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Results and Analysis of Static and Dynamic Multipath in a Severe Atmospheric Environment

Eli Kolton



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September 1986

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RESULTS AND ANALYSIS OF STATIC AND DYNAMIC MULTIPATH IN A SEVERE ATMOSPHERIC ENVIRONMENT

Eli Kolton*

This is a final report that describes a project to analyze and evaluate multipath static and dynamic statistics of data recorded in severe ducting and refraction environments. The results shown here were derived by numerical analysis from experimental data gathered in 1984. Some of the results presented are new and have not been published before. If severe enough, these dynamic multipath effects are vital for protection methods such as equalization of wideband digital radio. Various cross-sections of analysis schemes are presented together with results and discussion.

1. INTRODUCTION AND OBJECTIVE

This report presents and describes an effort to investigate, analyze, and evaluate various multipath phenomena based on data recorded by the Institute for Telecommunication Sciences (ITS) in two different periods of time at the Pacific Missile Test Center, Point Mugu, California (Hubbard, 1979 and 1983). A very broad type of investigation is performed on the data and many aspects of multipath were looked into, processed, and analyzed. The more significant results are published in this report. Some of the analysis cross-sections that are published here have not appeared in the open literature to the best of our knowledge. In the process of the development of the analysis software for this project, an effort was made to extract from the data as much statistical information as possible to be able to present a complete view of the multipath phenomena. The various analysis cross-sections that were chosen should support designers of equalizers and protection schemes for wideband digital receivers as well as the development of wide-band laboratory simulators like the one under development now at ITS (Hoffmeyer and Hartman, 1984).

The project reported here was divided into two stages. The first stage was the definition of the various analysis schemes and the development of the supporting software (27 computer programs). The second stage was the actual analysis of multipath data.

Two unpublished internal reports, Multipath Analysis Software Package (MASP), and Upgrade of the Multipath Analysis Software Package, were completed

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during the first phase of the project. The first of these internal reports presents a description of the specially developed software package, including the rationale behind various programs, and serves as an operating guide for the Multipath Analysis Software Package (MASP).

The second internal report describes an upgrade of the MASP. This upgrade enables the user to analyze various statistics of a possible second multipath component (three-component impulse response).

The analysis was performed with two main objectives in mind:

- 1) To identify general statistical properties of multipath.
- 2) To discover dynamic statistical properties of multipath.

Under the general statistical properties of multipath, the multipath delay and power statistics were investigated, as well as abnormal multipath delay and power statistics, multipath phase statistics, the recorded impulse response width statistics for the -1, -3, -10 dB levels, and the delay versus power statistics.

Under dynamic multipath statistical properties, the rate of change in multipath delay, power, and phase were investigated, as well as the rate of collapse and development of multipaths plus the duration of an "abnormal" multipath.

Nearly 200,000 impulse responses were analyzed in the second stage of the project. The results are presented and discussed in this report.

In Section 2, some background and experimental layout of Point Mugu experiments are presented. This background seems to be needed for a better understanding of the results. For a complete description of the Point Mugu experiments, the reader is referred to Hubbard (1979, 1983). In Section 3, we present a short description of our evaluation scheme. In Sections 4, 5, and 6, the results of the second stage of the project are presented and discussed.

Summary, conclusion, recommendations, and plans for the future are presented in Section 7.

No meteorological data are analyzed in this report since no such information was available on time. It is believed that this project marks a beginning of better understanding of multipath effects on digital radio channel performance. With the help of MASP, ITS field experiments can be upgraded to semi-real-time processing of multipath data, as well as to analyzing in the field various channel parameters like antenna alignment, etc.

2. BACKGROUND AND EXPERIMENT LAYOUT

The analyzed data presented in this report come from several experiments conducted in the Pacific Missile Test Center, Point Mugu, California. The experiments were conducted by ITS and reported by Hubbard (1979, 1983).

The objective of the experiments was to evaluate the performance of digital microwave systems in anomalous propagation conditions. Simultaneous measurements were made of the performance of high bit-rate digital radio systems and the propagation conditions in the radio transmission channel. The transmission channel was monitored with the use of the ITS pseudorandom noise (PN) channel probe (Linfield et al., 1976). It is the output data from this PN probe that are analyzed and evaluated in this report. Other data concerning the performance of the receivers have been analyzed elsewhere (Hubbard, 1979, 1983). The anomalous propagation condition of interest is that of multipath. In the atmosphere it can be created by either refractive effects or superrefractive height profiles that produce strong ducting conditions. The area of southern California is known to be affected by strong radio meteorological disturbances caused usually by a marine layer of moist air that is developed over water and causes a temperature inversion. This temperature inversion results in a superrefractive layer in the propagation path. Most severe anomalous propagation conditions develop usually during the summer and early fall months.

The experiments were conducted on a 65-mile (104.6-km), over-water link between Laguna Peak at Point Mugu, and San Nicolas Island. Two PN probe receivers were operating at 8.6 GHz in a space-diversity mode.

The transmitter was located in San Nicolas Island, 278 meters above mean sea level and the receivers were located at Laguna Peak 427 meters above mean sea level. The transmitting and receiving antennas were 10-ft (3-m) parabolic reflectors (3 dB beamwidth of 0.8°).

The transmitting antenna was located 21 meters above ground and the space diversity receiving antennas were located 9 meters and 36 meters above ground.

The channel probe uses a PN code length of 511 bits, clocked at a rate of 150 MHz. This clocking rate permits a multipath delay resolution of approximately 6.7 ns. The actual resolution is, however, much better as will be explained in Section 4.

Four data signals were available from the two PN probe receivers:

1. Power impulse response function from Channel A (the upper antenna)
2. Power impulse response function from Channel B (the lower antenna)
3. Cophase function for Channel B
4. Quadrature-phase function for Channel B.

The PN probe measures the impulse response using a correlation detection process in the receiver. This technique provides a time-bandwidth tradeoff in comparison with rf impulse measurements. (The interested reader is referred to Cox (1972), Linfield et al. (1976), and Bello et al. (1973) for a detailed description of the PN probe system.) The PN probe receiver was configured to generate responses at the rate of one impulse profile per second. This rate has proven adequate in other line-of-sight experiments (Hubbard, 1983).

The data analyzed in this report were recorded on a digital data acquisition system that permitted a true sample resolution of 2 ns with multipath delay measurements of up to 80 ns.

The data acquisition system was triggered by a specific occurrence of errors. The error event was detected by an error-burst measuring device connected to a prototype of the Digital Radio and Multiplex Acquisition (DRAMA) receiver that was under development by the military. During periods of error-free operation, the data acquisition system did not record data.

Several DRAMA receivers with different operating configurations were tested at the same time. Any one of the four error burst measuring devices connected to the receivers could trigger the data acquisition system. One of the receivers was defined as a "reference receiver." The reference receiver had no multipath equalizer, and no configuration changes were made on that receiver during the long months of the experiment. Thus, the PN probe data that were gathered were not affected by the different tests made on the rest of the DRAMA receivers. The DRAMA receivers were operating in the 8 GHz range, a few hundred megahertz below the PN probe center frequency.

3. EVALUATION SCHEMES OF THE MULTIPATH PHENOMENA STRUCTURE

3.1 Introduction

The evaluation of multipath data gathered during the Point Mugu experiment is based on 27 computer programs that were developed for this project. The multipath analysis software package (MASP) was developed on a minicomputer DEC/LSI-11¹, which is used as a CPU (Central Processing Unit) of the PN probe data acquisition system. The programs were written in FORTRAN-IV, and the complete list of programs developed is presented in the Appendix.

The analysis programs were developed under five different categories:

1. Programs to evaluate and process raw data
2. Programs to analyze processed data
 - 2.1 General statistical properties of multipath
 - 2.2 Dynamic statistical properties of multipath
3. Applications
4. Data file statistics
5. Utility programs for handling large data files

Only the first three categories of programs will be described here briefly.

Impulse responses from both channels were used for the analysis and so were the cophase and quadrature phase functions from Channel B.

Real (ZULU) experiment time is associated to each impulse response analyzed for future possible correlations with other data. The following is a brief description of the first three categories of programs.

3.2 Analysis and Evaluation of Raw Data

The main program in this group is the so-called "multipath pattern recognition algorithm." The main purpose of this program is to detect and evaluate the main (direct) and multipath component from a 1-s impulse response.

¹Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

The raw data used by this program are the impulse responses for both Channels A and B and the cophase and quadphase functions for Channel B. The algorithm performs many tasks including the detection of all possible types of multipath within the recorded impulse response.

A few distinctive types of multipath are present in the Point Mugu data, and as such are identified, analyzed, and evaluated by the algorithm. They are summarized here:

- o "REGULAR MULTIPATH" (Figure 1) - This occurs when the amplitude of the direct signal is stronger than the reflected or refracted signal. The sign of the group delay is the same as the amplitude response. This situation is called the "minimum-phase case."
- o "HIDDEN MULTIPATH" (Figure 2) - These kinds of impulse responses are due to the fact that two or more distinctive peaks could not be resolved due to inadequate measuring resolution. Hidden multipath can be resolved by detecting and identifying the deformation of the theoretical impulse response envelope. Care was taken not to confuse hidden multipath with other deformations that could be caused by inadequate sampling during the recording period of the experiment. Threshold values are used in these tests for recognition and detection of "Hidden Multipath." They rely on statistical behavior of large numbers of responses which were analyzed prior to the final estimation of their values.
- o THREE COMPONENTS WITHIN THE RESPONSE (Figures 3 and 4) -A small number of impulse responses will show three components. There is one main response that is usually associated with the direct signal and two multipath components. The algorithm scales the two multipath components by their power relative to the direct ray component and classifies them as first and second multipath components accordingly.
- o "ABNORMAL MULTIPATH" (Figure 4) - The amplitude of the reflected or refracted signal is stronger than the direct signal. This is known as "nonminimum phase case."
- o A combination of either two or three of the above-mentioned types of multipath.
- o Broadening of the impulse response without a deformation of the impulse response envelope (Figure 5).

The identification and detection of multipath within a given impulse response rely on several methods of detection. Distinctive types of multipath are detected by recognizing particular peaks in the response. For the "Hidden Multipath," a set of tests applied to the slope (derivative) of the impulse

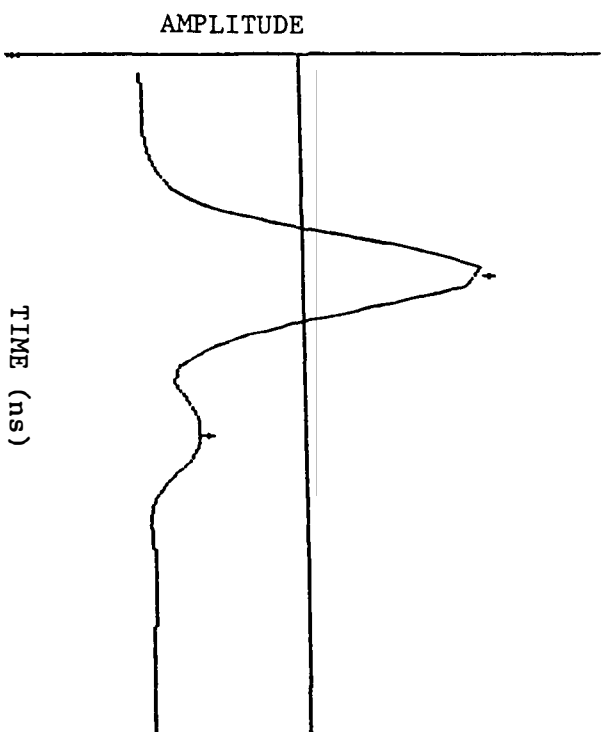


Figure 1. An example of "minimum phase" impulse response.

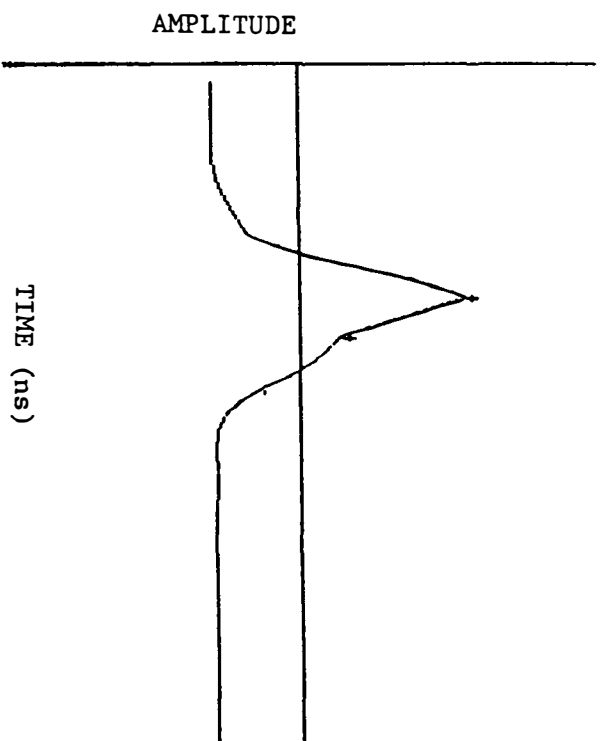


Figure 2. An example of "hidden multipath".

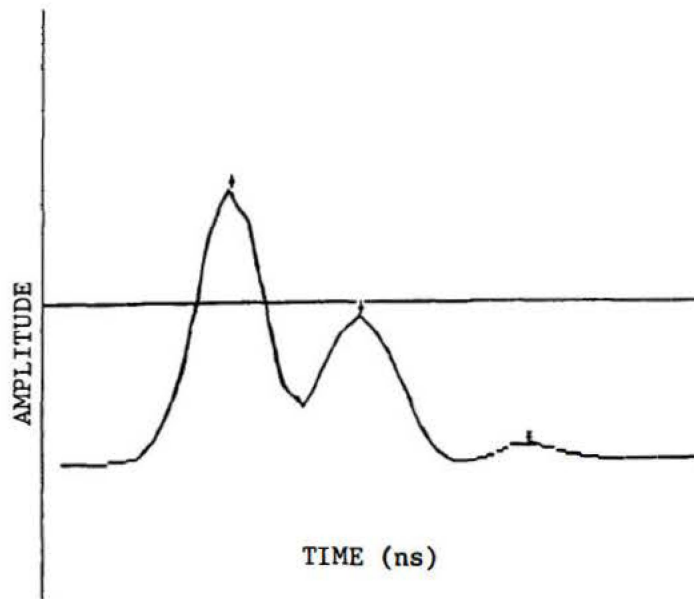


Figure 3. An example of two multipath components within an impulse response.

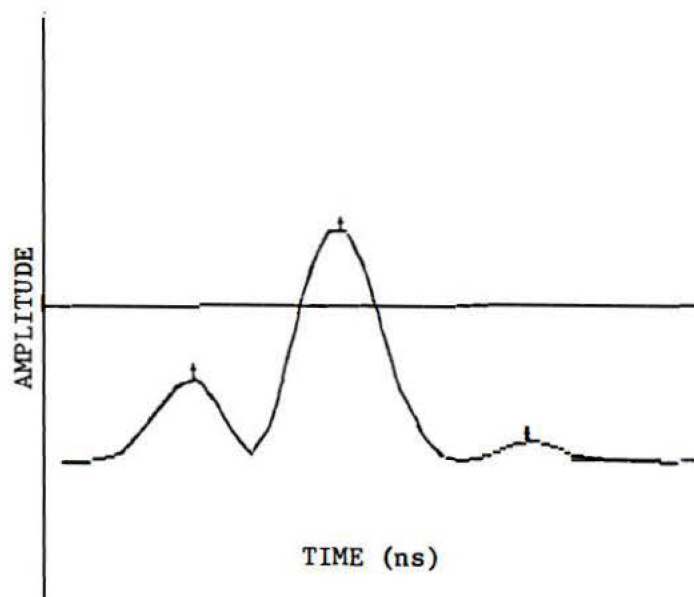


Figure 4. An example of abnormal or "nonminimum phase" multipath.

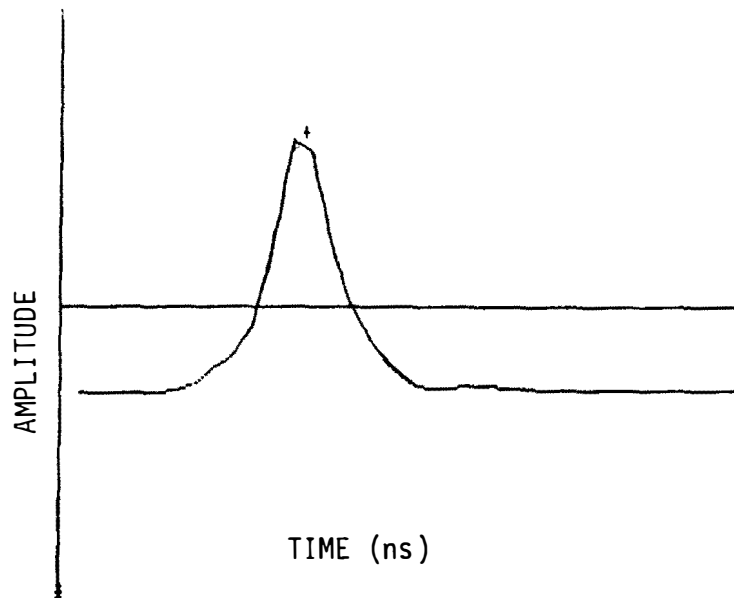
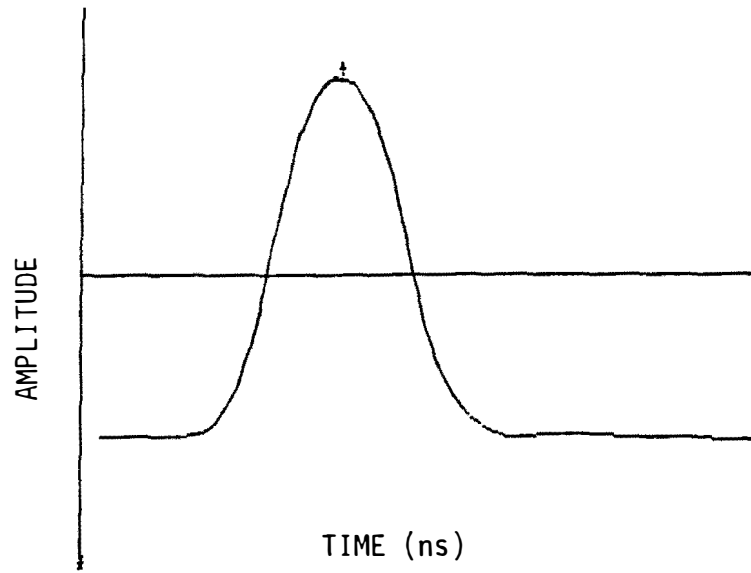


Figure 5. Broadening and nonbroadening of the impulse response.

response curvature will detect a deformation of the total impulse response envelope and associate specific deformations with multipath. The broadening of the impulse response cannot be detected by the above-mentioned tests, but it influences the statistics of the impulse response width, to be explained and discussed later.

The following is a short description of the type of raw data evaluation done by the multipath pattern recognition algorithm. After a positive identification and detection of multipath have been made and the multipath has been categorized for further study, the following process takes place within the algorithm.

1. Multipath power for first and possibly second multipath is measured. First multipath power is measured versus the direct response power in decibels and second multipath power is measured versus the first multipath power in decibels.
2. Multipath occurrence time is corrected for possible slight shifts due to the sampling process.
3. Delay of first and second multipath are measured from the direct signal peak.
4. The phase of the multipath component versus the direct signal is measured by using the co- and quad- functions (for Channel B only).
5. The impulse response width for the -1 dB, -3 dB, and -10 dB levels is measured.

The algorithm uses six codes for each channel to indicate and distinguish the following cases:

Code A - No multipath was found within the impulse response.

Code B - Abnormal (nonminimum phase case) multipath was detected.

Code C - Nonconsecutive response was detected, i.e., the new impulse response is not consecutive in time with the former impulse response. This fact is used later for the analysis of dynamic properties of multipath.

Code D - The derivative method (analyzing the impulse response slopes for possible deformations) was used to detect and evaluate a "hidden multipath."

Code E - Two multipath components were detected within the impulse response, i.e., there are a total of three components within the response.

Code F - There was a need to use the sum of the squares of the cophase and quadphase functions in order to resolve the correct delay for Channel B.

This last code deserves some explanation. The co- and quadrature functions were used during the experiment to evaluate the impulse response (see Cox, 1972; Linfield et al., 1976), by taking the sum of their squares. A test to evaluate the delay using the sum of the squares and the impulse response was performed during the development stage of MASP. It was found that for some percentage of the cases analyzed, a shift of delay of + or - 1 sample was detected. In the final evaluation algorithm, the delay for Channel B was evaluated by using both the impulse response and the sum of the squares information. But whenever there was a shift of + or - 1 sample, the delay was evaluated by using only the sum of the squares and code F was registered.

The data processed by the multipath pattern recognition program was preserved by loading onto a hard disc for further evaluation.

3.3 Analysis and Evaluation of Processed Data

In the following a very general description of the set of programs to analyze processed data will be given. For ease of use and explanation of the data processing, the programs for evaluation of processed data are divided into two major groups:

- analysis and calculation of multipath general statistics
- analysis and calculation of multipath dynamic statistics.

3.3.1 Analysis and Calculation of Multipath General Statistics

The following are cross-sections of general multipath analyses performed on the Point Mugu impulse response data.

1. Calculation of multipath delay statistics of the first and second multipath components. This task was performed on all of the responses having multipath of any kind in them.
2. Calculation of multipath relative power statistics of the first and second multipath components. These calculations were performed on all the responses having multipath of any kind in them.
3. Calculation of abnormal multipath delay statistics. This was done on abnormal multipath or "nonminimum phase" cases only.

4. Calculation of abnormal multipath power statistics. These tests were performed on abnormal multipath data only.
5. Calculation of multipath phase statistics. This test was performed on Channel B data only, using the cophase and quadphase information. The relative phase is figured by calculating the phase associated with the detected peaks, and taking the absolute value of their difference. The phase at each peak is calculated by finding the arctangent of the ratio of the instantaneous quadphase function value divided by the cophase function value.
6. Scattergram of the delay versus relative power of the first multipath component.
7. Calculation of the delay versus power statistics. In this test the power of the multipath is divided into 15 quantization levels. For each level, the delay in the data file is searched and accumulated. The delay statistics are calculated and the 10%, 50%, and 90% values for each relative power level are presented.
8. Scattergram of the first multipath component power versus the second multipath power.
9. Calculation of impulse response width for the -1, -3, and -10 dB levels below the direct signal peak. The total width of the impulse response is measured.

3.3.2 Analysis and Calculation of Multipath Dynamic Statistics

The following are cross-sections of dynamic multipath analyses performed on the processed data. Some of the analysis schemes were suggested in a paper by Hubbard (1984).

1. Calculation of the statistics of the rate of change in multipath power. For this test only data that are consecutive in time are considered. The change in multipath powers between two consecutive multipath relative powers is calculated. Since the impulse response was measured every second, the units for the rate of change in power are dB per second.
2. Calculation of the statistics of rate of change in delay. These tests were performed on data that are consecutive in time. The change in delay between two consecutive multipath delays is calculated and presented as rate of change of delay, with units of nanoseconds per second.
3. Calculation of the statistics of rate of change in multipath phase. Only data that are consecutive in time are considered, the units are radians per second.

4. Calculation of statistics of abnormal multipath duration. Only consecutive abnormal data are considered for this test. The duration of all abnormal cases is measured and presented in a form of a cumulative distribution plot.
5. Calculation of statistics of the duration of multipath collapse and development. Only data that are consecutive in time are considered for these tests. A collapse of a multipath is defined as the time that elapses from the emergence of a new multipath until its collapse. A development of a multipath is the time that elapses from the collapse of the last multipath until the development of a new multipath component within a consecutive impulse response. The development and collapse times are measured and are presented as a cumulative distribution plot.

3.3.3 Evaluation of In-Band Amplitude Slope Statistics (Application)

Several researchers have shown experimental proof of in-band amplitude slope (or dispersion) influence on wideband digital receiver performance (Morais, 1979; Barnett, 1979; Anderson, 1979; and others). There have also been attempts to tie receiver performance degradation to delay and phase slopes. We have made an attempt here to calculate and present the in-band amplitude slope statistics of both PN probe channels.

The algorithm calculates in-band amplitude slope for a given receiver bandwidth. A hypothetical receiver bandwidth is implemented on both PN probe calculated frequency spectra. The in-band amplitude slope is calculated for each impulse response by using the delay and the relative power found for that response and assuming a two-ray multipath model (see Figure 6). In addition, a switch that selects between instantaneous minimal calculated slopes of Channel A and Channel B was programmed. The outcome of this analysis is a three-graph plot that presents the slope statistics of Channels A and B and the switch.

Since the hypothetical bandwidth of a receiver is implemented on a given selective fade such that one end of the bandwidth is associated with a null within the spectra (see Figure 6), the calculated in-band amplitude slope represents the worst-case slope.

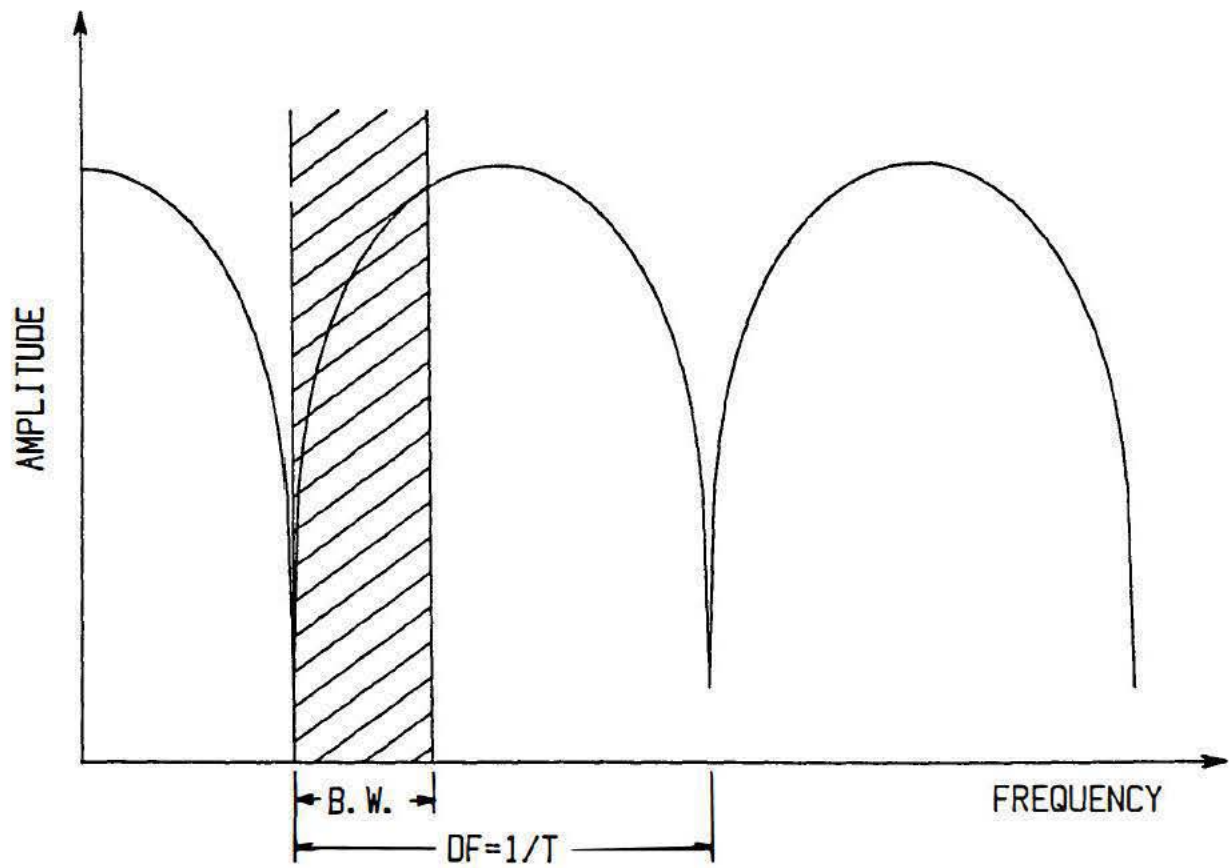


Figure 6. Implementing receiver's bandwidth on a selective fade spectrum.

4. RESULTS AND DISCUSSION OF MULTIPATH STATICS

4.1 Introduction

A fairly large amount of data from various Point Mugu experiments has been collected at ITS. Two periods of time were selected for analysis of data presented here. Nearly 200,000 impulse responses were evaluated from data gathered during the months of March and August, 1984. The following criteria were used to select the data for analysis.

- o Since the data acquisition system was activated by a burst of errors detected in any one of the DRAMA radios, the size of consecutive raw data blocks recorded by the data acquisition system corresponds to the duration of atmospheric disturbances. Typically, the data selected for analysis had long periods of consecutive data blocks.
- o Data selected for analysis had to have an average signal-to-noise ratio of 15 dB or higher on both Channels A and B.
- o Use was made of the experiment log book to eliminate selection of data recorded in periods of equipment failure. The final data selected for analysis is dated March 22-25, 1984 and August 29-30, 1984.
- o No meteorological data were available to support the data selection.

Table 1 summarized the multipath existence for the two time periods selected. It can be seen from Table 1 that multipath is present for at least 70 percent of the time for the "August data" and about 21 percent of the time for the "March data."

Table 1 should be used for the interpretation of various cumulative distribution functions to be presented in the following sections.

In the course of analysis and evaluation of the data, it became clear that for some percentage of time a second multipath component is detected within the impulse response. This led us into further development and upgrade of the analysis software. Data with two multipath components have been analyzed. The results are presented separately because the interpretation is quite different from the single multipath component case (two-ray model). There is a justification in this kind of separation of analysis since for most of the time the two-ray model is adequate to describe the channel.

Table 1. Statistics of Multipath Existence on Both Channels for the Two Time Periods Selected for Analysis

Total Experiment Time (s)	Total Time Recorded on Both Channels		Number of Impluse Responses with Multipath			
	In Seconds	In % of Total Expected Time	CH-A in Seconds	CH-A % of Recorded Time	CH-B in Seconds	CH-B % of Recorded Time
March Data						
152,979	43,291	28%	33,631	77%	31,420	72%
August Data						
47,427	45,600	96%	33,588	73%	28,120	61%

Due to computer memory limitations, we can only present distributions based on a maximum of 5000 impulse responses at one time. It is expected that in the future much larger samples will be analyzed.

4.2 Distribution of Multipath Power

Multipath cumulative power distributions of three sample periods from the "March data" and three sample periods from the "August data" were calculated and are presented in Figures 7 through 12. Each figure presents the multipath power distribution (highest multipath component) for Channels A and B. The distributions for both channels refer to the same period of sample time. The following conclusions can be drawn from the data.

- o The median multipath power in Channel B is always lower than the median in Channel A. Typical differences in the median values are 8 to 5 dB and only for one case is the difference as low as 2 dB.
- o An average multipath power median is -4 dB for Channel A and -9.2 dB for Channel B. No significant change in multipath power statistics can be found by comparing the "March" and "August data." For both periods, Channel A was under significant multipath influence for longer time than Channel B. For example, multipath power larger than -6 dB was measured between 60 and 70 percent of the time on Channel A and 15 to 40 percent of the time on Channel B.
- o There seems to be a high resemblance between various distributions of the same channel at different times.
- o None of the data are normally distributed, though Channel A distributions are closer to normal distributions than those of Channel B.
- o It seems that Channel A is affected for a very short time by signal enhancement. No such indication is seen in Channel B.

It should be noted that the resolution in measuring relative power for cases with high relative multipath power can be low. To understand the reasons, the reader is referred to Figures 1 through 4. As can be seen in a few cases, the actual peak of the response is not always well defined. This happens due to low sampling rate in the data system. No attempt was made to correct the measured power, and thus any error that might result in calculating the relative power.

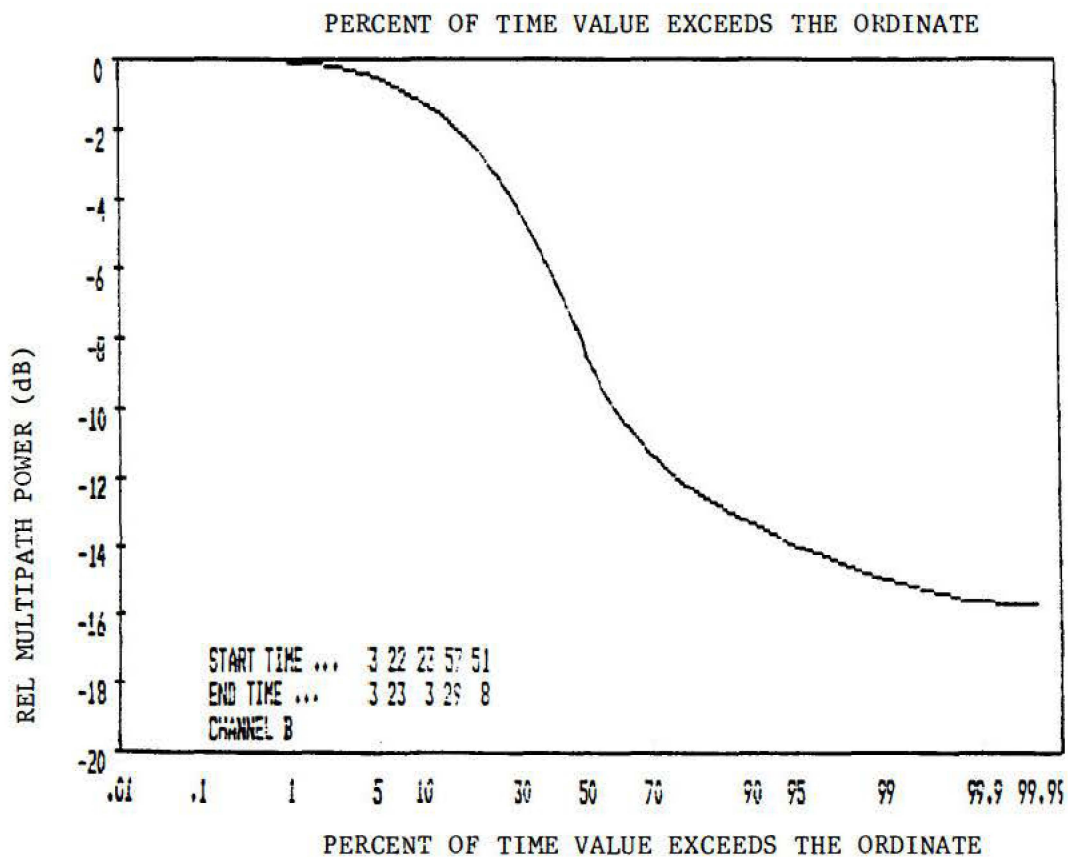
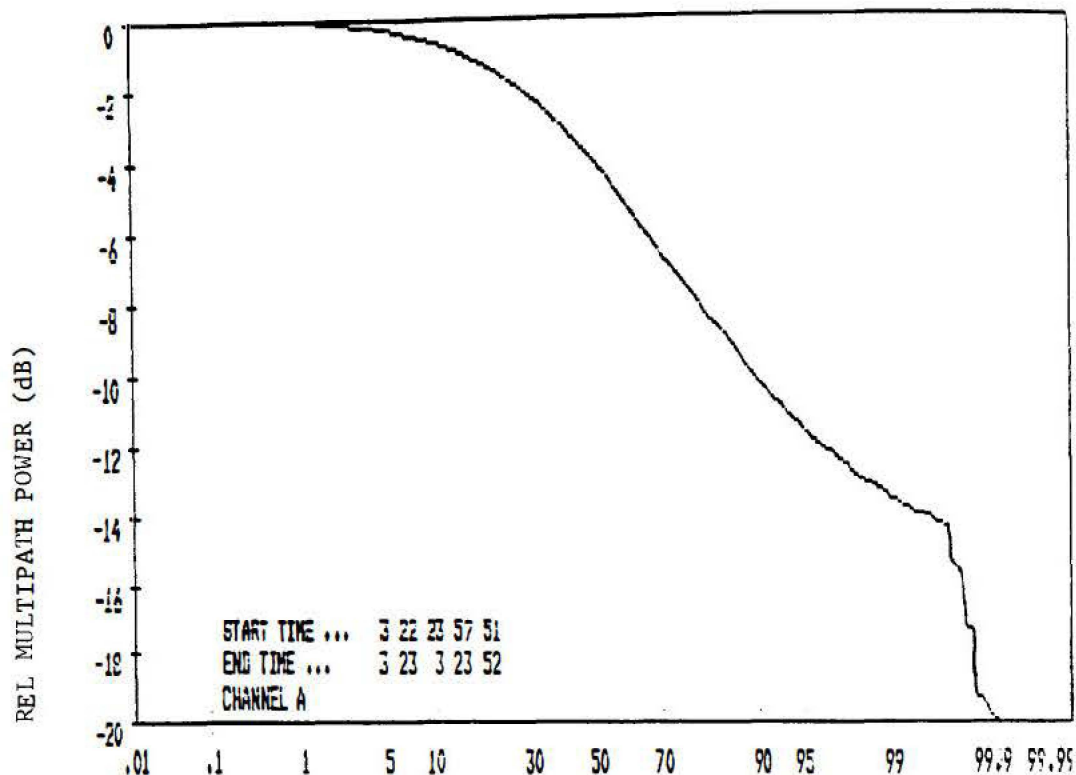


Figure 7. Sample of cumulative power multipath distributions for March 22 and 23.

