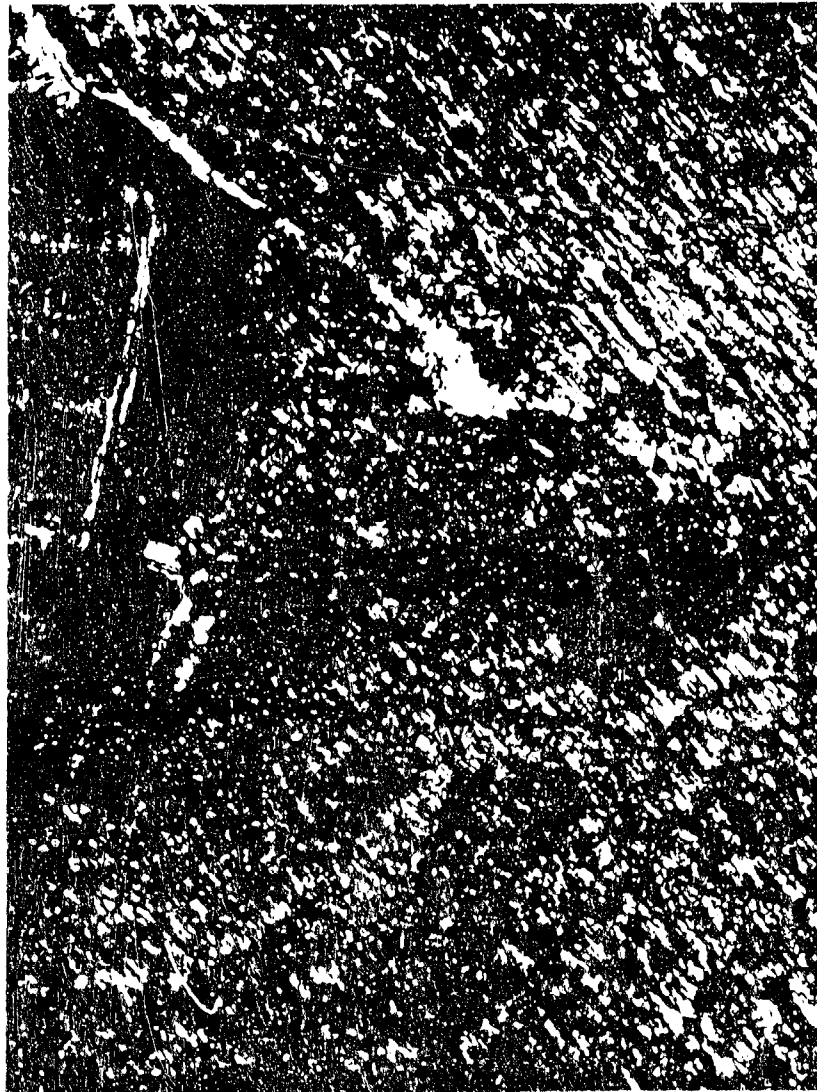


Figure 3-1: Coventry Site Photo

UCONN Forest: Trunk Density (Stems/Acre)

Contour: [Minimum, (Interval), Maximum] : [300, (100), 1300]

Distances in Feet

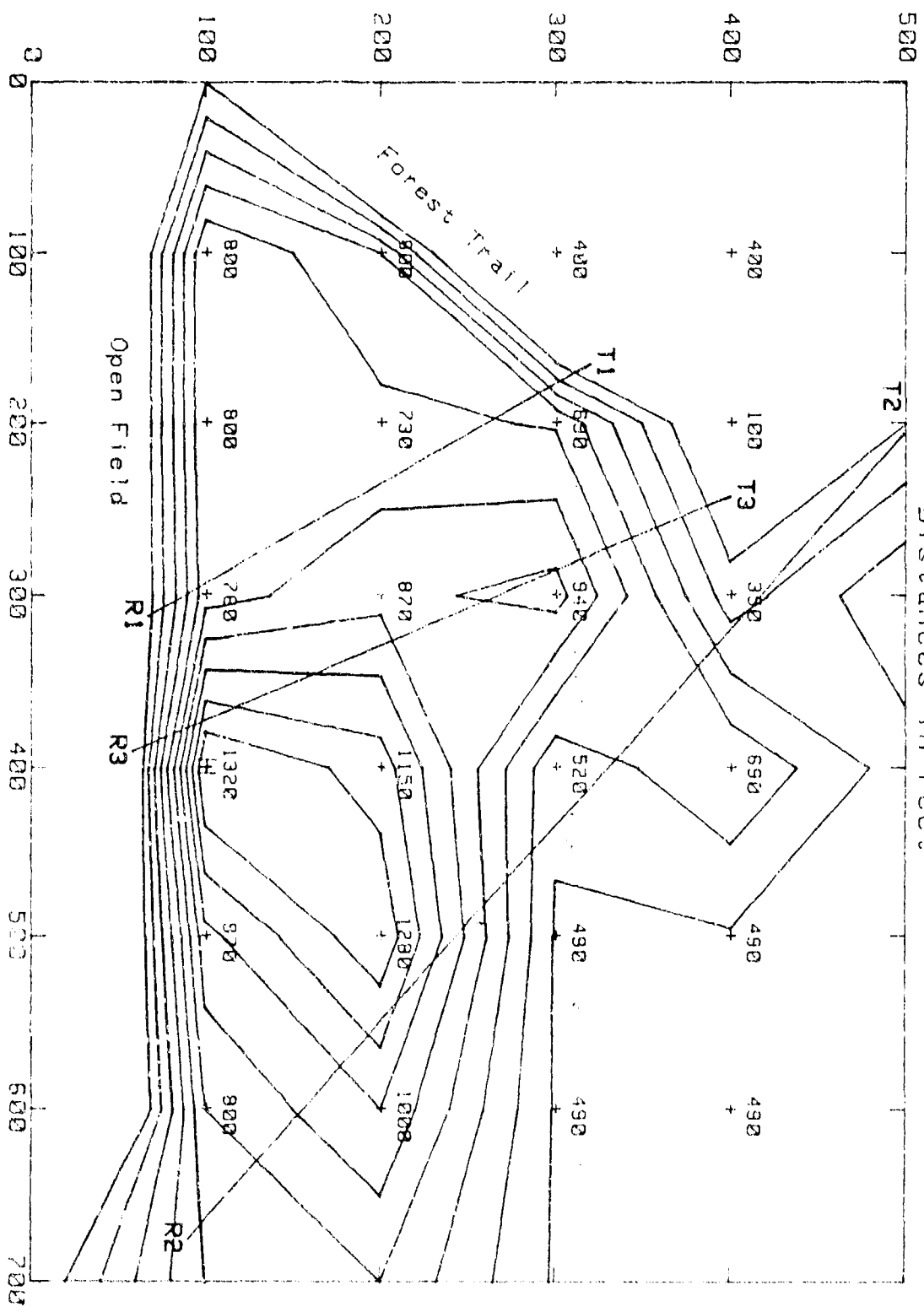


Figure 3-3: Coventry Trunk Density Contours (1987)

UConn Forest: Average Trunk Diameter (inches)
 Contour: [Minimum, (Interval), Maximum] : [0, (1), 7]
 Distances in Feet

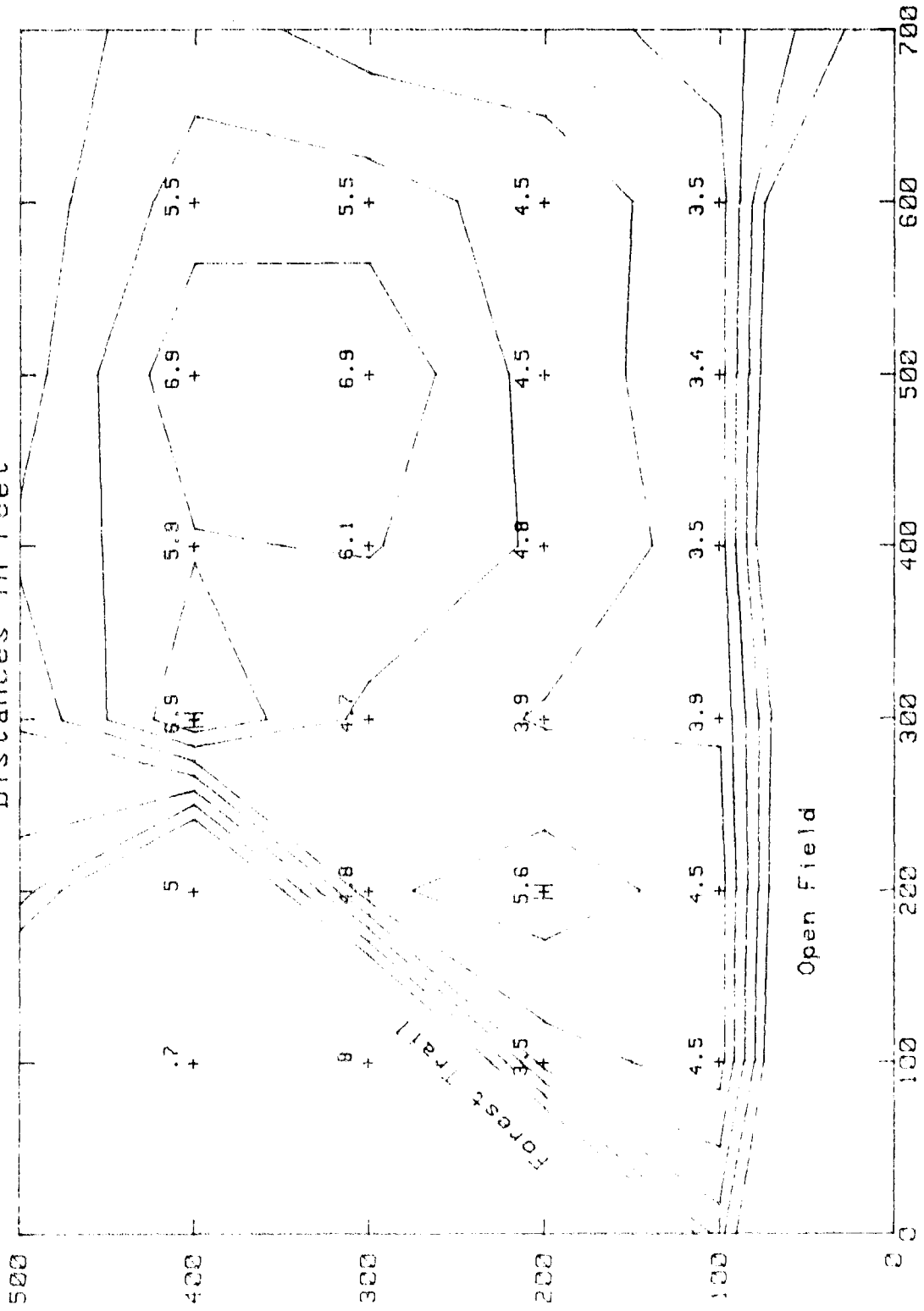


Figure 3-4: Coventry Average Trunk Diameter Contours (1987)

UCONN Forest (17 20-ft Radius Plots)
 Trunk Diameter Histogram (November 1987)

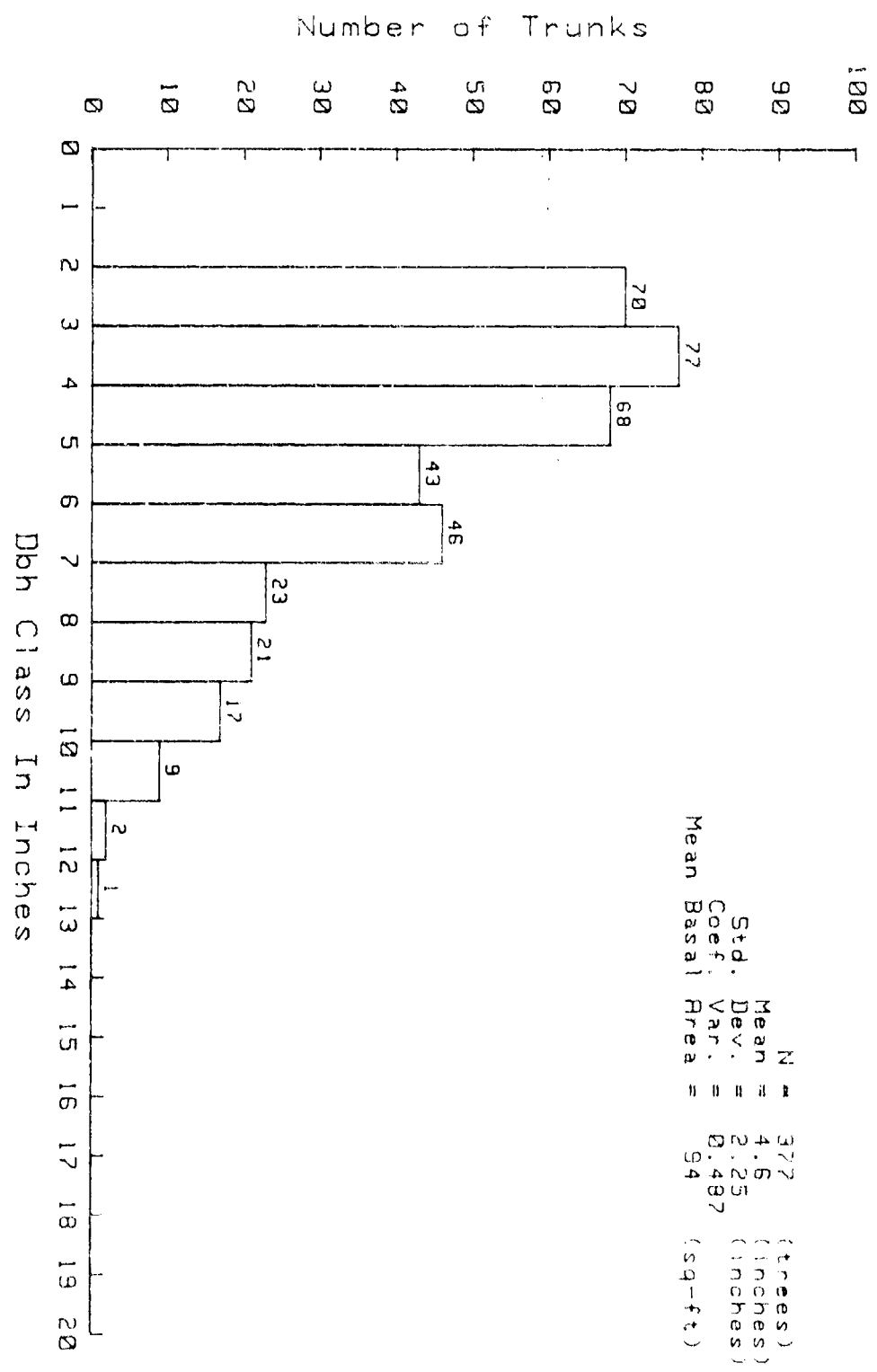


Figure 3-5: Coventry Trunk Diameter Histogram (1987)

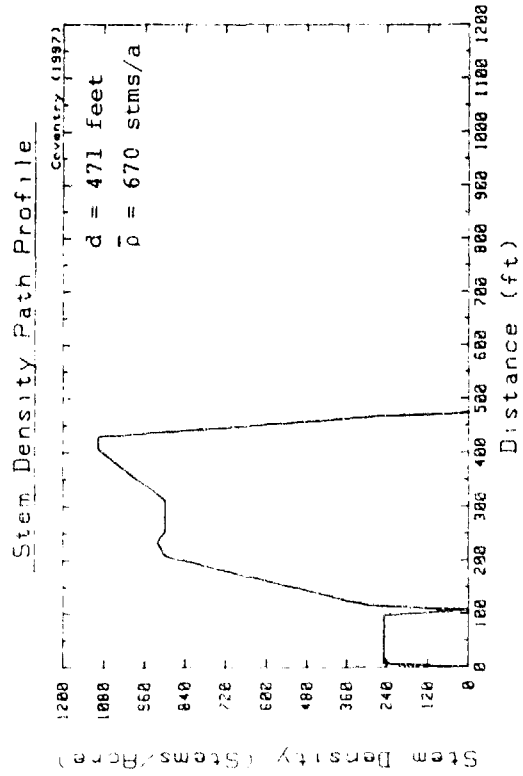
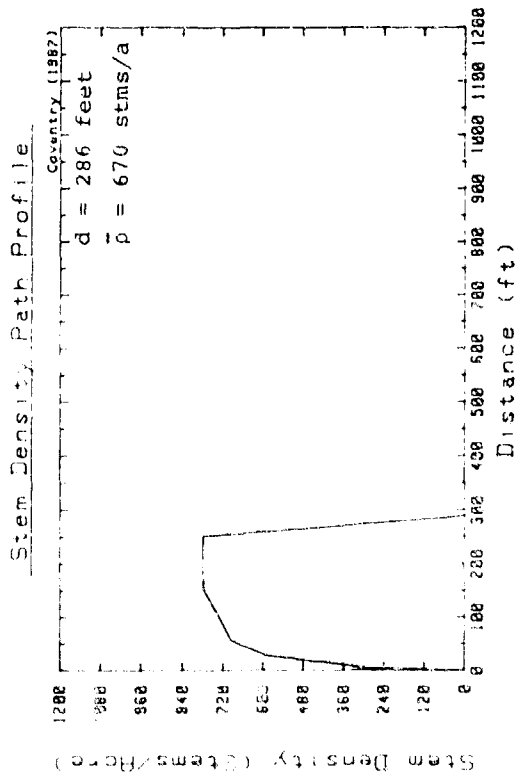
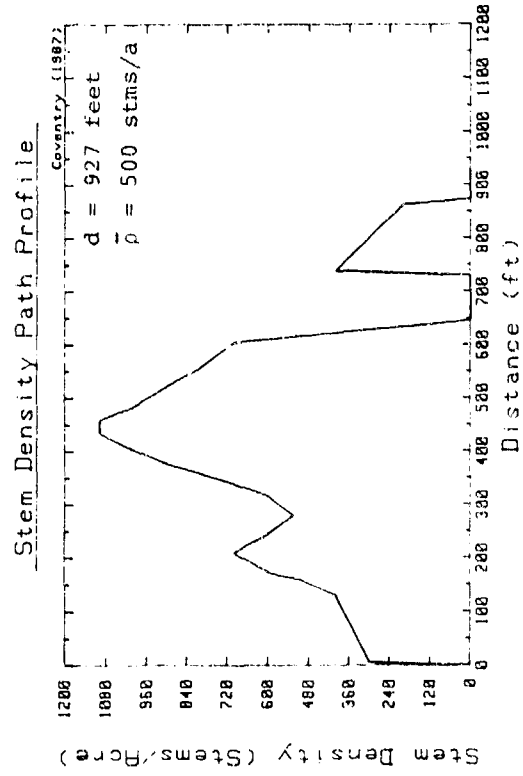
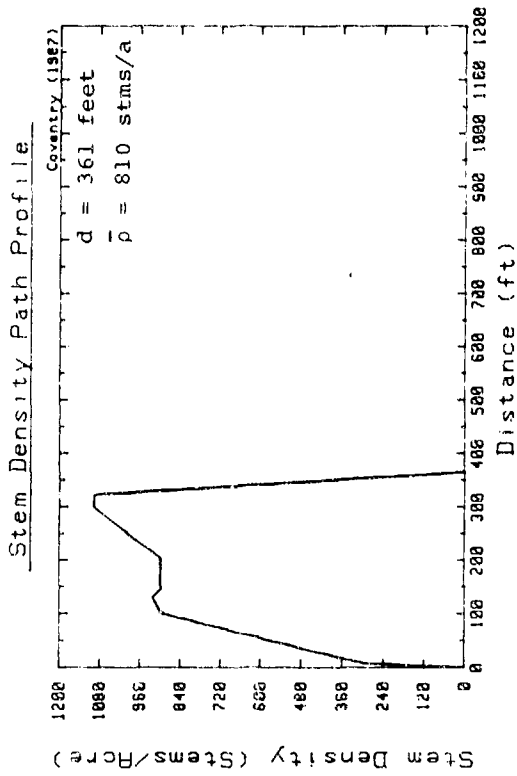


Figure 3-6: Stem Density Path Profiles (Coventry, 1987)