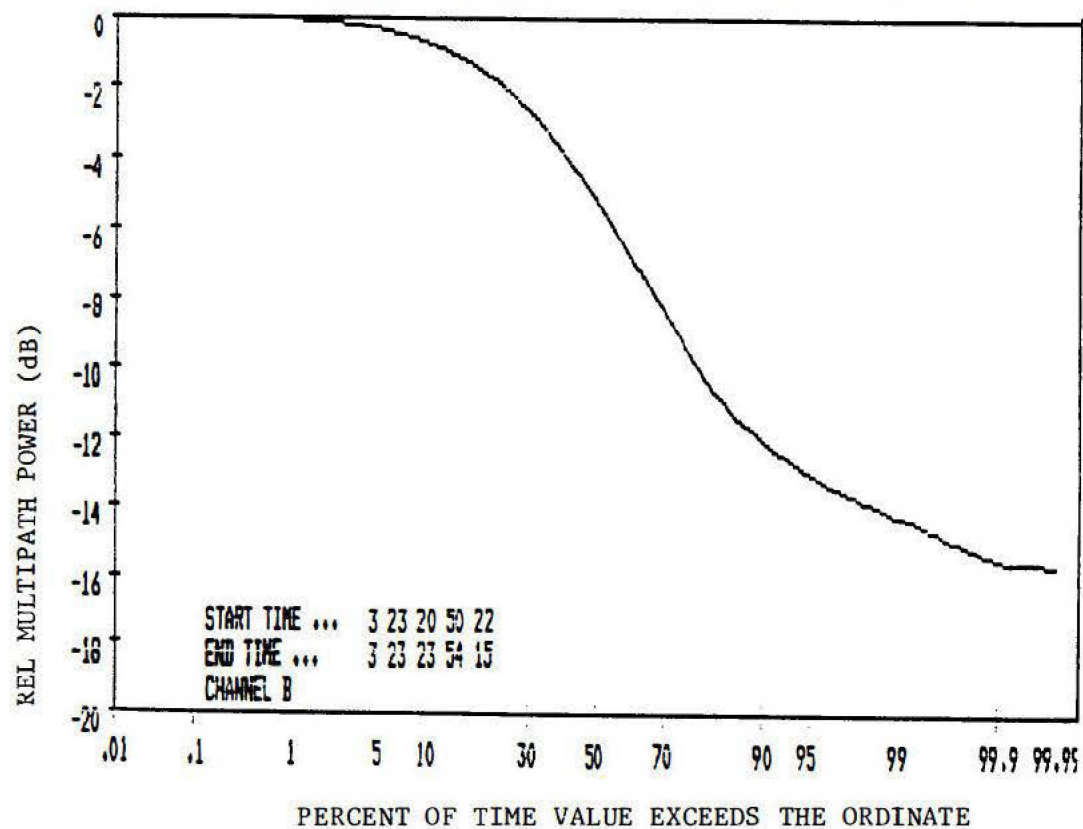
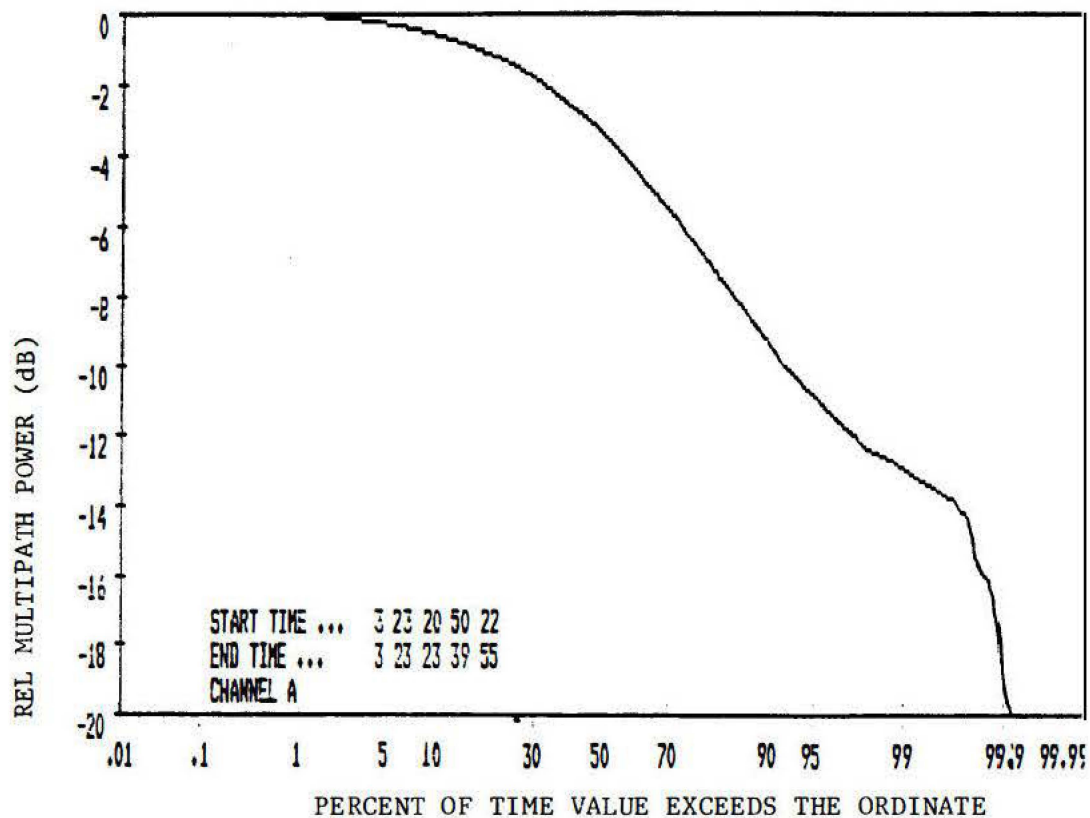


Figure 8. Sample of cumulative power multipath distributions for March 23.

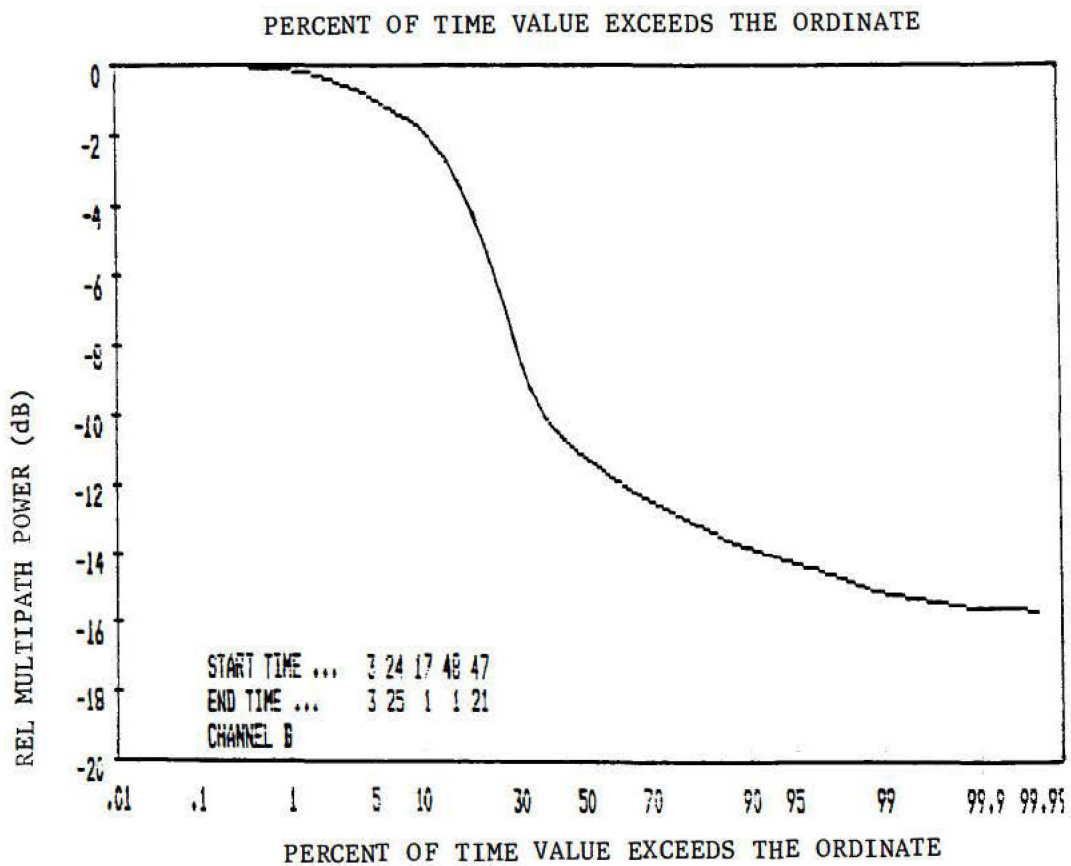
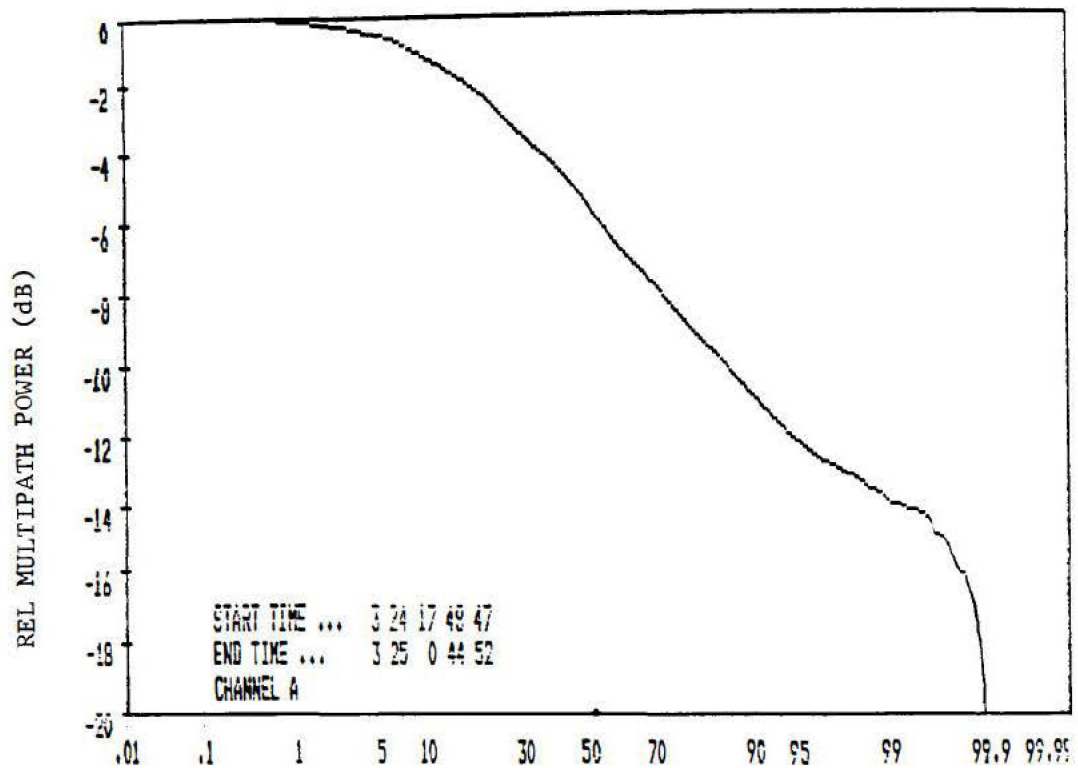


Figure 9. Sample of cumulative power multipath distributions for March 24 and 25.

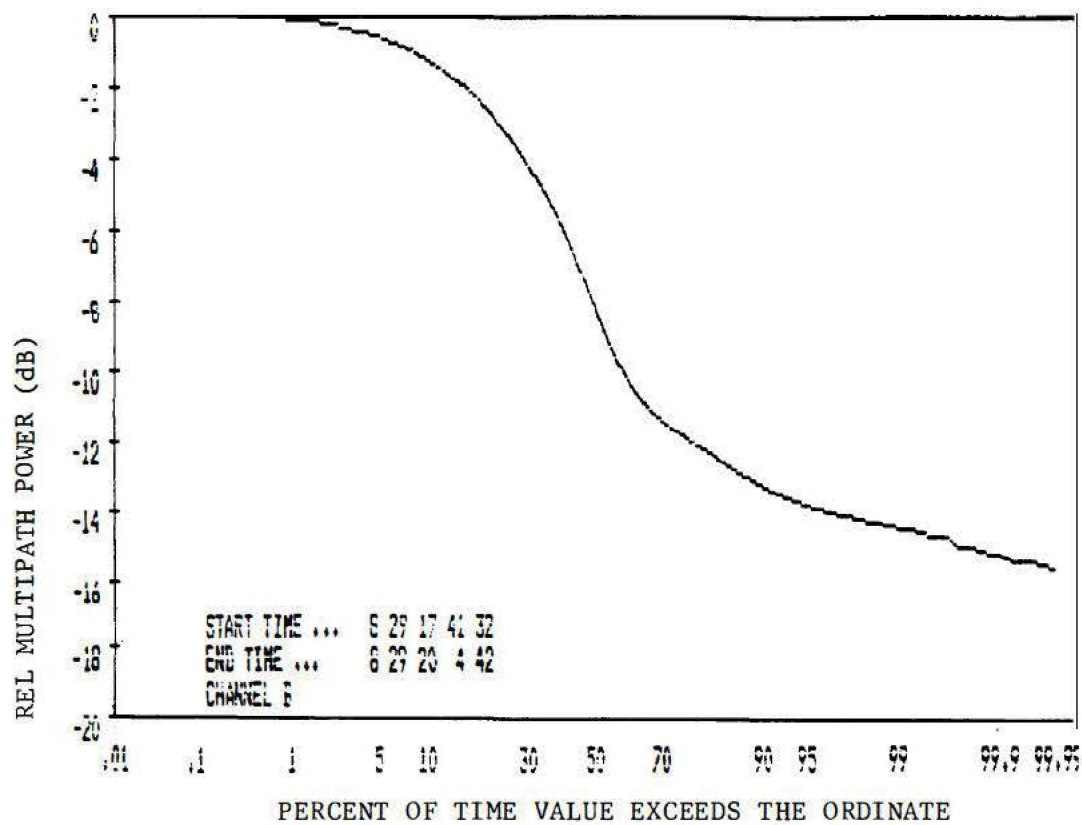
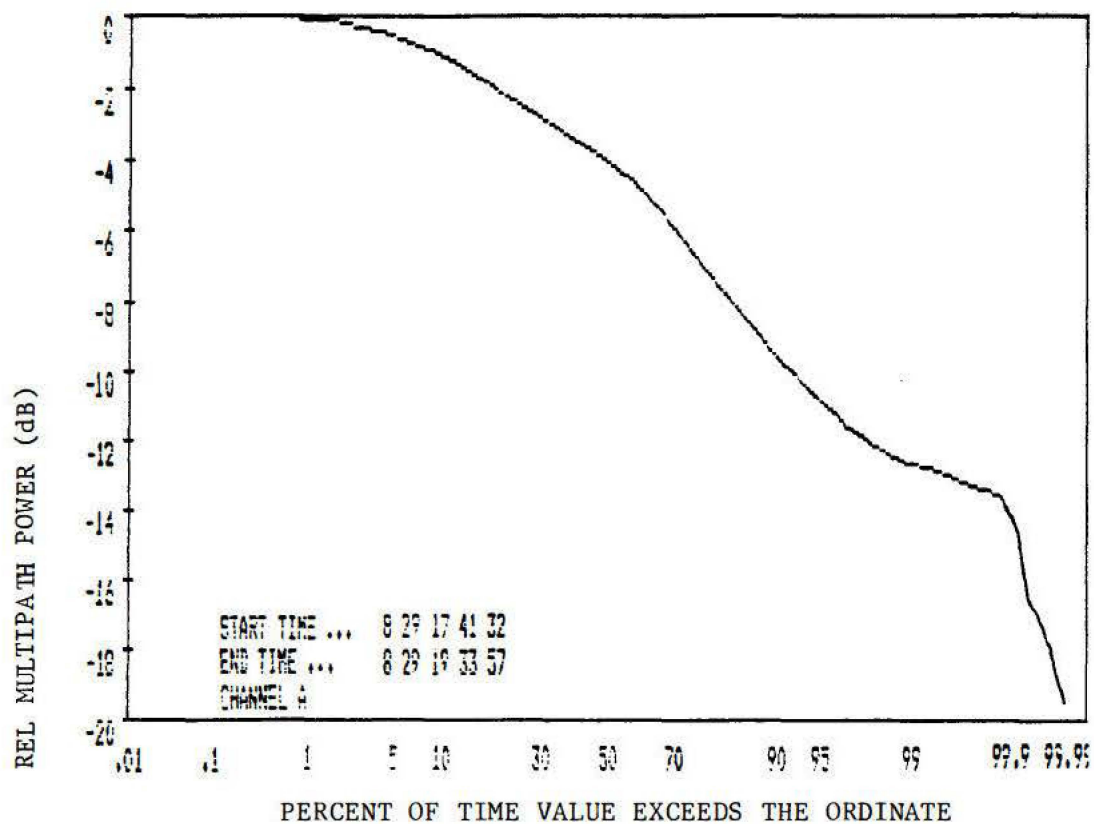


Figure 10. Sample of cumulative power multipath distributions for August 29.

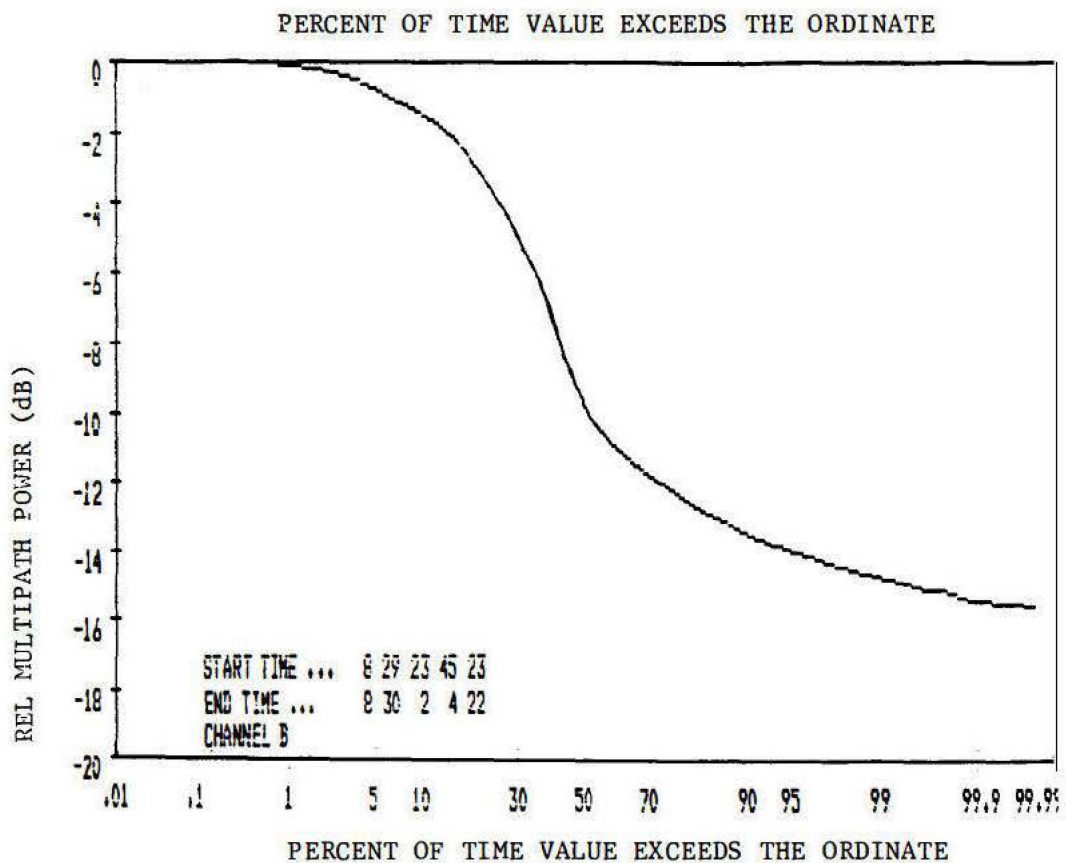
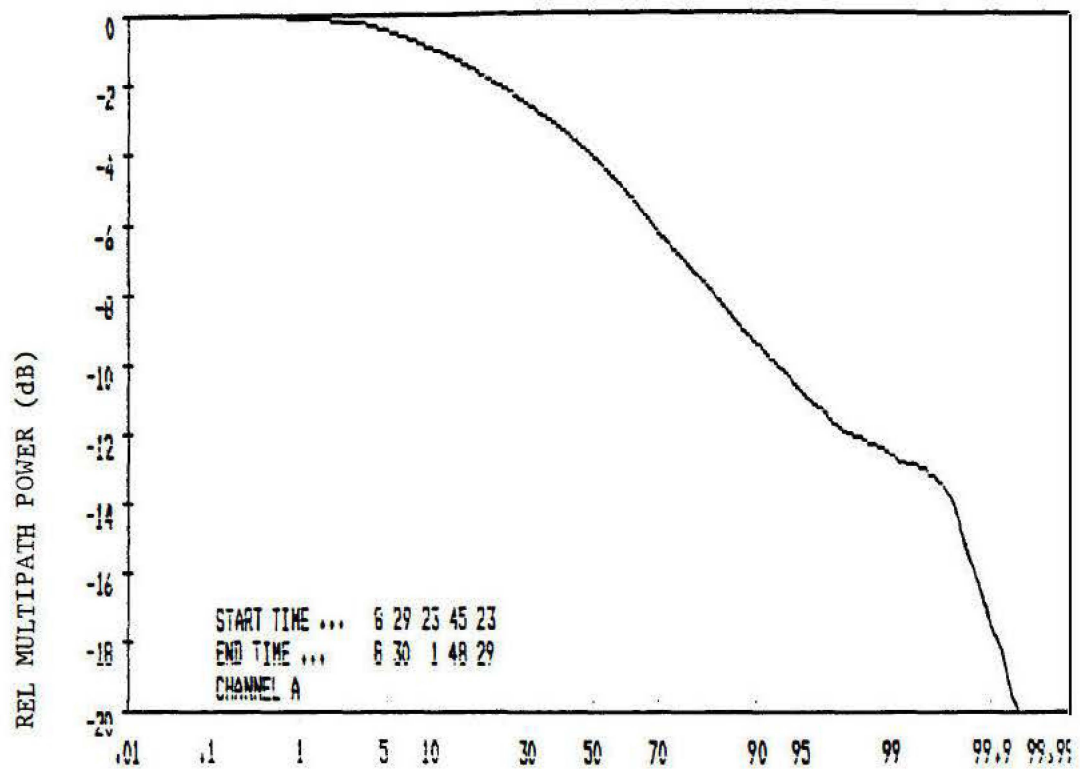


Figure 11. Sample of cumulative power multipath distributions for August 29 and 30.

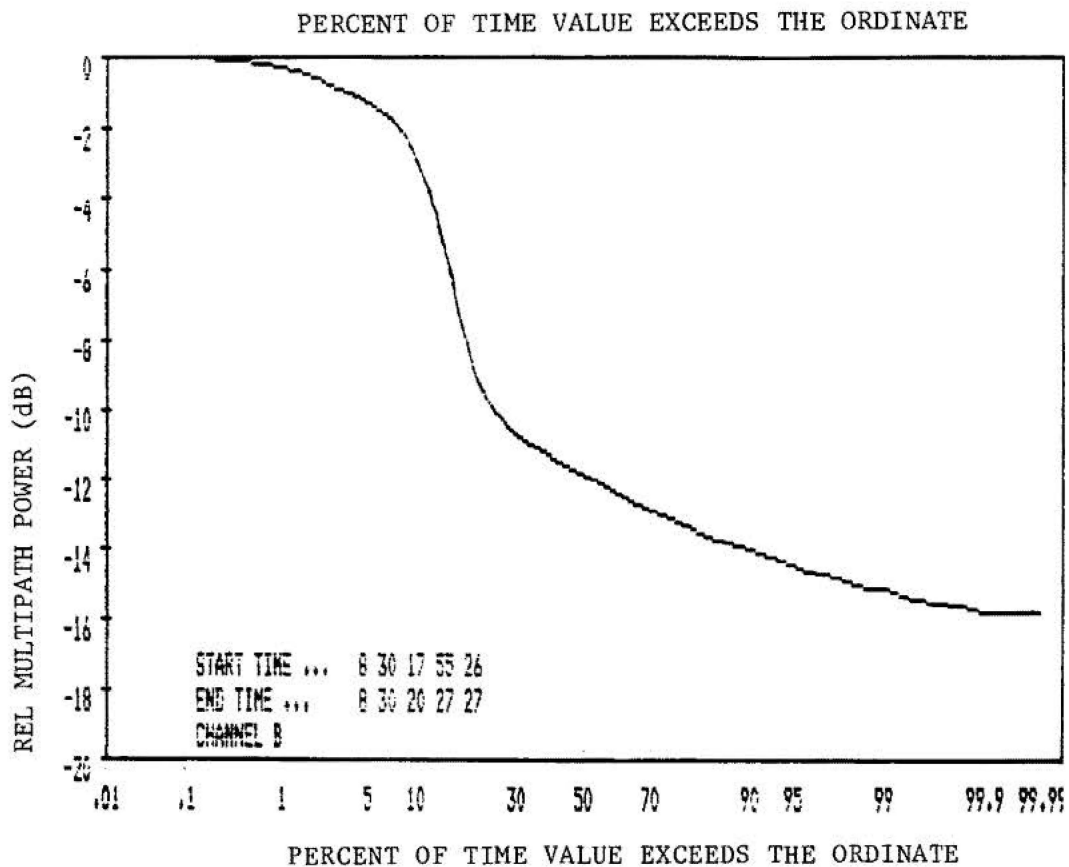
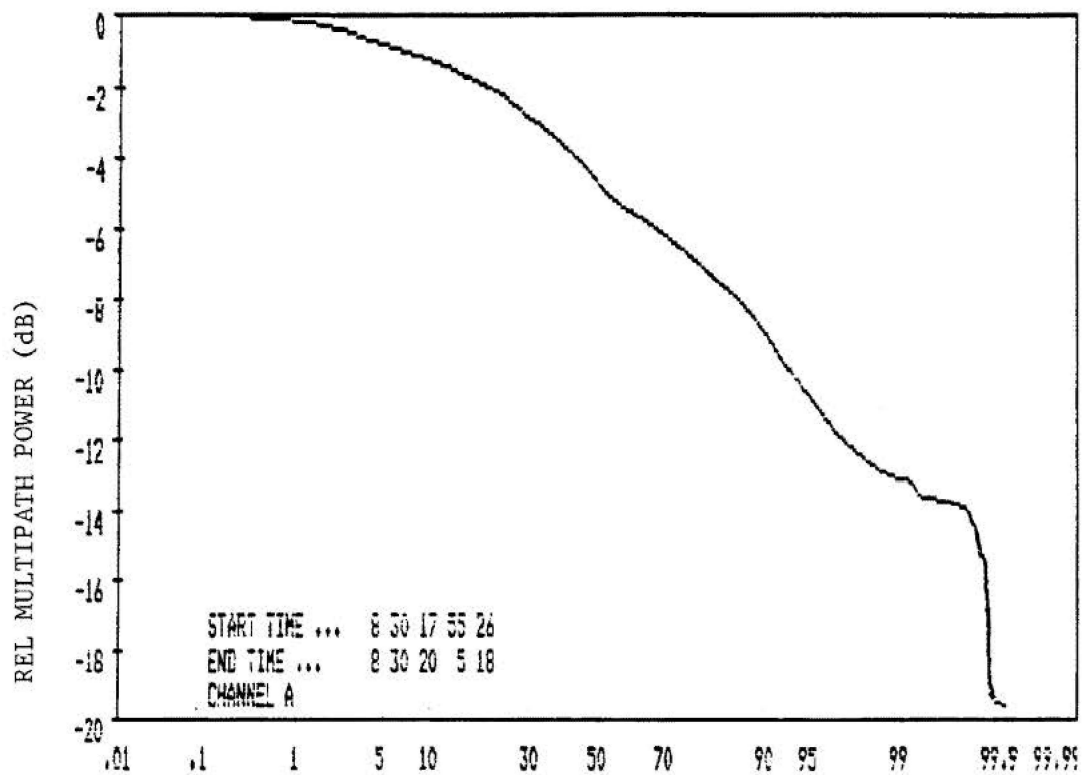


Figure 12. Sample of cumulative power multipath distributions for August 30.

4.3 Distributions of Multipath Delay

Multipath cumulative delay distributions for the same sample periods discussed in Section 4.2 are presented here. Each one of Figures 13 through 17 presents the distribution of delays for Channels A and B.

From the data presented, the following conclusions can be drawn.

- o For most of the distributions presented, the delay is normally, or near normally distributed.
- o Multipath delay medians for Channel B are higher than those for Channel A. Typical delay medians for Channel A are between 6 and 12 ns, and 12 to 21 ns for Channel B.
- o Longer delays were measured on Channel B than on Channel A.
- o The delay recorded on August 30 (Figure 17) between 17:55 and 20:20 ZULU time (8 am to 11 am local time) deviates sharply from a normal distribution. For this period of time, 54% of the seconds were recorded meaning that for more than half of the time within a 2-1/2 hour period, the error rate was unacceptable due to severe multipath and atmospheric conditions.

One can see from the cumulative distributions that the time resolution of measuring delays is as low as 1 ns.

It is interesting to compare at this point, two mathematical expressions for maximum delay suggested by Ruthroff (1971) and Hubbard (1984). Ruthroff's estimate is given by

$$\tau_m = 3.7 \left(\frac{D}{20} \right)^3 \text{ ns.} \quad (1)$$

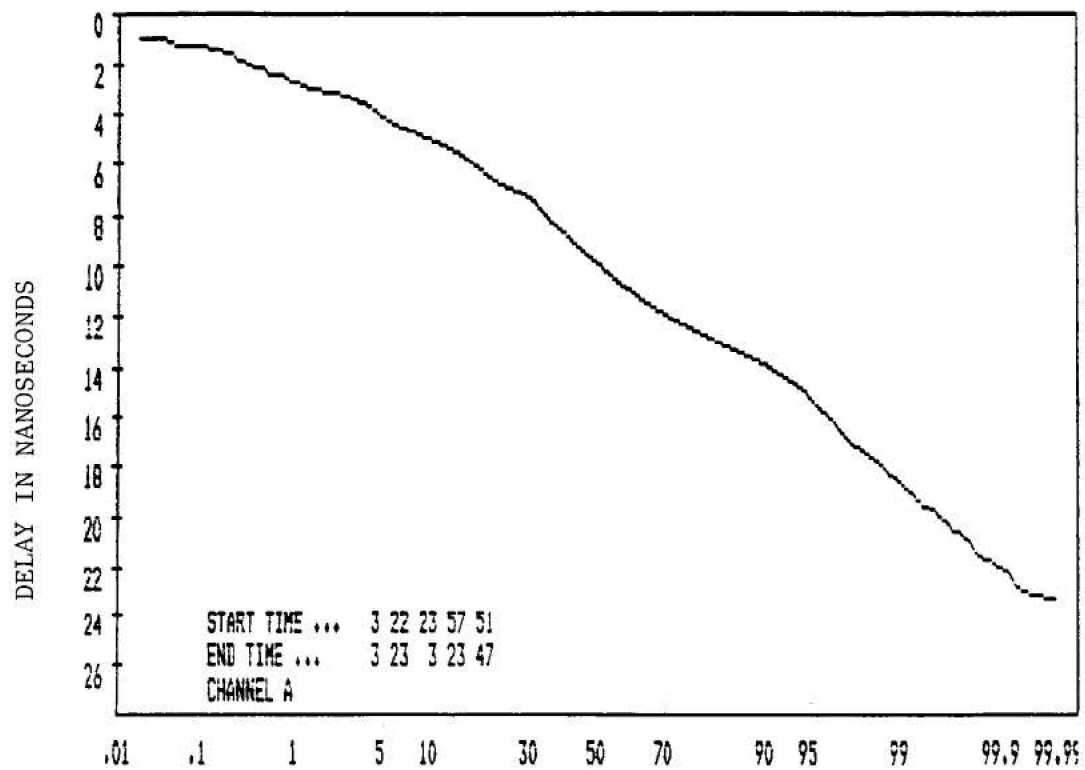
D = path length in miles.

In contrast to the cubic relationship to D, Hubbard has suggested a linear relationship given by

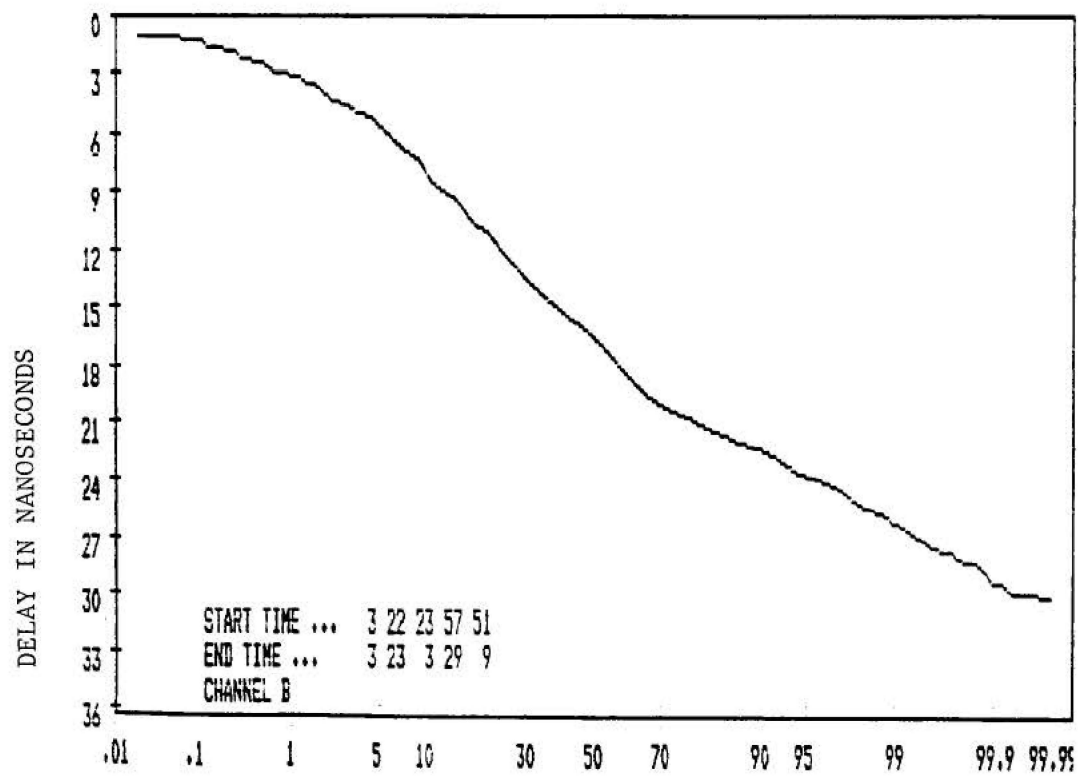
$$\tau_m = 1668 D \tan^2 \frac{\theta}{2} \quad (2)$$

D = path length in km

θ = half-power beamwidth in degrees.



PERCENT OF TIME VALUE IS LESS THAN ORDINATE



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

Figure 13. Sample of cumulative delay distributions for March 22 and 23.