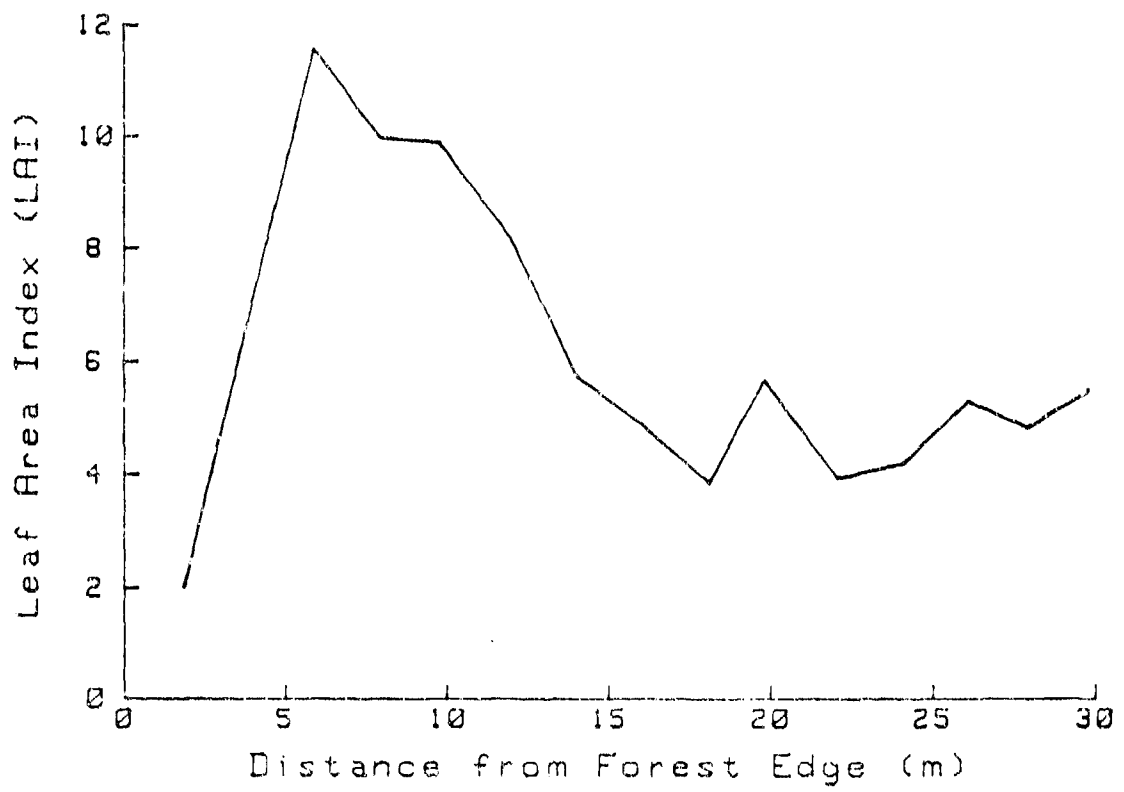


Figure 3-7: Coventry Leaf Area Index

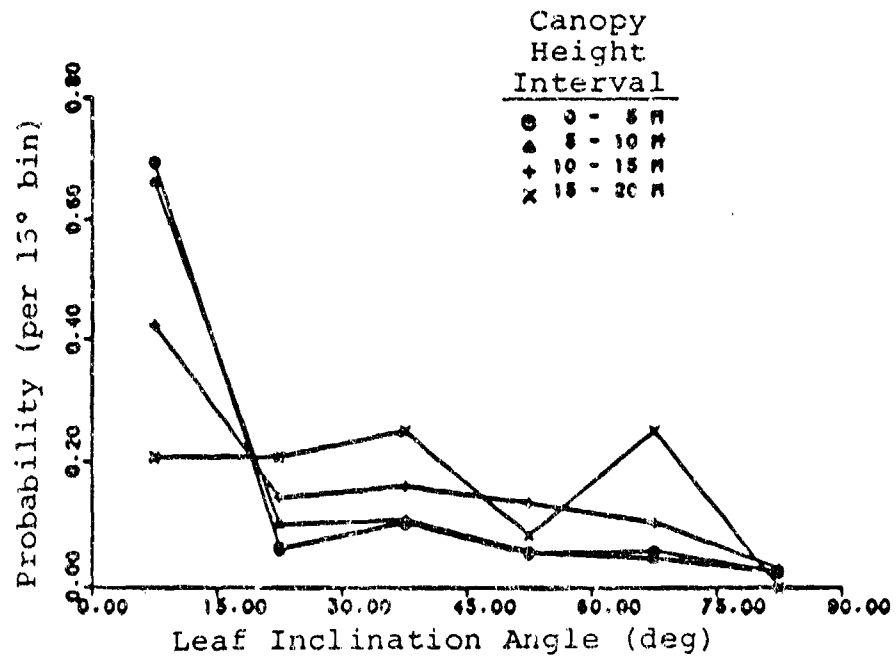


Figure 3-8: Coventry Leaf Inclination Angle Histogram

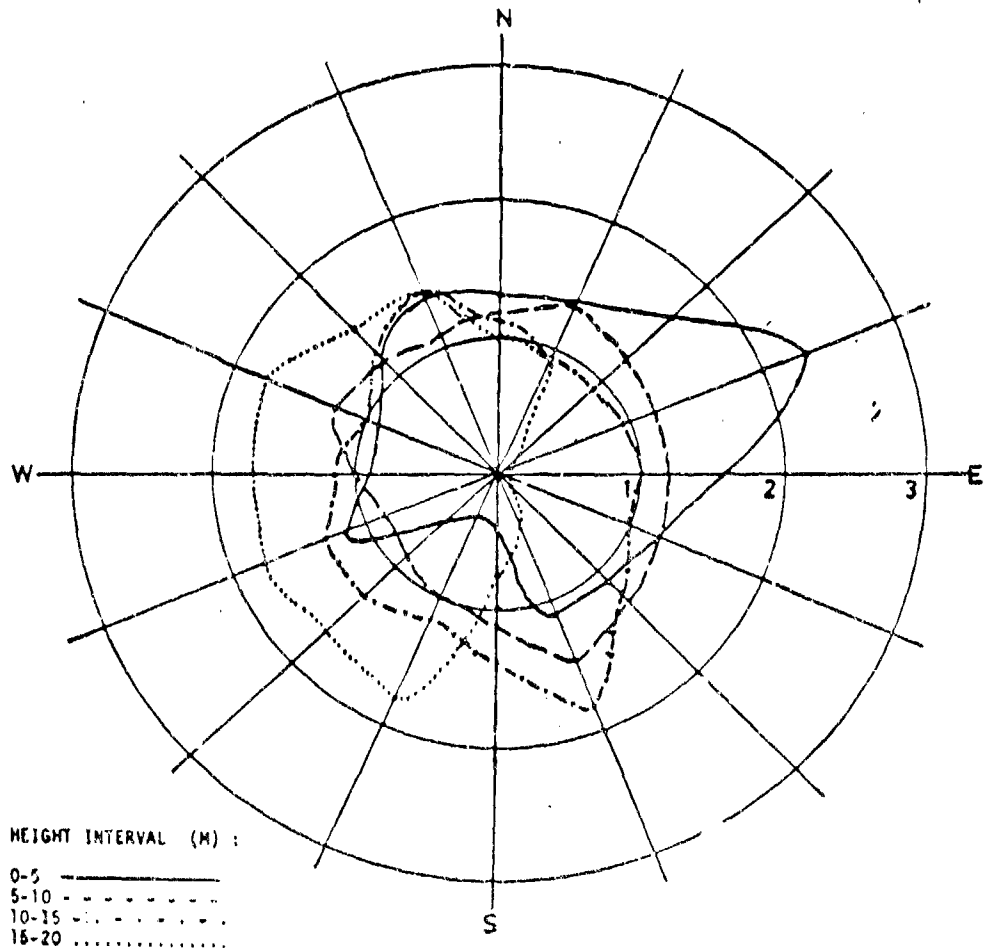


Figure 3-9: Coventry Leaf Azimuthal Angle Histogram

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, Δt , 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 Δt .

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 3-1: WPMS Capabilities

<u>General</u>	
Carrier frequency range	200-2000 MHz
Delay-spread range	1-20 μ -sec
Delay-spread resolution	1 nanosec
Doppler-spread range	15-240 Hz
Doppler-spread resolution	2 Hz (max)
TVIR amplitude resolution	0.1 dB
TVIR multipath amplitude resolution	-20 dB
Measurable path loss	155 dB (max)
<u>Antennas</u>	
Omnidirectional	Biconical
Directional	Log-Periodic Dipole
Transmitter polarization	V, H, RCP
Receiver polarization	V, H, RCP, LCP
Azimuthal range	360 degrees
Height range	5-65 feet
<u>Transmitters</u>	
Number	2
Frequency range	
XMTR no. 1	200-1050 MHz
XMTR no. 2	700-2000 MHz
Power output	100 W (max)
Modulation	Direct-Sequence BPSK Continuous Wave (CW)
DS code length (chips)	255, 511, 1023 or 2047
DS code rate	50, 125 or 250 MHz
Bandwidth (null-to-null)	100, 250 or 500 MHz
Control	Local or Remote (RCVR)
<u>Receivers</u>	
Number	2
Frequency range	200-2000 MHz
Noise figure	9 dB
Demodulation	Coherent Direct-Sequence BPSK Continuous Wave (CW)
DS code length (chips)	255, 511, 1023 or 2047
DS code rate	50, 125 or 250 MHz
Bandwidth (null-to-null)	100, 250 or 500 MHz
Control	Local computer
Input signal range	-95 - 0 dBm
Instantaneous dynamic range	50 dB
AGC (computer controlled)	1 dB increments