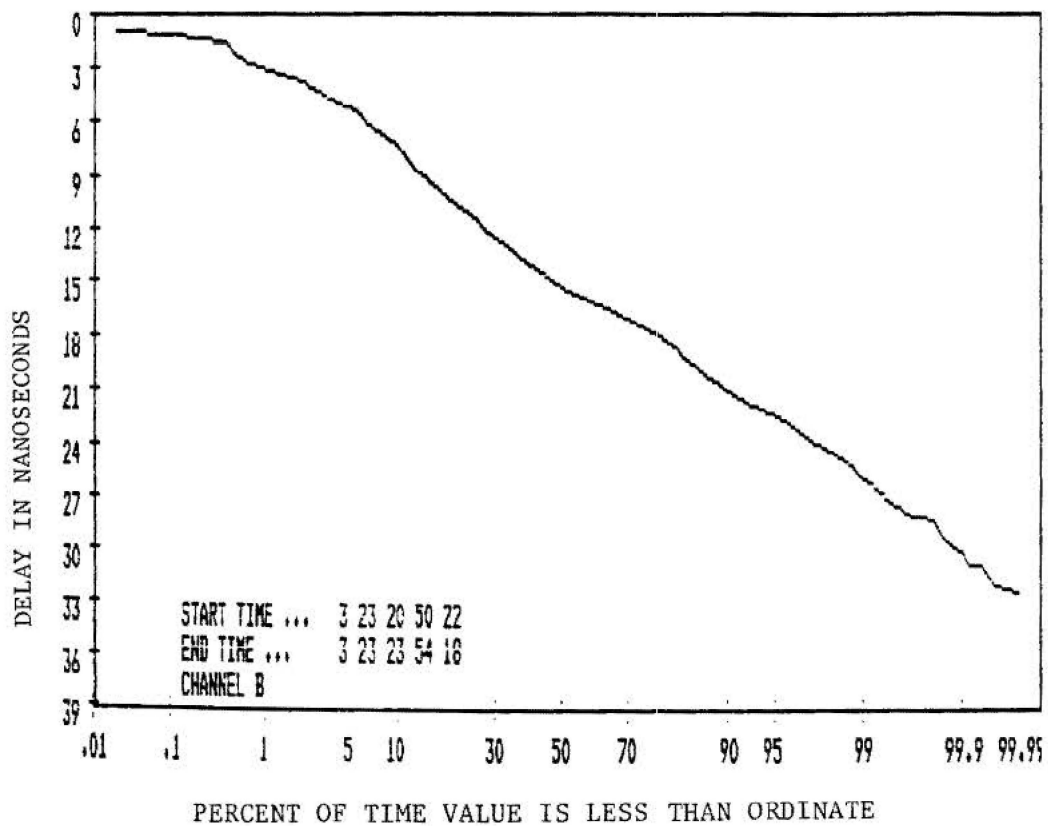
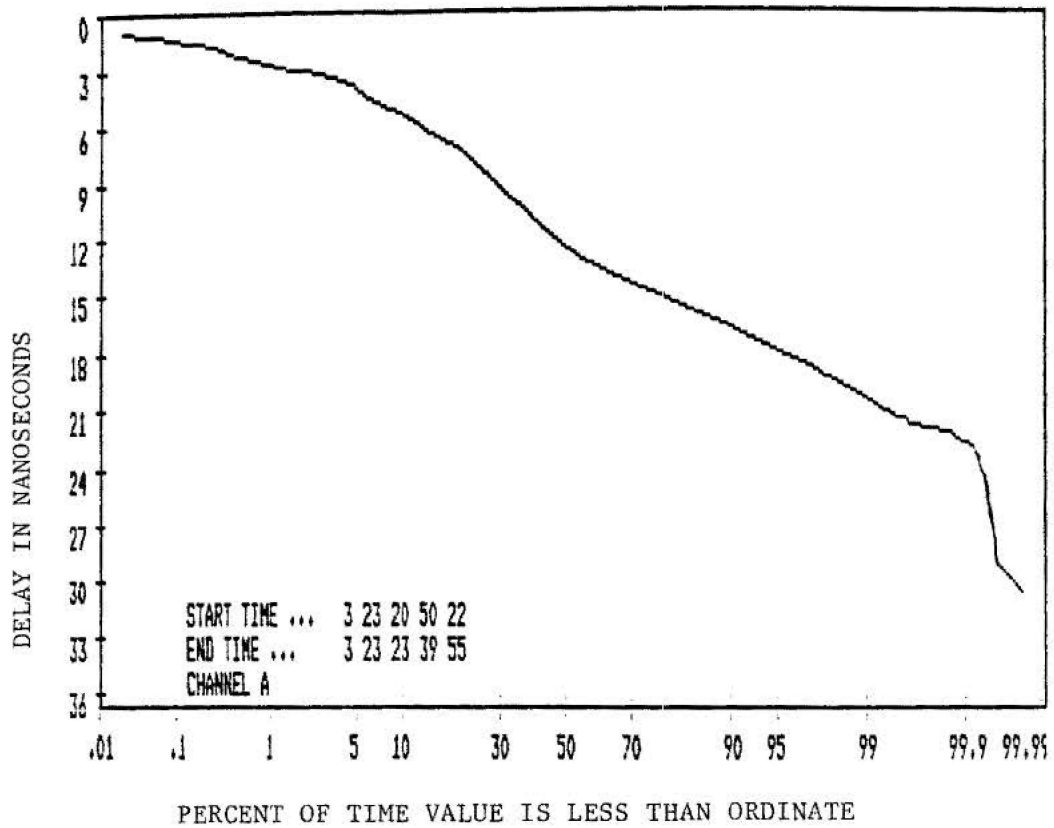


Figure 14. Sample of cumulative delay distributions for March 23.

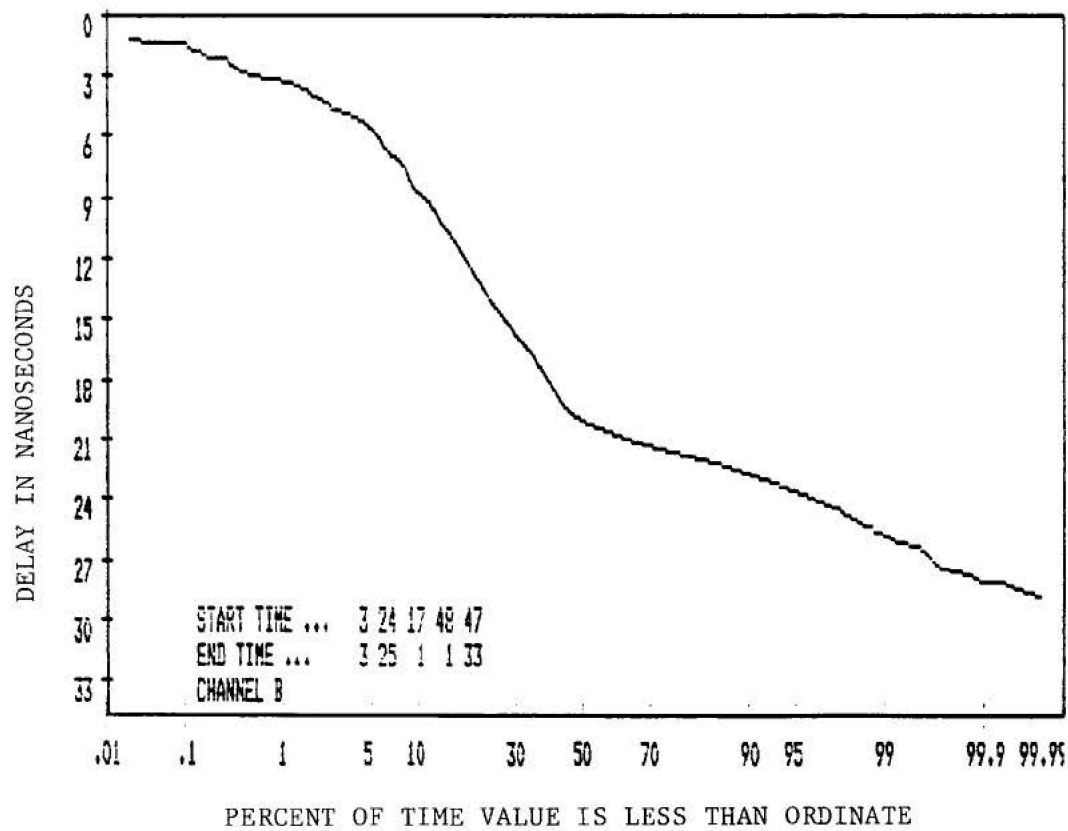
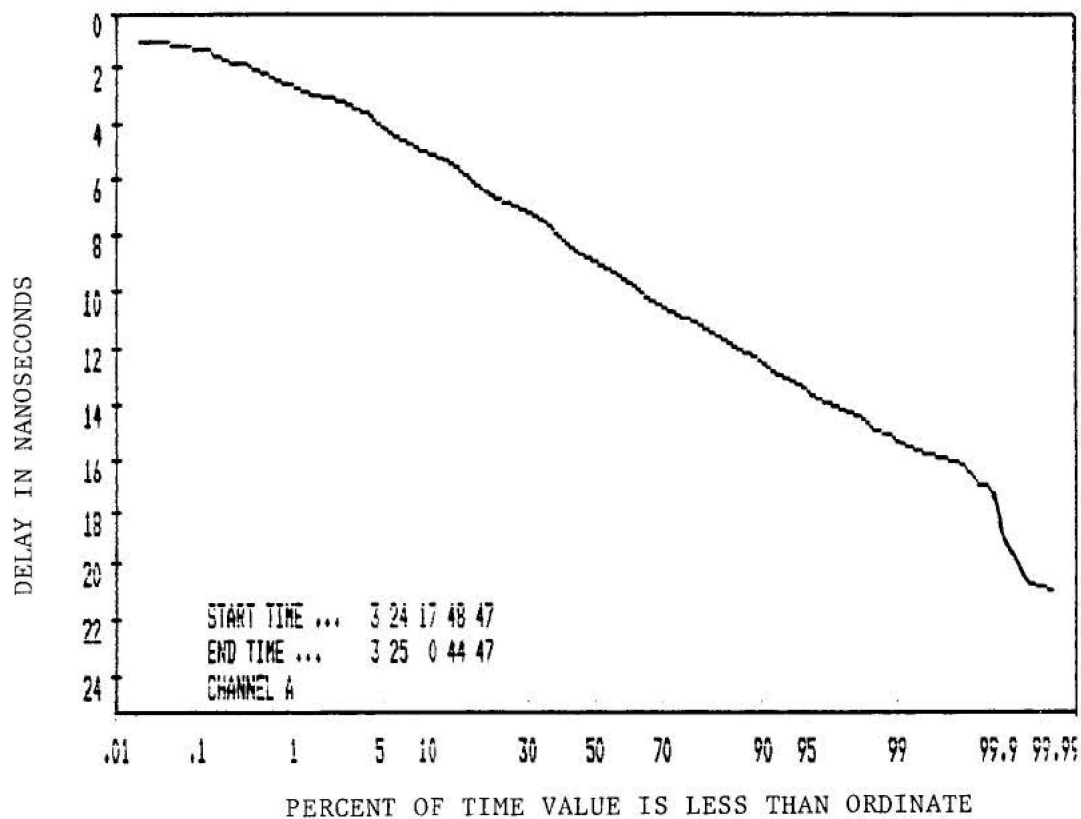
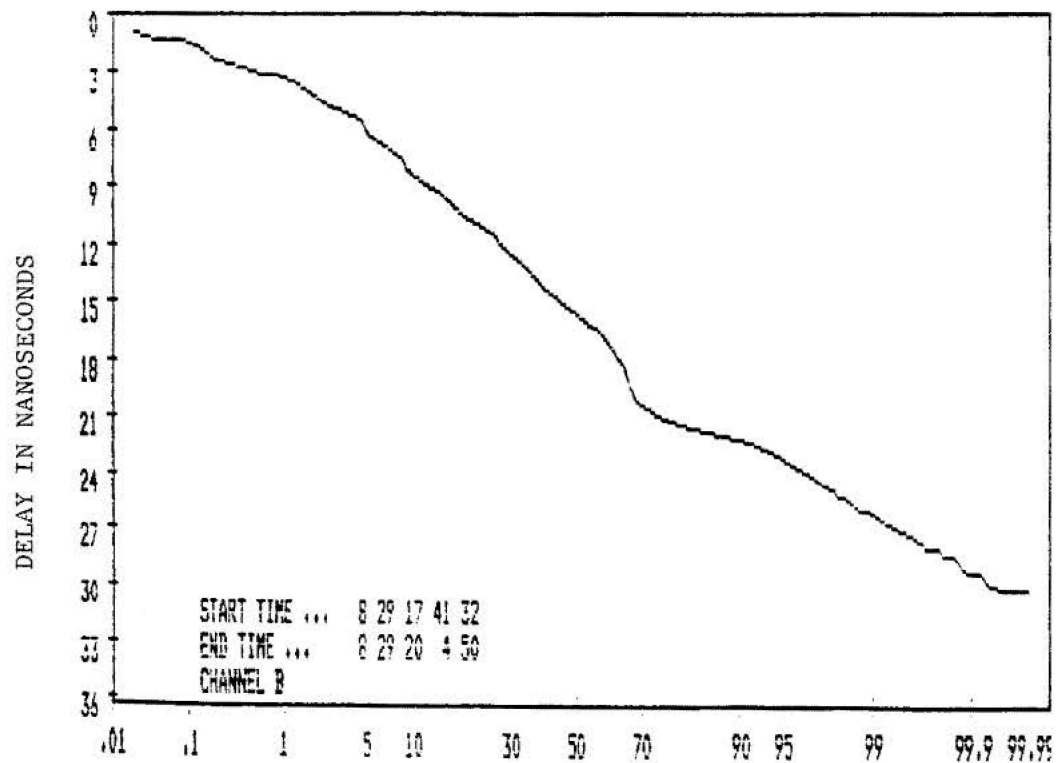


Figure 15. Sample of cumulative delay distributions for March 24 and 25.



PERCENT OF TIME VALUE IS LESS THAN ORDINATE



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

Figure 16. Sample of cumulative delay distributions for August 29.

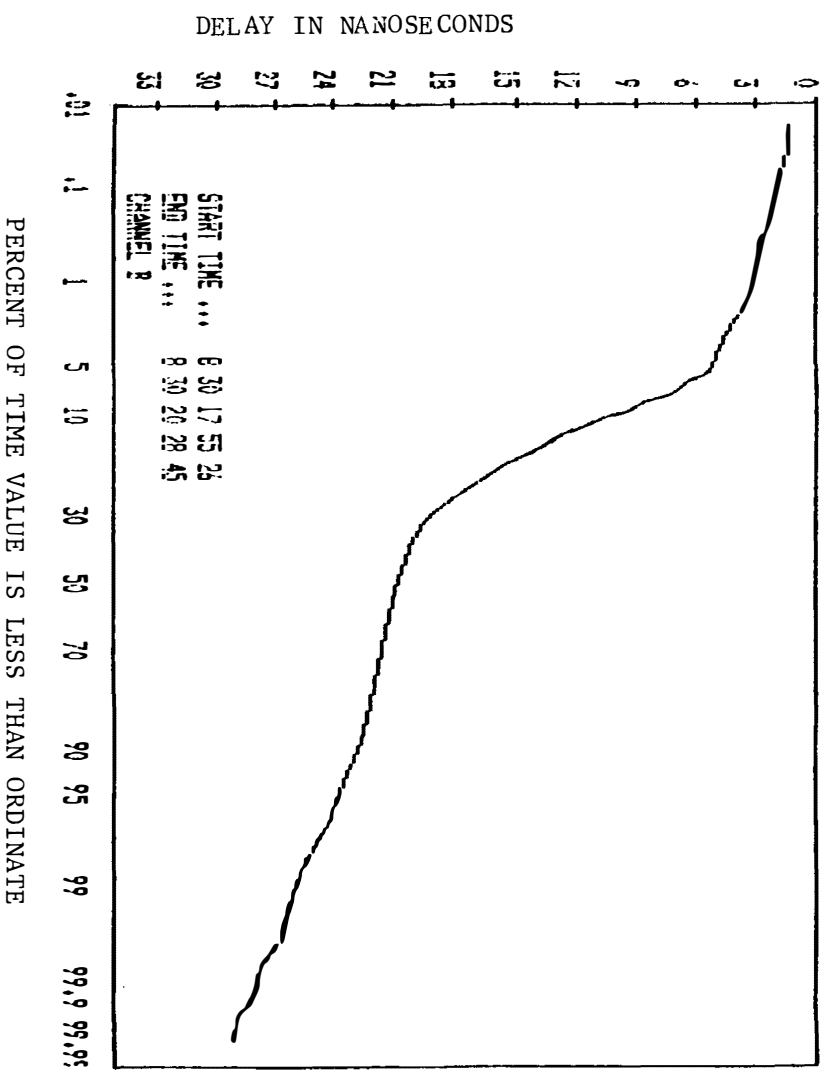
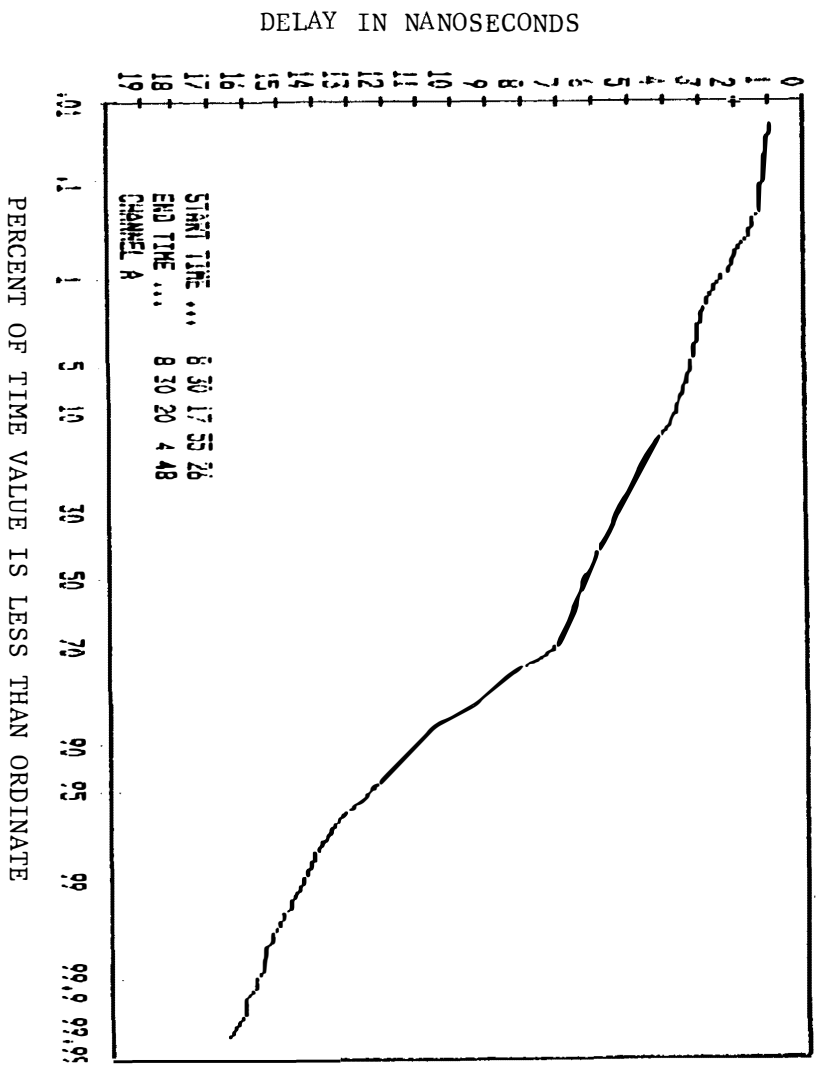


Figure 17. Sample of cumulative delay distributions for August 30.

The path length for the Point Mugu experiment was 65 miles (104.6 km), and the half-power beamwidth of the antennas was 0.8°. Under these conditions:

Equation 1 yields

$$\tau_m = 3.7 \left(\frac{65}{20}\right)^3 = 127 \text{ ns.}$$

Equation 2 yields

$$\tau_m = 1668 \cdot 105 \cdot \tan^2\left(\frac{0.8}{2}\right) = 8.53 \text{ ns.}$$

Equation 1 yields a maximum delay value that is much higher than the highest value recorded in these experiments, while 8.53 ns delay is a value close to the median delay found for Channel A.

4.4 Multipath Delay Versus Multipath Power

Two kinds of data representations are used to show multipath delay and multipath power relations.

Typical scattergrams of multipath power versus multipath delay are presented in Figures 18 and 19. These scattergrams show the scatter of data for the two channels, A and B, for the same sample time. The scattergrams are based on 5000 samples each.

The scatter of delay values associated with high relative multipath power is very wide. Typical scatter of delay values for relative power values between 0 and -3 dB is 16 ns, for Channels A and B.

A different structure of scattered data is present on each channel. Channel B tends to record higher delays than Channel A does. The slope of the scatter is steeper for the Channel A data than it is for the Channel B data. This is equivalent to saying that in Channel A, short delays associated with low relative power were recorded and in Channel B long delays associated with low relative power were recorded, and relatively short delays with low power were not recorded. We will analyze this behavior later, but it seems safe to conclude at this point that the Channel A and B antennas were not aligned the same way in elevation.

Although a wide scatter of data seems to exist on both channels, an attempt was made to determine if there is any statistical dependency between the delay and relative power. The median, the 10 and 90 percentiles of multipath delay versus quantized levels of multipath power are presented in

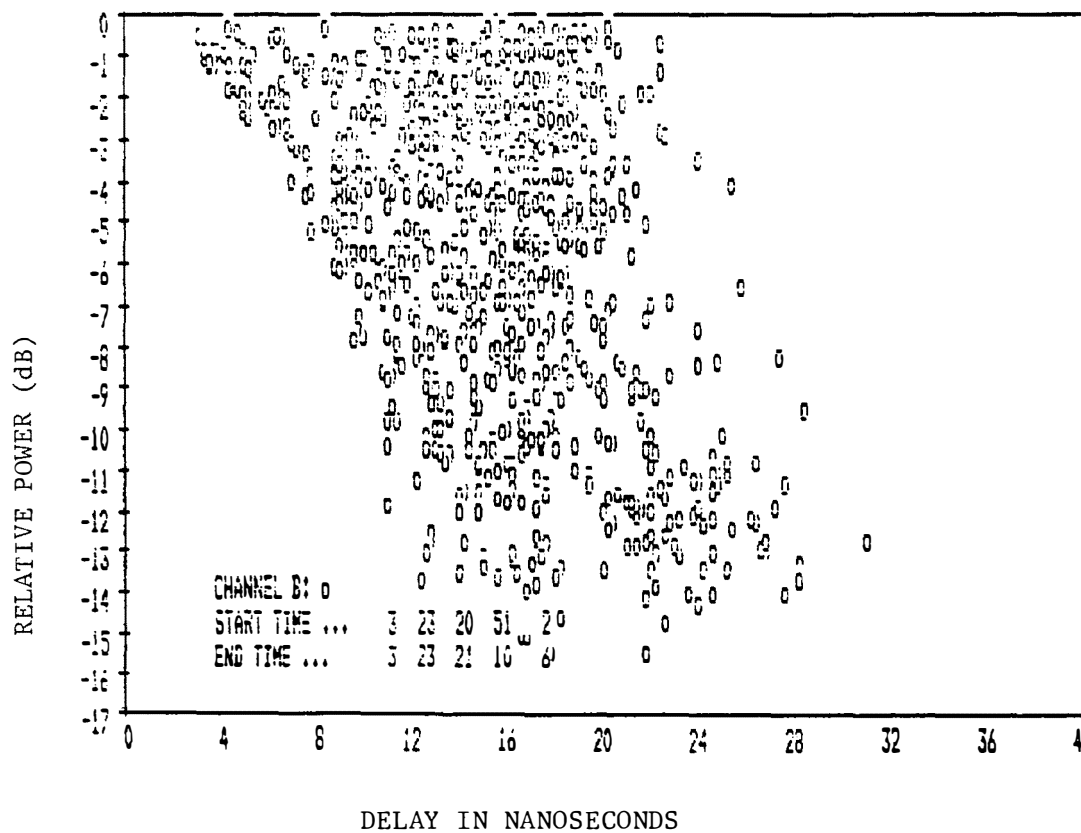
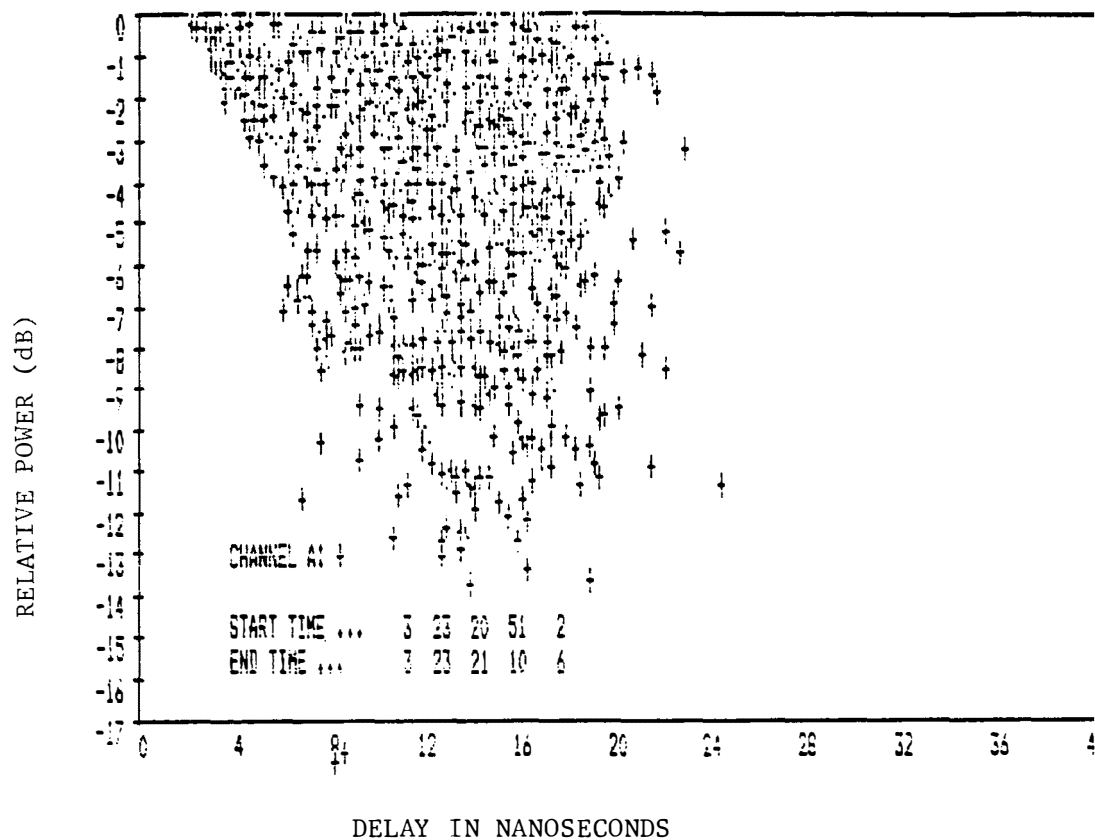


Figure 18. Scattergram of delay versus power for Channels A and B for March 23.

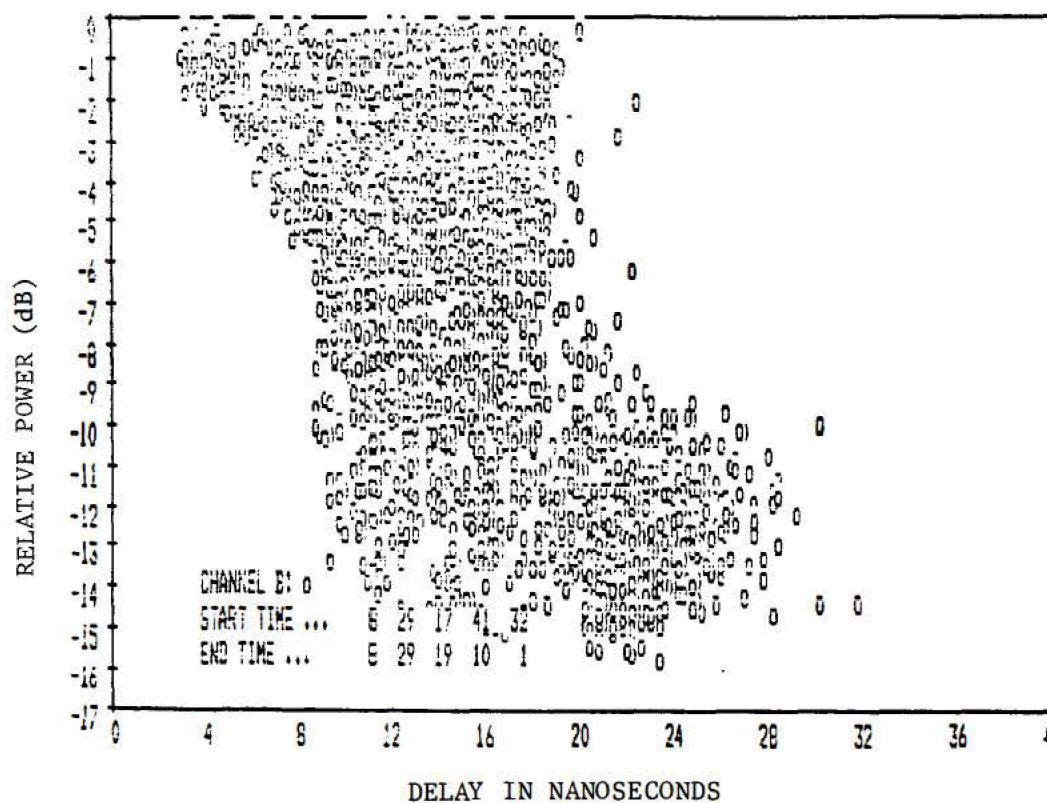
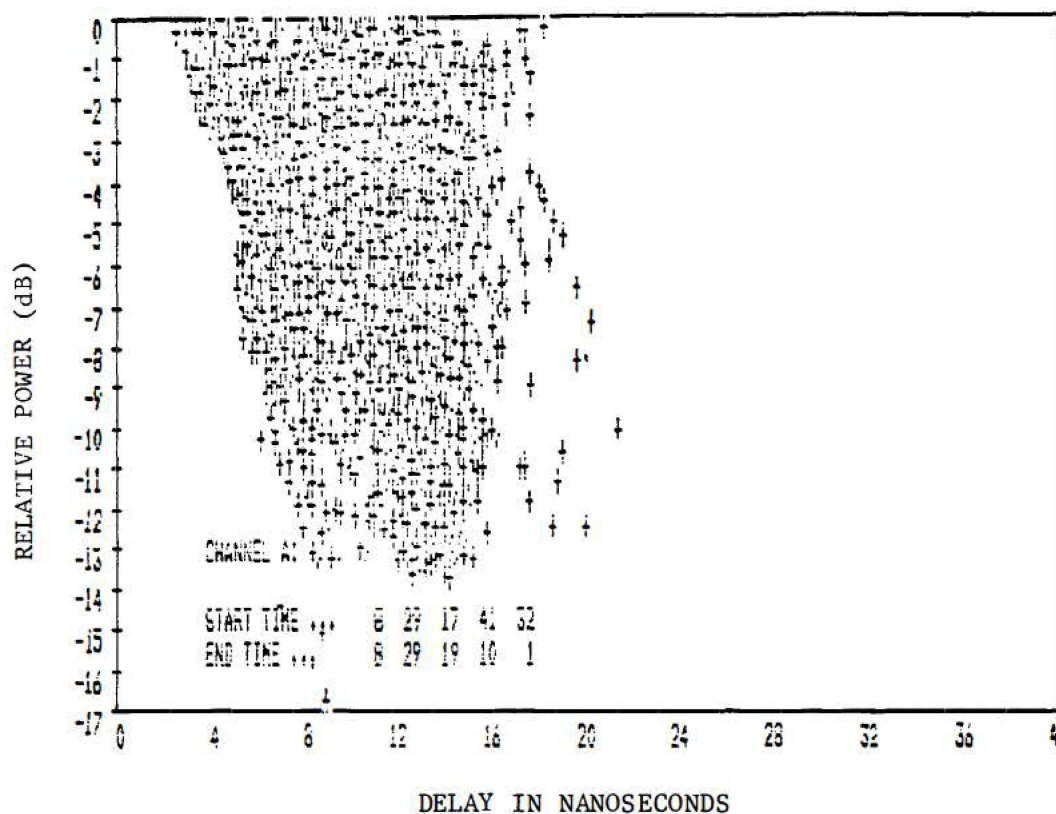


Figure 19. Scattergram of delay versus power for Channels A and B for August 29.

Figure 20. The two plots refer to Channel A at different time periods, and each plot is based on 2000 impulse responses. Although a slight trend of all three quantile delays can be seen on the "March data" in Figure 20, no such clear trend exists for the "August data."

Upon evaluating a few more of the ITS tests, it became more apparent that no firm statistical dependency exists between multipath delay and power.

4.5 Distribution of Multipath Phase

Multipath relative phase measured on Channel B only is presented here. It was shown by Cox (1972) that the cophase and the quadphase functions can be expressed as:

$$I(t) = \sum_i a_i R_s \left(\frac{t}{k} - \tau_i \right) \sin \theta_i$$

$$Q(t) = \sum_i a_i R_s \left(\frac{t}{k} - \tau_i \right) \cos \theta_i$$

where

R_s is the time autocorrelation function of the signal,

a_i is the amplitude of the i component,

τ_i is the i component delay, and

θ_i is the i component phase.

It can be seen that the ratio of these expressions (I/Q) reduces to the $\tan \theta_i$. Thus, by taking the arctangent of this ratio, the relative phase between the direct signal and the multipath component can be determined.

Some relative phase distributions were calculated for the two periods of time under evaluation. It was found that the phase distribution calculated for the "March data" differs from the distribution calculated for the "August data."

The March phase distributions seem to be normally distributed for longer periods of time than the August phase distributions. Distributions for March and August data are presented in Figures 21 and 22, respectively.

4.6 Abnormal Multipath Statistics

The term "abnormal multipath" stands for the special cases of "nonminimum phase" responses. The following statistical properties were investigated using

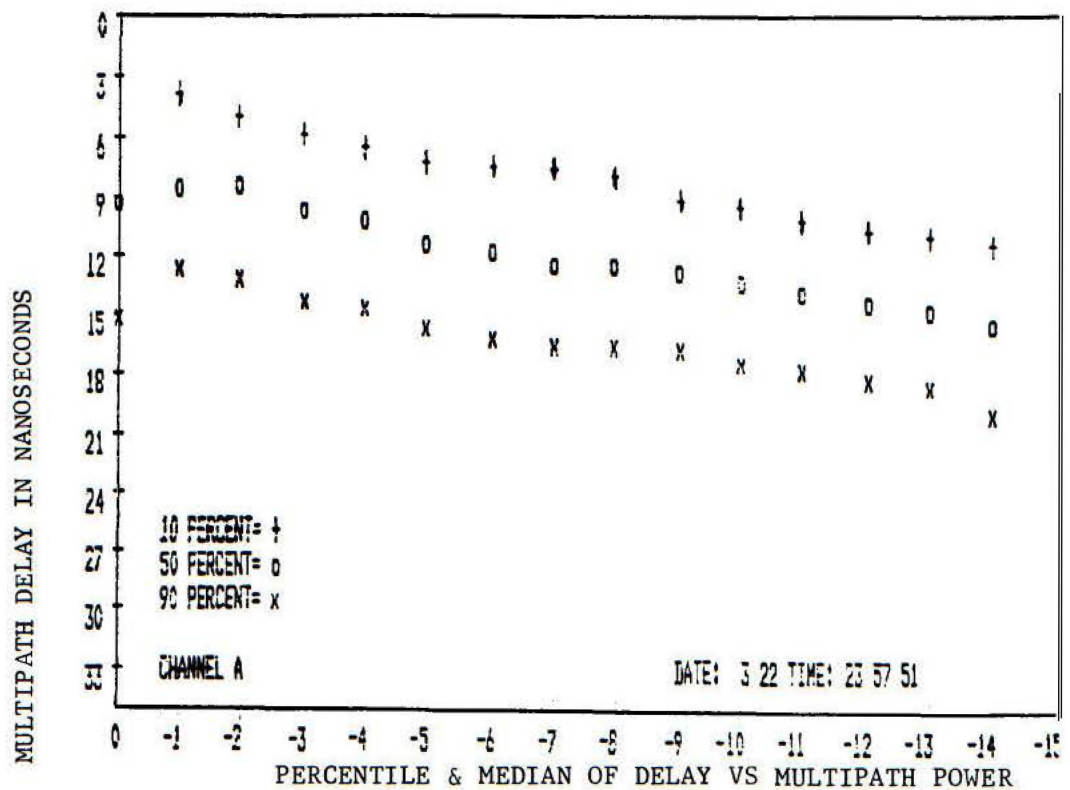
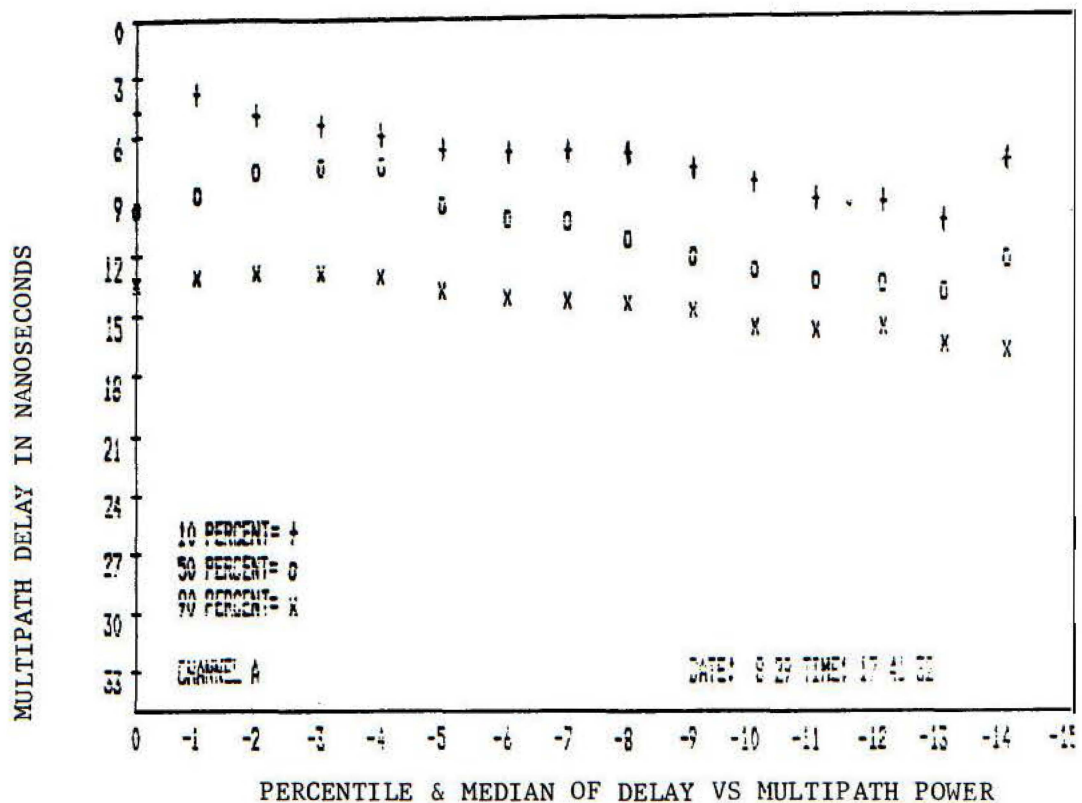


Figure 20. Delay distributions versus quantized relative power for March 22 and August 29 data.

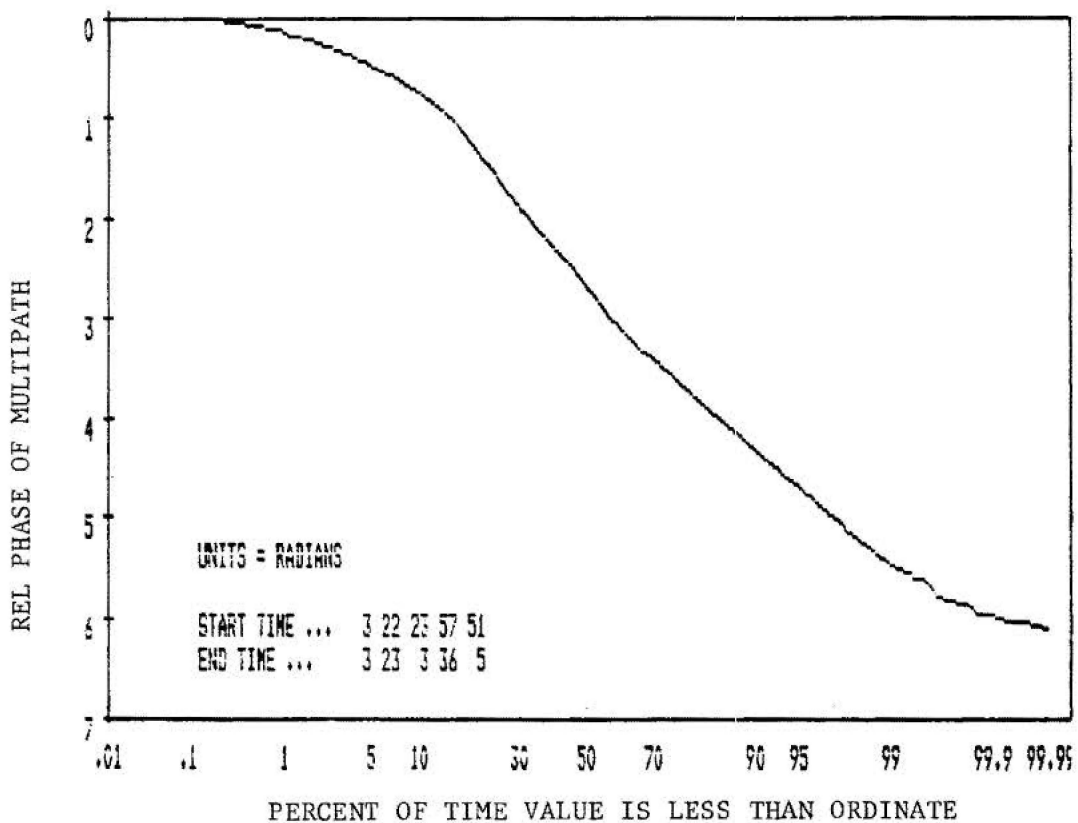
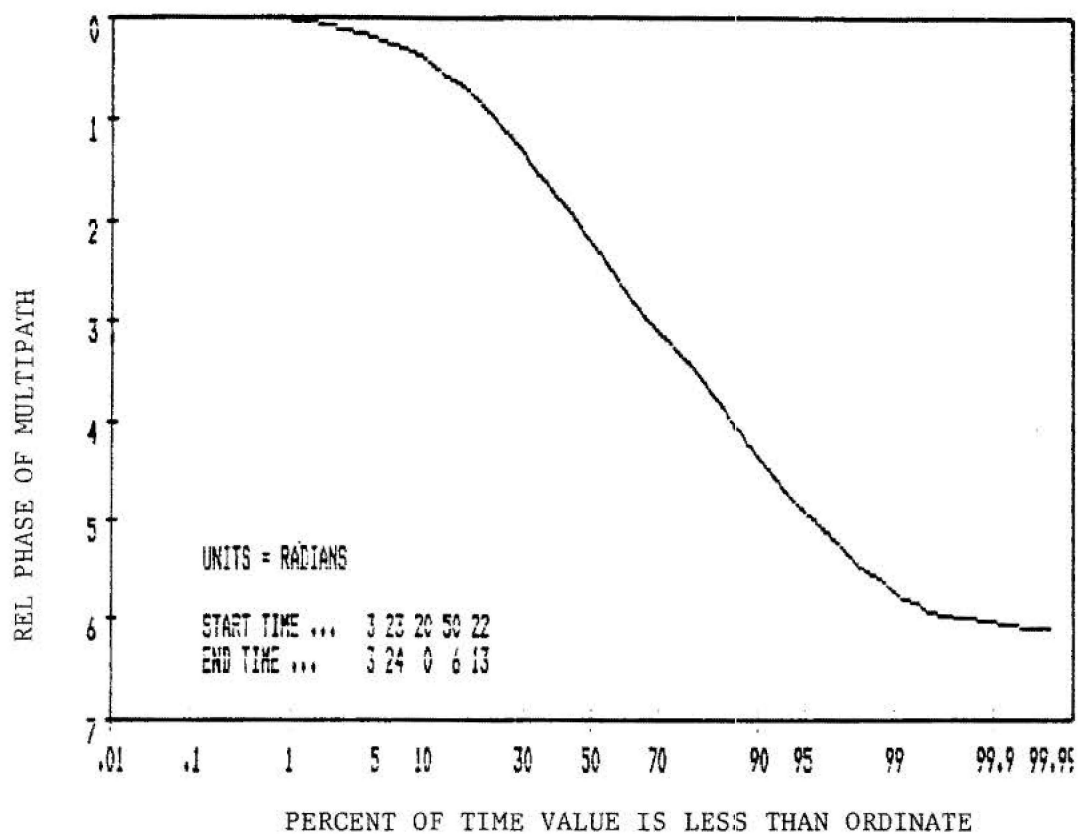


Figure 21. Multipath phase distributions for March 22 to 24.

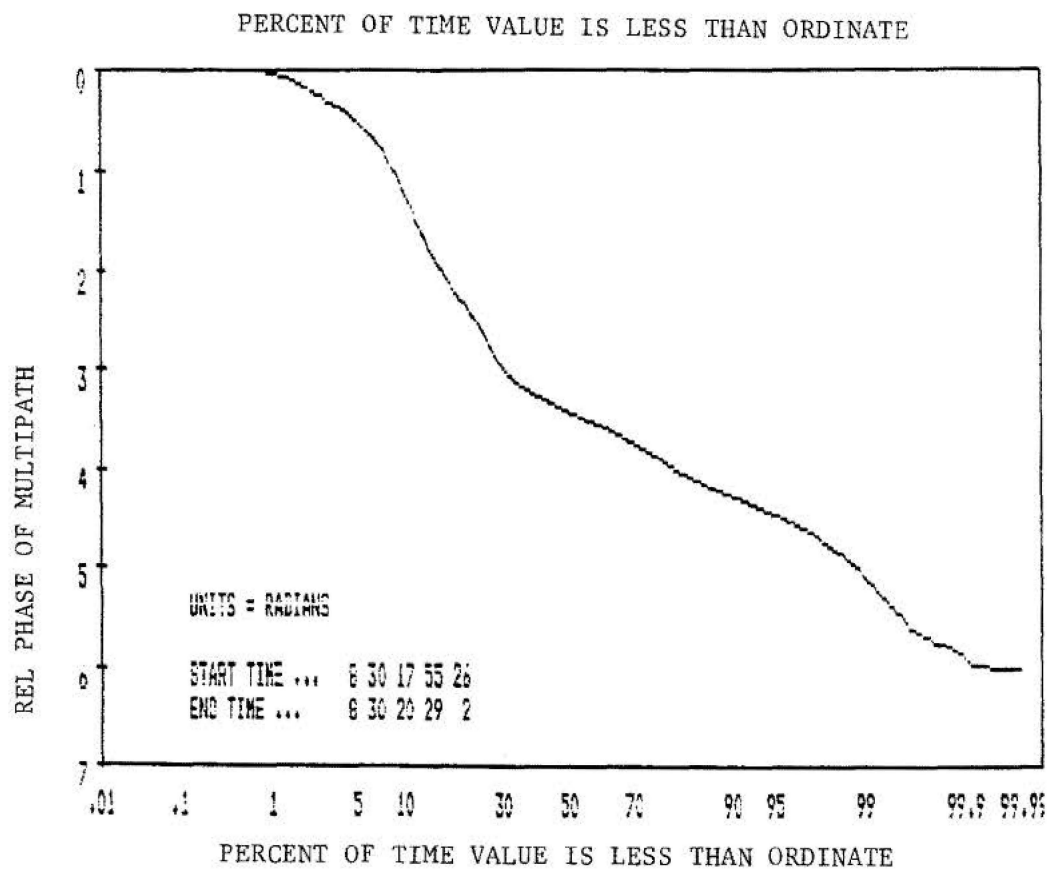
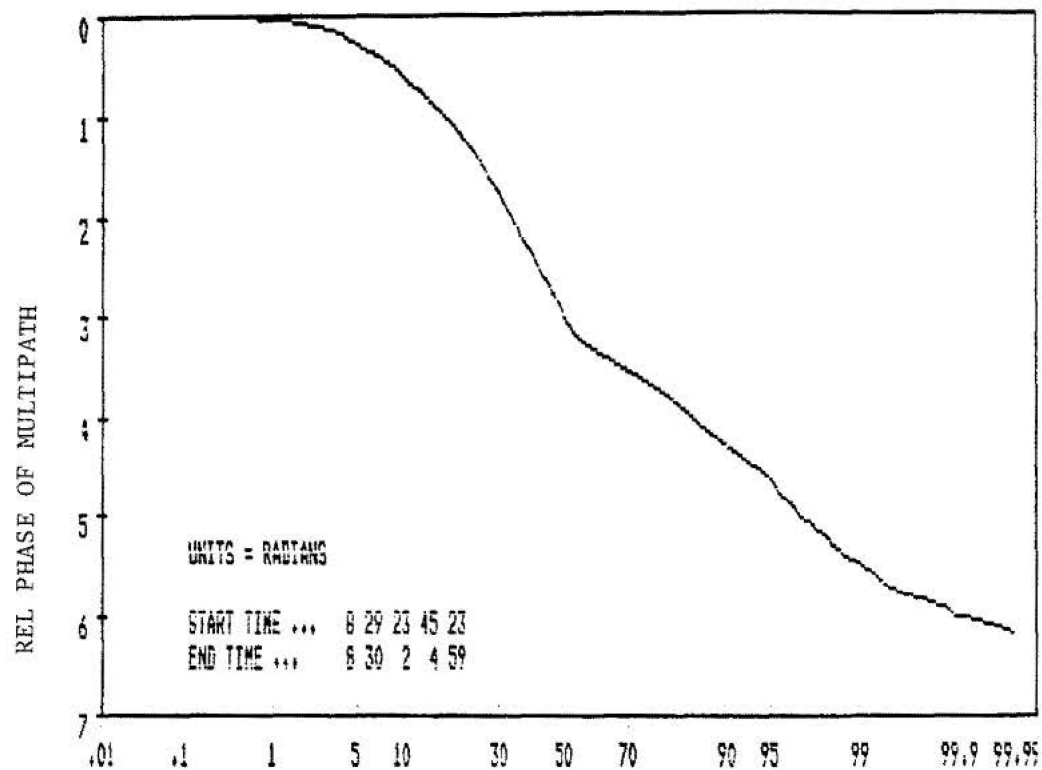


Figure 22. Multipath phase distributions for August 29 and 30.

the "nonminimum phase" data in order to gain some understanding of the phenomena.

- The frequency of the phenomena
- The duration of abnormal multipath phenomena
- The distributions of delays associated with the phenomena
- The distributions of relative power associated with the phenomena.

The "nonminimum phase" can cause a loss of the sync in the receiver when the phenomenon appears or disappears. An attempt to correct the in-band amplitude slope for a case of "nonminimum phase" case is not trivial, and in most of the cases will increase the magnitude of the delay slope (Allen, 1984).

Table 2 summarizes the relative amount of time that the propagation path exhibits "nonminimum phase" multipath. From Table 2 it can be seen that the propagation path exhibits "nonminimum phase" conditions for an appreciable amount of time. It is interesting to note that Channel A exhibits these conditions more often than Channel B does. It is shown also that more impulse responses with multipath components were detected for Channel A than for Channel B.

The large fraction of time that an abnormal multipath was found to exist on both channels and in particular on Channel A is striking. No other publication with this kind of information was found and no comparison with other data could be made.

The duration distributions of abnormal multipath were calculated and some typical results are presented in Figures 23 and 24. Nearly 40 percent of the time the duration of the phenomenon is only 1 s. And since the time resolution for our analysis is 1 s, (one impulse response was recorded each second), the actual time for these cases may be shorter. Longer time durations are typically found for the "August data." No significant distinction was found between the abnormal duration behavior of the two channels.

Four cumulative distributions of abnormal multipath relative power are presented in Figures 25 and 26. For 1 percent of the time the amplitude of the abnormal multipath is very near to the direct ray power (by definition it cannot be equal or larger). The reader is referred to Section 4.2 for the discussion on power measurement resolution.

Examples of cumulative distributions of delays for the abnormal multipath case are given in Figures 27 and 28. These cumulative distributions are based

Table 2. Relative Amount of Time that the Propagation Path Exhibits
"Nonminimum Phase" Response

Date	Total Number of Impulse Responses Recorded	Total Number of Responses with Multipath		Number of Responses with Nonminimum Phase			
		CH-A	CH-B	CH-A		CH-B	
March 22	14,511	12,025	11,201	3,751	(31%)	3,067	(27%)
March 23	15,115	13,525	12,077	6,004	(44%)	5,180	(42%)
March 24	13,665	8,081	8,142	2,484	(30%)	915	(11%)
August 29 (1)	15,215	12,373	9,656	6,913	(55%)	4,122	(42%)
August 29 (2)	15,180	11,094	9,532	6,582	(59%)	4,391	(45%)
August 30	15,205	10,121	8,932	2,634	(26%)	637	(7%)

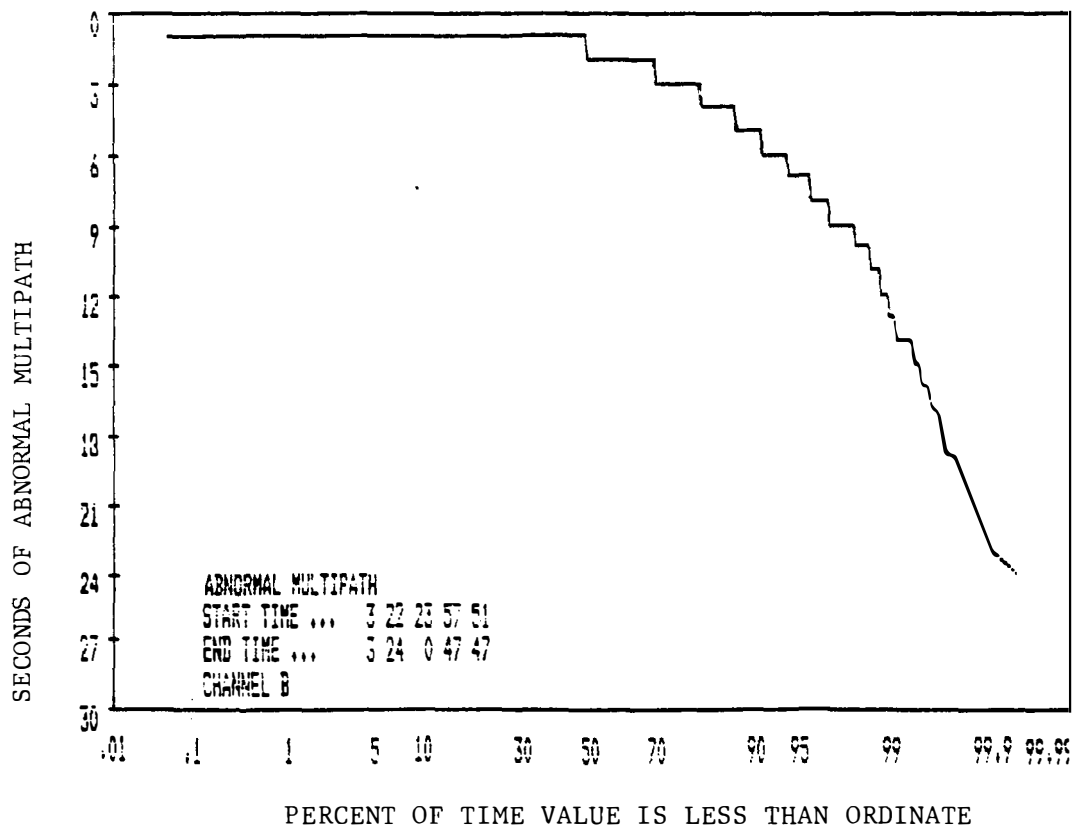
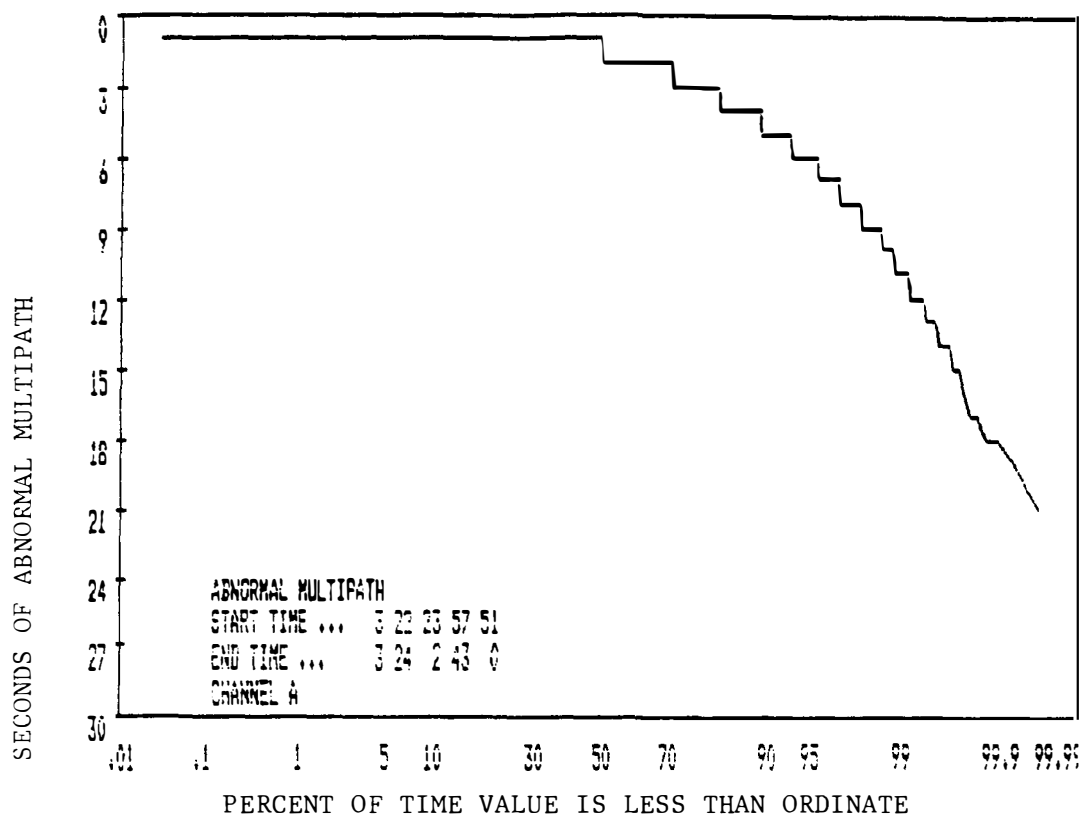


Figure 23. Distributions of abnormal multipath duration for March 22 to 24, Channels A and B.

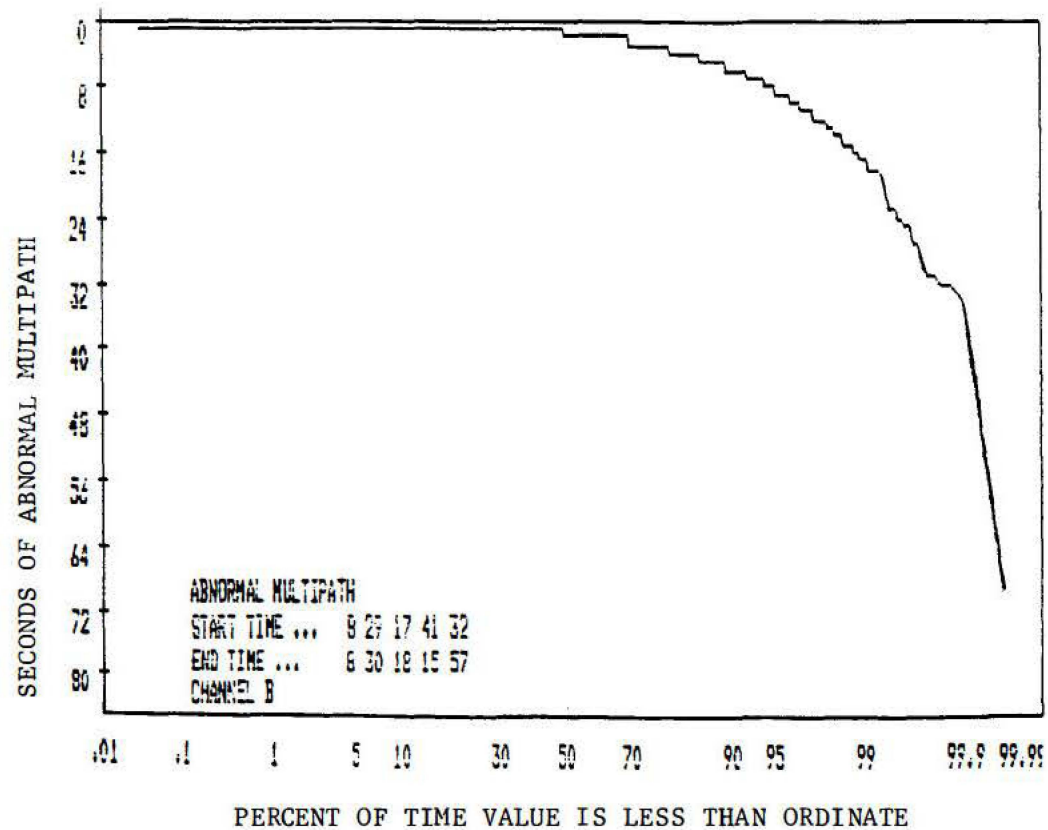
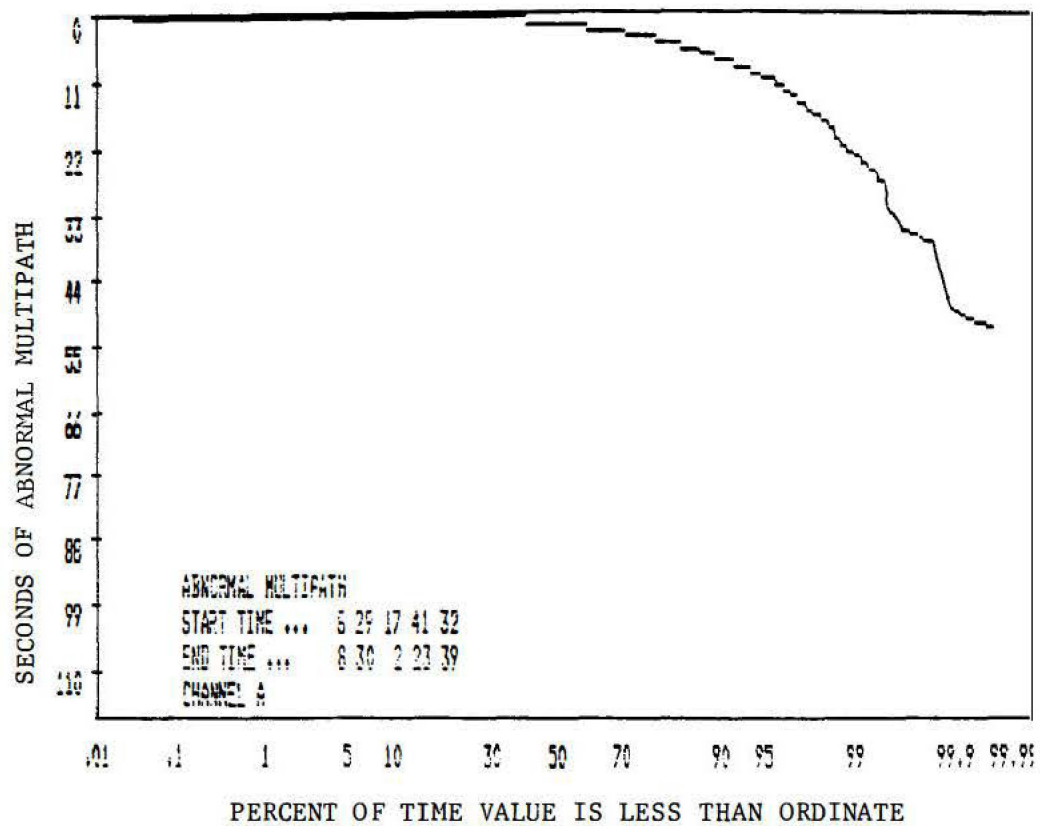


Figure 24. Distributions of abnormal multipath duration for August 29 and 30, Channels A and B.

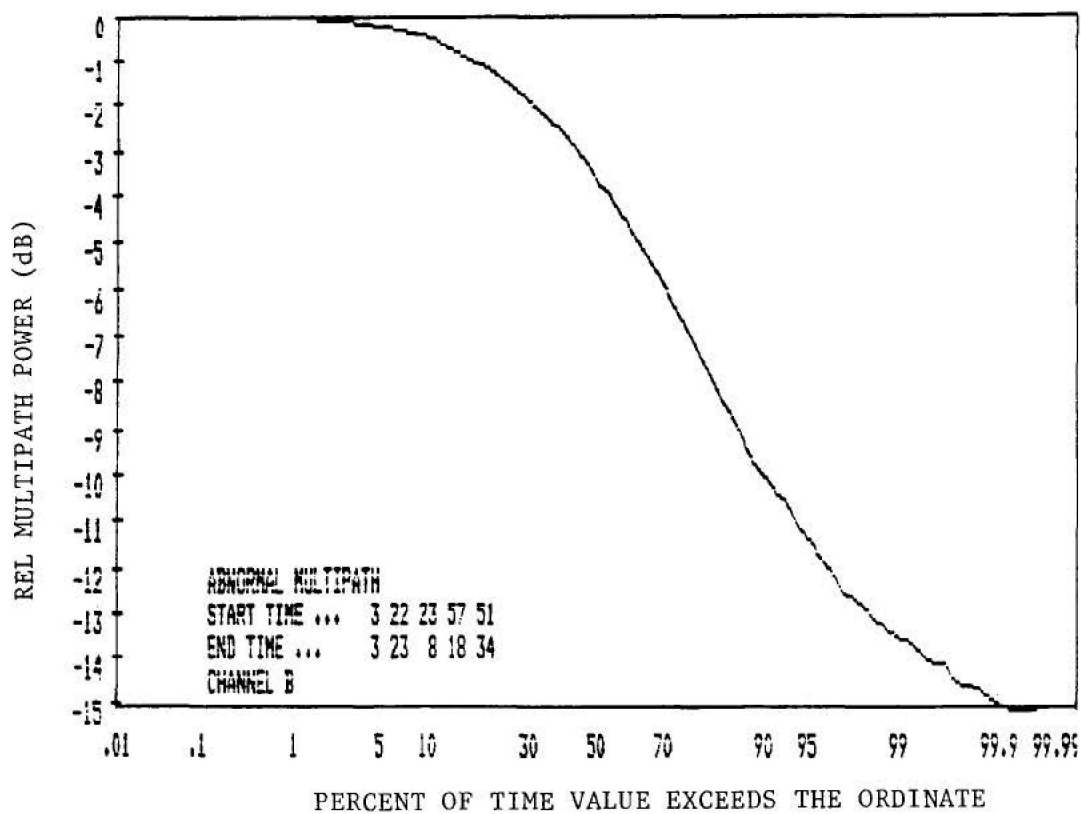
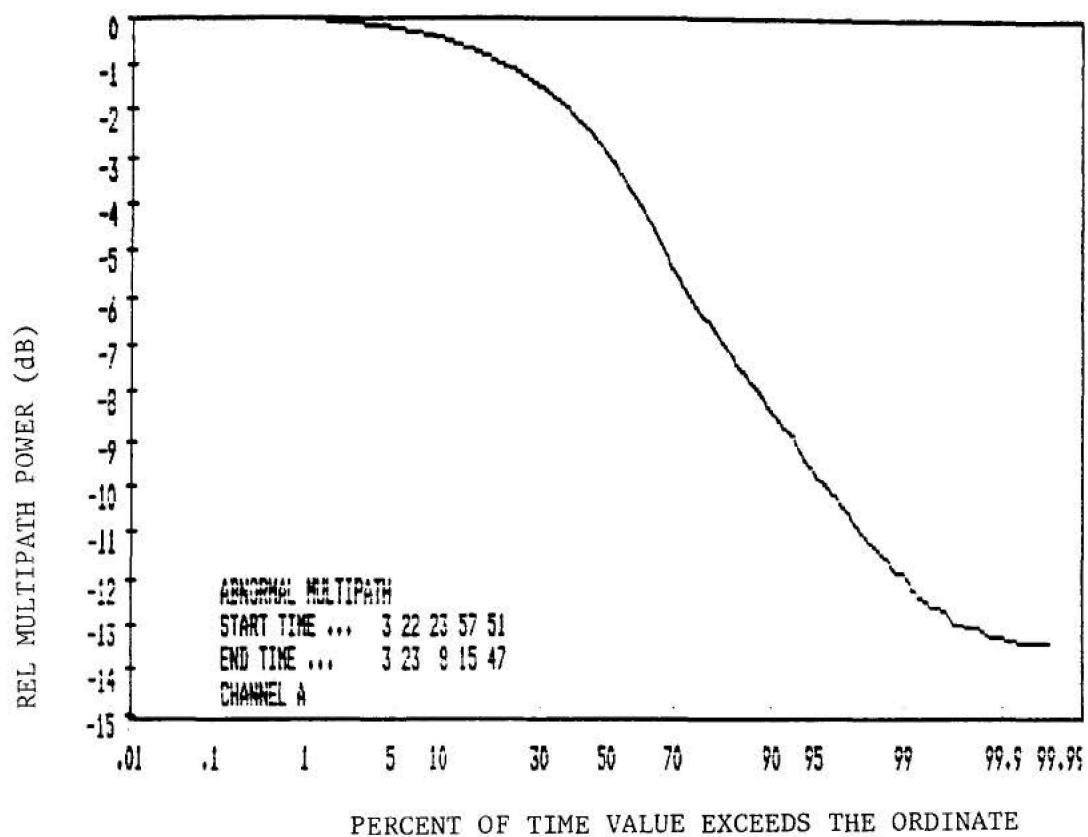


Figure 25. Distributions of abnormal multipath power for March 22 and 23.

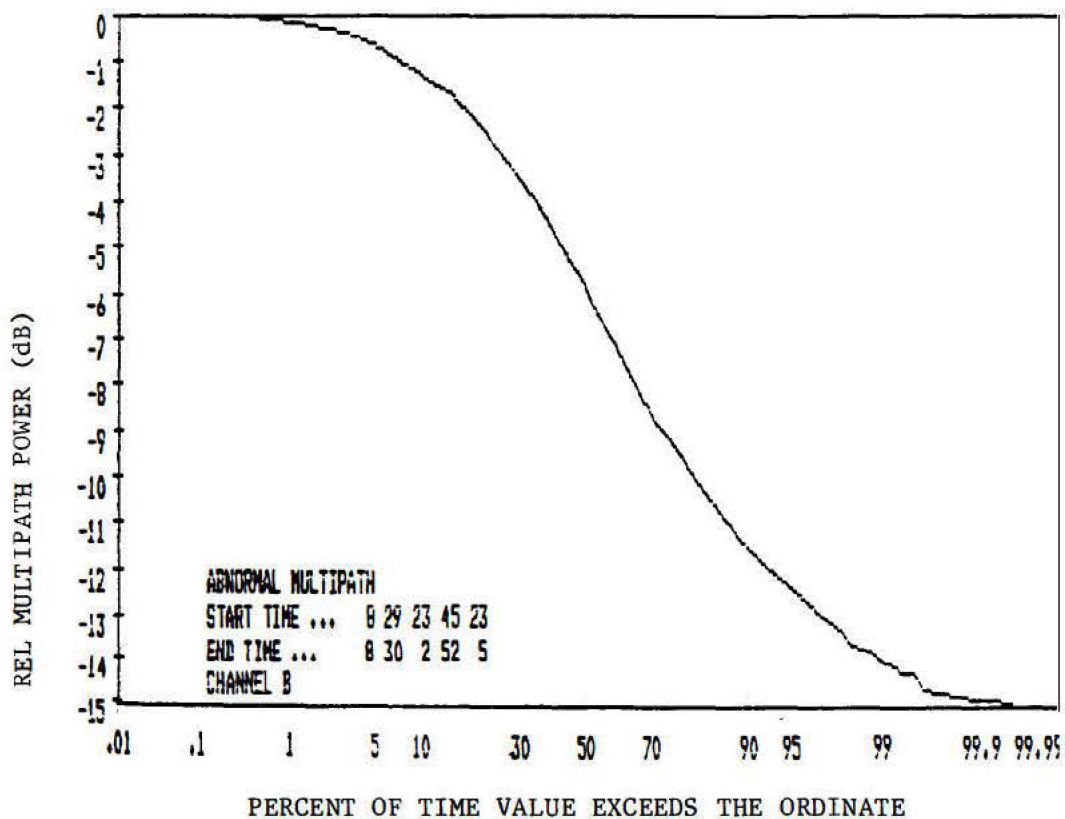
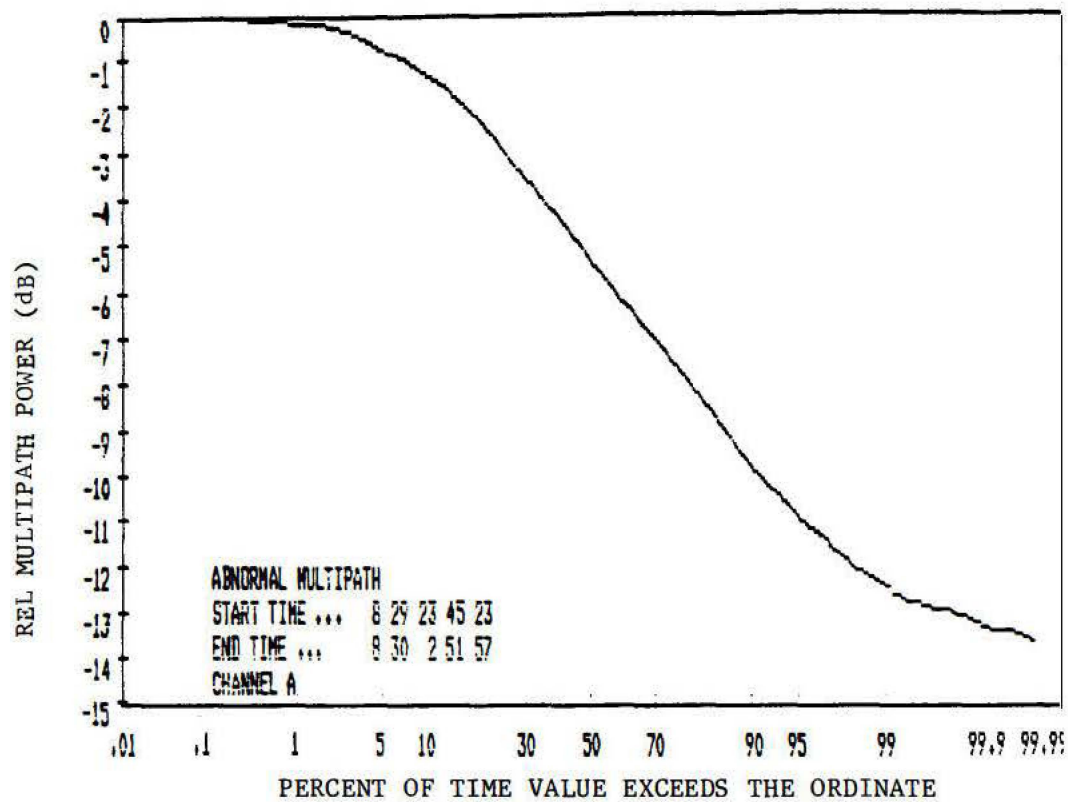


Figure 26. Distributions of abnormal multipath power for August 23 to 30.