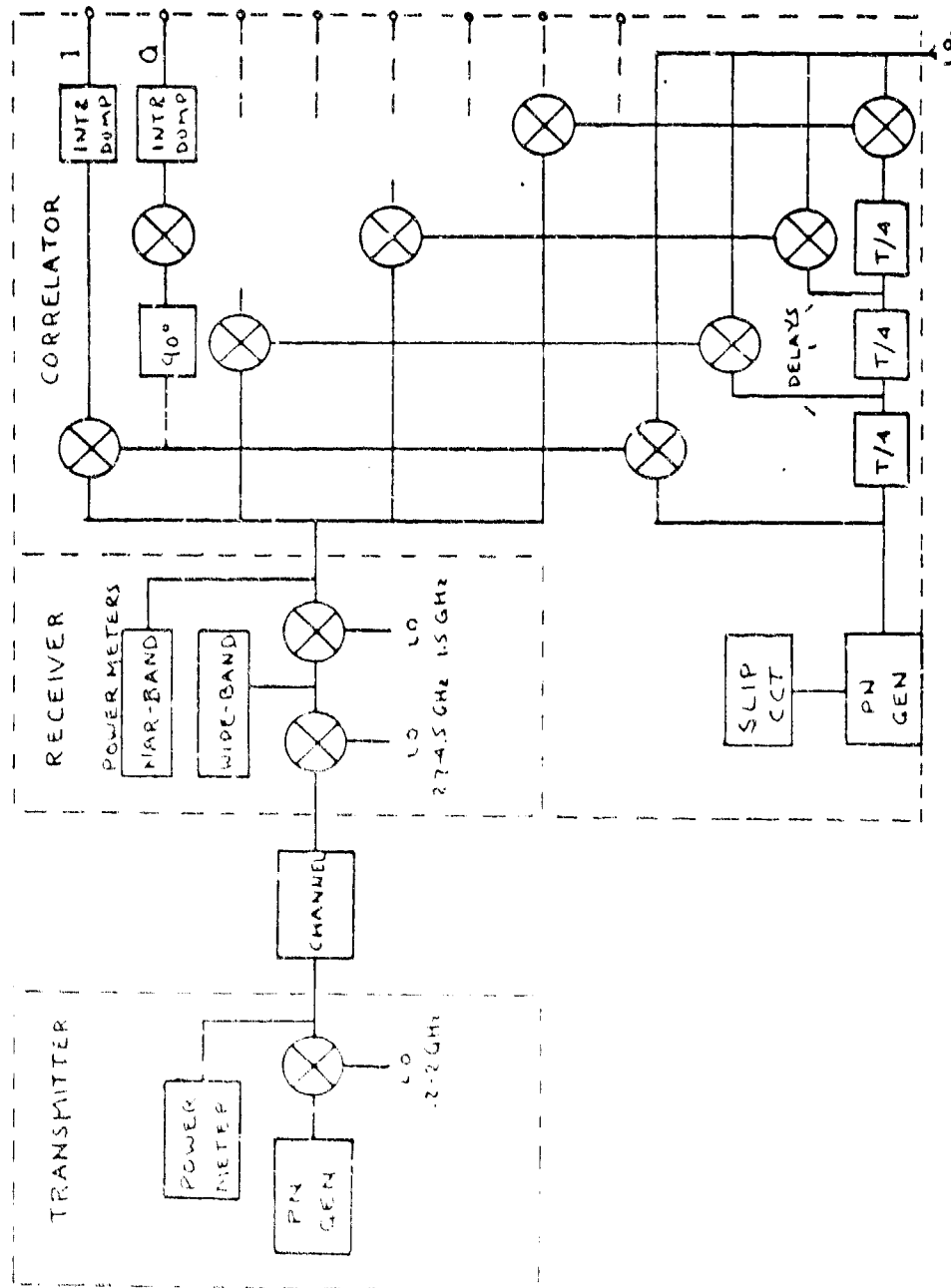


Figure 3-10: WPMS Block Diagram

WPMR Raw Data Format

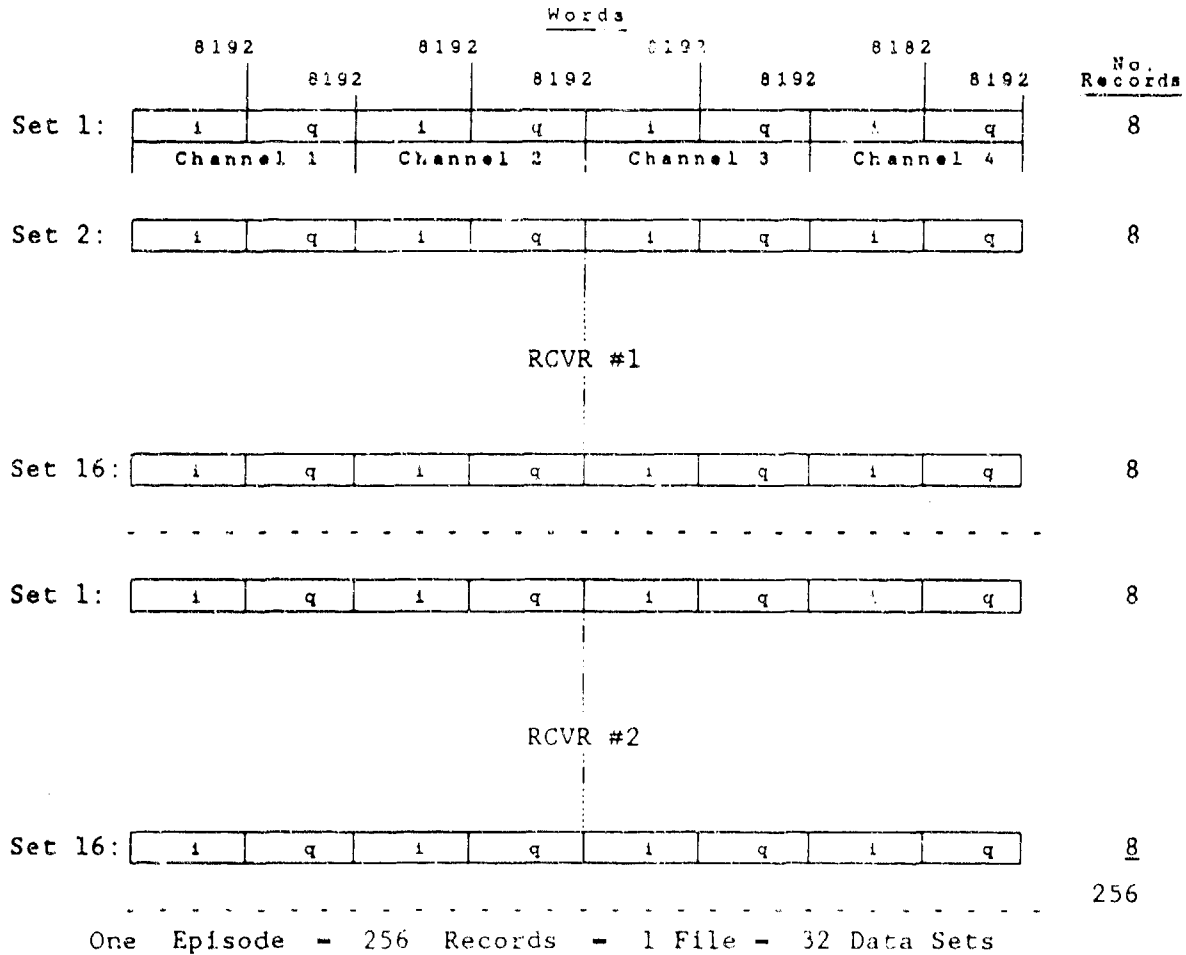


Figure 3-11: WPMR Raw Data File Format

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 (256 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.

Tape xxx File y

Record Number	Column																		
	1	6											61	62					117
0	"TxxxFyHDRA"																		
48																			
	R	1	2	3	4	5	6	7	8	9	¹ 0	¹ 1	¹ 2	¹ 3	¹ 4	¹ 5	¹ 6		
49	1																		
50	2																		
51	3																		
	.	"TxxxFyAA"							"TxxxFyBA"										
	.																		
	.																		
	.																		
L+48	L	= code length																	
L+49	1																		
	2																		
	3																		
	.	"TxxxFyCA"							"TxxxFyDA"										
	.																		
	.																		
	.																		
2L+48	L	= code length																	
2L+49	* "Trailer"																		
2L+88																			

Figure 3-12: GWU Reduced Data Set File Format

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 BDAT 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 PTVIR $P(\tau_k)$ 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, $P(\tau_k)$ is an exponentially-distributed random variable (the received voltage then being Rayleigh-distributed). Fluctuations in $P(\tau_k)$ 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 PTVIR

Tape&File: temp Date: 08/24/87 Time: 24:00

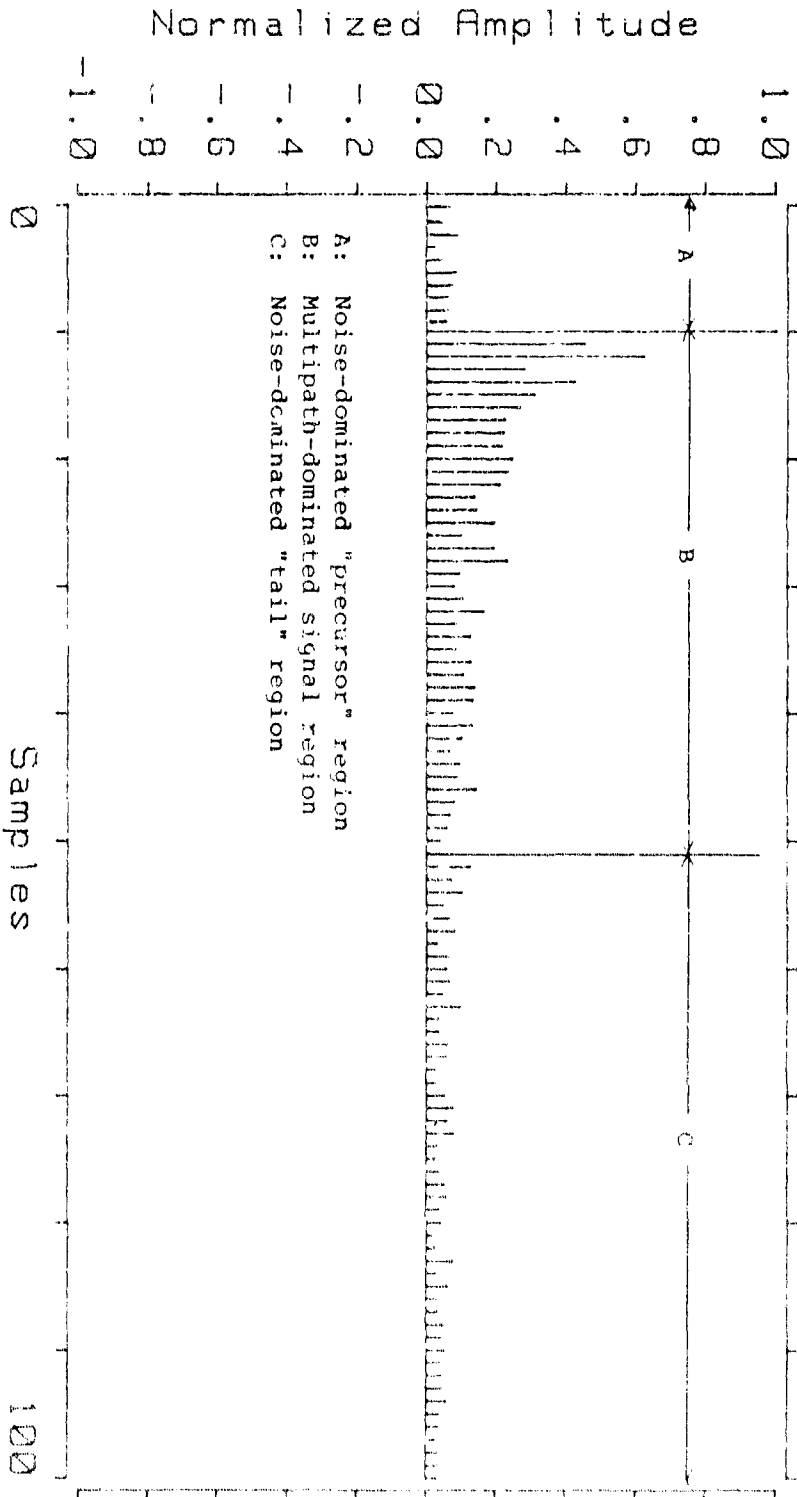


Figure 3-13: PTVIR Precursors and Tails

[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

$$T_{rog} = \sqrt{m_2 m_0 - m_1^2} / m_0 \quad (3-3)$$

where the moments m_k are defined by

$$m_0 = \int_0^T Q(\xi) d\xi = \sum_0^K P(\tau_k) \quad (3-4)$$

$$m_1 = \int_0^T \xi Q(\xi) d\xi = \sum_0^K \tau_k P(\tau_k) \quad (3-5)$$

$$m_2 = \int_0^T \xi^2 Q(\xi) d\xi = \sum_0^K \tau_k^2 P(\tau_k) \quad (3-6)$$

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 $P(\tau_k)$. The mean delay (center-of-gravity) of the PTVIR is given by

$$T_{avg} = m_1 / m_0 \quad (3-7)$$

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_{min} . Excess delay, the difference between T_{avg} and T_{min} , is

$$T_{exc} = T_{avg} - T_{min} \quad (3-8)$$

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

$$T_{spr} = T_{exc} + T_{rog} \quad (3-9)$$

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 PT VIR. Begin the calculation of the moments (m_k) when a PT VIR sample reaches one-quarter of that peak for first time. When the PT VIR 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 PT VIRs 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:

Tp/Fi	Tape and File Numbers (SRI Archive)
Date	Date of data acquisition
Range	Transmitter/Receiver Antenna Separation
Ht	Transmitter/Receiver Antenna Height
Ant	Transmitter/Receiver Antenna Type: L = log-periodic O = Omni-directional Upper case = vertical polarization Lower case = horizontal polarization
Channel Noise Nmin, Nsig	Estimated noise power floor of the PT VIR (relative to peak power) and its standard deviation (relative to noise floor)
Delay Spread	Delay Spread Moments (Episode Average)
\bar{T}_{exc}	Excess Delay [Eq. (3-8)]
\bar{T}_{rog}	Radius-of-Gyration [Eq. (3-3)]
\bar{T}_{spr}	Delay Spread [Eq. (3-9)]
σ_{spr}	Standard Deviation of \bar{T}_{spr}

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

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

[Coventry, Connecticut - 1987]

Tp/Fi	Date	Range (ft)	Ht (ft)	Ant	Freq (MHz)	Channel Nmin (dB)	Noise Nsig (dB)	Delay Spread			
								T _{exc} [-----nano-seconds-----]	T _{rog}	T _{spr}	σ _{spr}
----- Trunks (Summer) -----											
T225F1	09/01	927	12	LL	451	-27.2	0.3	240	256	496	14
" F2	"	"	"	"	751	-17.6	0.0	240	184	424	62
" F3	"	"	"	"	1251	-14.3	0.8	-	-	-	-
" F4	"	"	"	"	1751	-10.4	0.7	-	-	-	-
" F6	"	471	12	"	451	-35.3	-0.5	44	60	104	10
" F7	"	"	"	"	751	-34.3	-0.6	40	44	84	2
" F8	"	"	"	"	1251	-36.6	-0.9	32	44	76	4
T247F1	09/03	"	20	"	1751	-33.4	0.2	24	36	60	4
----- Canopy (Summer) -----											
T226F1	09/01	927	38	LO	451	-37.0	-0.2	20	48	68	2
" F2	"	"	"	"	751	-31.7	-0.3	24	60	84	6
" F3	"	"	"	"	1251	-33.3	0.0	16	44	60	9
" F4	"	"	"	"	1751	-16.0	-0.4	40	44	84	38
----- Canopy (Autumn) -----											
T264F5	11/09	"	"	OL	451	-40.0	-0.3	20	65	85	4
T273F1	11/10	"	"	LL	451	-34.7	-0.1	20	52	72	2
" F5	"	"	"	"	451	-36.2	-0.3	28	60	88	2
T285F4	11/11	"	"	"	451	-36.6	-0.2	28	56	84	8
" F8	"	"	"	"	451	-35.9	0.6	28	60	88	5
T264F6	11/09	"	"	OL	699	-39.6	-0.3	16	48	64	4
T273F2	11/10	"	"	LL	699	-38.6	-0.2	20	56	76	2
T285F5	11/11	"	"	"	699	-39.2	-0.2	36	72	108	12
T264F7	11/09	"	"	OL	1251	-23.7	-0.6	116	136	252	50
T265F1	11/09	"	"	"	1751	-15.4	-0.4	76	68	144	49
T286F1	11/11	361	"	LL	1251	-34.6	-1.0	56	84	140	6
" F5	"	"	"	"	1251	-39.8	0.3	32	72	104	2
" F2	"	"	"	"	1751	-27.3	-0.2	72	98	170	27

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

[Coventry, Connecticut - 1987]

Tp/Fi	Date	Range (ft)	Ht (ft)	Ant	Freq (MHz)	Channel Nmin (dB)	Noise Nsig (dB)	Delay Spread			
								T _{exc} (nano-seconds)	T _{reg} (nano-seconds)	T _{spr} (nano-seconds)	σ _{spr}
----- Trunks (Summer) -----											
T225F5	09/01	927	12	11	451	-36.2	-0.2	16	28	44	6
" F6	"	"	"	"	751	-31.3	-0.1	24	48	72	18
" F7	"	"	"	"	1251	-16.6	0.4	40	48	88	37
" F8	"	"	"	"	1751	-9.4	0.5	-	-	-	-
T247F2	09/03	471	20	"	451	-34.3	-0.4	24	24	44	0
" F3	"	"	"	"	751	-34.6	0.0	20	32	52	4
" F4	"	"	"	"	1251	-38.1	-0.7	16	32	48	3
" F5	"	"	"	"	1751	-25.1	-0.5	28	44	72	7
----- Canopy (Summer) -----											
T226F5	09/01	927	38	"	451	-35.2	-0.4	20	40	60	7
" F6	"	"	"	"	751	-34.3	0.0	4	24	28	10
" F7	"	"	"	"	1251	-38.2	0.1	4	16	20	5
" F8	"	"	"	"	1751	-23.8	-0.7	12	28	40	12
----- Canopy (Autumn) -----											
T264F1	11/09	"	42	"	451	-36.6	-0.2	16	24	40	0
T265F2	"	"	38	"	451	-35.8	-0.3	12	32	44	8
T273F3	11/10	"	"	"	451	-36.9	-0.5	16	36	52	3
T285F6	11/11	"	"	"	451	-37.9	0.1	16	36	52	8
T264F2	11/09	"	42	"	699	-41.9	0.1	8	28	36	13
T265F3	"	"	38	"	699	-41.5	0.0	8	36	44	2
T273F4	11/10	"	"	"	699	-38.8	0.4	12	28	40	10
T285F7	11/11	"	"	"	699	-40.5	-0.6	8	28	36	9
T264F3	11/09	"	42	"	1251	-40.2	-0.1	8	28	36	8
T265F4	"	"	38	"	1251	-39.3	0.3	12	44	56	6
T286F3	11/11	"	"	"	1251	-38.7	0.1	16	40	56	2
T264F4	11/09	"	42	"	1751	-33.9	-0.4	8	20	28	4
T265F5	"	"	38	"	1751	-25.9	-0.2	12	32	44	13
T286F4	11/11	"	"	"	1751	-36.2	0.3	20	44	64	4

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_{\min}) and the standard deviation of the delay spread (σ_{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 so 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 451 MHz) can be attributed to the different biophysical parameters characterizing the sites [337 stems/acre at South Perry versus 769 stems/acre at Coventry; 9.4 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 [T_{exc} and T_{log} , 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

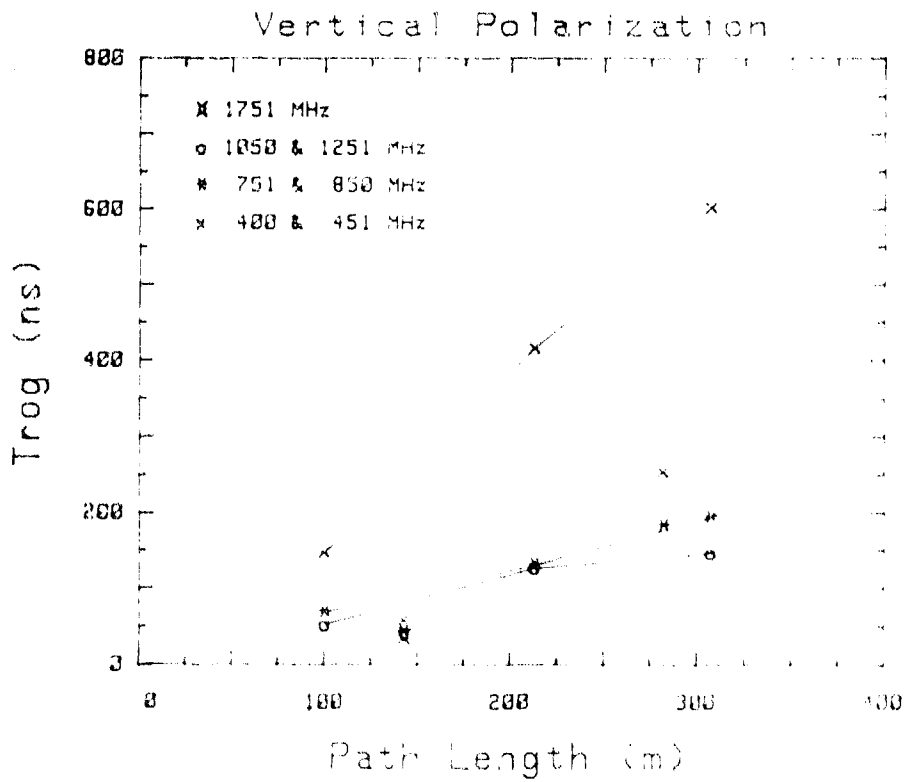
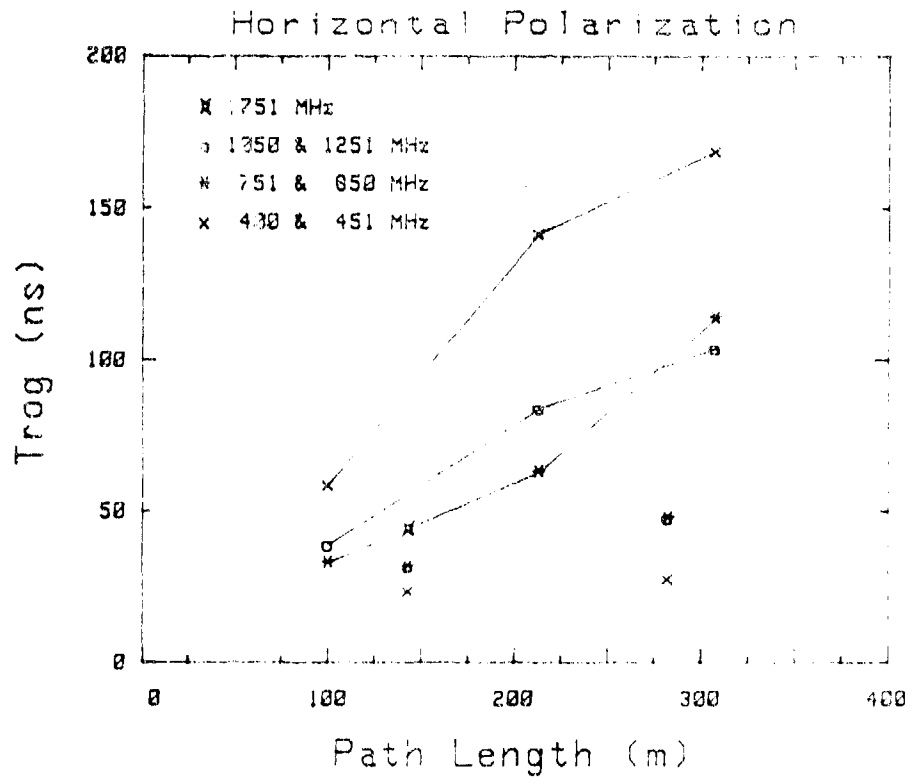