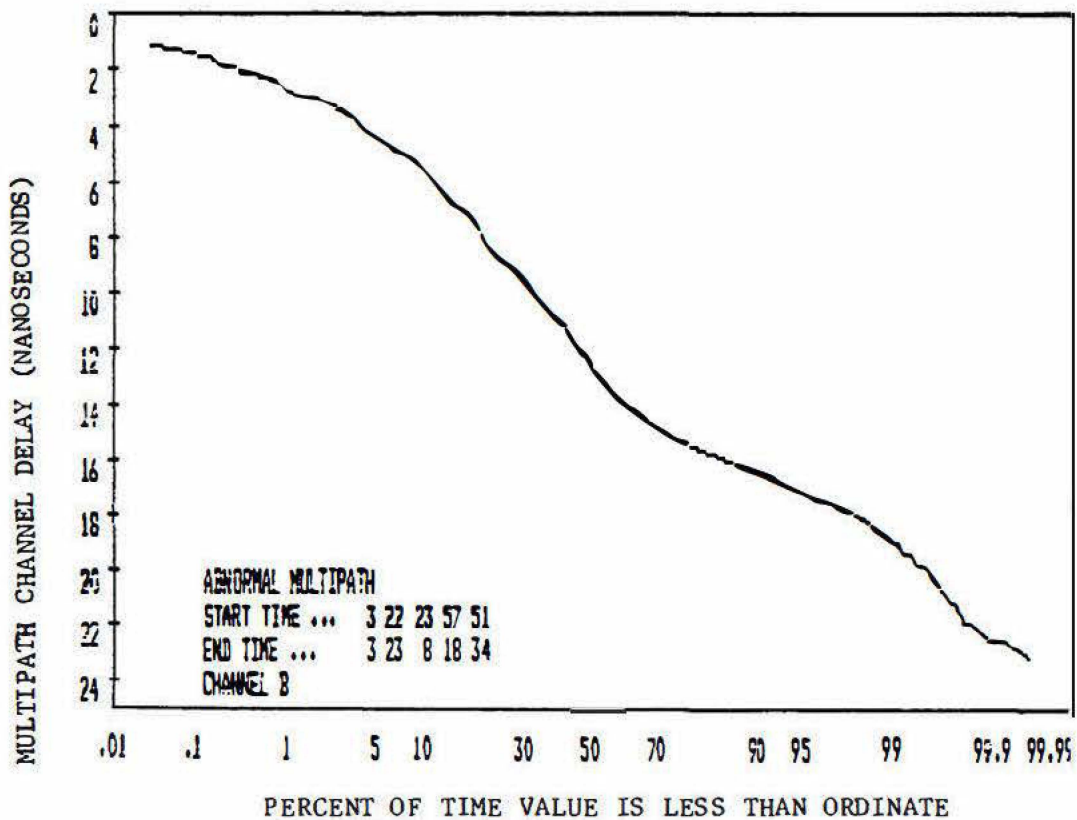
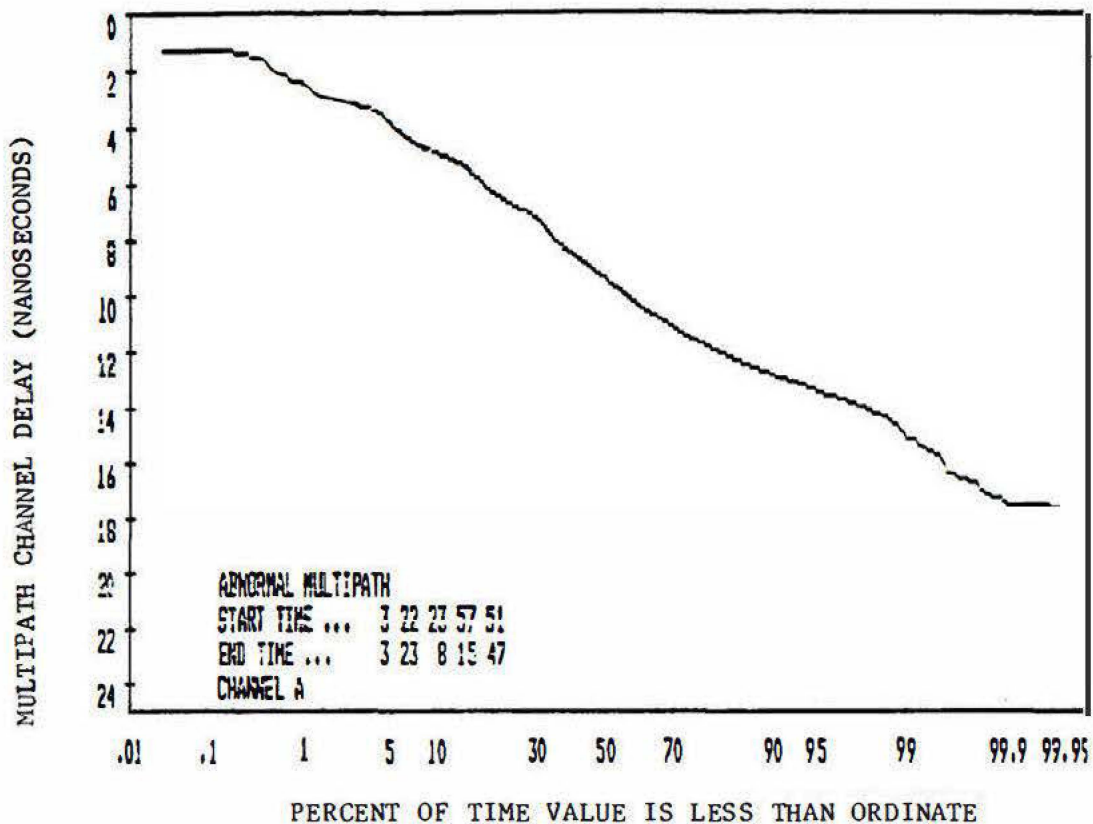


Figure 27. Distributions of abnormal multipath delays for March 22 and 23.

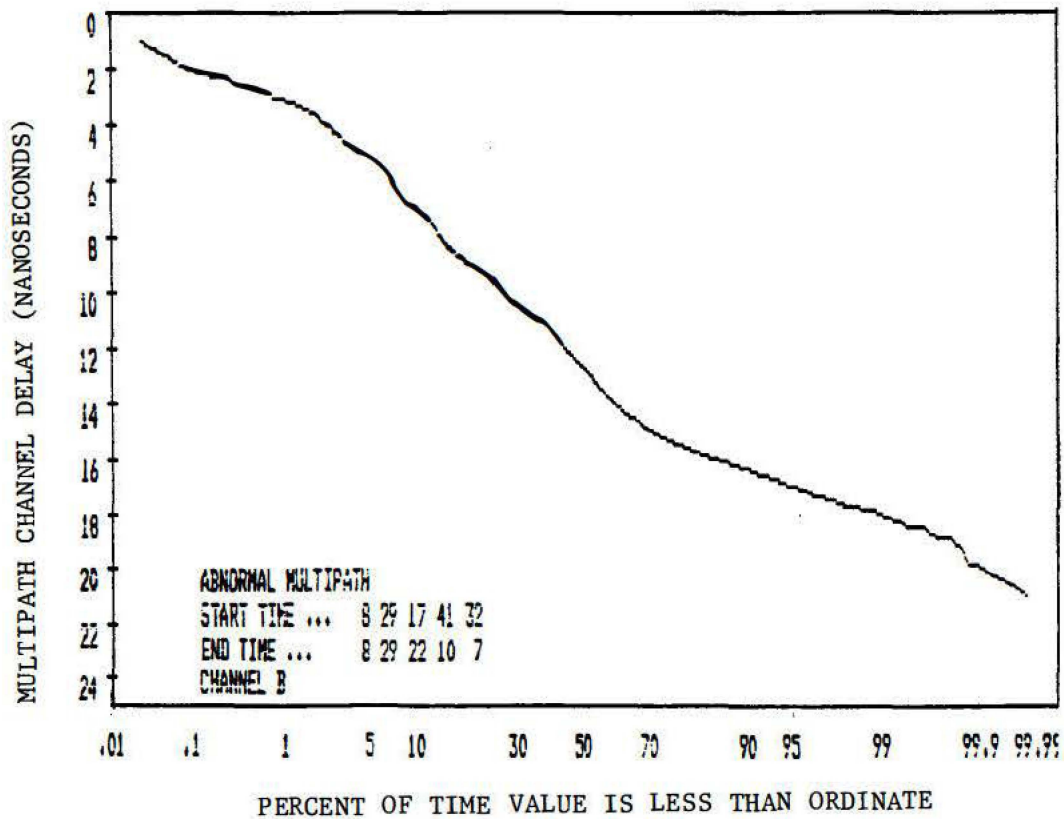
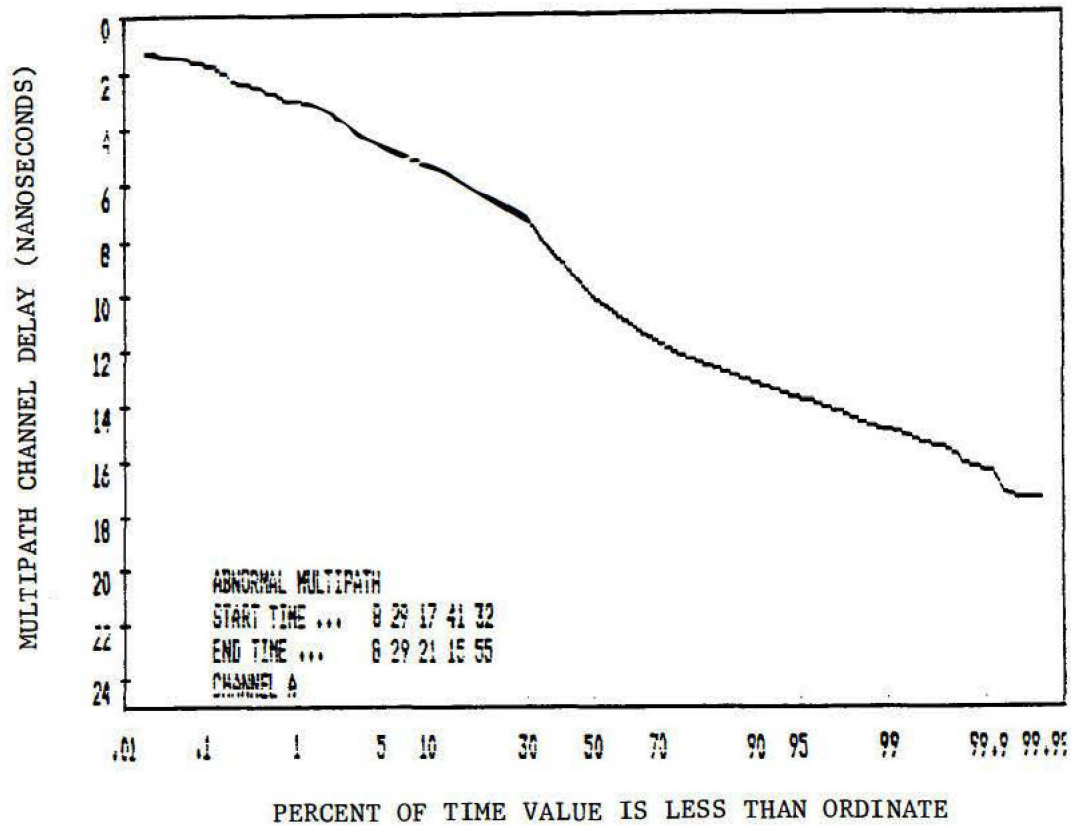


Figure 28. Distributions of abnormal multipath delays for August 29.

on a sample of 5000 impulse responses. It is interesting to note that delays of up to 22 ns were recorded on both channels. However, the median abnormal delays for Channel A are consistently smaller than those for Channel B by about 3 to 4 ns. Like the total multipath delay distributions, the abnormal delay distributions tend to be nearly normally distributed.

5. RESULTS AND DISCUSSION OF MULTIPATH DYNAMICS

This section is divided into six subsections. In these subsections results of various dynamic properties of multipath are presented and discussed. The topics to be covered are in that order: multipath power, multipath delays, multipath phase, collapse and development of multipath, impulse response width and amplitude slope. The data are based on the same measurement periods from March 1984 and August 1984 that were presented before.

It is believed that the data presented in this section will be of great value to those researchers and system developers interested in equalizer performance under severe path conditions.

5.1 Rate of Change in Multipath Power

The rate of change in power is calculated by measuring the change in multipath power between two time consecutive or successive impulse responses. Only time-consecutive responses were analyzed. A nonmultipath impulse response that follows a response with a multipath component was included in the calculation of change of power, since a collapse of a multipath is a dynamic change in the channel transfer function. The units that are used in the presentations are decibels per second (dB/s). In Figures 29 through 31, three examples of cumulative distributions of rate of change in multipath power are presented.

Note that for some 10 percent of the time, the rate of change is insignificant. Typical median values are 4 dB/s on both channels. Channel A has higher rates of change in power for the 99 and above percentiles. These high values are due to signal enhancement that appears to exist on the Channel A path only as was mentioned before in Section 4.2.

5.2 Rate of Change in Multipath Delays

The rate of change in multipath delays is calculated by measuring the change in multipath delay between two time-consecutive impulse responses. Only

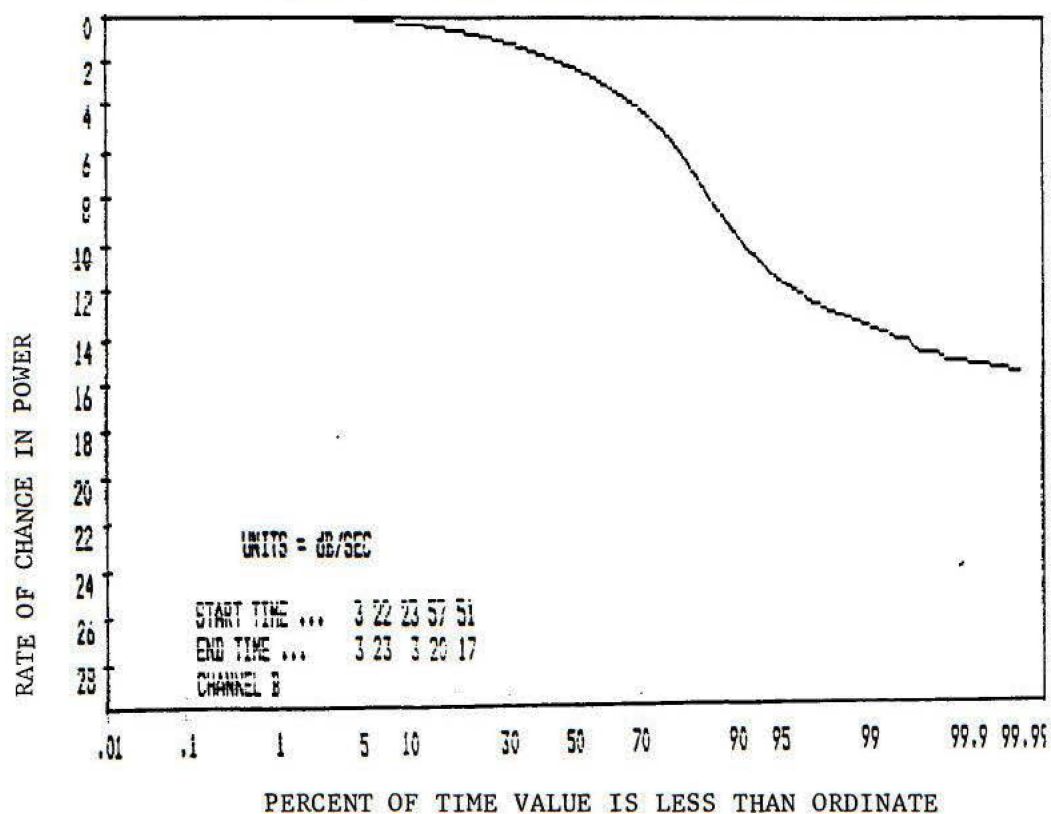
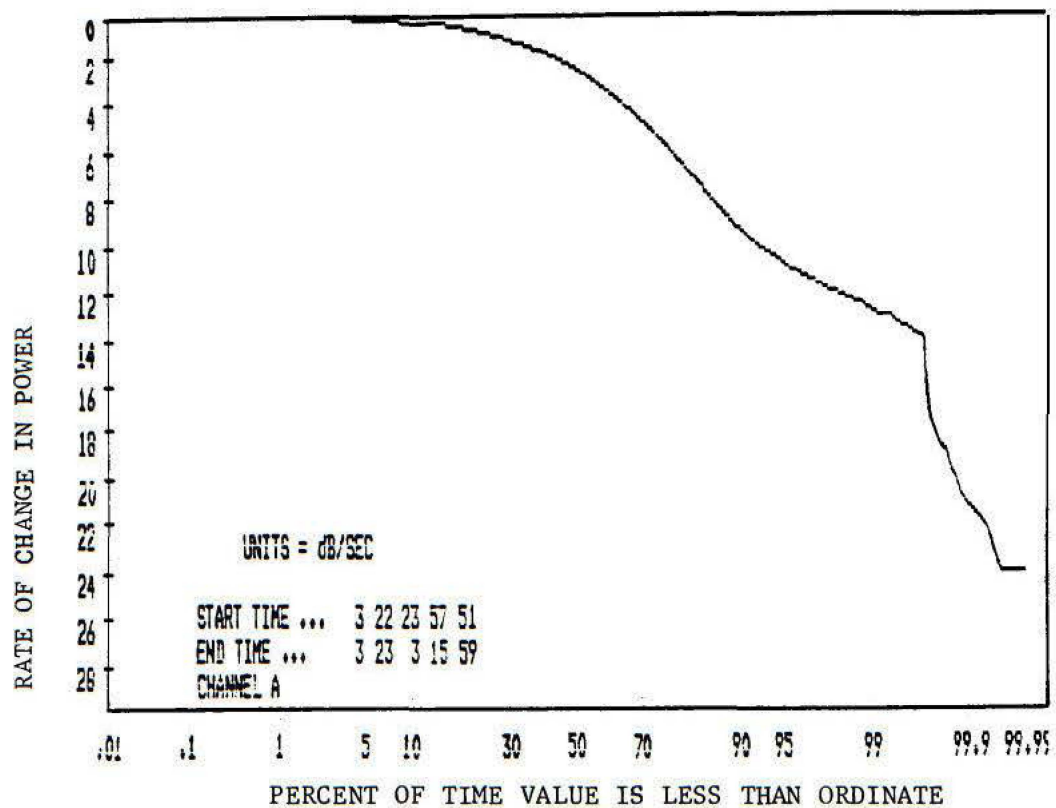
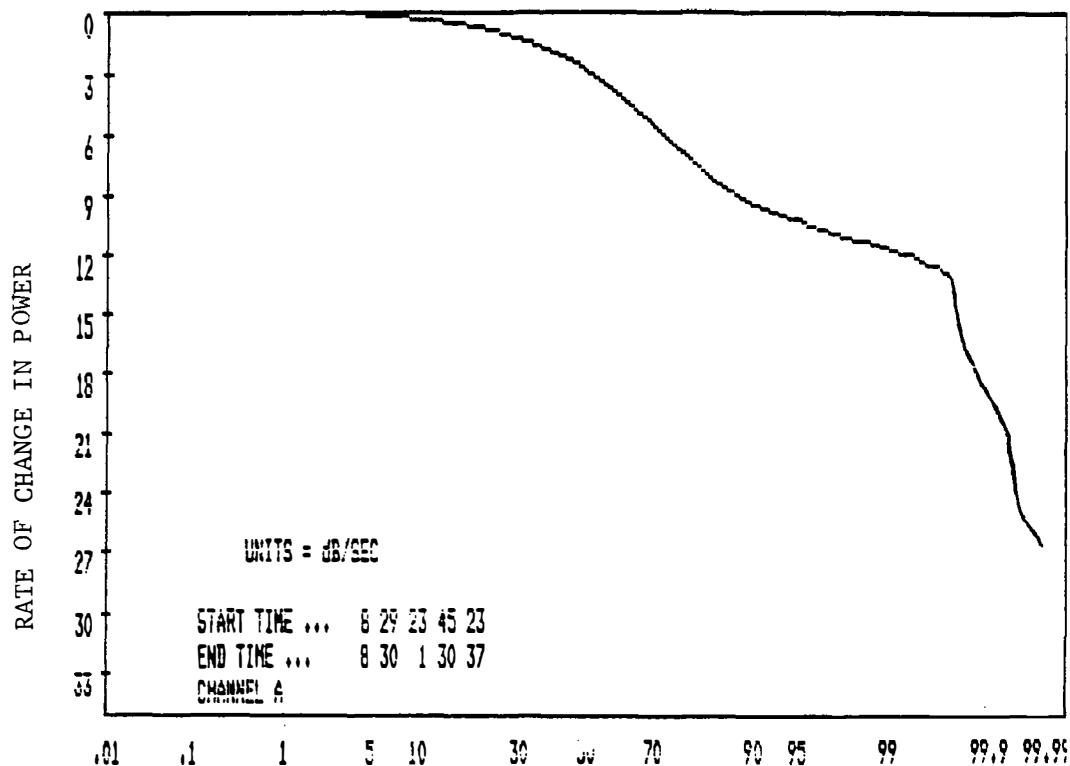
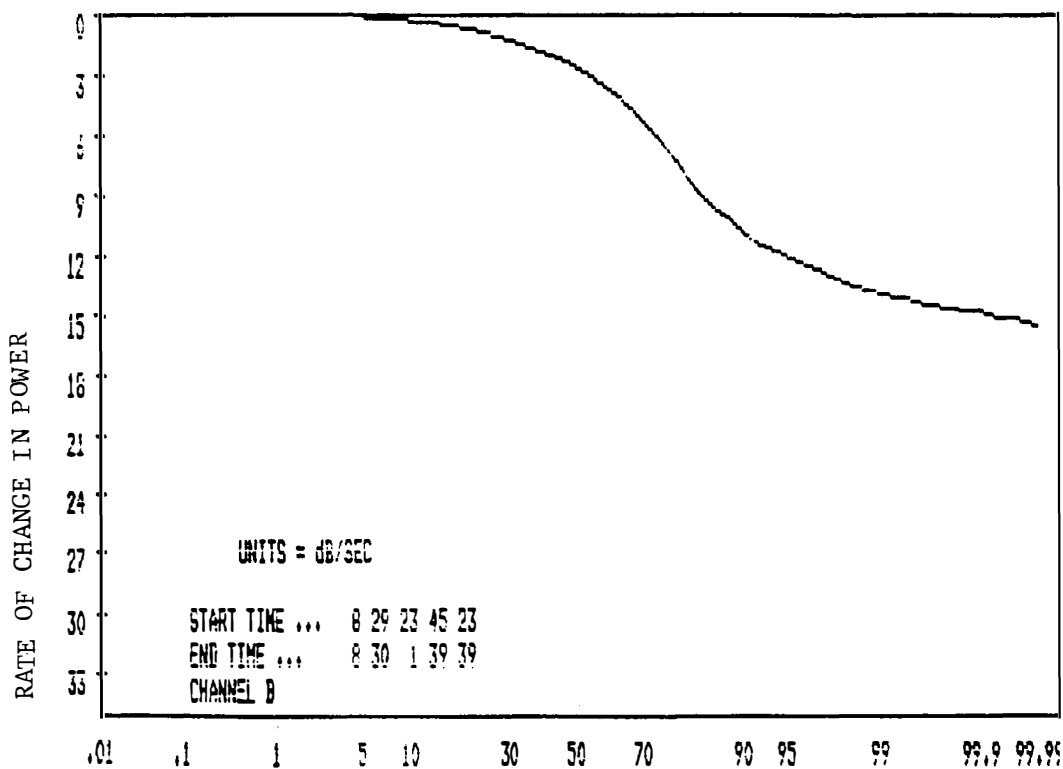


Figure 29. Distributions of rate of change in power for March 22 and 23.



PERCENT OF TIME VALUE IS LESS THAN ORDINATE



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

Figure 30. Distributions of rate of change in power for August 29 and 30.

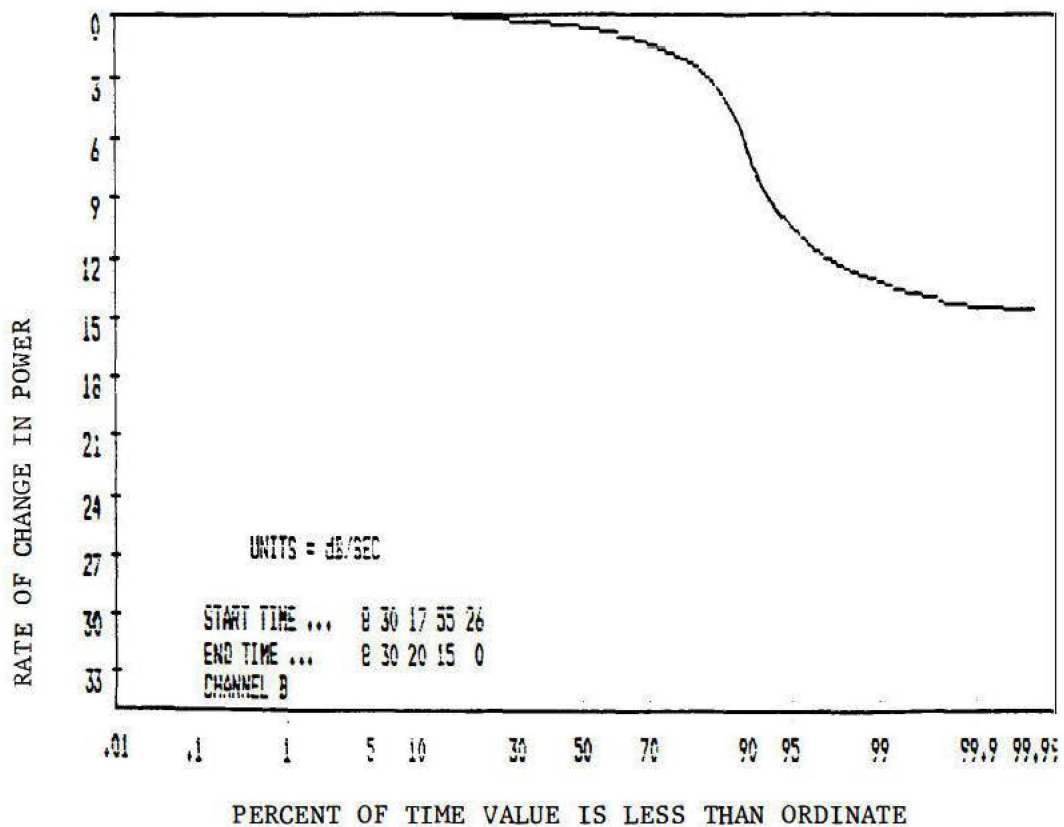
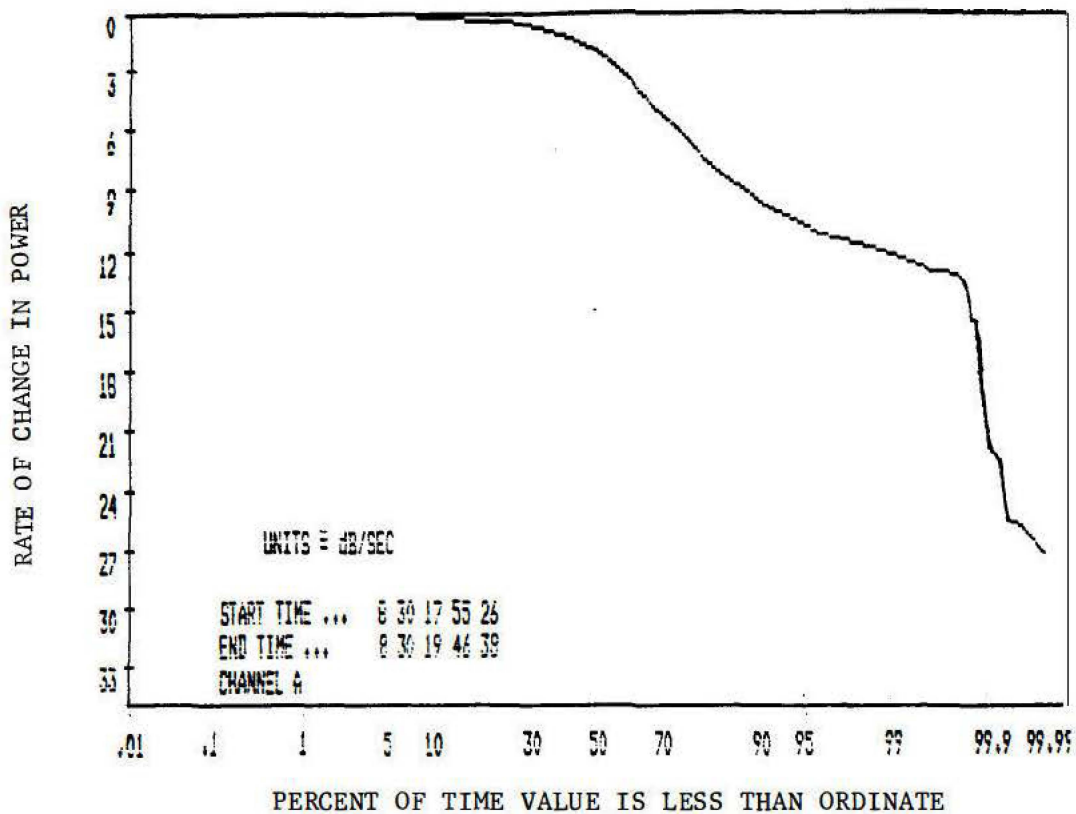


Figure 31. Distributions of rate of change in power for August 30.

time-consecutive responses having multipath components were analyzed with the exception of the first nonmultipath response that follows (as explained in Section 5.1). The units that are used are nanoseconds per second (ns/s). In Figures 32 through 34, six typical cumulative distributions of rate of change in delay are given. Each graph is based on 5000 impulse responses.

Once again one notes a difference between Channel A and Channel B distributions. As pointed out in Section 4.3, the delays registered on Channel B are typically longer than those registered on the Channel A propagation path. The proportional higher rates of change for Channel B are due to the same behavior. A change in delay is associated with a change in the spectral transfer function of a channel. It is easy to visualize the phenomenon for a "two-ray" multipath model. A change in delay corresponds to the movement of the transfer function (including nulls) to the left or to the right. This causes rapid changes in the in-band amplitude slope of the channel, which in turn degrades the receiver performance.

It should be emphasized that one has to associate the specific instantaneous power with the rate of change of delay in order to appreciate the full impact of the rate of change in delay on the receiver performance.

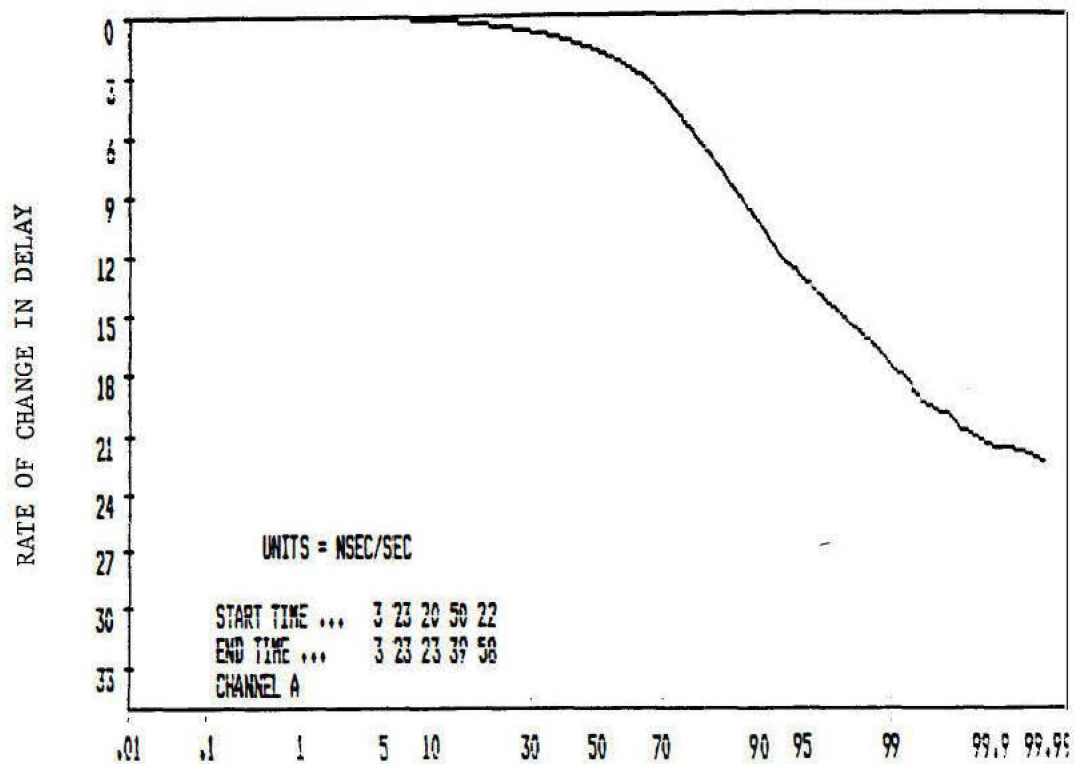
Median values for rate of change in delay for Channel A are 4 ns/s and median values for Channel B are 2 to 7 ns/s. The shapes of the distributions for Channels A and B are different. Rate of change in delays for Channel B are larger than those for Channel A due to Channel B antenna tilt. No significant differences between the "March" and "August data" were found.

5.3 Rate of Change in Multipath Phase

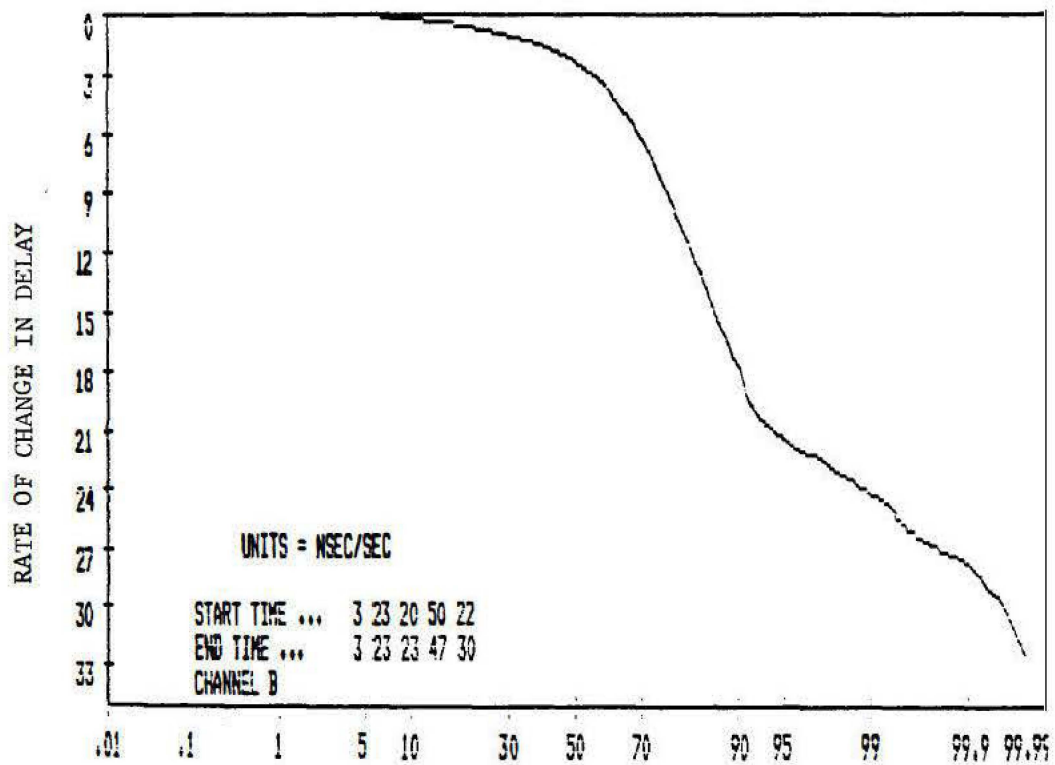
The rate of change in multipath phase is estimated from the difference in the relative phases of two consecutive Channel B impulse responses. The units used are radians per second (rad/s). Typical cumulative distributions of rate of change in phase are presented in Figures 35 through 37. Typical median values found for this rate of change are 0.3 to 2 rad/s. Between 5 and 10 percent of the time, the rate of change is near zero while for 99.9 percent of the time, the rate of change becomes maximal.

Rate of change in phase should have the same effect on the in-band amplitude slope as the rate of change in delay (see Section 5.2).

The following is an application to the rate of change in phase data. Changes in phase and delay are due to the movement of the refracting or



PERCENT OF TIME VALUE IS LESS THAN ORDINATE



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

Figure 32. Distributions of rate of change in delay for March 23.

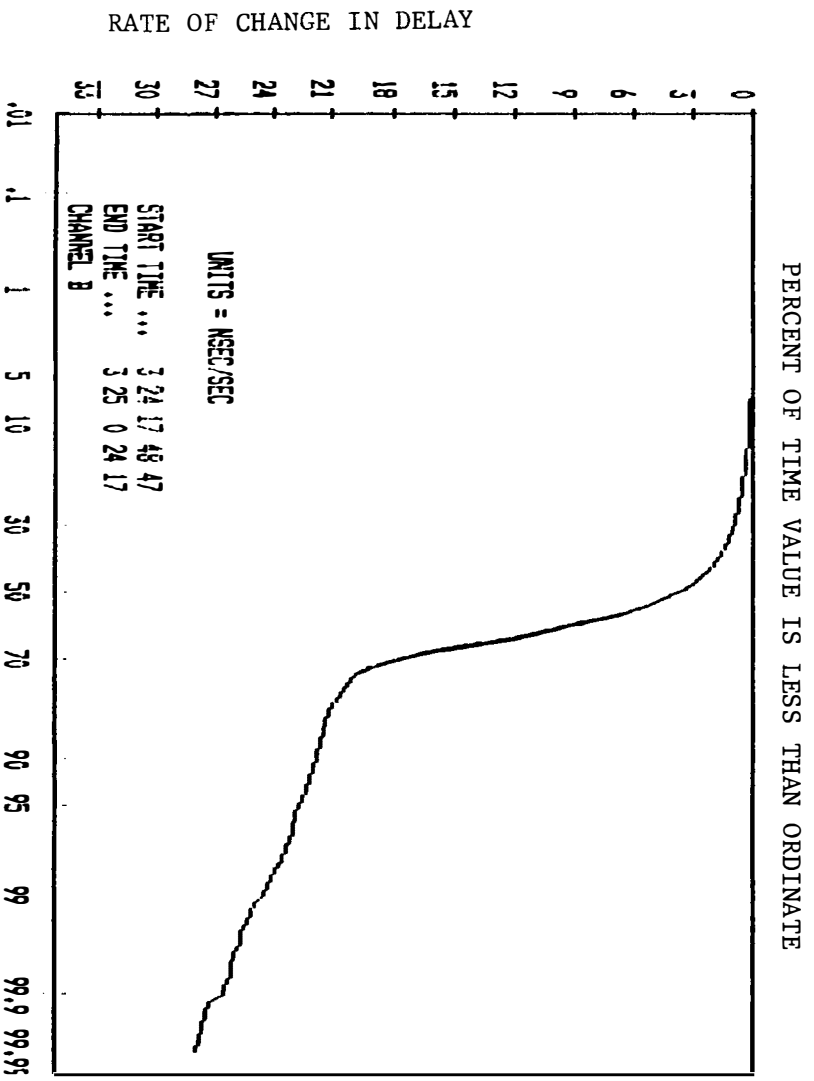
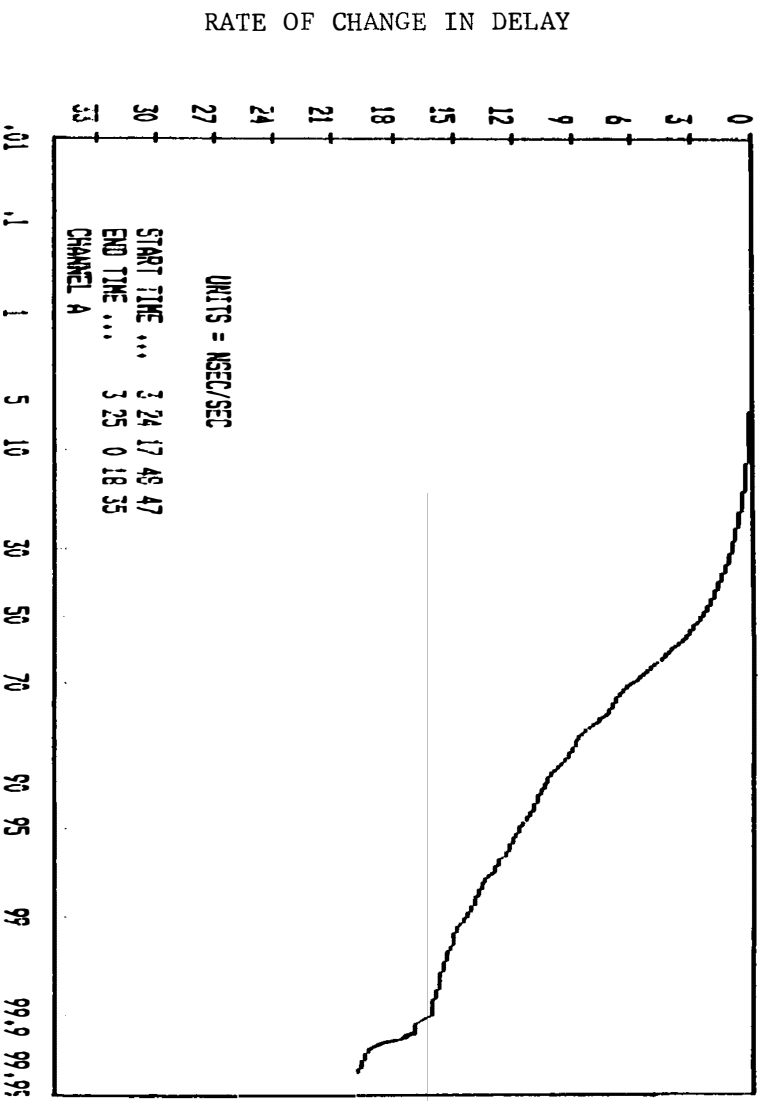
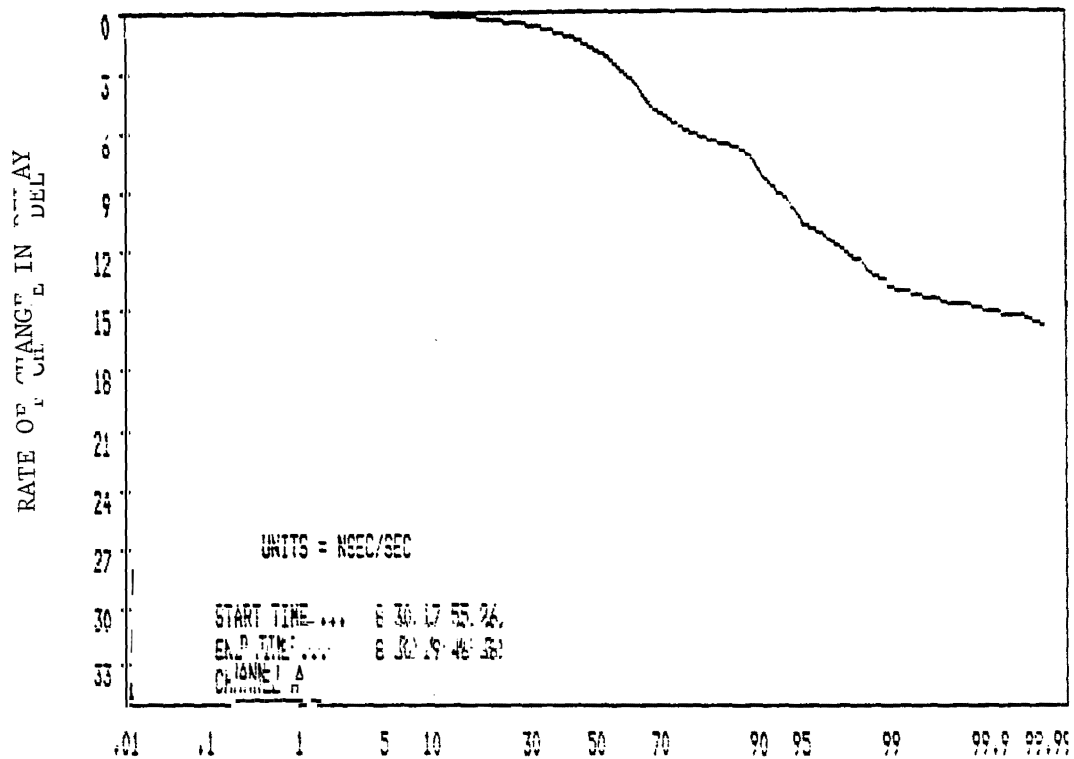
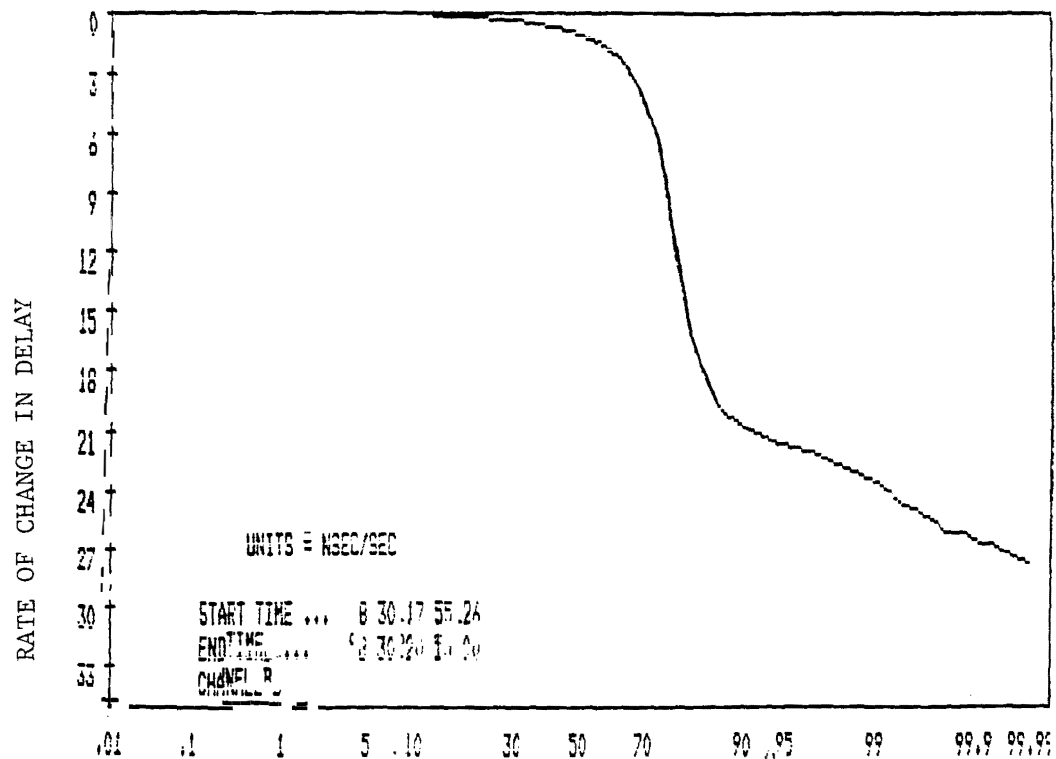


Figure 33. Distributions of rate of change in delay for March 24 and 25.



PERCENT OF TIME VALUE IS LESS THAN ORDINATE



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

Figure 34. Distributions of rate of change in delay for August 30.

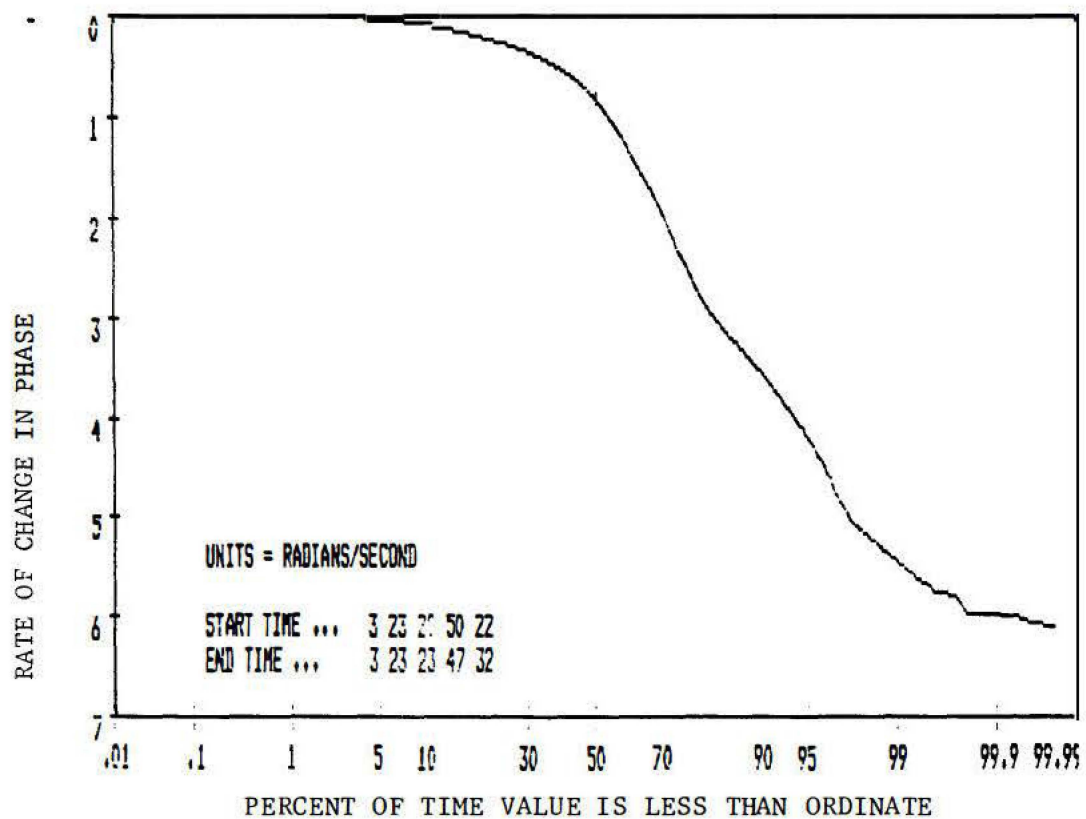
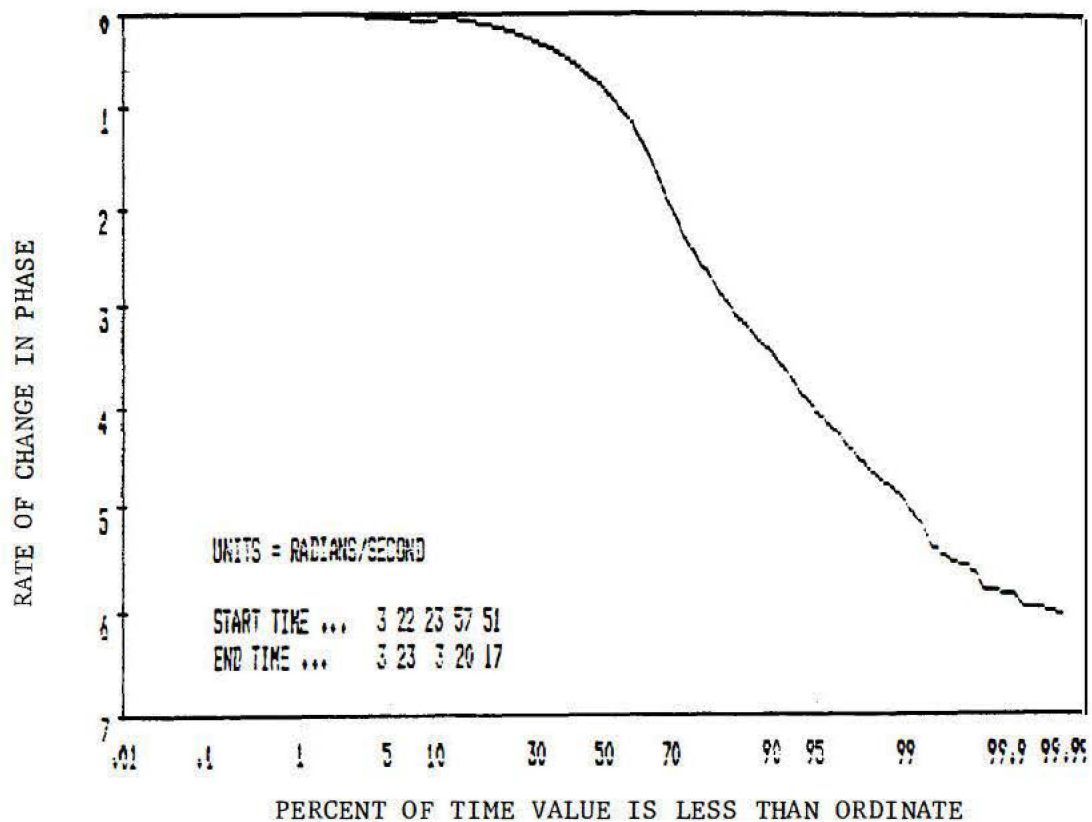


Figure 35. Distribution of rate of change in phase for March 22 and 23.

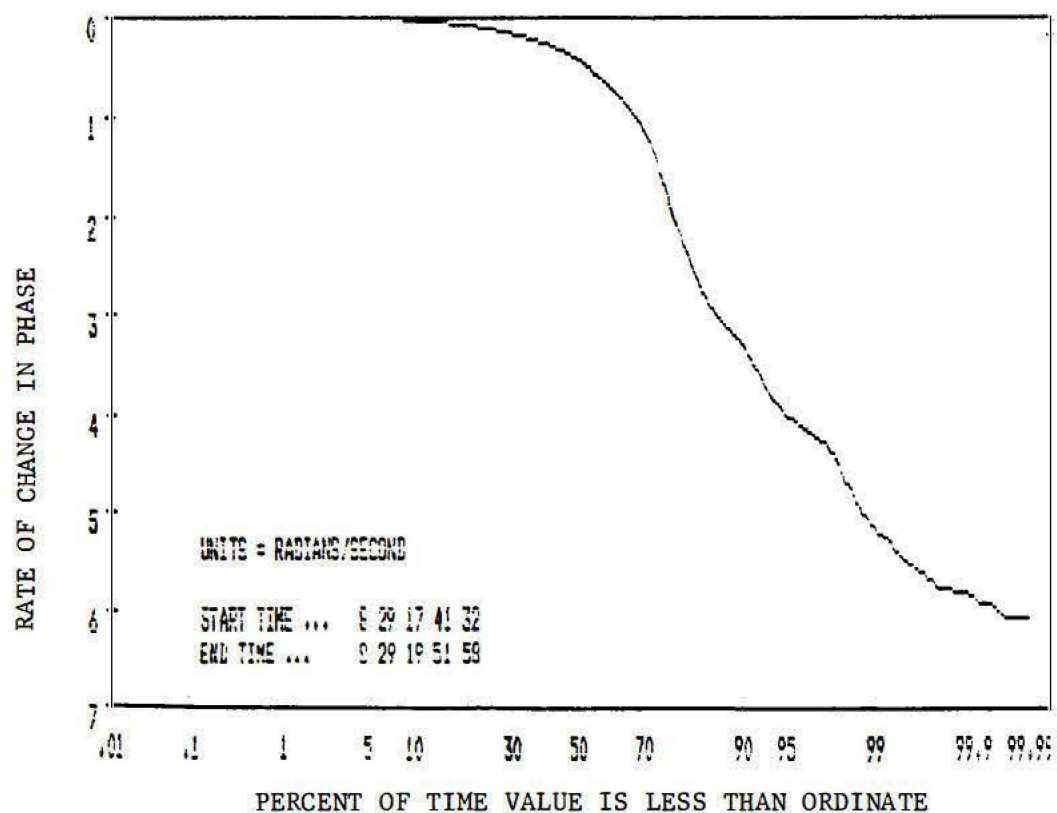
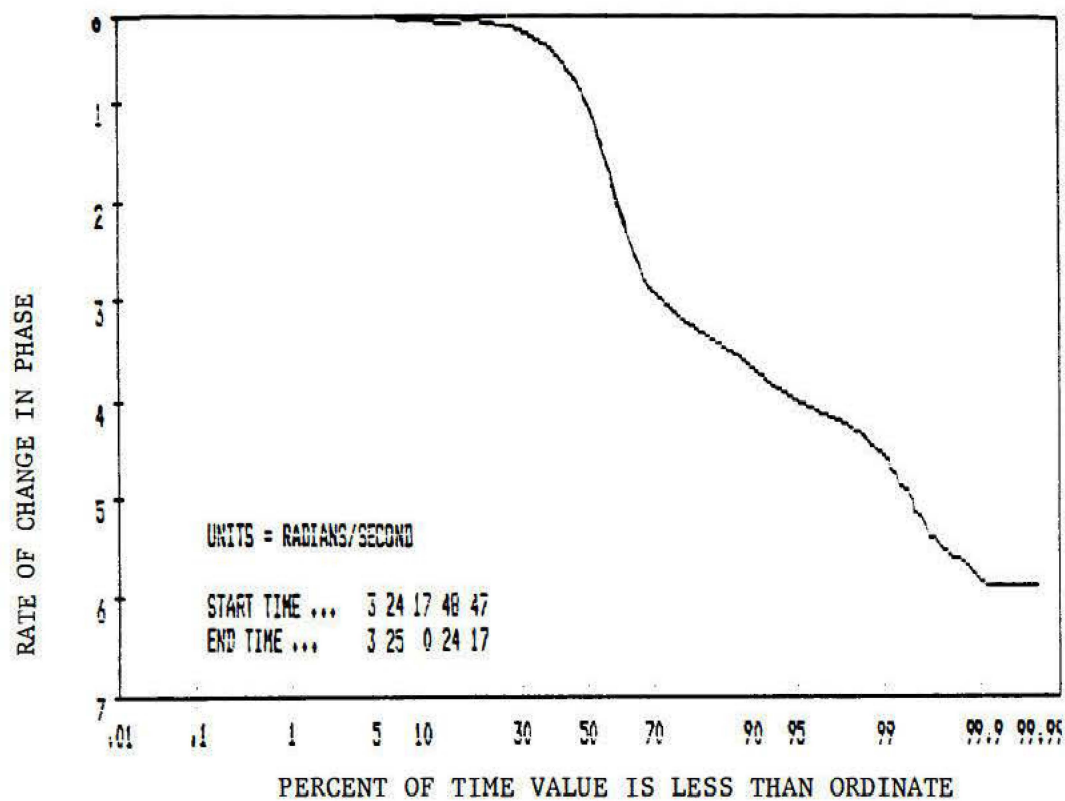
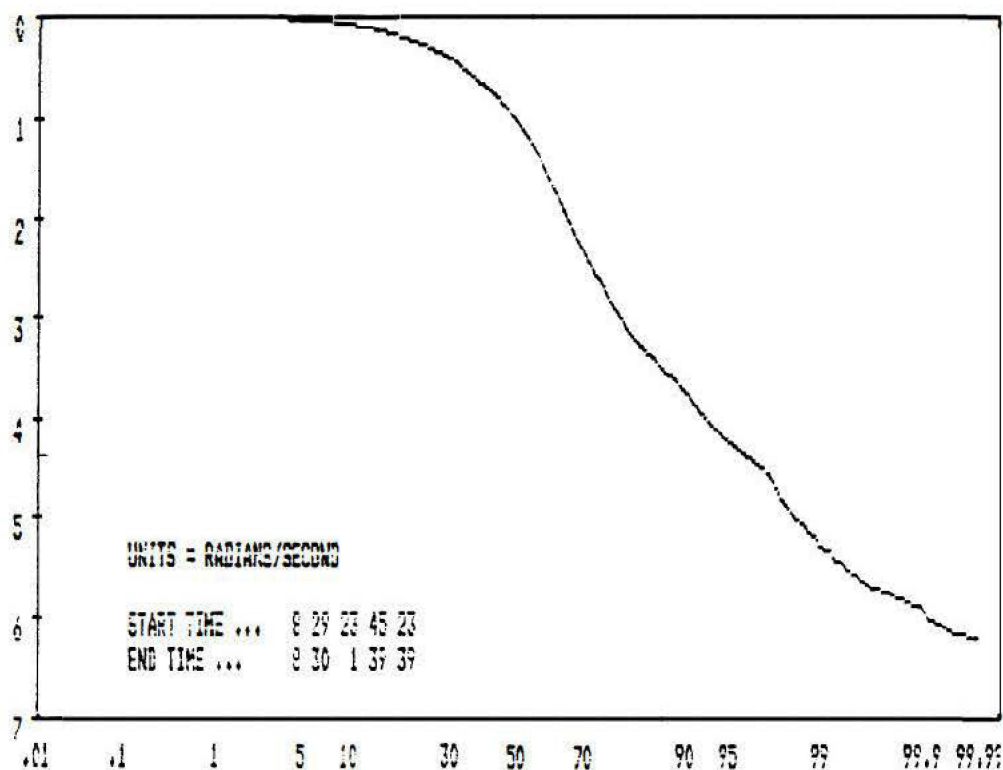


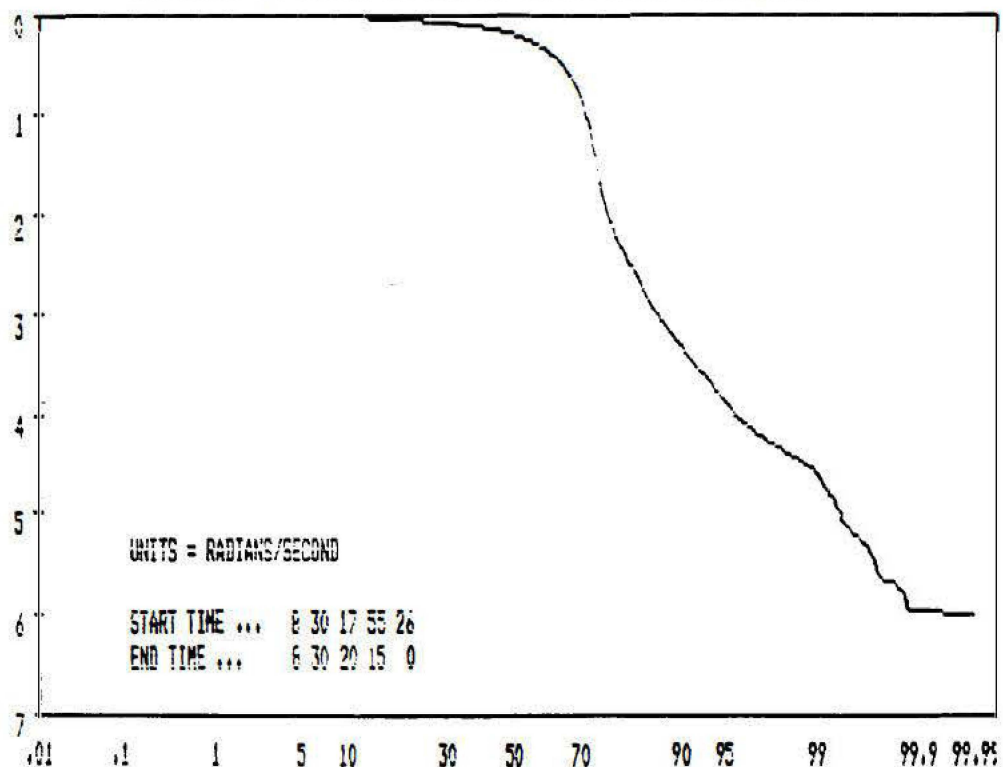
Figure 36. Distributions of rate of change in phase for March 24 and 25, August 29.

RATE OF CHANGE IN PHASE



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

RATE OF CHANGE IN PHASE



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

Figure 37. Distribution of rate of change in phase for August 29 and 30.

reflecting layer. Given the rate of change in phase or delays, one can, under several assumptions, calculate the speed of the dominant layer that supports the reflection. Bullington (1971) gives the following simple mathematical expression for the average vertical velocity of atmospheric irregularities.

$$\bar{v} = \frac{1}{\pi} (H_n - H_{n-1}) \frac{d\theta}{dt}$$

where $\frac{d\theta}{dt}$ is the rate of change in phase caused by an echo source moving vertically through a thickness $(H_n - H_{n-1})$ at a velocity v . H_n is the height of the n th Fresnel zone and $H_n - H_{n-1}$ is the thickness of the n th Fresnel zone.

5.4 Duration of Collapse and Development of Multipath

If the tests for rate of change in power, delay, and phase are aimed toward the understanding of multipath micro dynamics, then the following analysis serves to investigate the dynamics on a larger scale. In particular, we will look into the complete development and collapse of multipath events.

As defined in Section 3.3.2.1, the collapse time of a multipath is the elapsed time between the emergence of a multipath until it disappears. The time is measured by counting only time-consecutive impulse responses in which multipath occurs. The development time is defined as the time that elapses between the last collapse and the new emergence of multipath, again on time consecutive responses only and for full uninterrupted cycles. We refer here to the time periods only. The strength of the multipath phenomena enters only in classification of a response as having or not having multipath.

In Figures 38 and 39, cumulative distributions of collapse and development are shown. They are based on 5000 responses each. Note that the development time periods are always shorter than collapse time periods. This should probably be of no surprise, since data were collected when a burst of error was detected in one of the receivers. For about 30 percent of the time the multipath duration is of the order of one second or less. Median values are 4 seconds for collapse time and a little bit less for development.

Comparing data for the August and March periods, one finds that larger values for collapse and development are found in the summertime. The largest values found are 140 seconds in the "August data" and 63 seconds in the "March data."

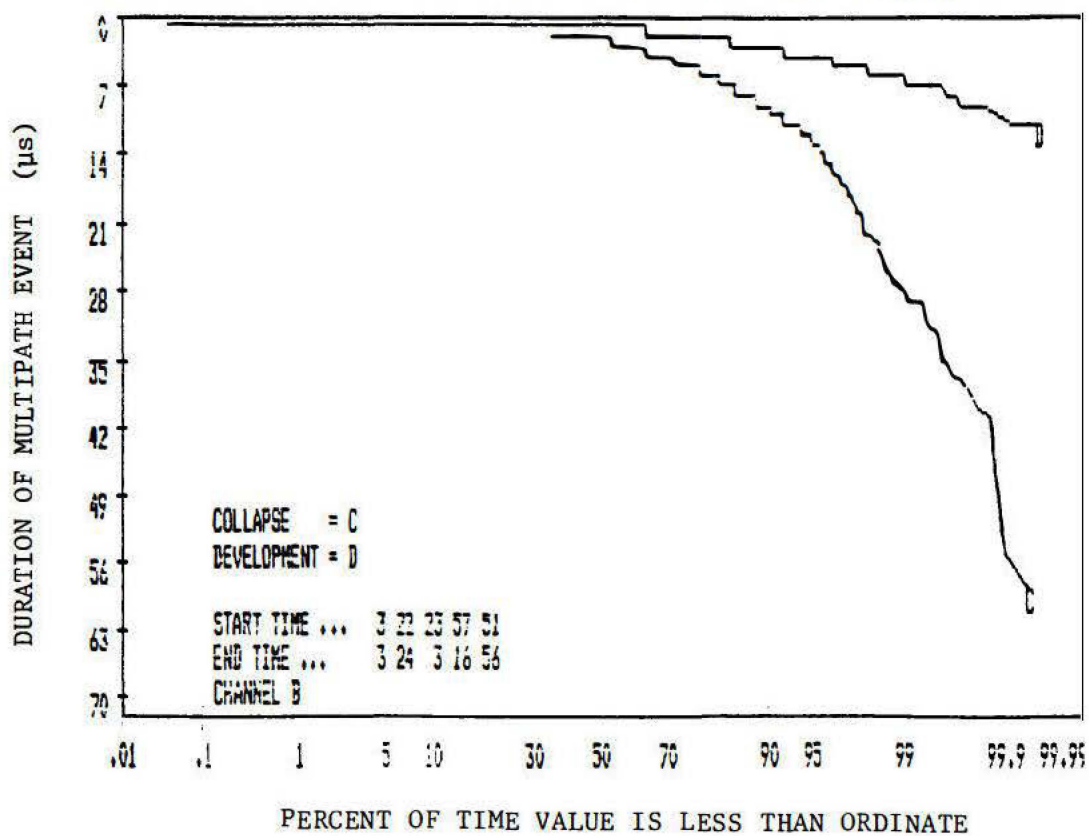
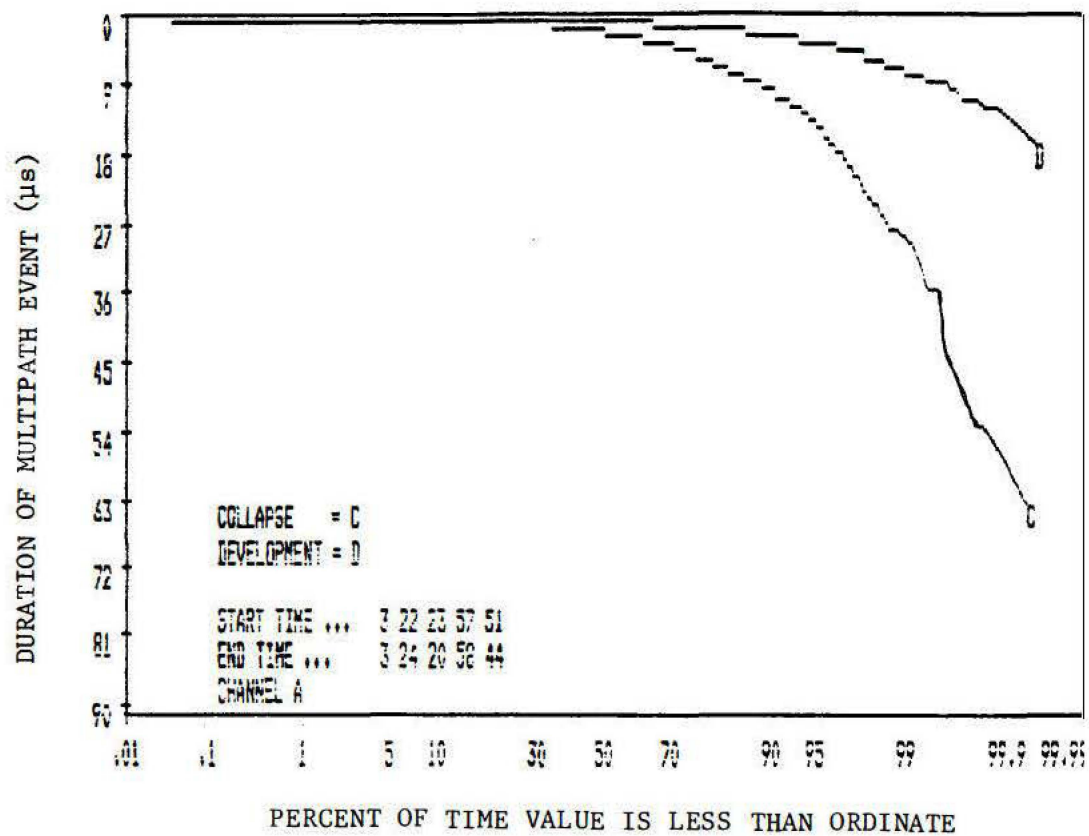


Figure 38. Distributions of duration of a multipath event (development and collapse) for March 22 and 24.