Figure 4-1: Delay Spread Path Length Determination

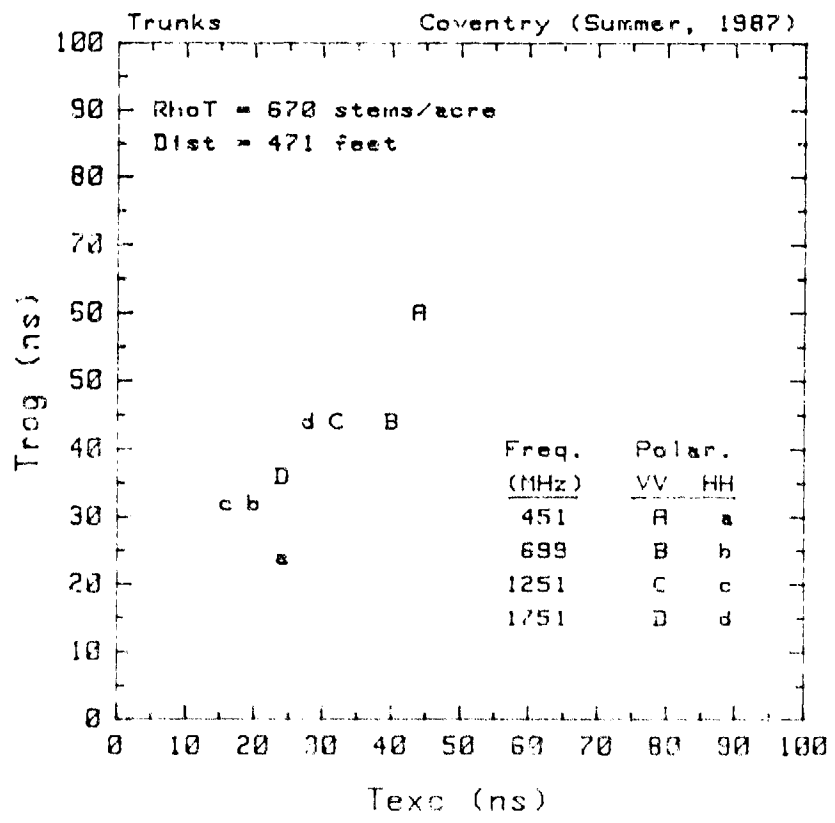


Figure 4-2: Delay Spread Plots

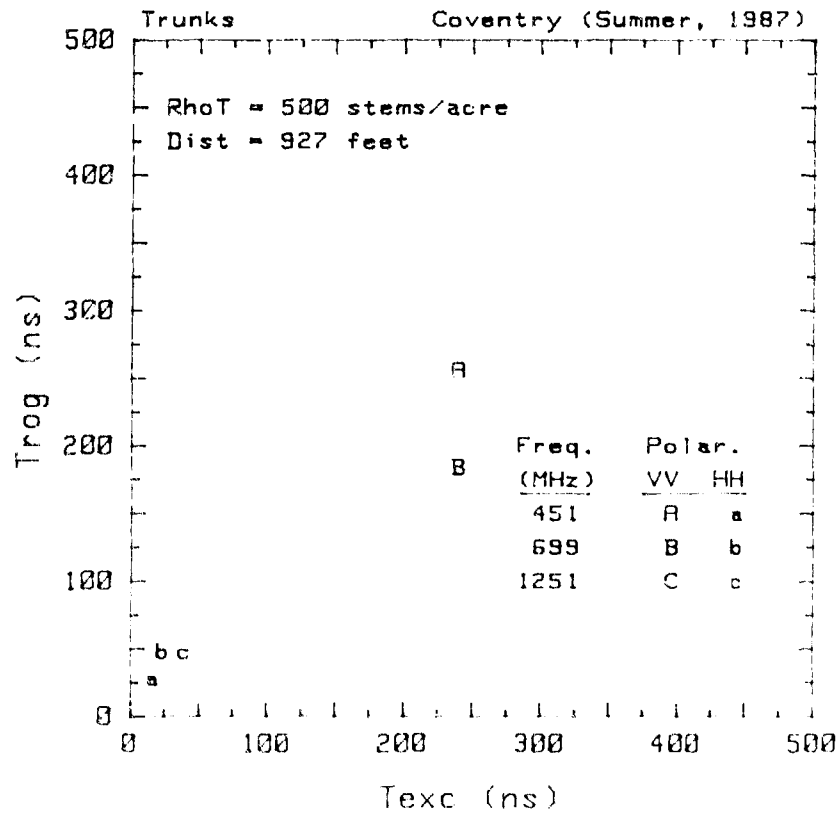


Figure 4-3: Delay Spread Plots

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_{rog} is several times larger than the first-moment T_{exc} . 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.

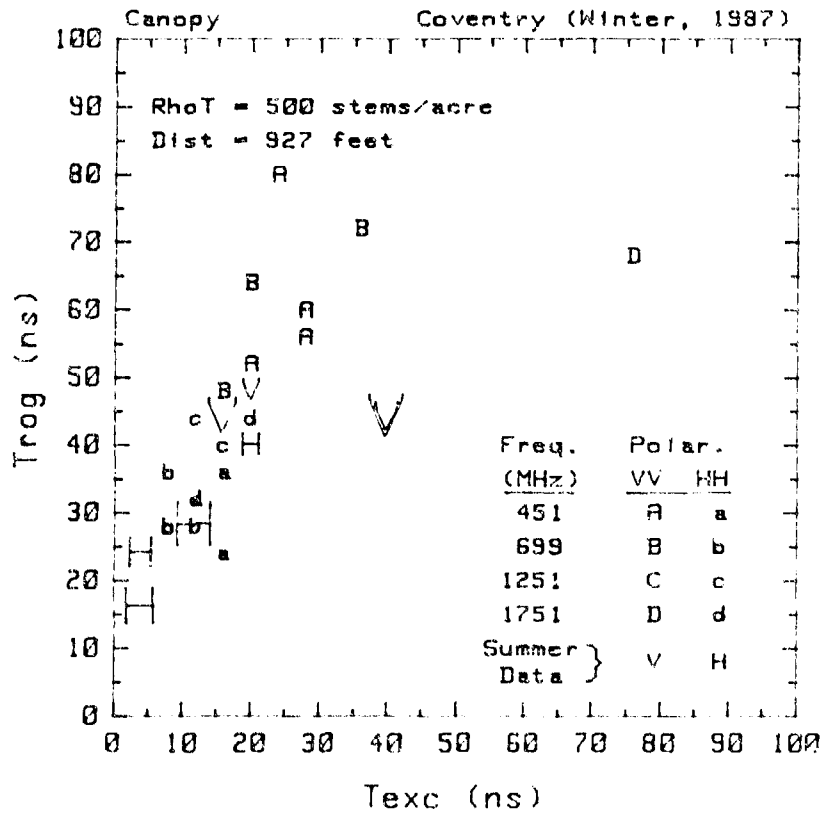


Figure 4-4: Delay Spread Plots

5.0 References

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APPENDIX A:

PROGRAM TP-6

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```

ftn77
$MSEG 5
$FILES(1,1)
  program tp6(,95)
  ema bufi,bufq,power
  integer trimlen
  character*1600 string
  integer b1(8192),b2(8192)
  integer bufi(8192),bufq(8192),bufd,sorti(511),sortq(511)
  real power(511,16)
  integer 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

C                               INDEX=1 FOR RECEIVER, =2 FOR TRANSMITTER
  INTEGER*2
-      IATYP(2),         ! ANTENNA CODE:1=OMNI 2=VERTICAL
C                               3=HORIZONTAL 4=RH
C                               !
C                               5=LH (RCVR ONLY)
-      IALOC(2)          ! =1 ANTENNA ON MAST, =2 ON ROOF,
C                               =3 ON TRIPOD

  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),AHGT)
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,iostat=ios, 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(10,('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
```

```
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'))
```

```
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)
      iavi = sorti(256)
      iavq = sortq(256)

```

```

      ! end DC Bias determination

```

```

do m = 1, 511

```

```

  x =

```

```

1      ((float(bufi(m+ iloc))- float(iavi))**2.0 +
2      ((float(bufq(m+ iloc))- float(iavq))**2.0

```

```

      if( x .gt. 0.0 ) then
        power(m,iset) = 10.0*ALOG10(x)
      else
        power(m,iset) = -99.
      end if
    end do ! m

```

```

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

```

```

10  continue

```

```

END DO      ! iset do loop

```

```

do 20 i=1,511
20  write(10,'(i5,16f7.2)') i,(power(i,iset),iset=1,16)

```

```

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

```

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APPENDIX B:

PROGRAM TRANSFER

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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
  WRITE(11,5) TXT
100
C [Display Header on Screen]
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 TAP1 NL' J
  'FILEDEF SEVIN1 DISK TEST FILE B'
  'MOVEFILE KEVIN1 SEVIN1' [Transfers file from tape to disk]
  'ASCTOEBC TEST FILE B TEST EBC B' [Converts file from ASCII to EBCDIC]
  'FILEDEF 10 DISK TEST EBC B'
  'FILEDEF 11 DISK' 'F' || I || 'HDR' 'DATA B (LRECL 109' [File Header]
  'FILEDEF 12 DISK' 'F' || I || 'A' 'DATA B' [PTVIRs 1-8, RCVR1]
/* FILEDEF 13 DISK' 'F' || I || 'B' 'DATA B' [PTVIRs 9-16, RCVR1]
  'FILEDEF 13 DISK' 'F' || I || 'C' 'DATA B' [PTVIRs 1-8, RCVR2]
/* FILEDEF 14 DISK' 'F' || I || 'D' 'DATA B' [PTVIRs 9-16, RCVR2]
  'FORTGO TRNSFR' [Executes Fortran Program TRNSFR]
  'TAPE REW'
END
```

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APPENDIX C:

PROGRAM ECKUP

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```

10 ! BCKUP - On Blue ? - 3/15/90
20 !
30 OPTION BASE 1
40 DIM Suf$(3)[8]
50 DATA "EDRA _____", "AA _____", "CA _____"
60 READ Suf$(*)
70 FOR I=1 TO 4
80   FOR J=1 TO 3
90     Sor$="F"&VAL$(I)&Suf$(J)
100    Sor$=Sor$[1,10]
110    Des$="T226F"&VAL$(I MOD 9)&Suf$(J)
120    Des$=Des$[1,7]&"A"
130    PRINT Sor$,"      ",Des$
140    COPY Sor$&":HP8290X,700,0" TO Des$&":CS80,705"
150  NEXT J
160  PRINT
170 NEXT I
180 END

```

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APPENDIX D:

PROGRAM KELVIN

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```

10 ! KELVIN - On Blue #?? - 3/7/90
20 !
30 ! This Program Reads an ITS ASCII Data File From Disc, Rewrites It
40 ! as a STAT Package-Compatible BDAT Data File on disc, and produces
50 ! Summary Data Sheets. [Delay Spread is not calculated.]
60 !
70 OPTION BASE 1
80 REAL Sc(20)
90 DIM T$(80),Vn$(50)[10],Sn$(20)[10]
100 DIM A$(50)[74],B$(513)[74],Y(8,511),Tp$(6)[4],Rc$(4)[2]
110 DATA "T247","T226","T225","T273","T264","T285"
120 DATA "R1","R3","R2","R4"
130 READ Tp$(*),Rc$(*)
140 C=1
150 INPUT "ENTER the number of the file to be copied",C
160 Cc=C MOD 8
170 Tc=C DIV 8+1
180 PRINT CHR$(12)
190 PRINT
200 PRINT
210 MASS STORAGE IS ":HP82901,700,0"
220 ! Reading the Header
230 C$="F"&VAL$(C)&"HDRA _____"
240 ASSIGN @Inpath TO C$
250 ENTER @Inpath;A$(*)
260 GOSUB 610
270 ASSIGN @Inpath TO *
280 INPUT "Do you want to store this data on disc? [Yes=1 No=0]",Yn
290 IF Yn=0 THEN 1410
300 PRINT CHR$(12)
310 !
320 FOR L=1 TO 4 STEP 2 ! Set STEP to 1 to get all 16 TVIRs
330 C$="F"&VAL$(C)&CHR$(64+L)&"A _____"
340 C$=C$(1,10)
350 F$=Tp$(Tc)&"F"&VAL$(Cc)&Rc$(L)
360 DISP "Reading ASCII Data File "&C$
370 ASSIGN @Inpath TO C$
380 ENTER @Inpath;B$(*)
390 DISP "Processing ASCII Data from File "&C$
400 FOR J=3 TO 513
410 FOR K=1 TO Nv
420 Y(K,J-2)=10.0^(VAL(B$(J)[7*K-4,7*K+2])/10)
430 NEXT K
440 NEXT J
450 ASSIGN @Inpath TO *
460 ! Write First Record to Disc
470 DISP "Writing Header on Disc"
480 MASS STORAGE IS ":HP8290X,700,1"
490 CREATE BDAT F$,INT((8*Nv*No)/1280)+3,1280
500 ASSIGN @File1 TO F$
510 OUTPUT @File1;T$,No,Hv,Vn$(*),Ns,Sn$(*),Sc(*)
520 ! Write TVIRs (1-8) on Disc
530 DISP "Writing PTVIRs to Disc - "&F$
540 OUTPUT @File1,2
550 OUTPUT @File1;Y(*)
560 ASSIGN @File1 TO *
570 MASS STORAGE IS ":HP8290X,700,0"
580 DISP " "
590 NEXT L
600 GOTO 1410

```

```

610 ! Constructing the Header
620 DATA "PTVIR1","PTVIR2","PTVIR3","PTVIR4","PTVIR5","PTVIR6"
630 DATA "PTVIR7","PTVIR8","?","?","?","?","?","?"
640 FOR I=1 TO 15
650   READ Vn$(I)
660   NEXT I
670   Vn$(12)=A$(3)[60,65]&" 87"           ! Year must be changed manually
680   Vn$(16)=VAL$(L)
690   Vn$(17)=TRIM$(A$(47)[POS(A$(47),"Code length =")+14;5])
700   Vn$(18)=TRIM$(A$(48)[POS(A$(48),"Bandwidth =")+14;4])
710   Vn$(19)=TRIM$(A$(43)[POS(A$(43),"FREQ1 =")+7;7])
720   Vn$(20)=TRIM$(A$(50)[POS(A$(50),"TX antenna type =")+19;1])
730   Vn$(21)=" "
740   Vn$(22)=TRIM$(A$(46)[POS(A$(46),"TX ANTENNA DIRECTION=")+21;7])
750   Vn$(23)=TRIM$(A$(46)[POS(A$(46),"TX ANTENNA HEIGHT=")+18;7])
760   Vn$(24)=TRIM$(A$(49)[POS(A$(49),"RX antenna type =")+19;1])
770   Vn$(25)=" "
780   Vn$(26)=TRIM$(A$(45)[POS(A$(45),"RX ANTENNA DIRECTION=")+21;7])
790   Vn$(27)=TRIM$(A$(45)[POS(A$(45),"RX ANTENNA HEIGHT=")+18;7])
800   Bw=VAL(Vn$(18))
810   Nv=8
820   No=VAL(Vn$(17))
830   Ns=0
840   Fl$=Tp$(Tc)&"F"&VAL$(Cc)
850   T$="Tape&File: "&Fl$&" Date: "&Vn$(12)&" Time: "&Vn$(13)&" Experiment:
"&Vn$(14)&"("&Vn$(15)&")"
860   DISP ""
870   MASS STORAGE IS ":HP8290X,700,0"
880   Prnto=0
890   PRINT TAB(31),"WPMS File Description"
900   PRINT
910   PRINT TAB(7),T$
920   PRINT
930   PRINT
940   PRINT
950   PRINT TAB(10),"Charnel: "&Vn$(16)
960   PRINT
970   PRINT TAB(10),"Code Length: "&Vn$(17)&" Chips"
980   PRINT
990   PRINT TAB(10),"Bandwidth: "&Vn$(18)&" MHz"
1000  PRINT
1010  PRINT TAB(10),"Carrier Frequency: "&Vn$(19)&" MHz"
1020  PRINT
1030  PRINT TAB(10),"Transmitting Antenna:"
1040  PRINT
1050  PRINT TAB(18),"Type: "&Vn$(20)
1060  PRINT TAB(18),"Location: "&Vn$(21)
1070  PRINT TAB(18),"Direction: "&Vn$(22)&" Degrees"
1080  PRINT TAB(18),"Height: "&Vn$(23)&" ft"
1090  PRINT
1100  PRINT TAB(10),"Receiving Antenna:"
1110  PRINT
1120  PRINT TAB(18),"Type: "&Vn$(24)
1130  PRINT TAB(18),"Location: "&Vn$(25)
1140  PRINT TAB(18),"Direction: "&Vn$(26)&" Degrees"
1150  PRINT TAB(18),"Height: "&Vn$(27)&" ft"
1160  PRINT
1170  PRINT TAB(10),"Path Loss:"
1180  PRINT
1190  PRINT TAB(18),"Derived from WRSL: "&Vn$(30)&" dBm"

```

```
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$(35)&" dBm"
1290 PRINT
1300 IF (Printo=1) THEN GOTO Final
1310 INPUT "Do You Want This Information on Hard Copy? [Yes=1 No=0]",Pyn
1320 IF (Pyn=0) THEN GOTO Final
1330 PRINTER IS 9
1340 PRINT CHR$(13)
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
```

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APPENDIX E:

PROGRAM MELVIN

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```

10 ! MELVIN on Blue #?? - 3/12/90
20 !
30 ! This Program Reads SRI BDAT Data Files from Disc, Calculates
40 ! the Delay Spreads (second central moments) using the Altman
50 ! Algorithm (CyberCom Technical Report CTR-117-01, Section 4.3.3),
60 ! and produces Summary Data Sheets (op. cit., Table 4-4).
70 !
80 OPTION BASE 1
90 INTEGER P1,Pp(4),Dp,P,Q,Rf
100 REAL Sc(20)
110 DIM T$(80),Vn$(50)[10],Sn$(20)[10],Nn(20),Title1$(80),Title2$(80)
120 F$="T225F6R1"
130 ASSIGN @Path TO F$
140 ENTER @Path;T$,No,Nv,Vn$(*),Ns,Sn$(*),Sc(*)
150 Cf=1000/VAL(Vn$(13)) ! Sample interval in nanoseconds
160 Nc=C
170 ! Noise Window Definition
180 DATA 12,40,5
190 READ P1,Dp,Fac
200 ! INPUT "Noise-Window Start and Width (in Samples)?",P1,Dp
210 ! INPUT "Threshold/Noise = ? [Default = 5]",Fac
220 Pp(1)=P1 ! Location of first noise window
230 FOR J=2 TO 4
240 Pp(J)=Pp(J-1)+INT(Nc/4) ! Location of subsequent noise windows
250 NEXT J
260 !
270 ENTER @Path,2
280 ALLOCATE Z(No)
290 ALLOCATE Pk1(Nv),Avg(Nv),Sig(Nv),Sprd(Nv)
300 PRINT TAB(11),"PTVIR Nmin Nsig Start Mean Sigma Spread
"
310 FOR Typ=1 TO Nv ! PTVIR loop
320 ! Read PTVIRs from Disc
330 ENTER @Path;Z(*)
340 MAT SEARCH Z(*),LOC MAX;Pk
350 Zpk=Z(Pk)
360 Inc=INT((Nc+1)/8)
370 Rf=Pk-Pk MOD Inc+1-Inc
380 IF Rf=1 THEN 440
390 ALLOCATE Zt(Nc) ! Shifts PTVIR
400 MAT Zt= Z
410 MAT Z(1:No-Rf+1)= Zt(Rf:No)
420 MAT Z(No-Rf+2:No)= Zt(1:Rf-1)
430 DEALLOCATE Zt(*)
440 ! Finding rms noise within the windows
450 DATA 0,0,0,1,1,100000
460 RESTORE 450
470 READ S0,S1,S2,Pk,Flag,Nmin
480 FOR P=1 TO No
490 IF Z(Pk)<Z(P) THEN Pk=P ! Locates location of PTVIR max.
500 IF Flag=5 THEN 670
510 IF P<Pp(Flag) THEN 670 ! Rejects non-window noise samples
520 S0=S0+1
530 S1=S1+Z(P)
540 S2=S2+Z(P)*Z(P)
550 IF P>Pp(Flag)+Dp THEN
560 N(Flag)=INT(S1/S0)
570 Mm=S0*S2-S1*S1
580 IF N(Flag)<Nmin THEN
590 Ni=Flag

```