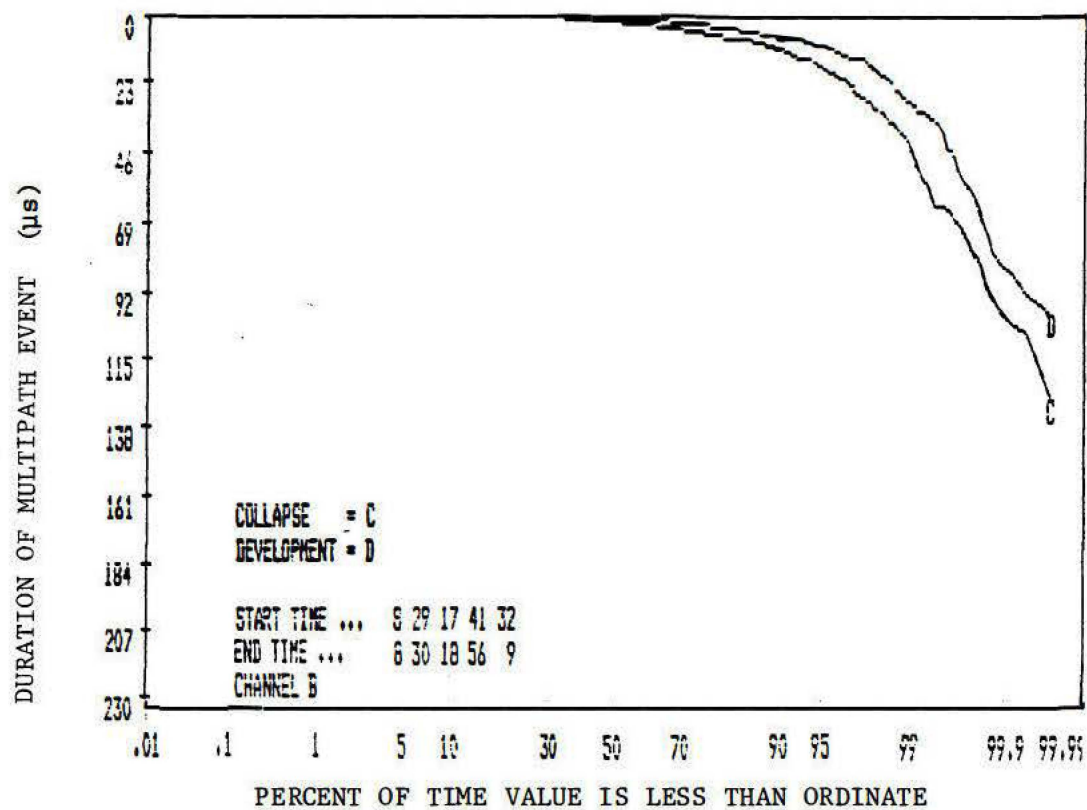
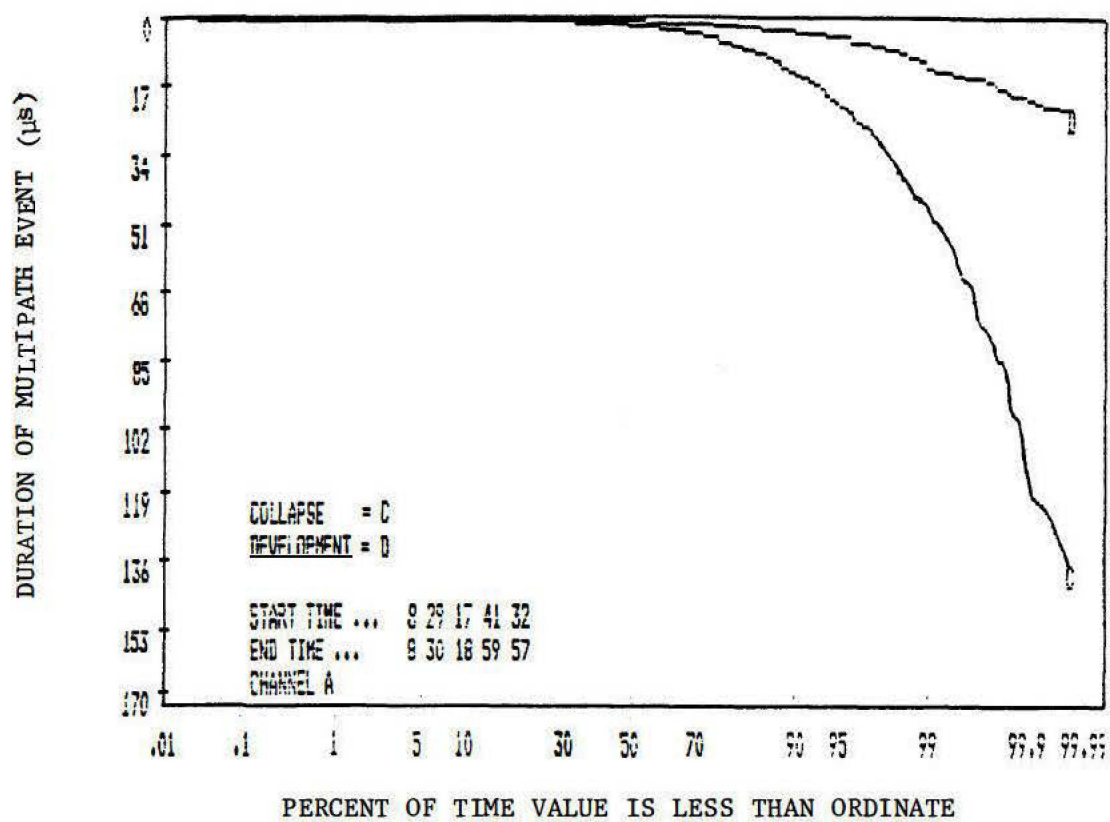


Figure 39. Distributions of duration of a multipath event (development and collapse) for August 29 and 30.

5.5 Impulse Response Width Statistics

The width of each impulse response is measured for three different power levels, -1, -3, and -10 dB. The three power levels were chosen in order to describe fully the statistics of the impulse response envelope. The power level refers to the highest peak power within the impulse response. The total width of the impulse response is measured for each particular power level. The PN probe data rate during the experiments was 150 Mb/s. The pulse width was 6.66 ns. The theoretical autocorrelation function (impulse response) for this pulse is twice the pulse width (see Linfield, et al., 1976), i.e., 13.33 ns. Figures 40 through 43 show a set of 24 cumulative distribution plots of impulse response width. Figures 40 and 41 refer to the "March data" and Figures 42 and 43 refer to the "August data."

Fairly wide responses were measured on both channels for most of the time. If the -10 dB level is to symbolize the base width of the pulse, then it is seen that for some 98 percent of the time this width exceeds 30 ns and henceforth the -10 dB level width is larger than the theoretical impulse response width associated with a nonmultipath impulse response. The data presented in Table 1 indicate that multipath was detected for some 61 to 77 percent of the recorded time (the time that a burst of error was detected on one of the wideband receivers under test). It is believed that the difference between the number of detected multipath impulse responses and the large percentage of time that a response wider than the theoretical impulse response was recorded (see Figures 40 to 43) is due to the "broadening" of the received response not associated with the deformation of the response envelope.

Skerjanec (1972) experienced broadening of received pulses (with a different test set) and concluded, based on Vogler's (1969) theoretical analysis, that broadening of a received pulse is due to reflections from abrupt atmospheric layers or possibly from ground reflections, rather than from small effects of atmospheric dispersion and absorption on the direct ray only. (Such effects of atmospheric dispersion and absorption are known to take place for carrier frequencies larger than 18 GHz.)

For very short time periods (Figures 41 and 43), narrower responses than the theoretical responses were recorded, the cause for this is due to severe power fading, where the impulse collapses below resolution of the probe.

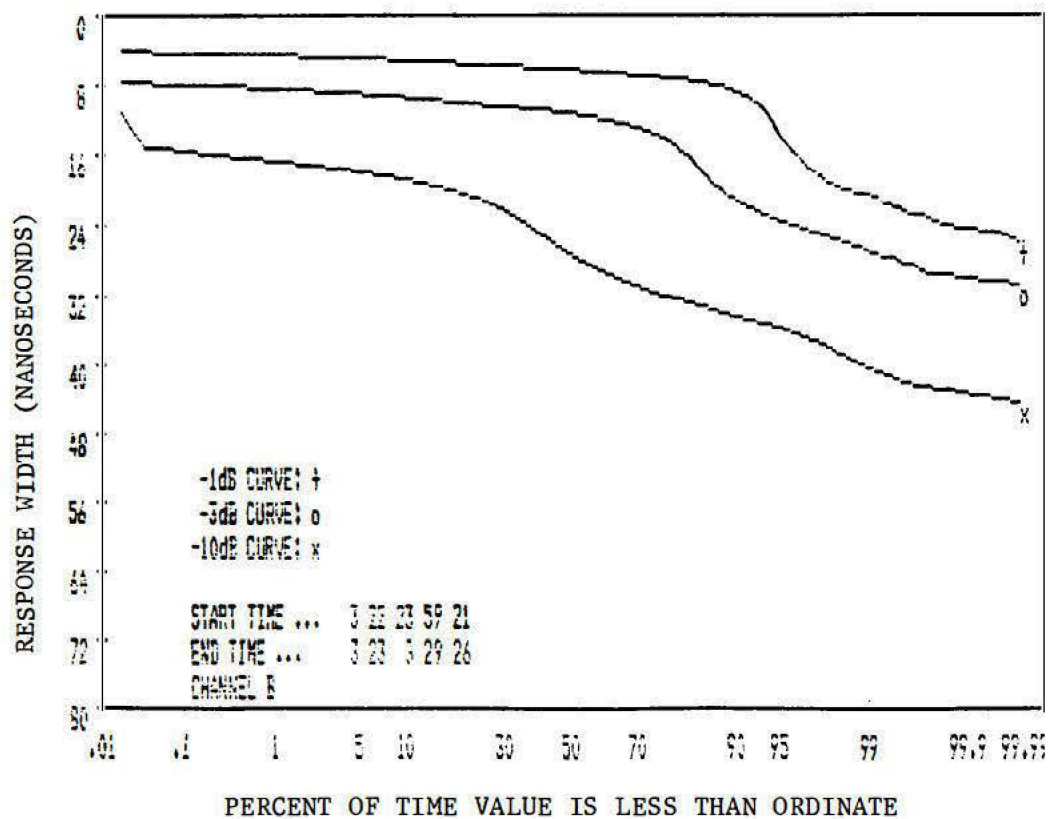
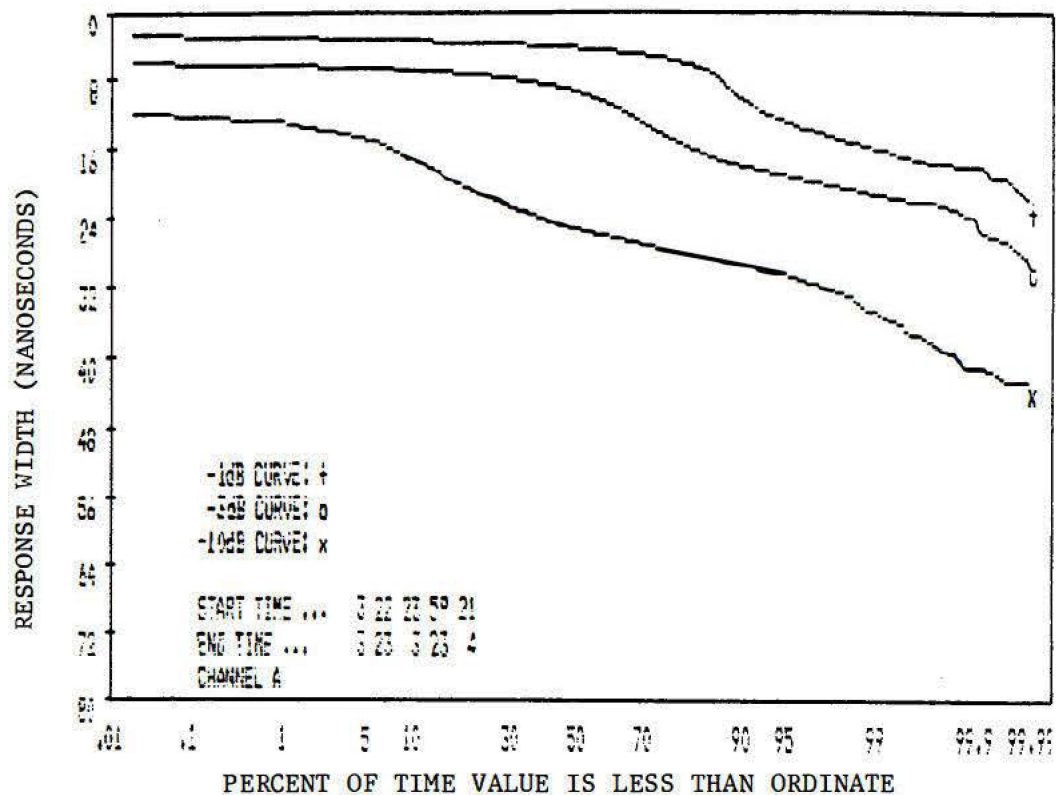


Figure 40. Distributions of impulse response width for Channels A and B for March 22 and 23.

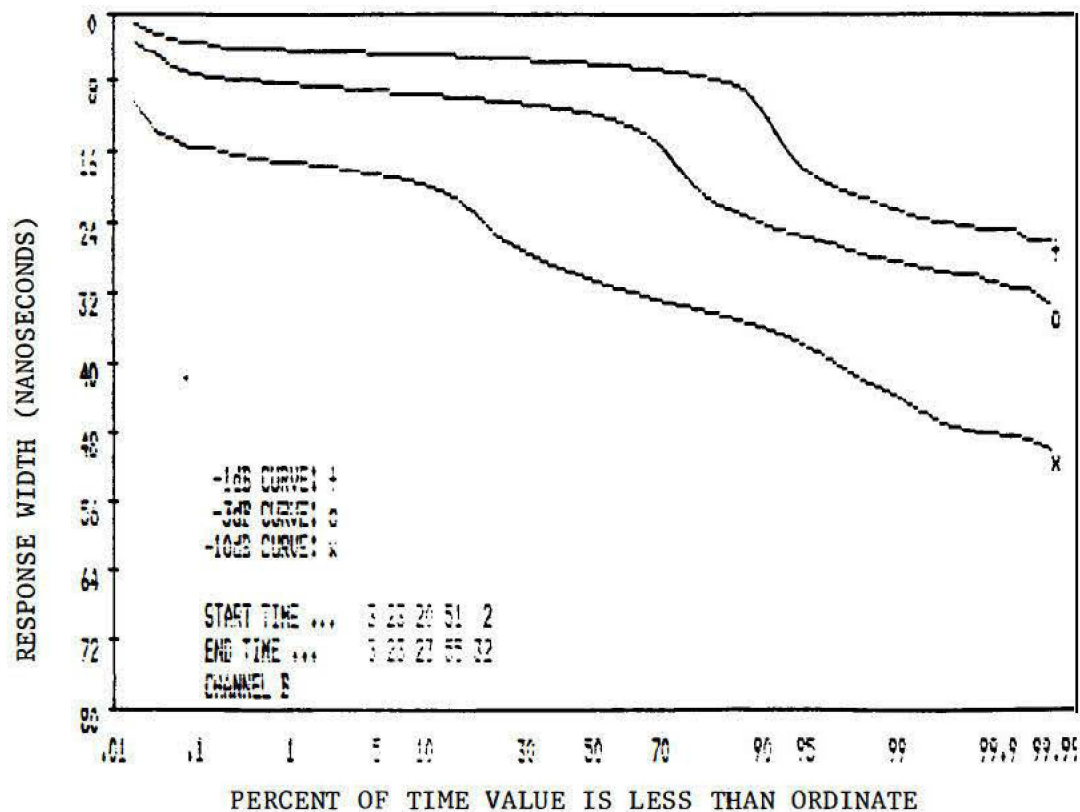
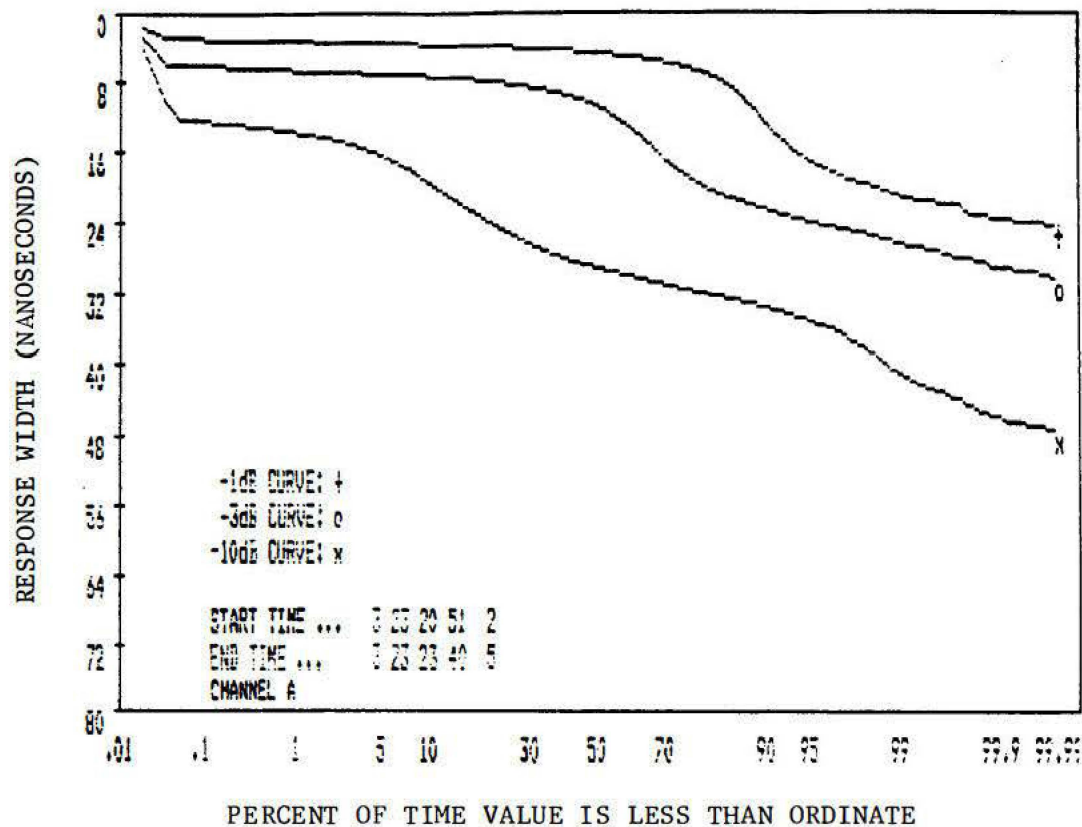


Figure 41. Distributions of impulse response width for Channels A and B for March 23.

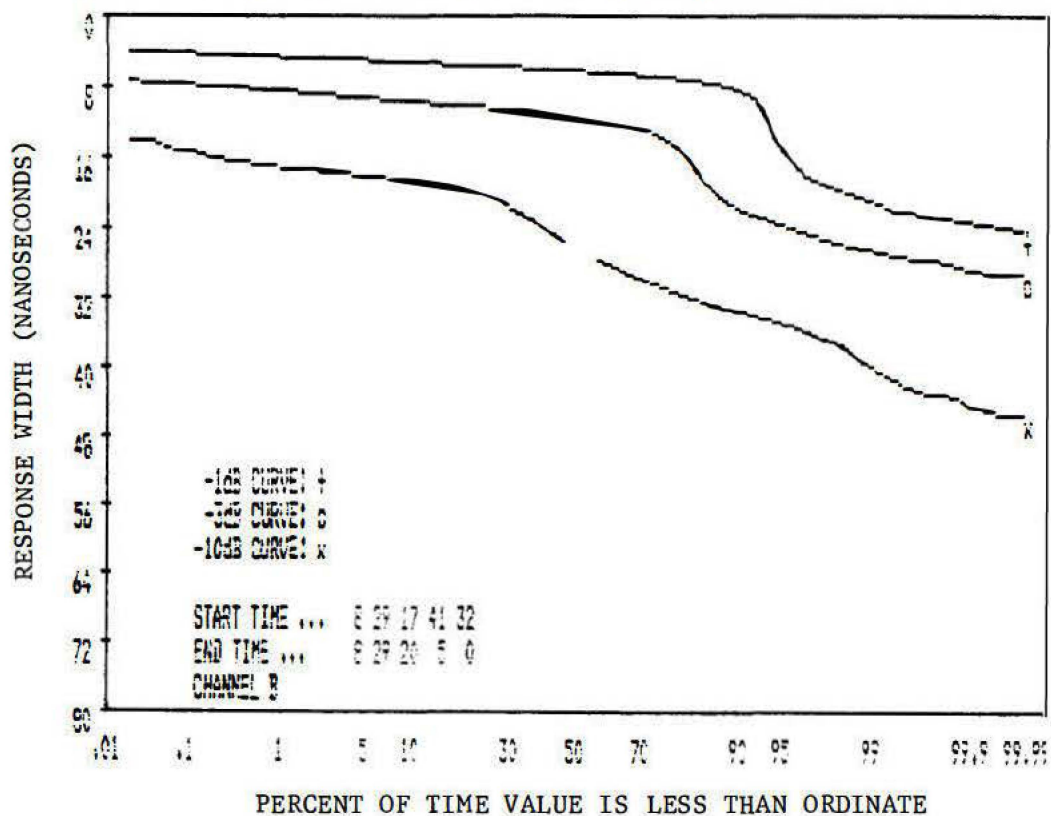
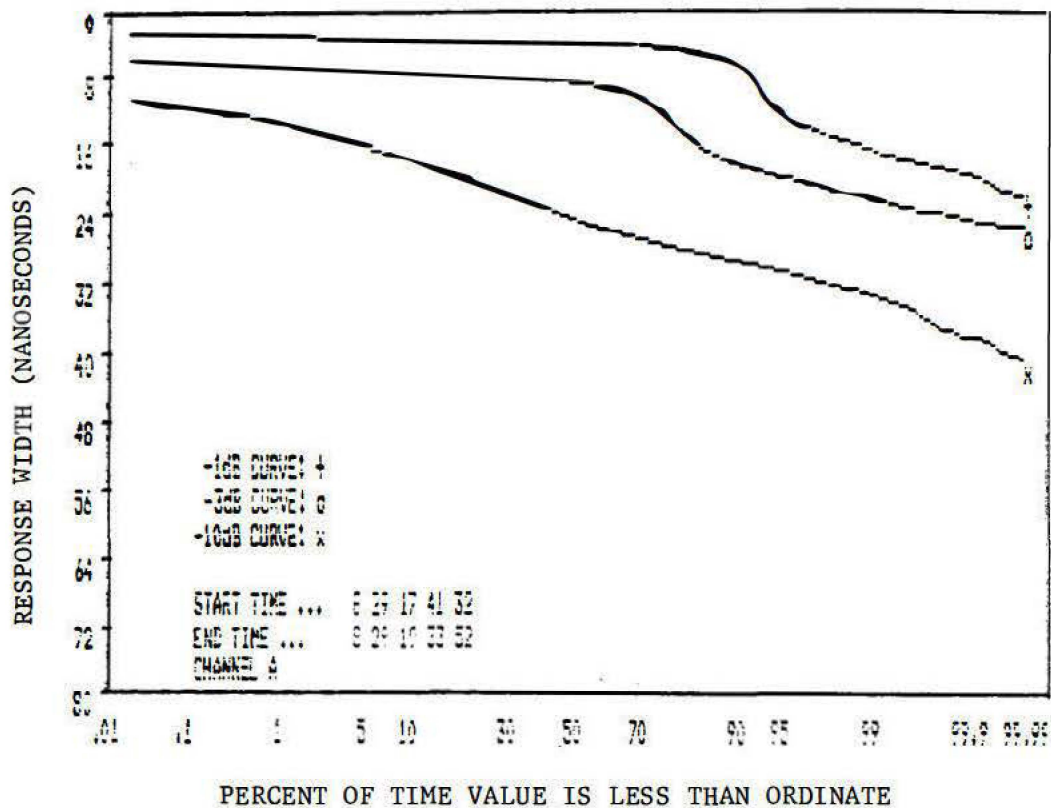


Figure 42. Distributions of impulse response width for Channels A and B for August 29.

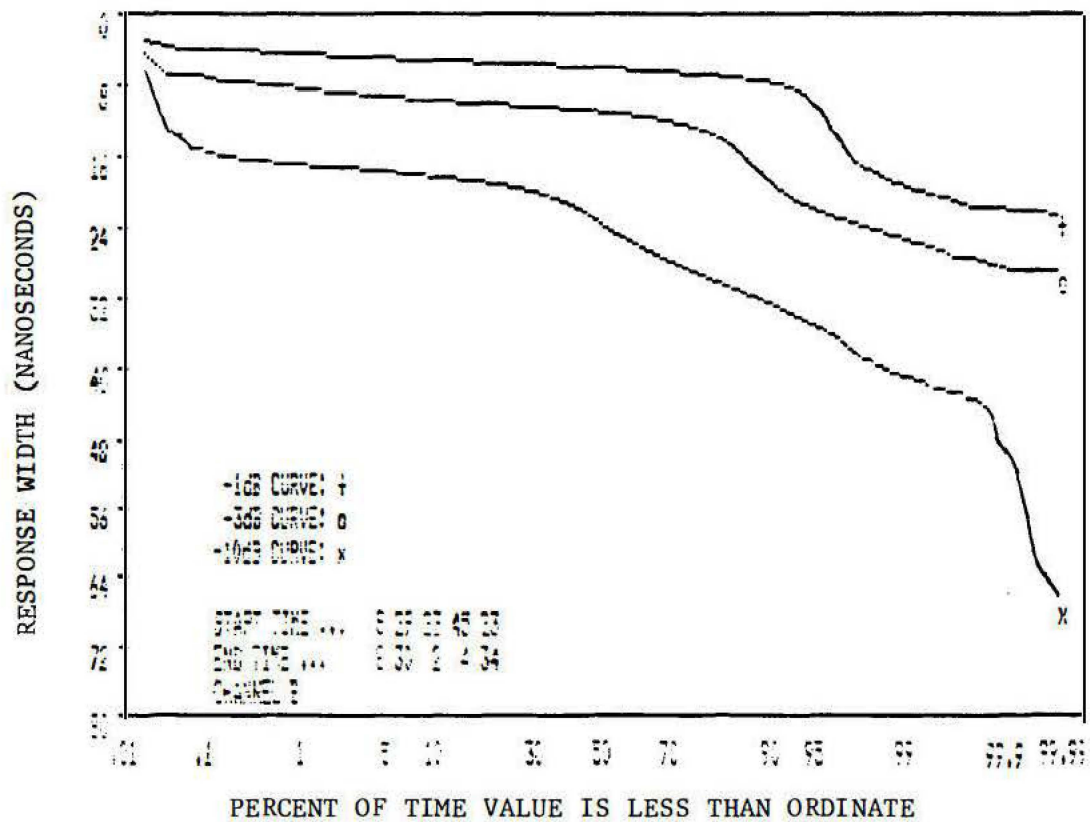
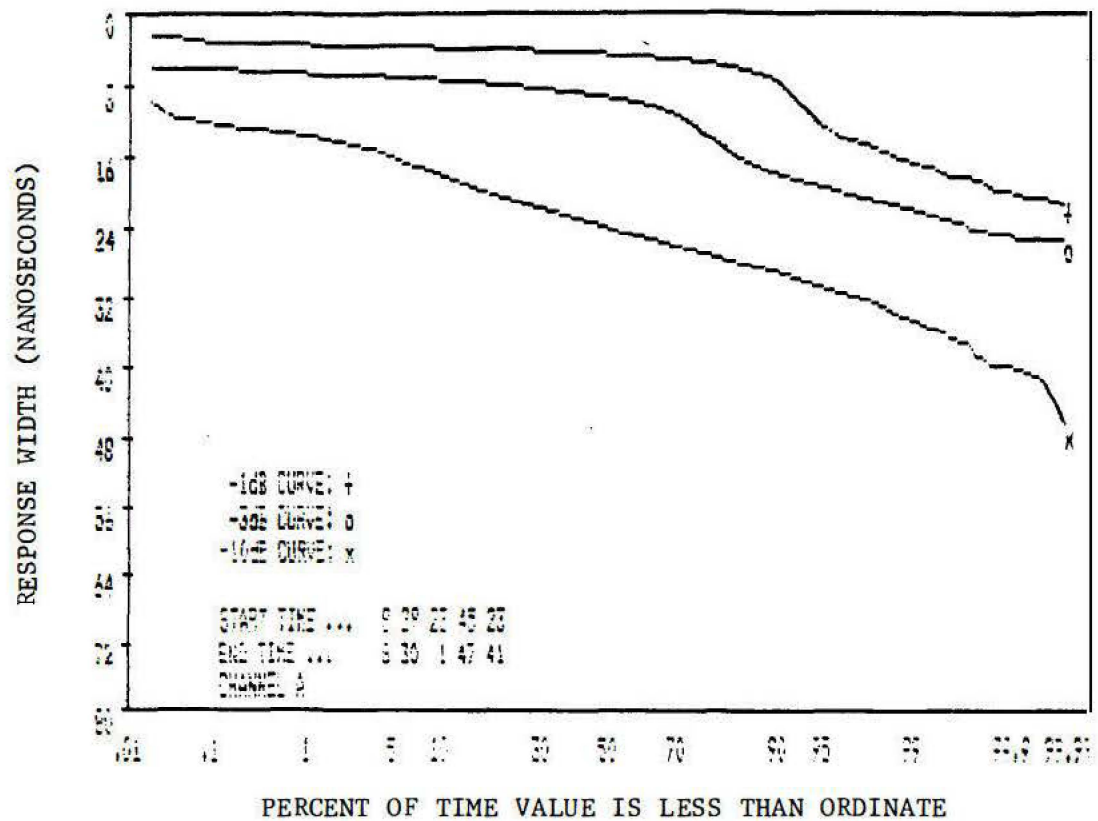


Figure 43. Distributions of impulse response width for Channels A and B for August 29 and 30.

It is interesting to note that the width for the -1 dB level becomes substantially greater for over 10 percent of the time. In these 10 percent cases, the typical widths recorded are over 16 ns.

Another interesting point to note is the very high impulse spreading found at the -10 dB level for 99 percent of the time and more. Typical width values are above 40 ns.

5.6 Amplitude Slope Statistics

This section presents results of in-band amplitude slope analysis. The definitions were introduced in Section 3.3.3. We would like to emphasize that the slopes calculated here are worst-case slopes, since for each slope calculation one side of the bandwidth was assumed to coincide with a spectrum null of the two-ray model (see Figure 6).

A hypothetical bandwidth of 40 MHz was selected. In each of the distributions to follow, Figures 44 through 47 refer to either Channel A, or B, and a third plot called "switch." "Switch" depicts the best instantaneous slope calculated on either Channel A or B. The interpretation of this third plot is as follows: these are the statistics of the smallest worst-case in-band amplitude slope that can be expected for a given receiver's bandwidth (i.e., 40 MHz), if an appropriate "diversity slope switch" could be realized.

In addition, the total number of seconds that each channel was "used" is accumulated and presented on every plot. Slope statistics provide a good measure of the propagation path quality since they are based jointly on the two most important multipath ingredients, the multipath delay and multipath power.

Typical cumulative amplitude slope distributions are presented, and they are based on a different sample size, as seen from the starting and ending time. Very large slopes are measured over 99 percent of the time on most of the examples. The large calculated slopes should be viewed carefully. Consider the top part of Figure 45, where in-band amplitude slopes recorded are larger than 2 dB/MHz. For a bandwidth of 40 MHz, this value implies a very deep null in the spectrum.

The reader is referred to the discussion on power measurement resolution in Section 4.2. It should be clear that this resolution limitation will cause very high fades to appear in the spectrum, mainly because of the logarithmic process that takes place in the slope evaluation. It is recommended not to refer to the high calculated slopes as meaningful. However, the distribution

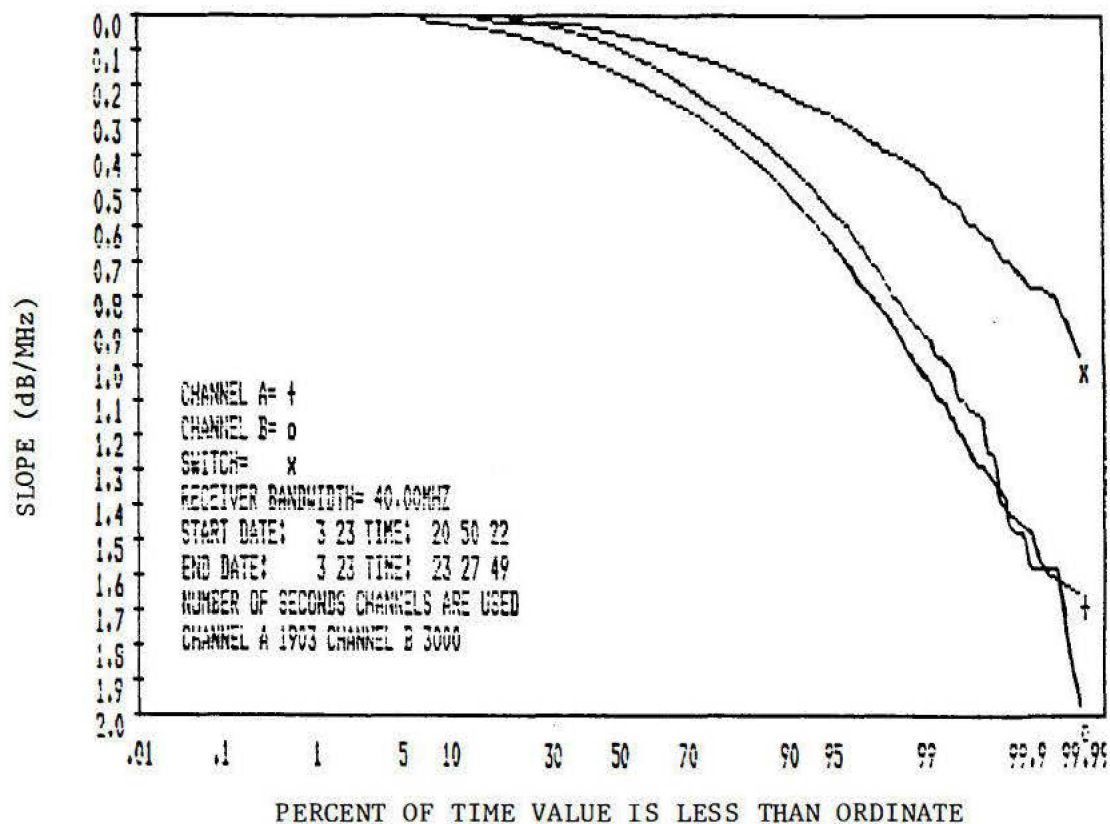
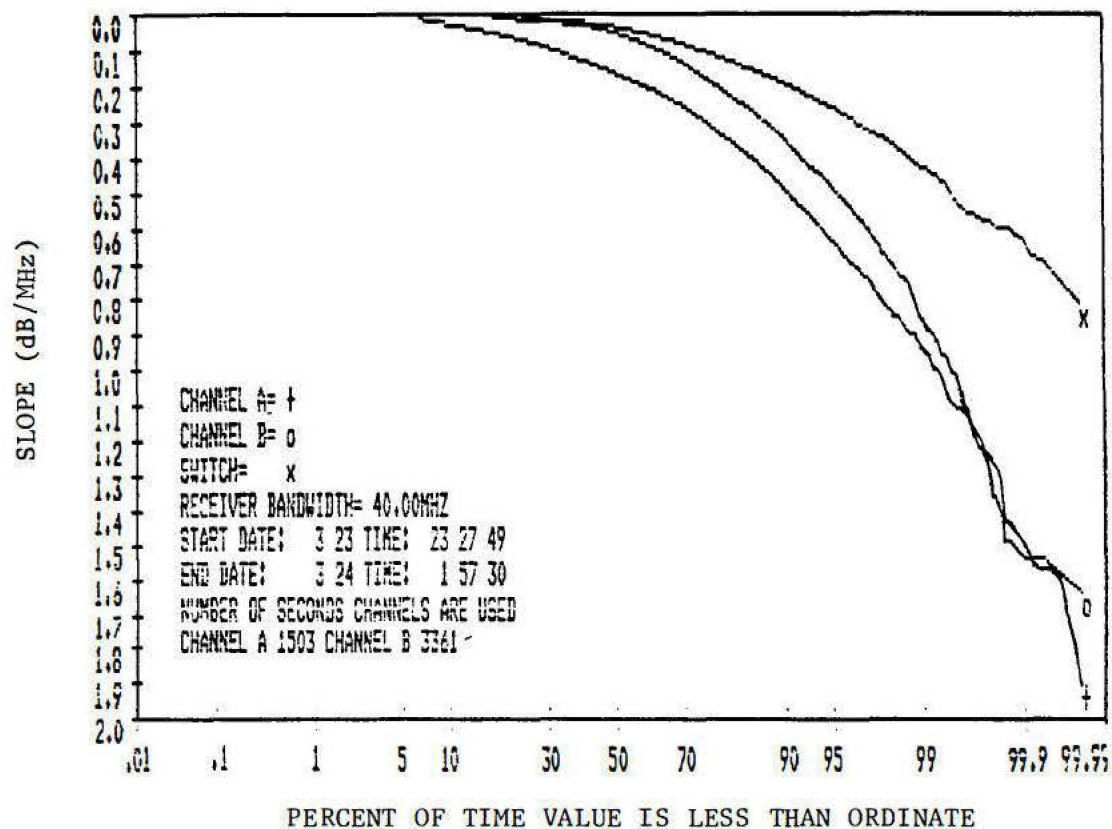
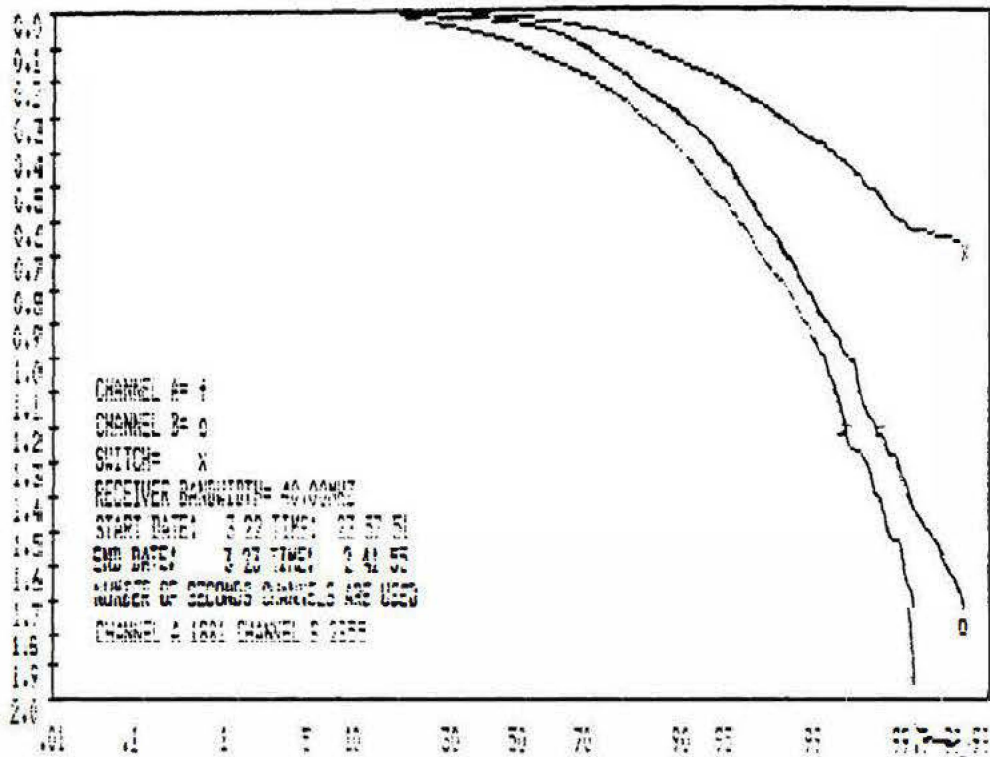


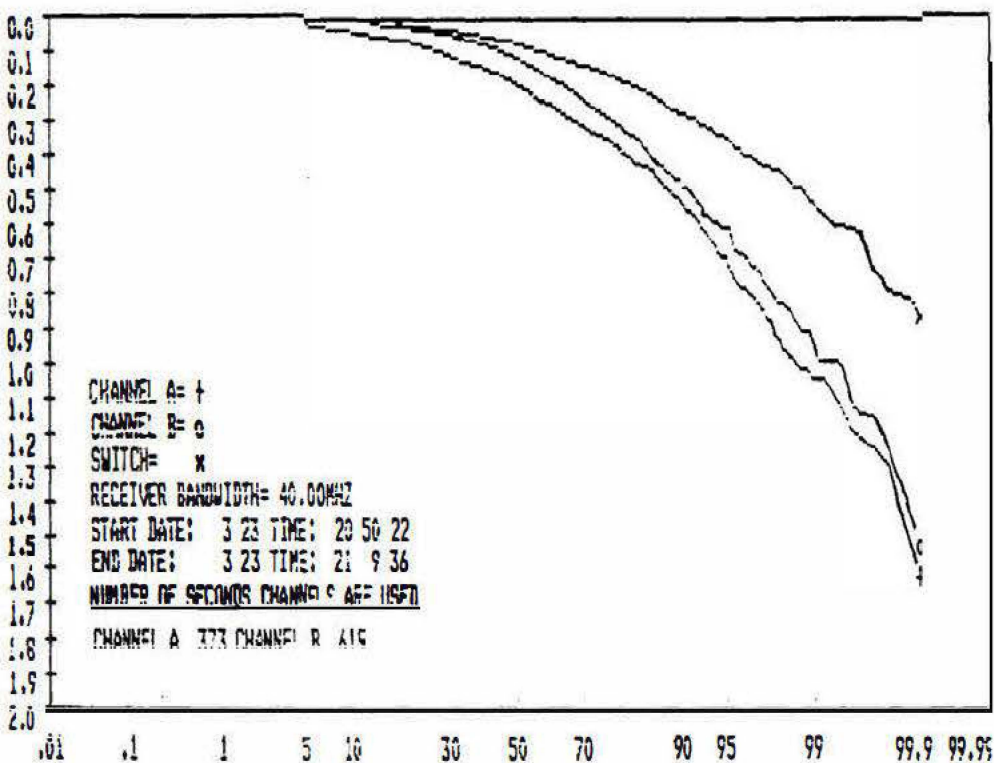
Figure 44. Distributions of in-band amplitude slopes for March 23 and 24.