```

600         Nmin=N(Flag)
610         Nsig=INT(SQR(Mm)/S0)
620         END IF
630         RESTORE 450           ! Re-initialize moments
640         READ S0,S1,S2
650         Flag=Flag+1         ! Identify next window
660     END IF
670 NEXT P
680 GOSUB 2030
690 GOTO 720
700 INPUT "Retain for Delay-Spread Calculation? [Yes=1 No=0]",Yn
710 IF Yn=0 THEN 1330
720 Nc=Nc+1
730 ! Calculation of Delay Spread
740 RESTORE 450
750 READ S1,S2,S3
760 RESTORE 450
770 READ Flg,Fig,Fog
780 S4=0
790 Jj=1
800 P2=1
810 Ct=10
820 Th=Fac*Nmin
830 FOR I=1 TO 10
840     Nn(I)=0
850 NEXT I
860 FOR Q=1 TO Nc
870     P=Q
880     IF Fog=1 THEN 1250
890     IF Flg=1 THEN 960
900     IF Z(P)>Zpk/4 THEN           ! Starts Integration
910         Flg=1
920         PK1(Typ)=P
930     ELSE
940         GOTO 1260
950     END IF
960     IF Fig=1 THEN 990
970     IF Z(P)<.5*Th THEN
980         Fig=1
990         IF Z(P)>2*Th THEN
1000            Jj=1
1010            Fig=0
1020            Su=0
1030            P2=0
1040            GOTO 1200
1050        END IF
1060        P2=P2+1
1070        Su=Su+Z(P)
1080        IF P2>Ct THEN
1090            Nn(Jj)=Su/Ct
1100            IF Jj=1 THEN 1160
1110            IF Nn(Jj)<.5*Th AND Nn(Jj-1)<.5*Th THEN
1120                Pend=P
1130                Fog=1
1140                GOTO 1240
1150            END IF
1160            Jj=Jj+1
1170            Su=0
1180            P2=0
1190        END IF

```

```

1200     END IF
1210     S1=S1+Z(P)
1220     S2=S2+Z(P)*Q
1230     S3=S3+Z(P)*Q*Q
1240     IF Z(P)<Fac*Th AND Fog=1 THEN 1260
1250     S4=S4+Z(P)
1260 NEXT Q
1270 Avg(Typ)=S2/S1
1280 IF Pk<Mid THEN 1300
1290 Avg(Typ)=Avg(Typ)+Mid
1300 Sig(Typ)=SQR(S3*S1-S2*S2)/S1
1310 Sprd(Typ)=INT(Avg(Typ)-Pk1(Typ)+Sig(Typ))
1320 PRINT USING Frmt1;Typ,Nmin,Nsig,Pk1(Typ),Avg(Typ),Sig(Typ),Sprd(Typ)
1330 NEXT Typ ! Next PTVIR
1340 Frmt1:IMAGE 11X,DD,2(4X,DDDDD),4(5X,DDDD)
1350 Strt=SUM(Pk1)/Nc
1360 Dspr=SUM(Sprd)/Nc
1370 PRINT USING Frmt2;Strt,Dspr
1380 Frmt2:IMAGE 8X,"Averages",20X,DDDD,23X,DDDD
1390 WAIT 2.5
1400 !
1410 ASSIGN @Path TO *
1420 DISP ""
1430 GRAPHICS 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: "&F$(8,8)
1600 PRINT
1610 PRINT TAB(10),"Code Length: "&Vn$(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:"
1820 PRINT
1830 PRINT TAB(18),"Derived from WRSL: "&Vn$(30)&" dBm"
1840 PRINT TAB(18),"Derived from PTVIR: "&Vn$(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"
2000 Frmt5:IMAGE 24X,"Minimum = ",4D," Spread = ",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 2090
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 O1)
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 !LINPUT Dummy$
2310 !IF Dummy$<>" THEN Main_title$=Dummy$
2320 Labql:Answer$="B"
2330 !INPUT "Bar (B) or Line (L) Graph (DEFAULT=B) ?",Answer$
2340 !IF Answer$<>"B" AND Answer$<>"L" THEN Labql
2350 Smin=First_pnt
2360 Smax=Last_pnt
2370 !DISP "Plot samples between Smin,Smax [DEFAULTS=(";First_pnt;",";Last_pnt
;)]";GCLEAR

```

```

2380 !INPUT Smin,Smax
2390 !IF Smax<Smin THEN 3110
2400 !First_pnt=Smin
2410 !Last_pnt=Smax
2420 GINIT
2430 IF Crt THEN PLOTTER IS 703,"HPGL"
2440 GRAPHICS ON
2450 Xr=.7 ! Reduced from .8
2460 Yr=.5 ! Reduced from .8
2470 Cr=Xr
2480 IF Xr>1 THEN Cr=1
2490 CSIZE 4*Cr,.6
2500 LORG 5
2510 LDIR 0
2520 PEN 1
2530 ON ERROR GOTO Skip1
2540 VIEWPORT 18*Xr+15,131*Xr+15,91*Yr+10,92*Yr+10! SET UP AXES
2550 WINDOW 0,8,0,1
2560 AXES 1,0,0,0
2570 VIEWPORT 18*Xr+15,131*Xr+15,25*Yr+10,26*Yr+10
2580 WINDOW 0,8,1,0
2590 AXES 1,0,0,0
2600 VIEWPORT 16*Xr+15,17*Xr+15,27*Yr+10,90*Yr+10
2610 WINDOW 1,0,0,1
2620 AXES 0,.1,0,0
2630 VIEWPORT 132*Xr+15,133*Xr+15,27*Yr+10,90*Yr+10
2640 WINDOW 0,1,0,1
2650 AXES 0,.1,0,0
2660 VIEWPORT 4*Xr+15,15*Xr+15,26*Yr+10,91*Yr+10
2670 WINDOW 0,1,-.02,1.02
2680 CLIP OFF
2690 FOR I=1 TO 0 STEP -.2
2700 MOVE .5,I
2710 LABEL USING Image1:I
2720 Image1:IMAGE MD.D
2730 NEXT I
2740 VIEWPORT 18*Xr+15,131*Xr+15,93*Yr+10,97*Yr+10
2750 WINDOW 0,1,0,1
2760 MOVE 0,.5
2770 LORG 2
2780 LABEL Ref_title$(1,19)
2790 LORG 8
2800 MOVE 1,.5
2810 LABEL Ref_title$(20,34)
2820 VIEWPORT 0*Xr+15,4*Xr+15,26*Yr+10,91*Yr+10
2830 WINDOW 0,1,0,1
2840 CLIP OFF
2850 LDIR PI/2
2860 MOVE .5,.5
2870 LORG 5
2880 LABEL "Normalized Power"
2890 LDIR 0
2900 VIEWPORT 18*Xr+15,131*Xr+15,20*Yr+10,24*Yr+10
2910 WINDOW 0,1,0,1
2920 MOVE 0,.5
2930 LORG 2
2940 LABEL VAL$(First_pnt)
2950 MOVE 1,.5
2960 LORG 8
2970 LABEL VAL$(Last_pnt)

```

```

2930     MOVE .5,.5
2990     LORG 5
3000     LABEL "Samples"
3010 Image2:IMAGE DDDDD
3020     LORG 2
3030     VIEWPORT 18*Xr+15,131*Xr+15,10*Yr+10,16*Yr+10
3040     WINDOW 0,1,0,1
3050     MOVE 0,.5
3060     Unit$="nsec"
3070     LABEL USING Image4;Samp_int,Unit$
3080 Image4:IMAGE "   Sample Interval:           ",MD.3DE,1X,K
3090     Ymax=0           ! DETERMINE Ymax
3100     PENUP
3110     FOR I=First_pnt TO Last_pnt-1
3120         IF ABS(Array(I))>Ymax THEN Ymax=AES(Array(I))
3130     NEXT I
3140     VIEWPORT 18*Xr+15,131*Xr+15,14*Yr+10,20*Yr+10
3150     WINDOW 0,1,0,1
3160     MOVE 0,.5
3170     LABEL USING Image3;Ymax
3180 Image3:IMAGE "   Maximum Power:           ",MD.3DESZZ," (=1)"
3190     VIEWPORT 18*Xr+15,131*Xr+15,27*Yr+10,90*Yr+10
3200     IF Ymax<>0 THEN WINDOW First_pnt,Last_pnt,0,Ymax
3210     IF Ymax=0 THEN WINDOW First_pnt,Last_pnt,-1,1
3220     !           PLOT POINTS
3230     MOVE First_pnt,0
3240     DRAW Last_pnt,0
3250     IF Answer$="B" THEN MOVE Smin,0
3260     IF Answer$="I" THEN MOVE Smin,Array(Smin)
3270     FOR I=Smin TO Smax-1
3280         IF Answer$="B" THEN
3290             MOVE I,0
3300             IF ABS(Array(I)/Ymax)<.01 THEN GOTO 3350
3310             DRAW I,Array(I)
3320         ELSE
3330             DRAW I,Array(I)
3340         END IF
3350     NEXT I
3360     IF Smin=First_pnt THEN 3400
3370     LINE TYPE 5,2
3380     MOVE Smin,-Ymax
3390     DRAW Smin,+Ymax
3400     IF Smax=Last_pnt THEN 3440
3410     LINE TYPE 5,2
3420     MOVE Smax,-Ymax
3430     DRAW Smax,+Ymax
3440     LINE TYPE 1
3450     VIEWPORT 3*Xr+15,146*Xr+15,104*Yr+10,110*Yr+10
3460     WINDOW 0,1,0,1
3470     CSIZE 5*Cr,.6
3480     LORG 5
3490     MOVE .5,.5
3500     LABEL Main_title$
3510     X=LEN(TRIM$(Main_title$))/2
3520     MOVE .5-(.6*5*Cr)/(141*Xr)*X,0
3530     !DRAW .5+(.6*5*Cr)/(141*Xr)*X,0
3540 Skip1:OFF ERROR
3550     PENUP
3560     PEN 0
3570     ON ERROR GOTO Subend

```

560 01=Ymax
3590 Subend:SUBEND