SLOPE (dB/MHz)



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

SLOPE (dB/MHz)



PERCENT OF TIME VALUE IS LESS THAN ORDINATE

Figure 45. Distributions of in-band amplitude slopes for March 22 and 23.

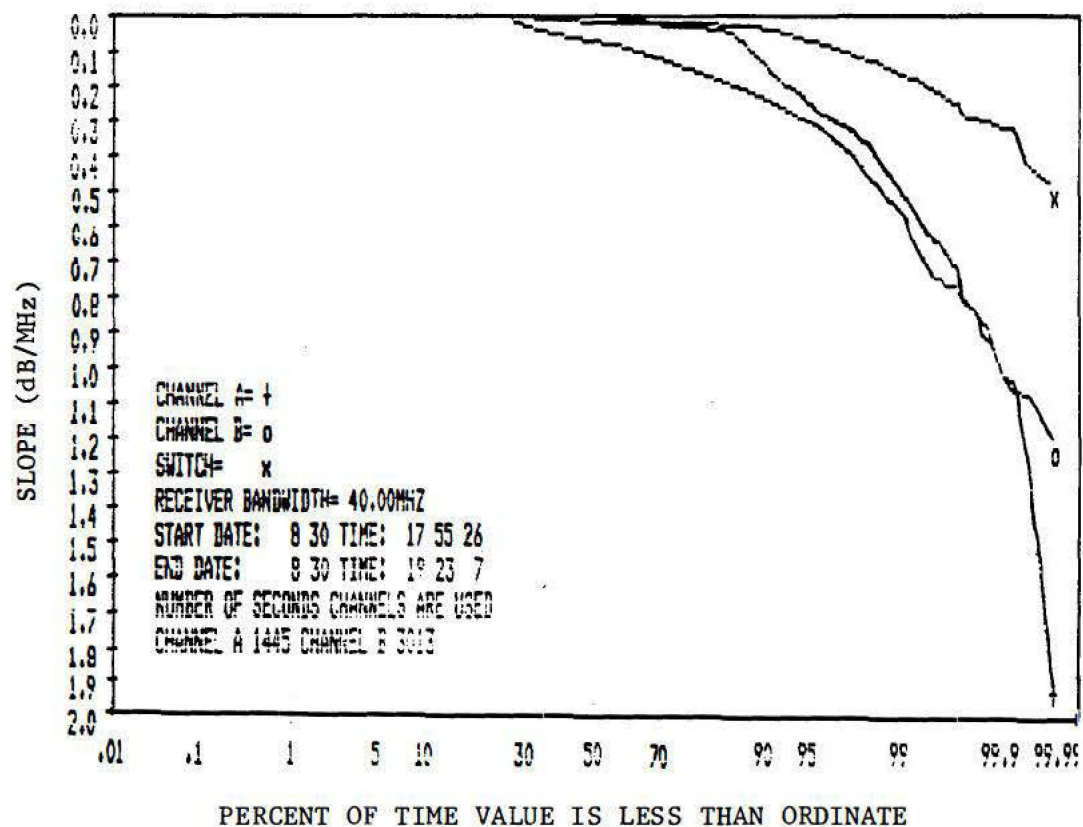
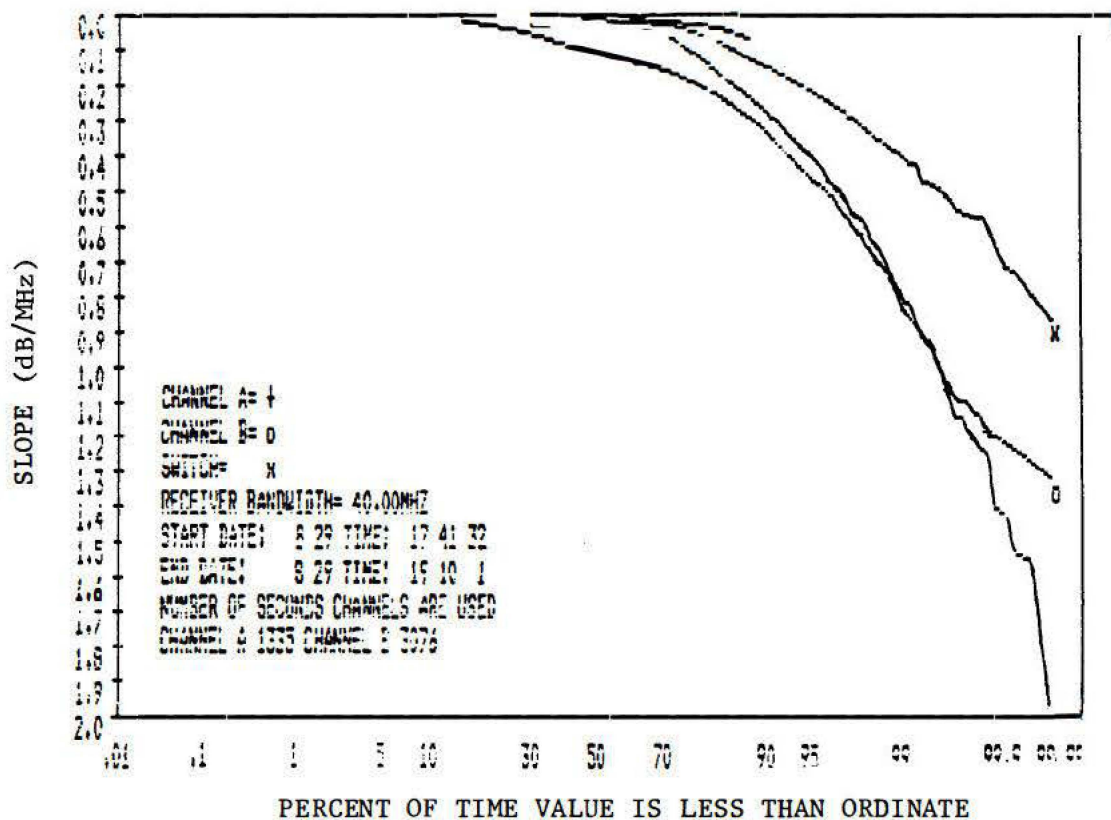


Figure 46. Distributions of in-band amplitude slopes for August 29.

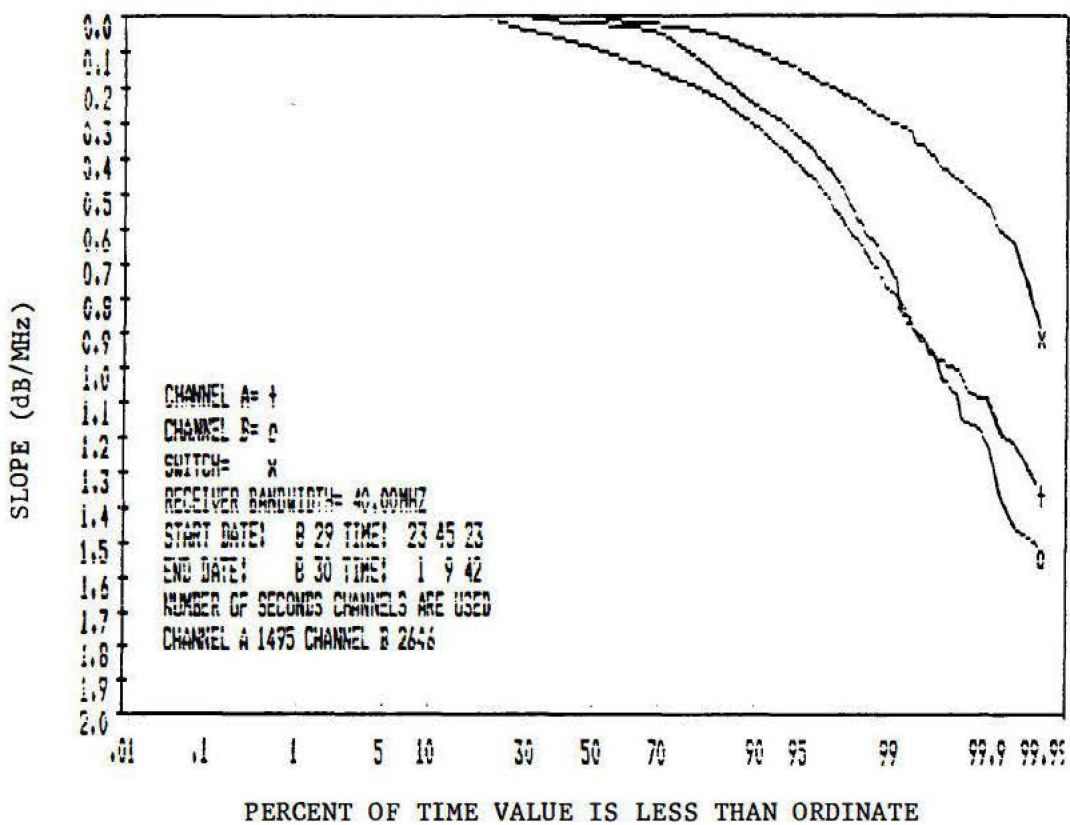


Figure 47. Distributions of in-band amplitude slopes for August 29 and 30.

for the medium and small slope values are to be taken as correct. One should also note that Channel B produces smaller instantaneous slopes than does Channel A. This is because Channel B was "chosen" for the switch graph more often. Thus while Channel B was recording larger delays (which acts to narrow the frequency displacement between two adjacent frequency nulls), the power associated with the delays was small and did not increase the in-band amplitude slope.

6. THREE-COMPONENT IMPULSE RESPONSES

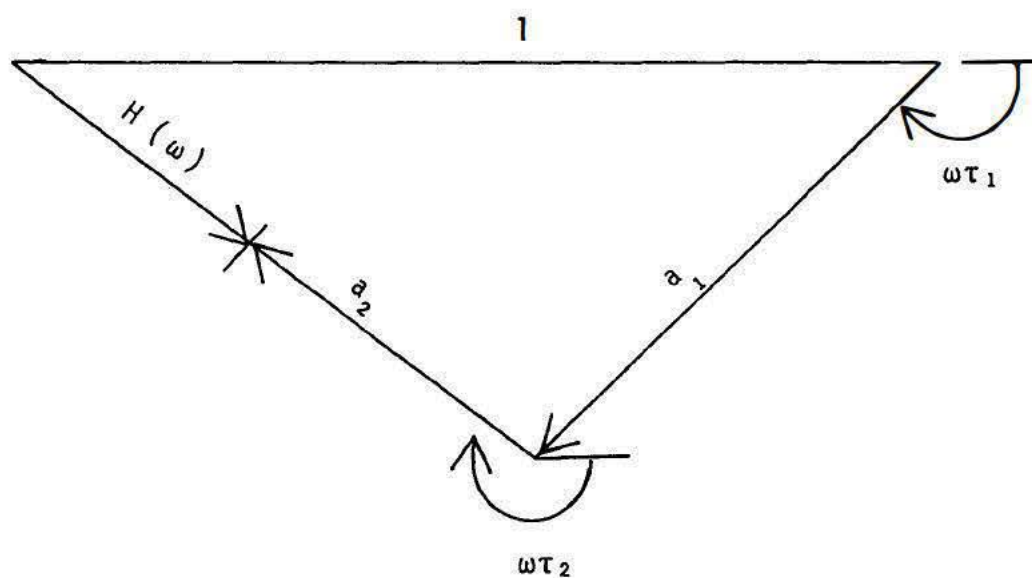
In this report the three-component impulse response is defined to consist of the main signal plus two multipath components. Before presenting detailed data, it may be advisable to show how often this two multipath component impulse response occurs. In a very general way, that question is answered in Table 3.

The percentages for two multipath components in Channels A and B, denoted as A(%) and B(%), respectively, refer to the total experiment time of column 2 in Table 3. Table 3 is useful for data interpretation that follows in this section. From Table 3 one can conclude that two multipath component impulse responses were detected between 2.1 and 11.3 percent of the time. It will be shown that a significant second multipath component exists for shorter periods. In the treatment of second multipath components the following tests and analyses were performed:

- Delay distribution of second multipath was calculated
- Power distribution of second multipath was calculated
- Scattergrams of first multipath power versus second multipath power were plotted.

At this point we would like to define the various components within the impulse response. In Figure 48, we introduce the vector representation for the two multipath component case magnitudes. a_1 and a_2 are measured with reference to the direct signal, and by definition $a_1 \geq a_2$. Thus, the multipath components are scaled and ordered by the power. Quantities τ_1 and τ_2 are the delays of the first and second multipath components and are measured from the direct signal peak.

Time Period	Total Experiment Time (s)	Total Number of Impulse Response Recorded	Total Number of Multipath Impulse Response		Number of Two-Component Multipath				
			A	B	A	A(%)	B	B(%)	
1. March 22 to 23	30,357	14,511	12,025	11,201	1,264	4.1%	1,720	5.6%	
2. March 23 to 24	32,901	15,115	13,525	12,077	2,433	7.3%	2,707	8.2%	
3. March 24 to 25	33,972	13,665	8,081	8,142	807	2.3%	730	2.1%	
4. August 29	16,449	15,215	12,373	9,656	1,015	6.1%	1,423	8.6%	
5. August 29 to 30	15,378	15,180	11,094	9,532	1,102	7.1%	1,747	11.3%	
6. August 30	15,600	15,205	10,121	8,932	857	5.4%	551	3.5%	



$$H(\omega) = 1 + a_1 e^{-j\omega\tau_1} + a_2 e^{-j\omega\tau_2}$$

Figure 48. Vector representation of two multipath component impulse response.

6.1 Statistics of Second Multipath Delay

The delay τ_2 of the second multipath component is measured from the direct signal peak. Positive delays refer to the minimum phase component (regular multipath component), whereas negative delays refer to a nonminimum phase component (abnormal multipath component). The reader is advised that the classification of the impulse response is done upon the first multipath component and the terms "abnormal" and "regular" are used here for description purposes only. In Figures 49 through 51, six cumulative distributions of delays are presented. For each time period, two distributions are shown for Channel A and B. On each plot the total number of three-component impulse responses is shown and the total number of impulse responses that were processed. (Note, this time is not the total experiment time explained in Section 6.)

The Channel A delay is distributed almost symmetrically, before and after the direct signal peak, whereas the Channel B data are not. In the Channel B data, the second multipath component is detected most of the time (97%) behind the direct signal peak. This feature is probably due to the fact that the Channel B antenna direction and alignment are preventing the reception of short delay and low power components. The delays that were measured are fairly long on both sides of the direct signal peak. The reader is advised that the sharp decline of the distribution near zero delay is due to the multipath detection resolution around the direct signal peak.

6.2 Statistics of Second Multipath Power

For reasons to be explained now, the distributions of second multipath power that are presented here do not refer to the direct signal power but to the first multipath power peak as explained in the upgrade of MASP. Let us go back to Figure 48 and visualize the vector representation of the three-component impulse response. Since $a_2 < a_1$ by definition, then a three-component response can become a two-component response for $a_2 \ll a_1$. Since at this stage of the research, joint distributions of first multipath power and second multipath power do not exist, one can get some feeling as to the significance of the second multipath (or in other words, the validity of a possible extension of the known "two-ray" model) by assuming a value a_2' relative to a_1 instead of to the direct ray signal, that makes the contribution of the second multipath appear negligible. For a value a_1 small enough, the

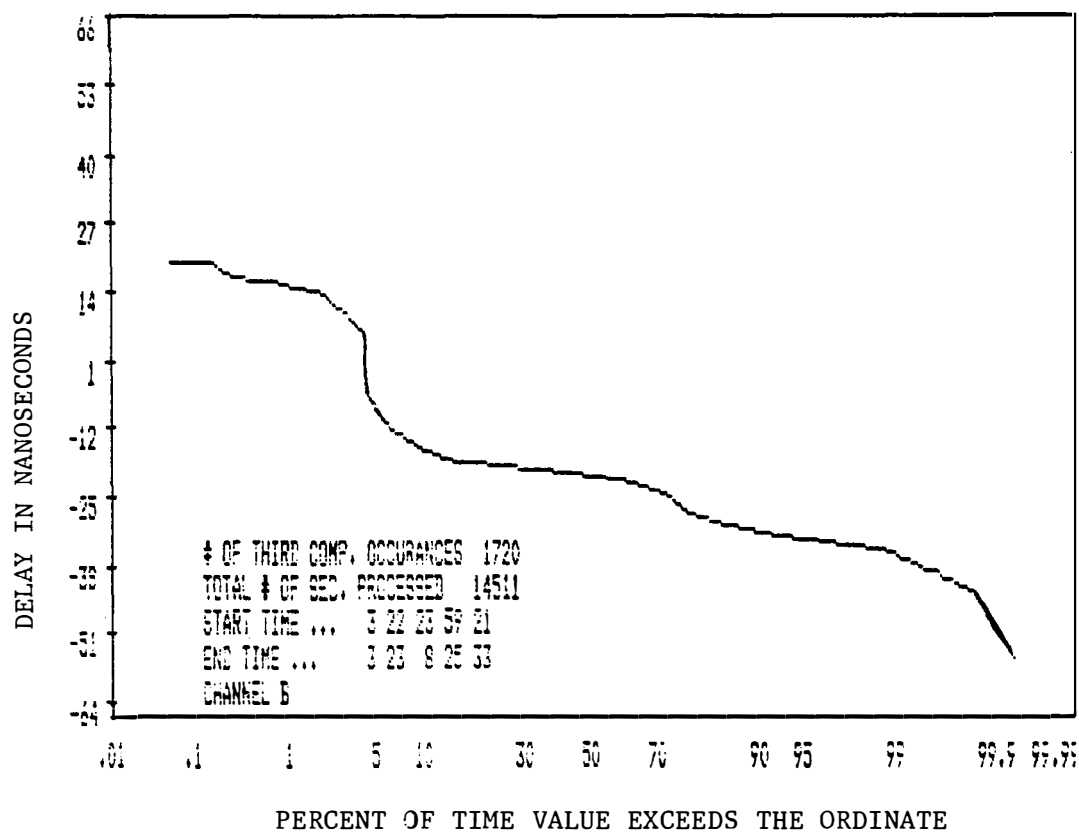
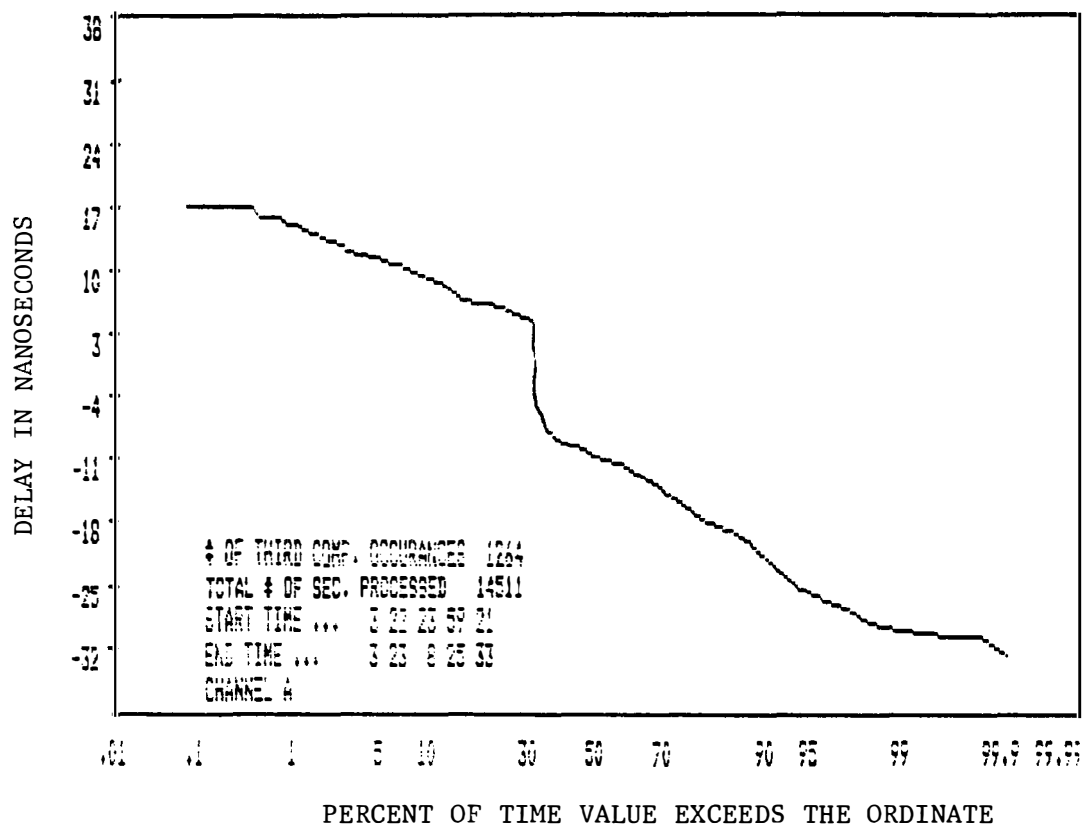


Figure 49. Distributions of second multipath component delays, Channels A and B for March 22 and 23.

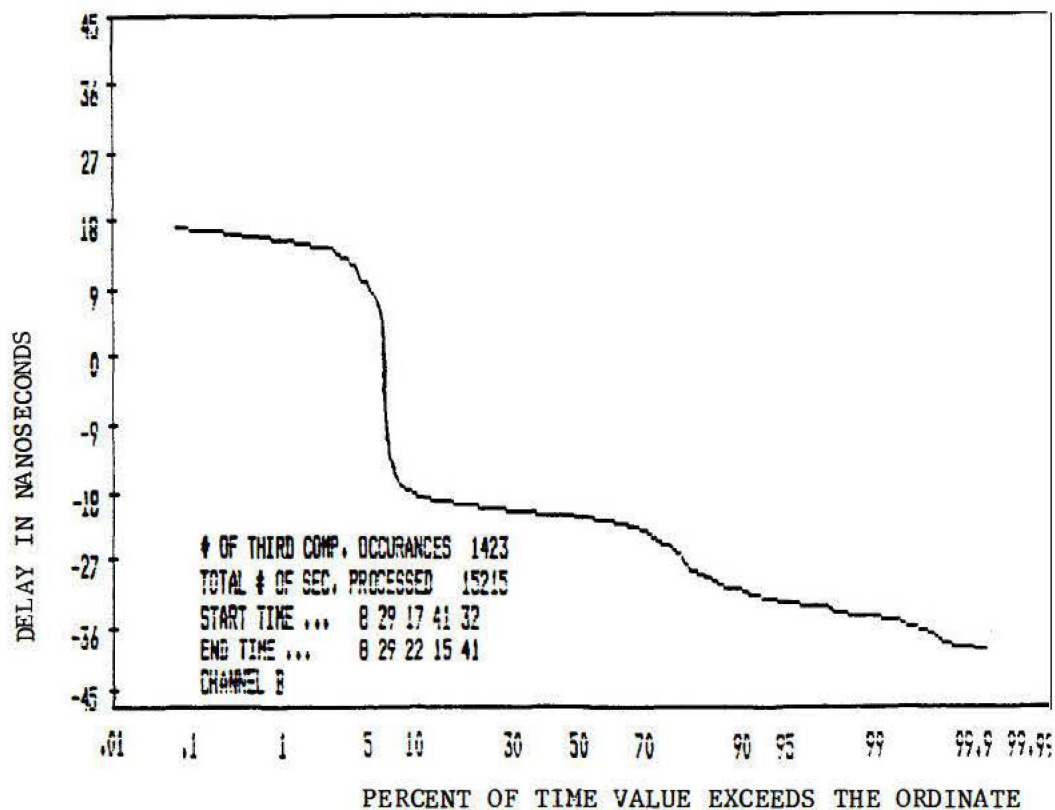
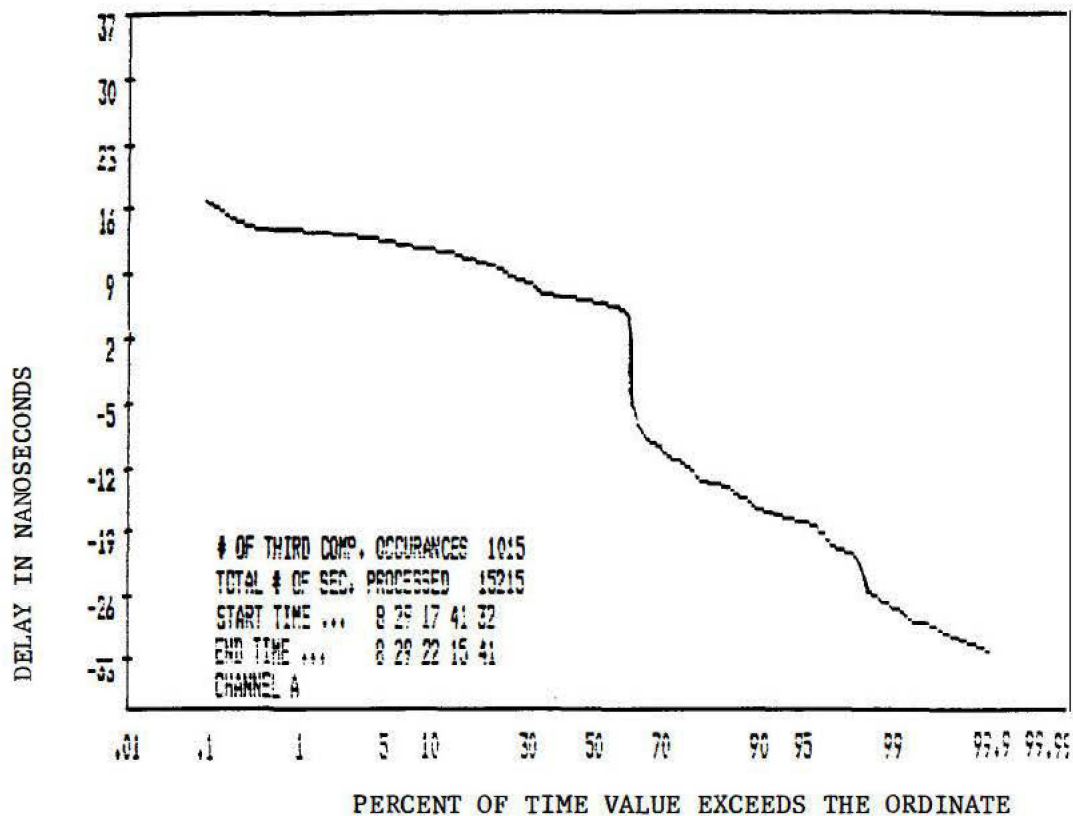


Figure 50. Distributions of second multipath component delays, Channels A and B for August 29.

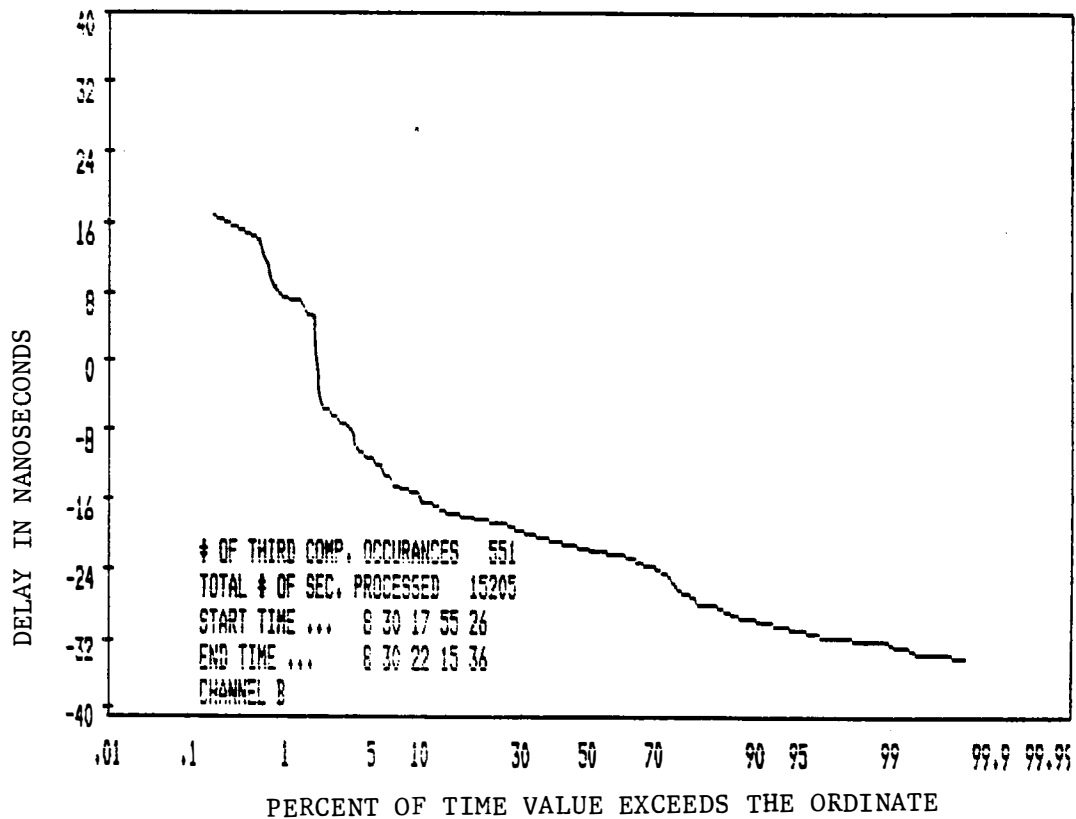
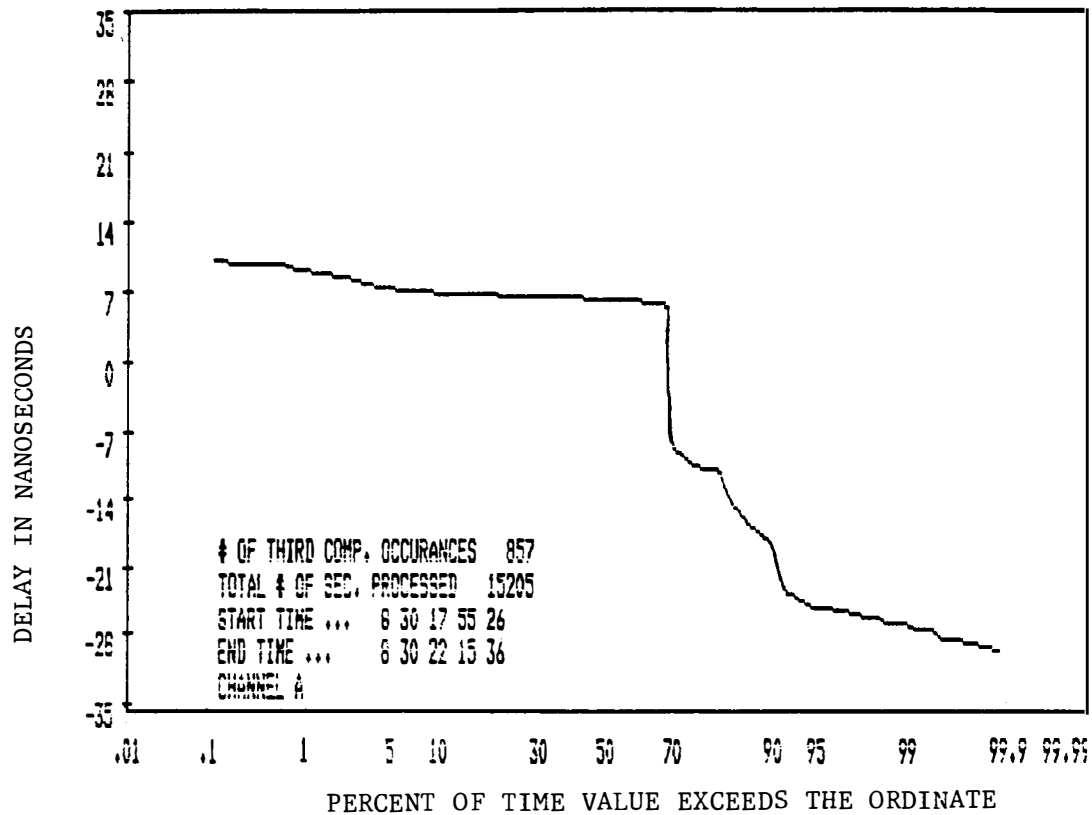


Figure 51. Distributions of second multipath component delays, Channels A and B for August 30.

phase or delay of the multipath becomes irrelevant. We will use this approach to extend the validity of the two-ray model. In Figures 52 through 54, cumulative distributions of second multipath power are presented. It is shown that Channel A distribution differs from Channel B distributions. Relative power measured in Channel A is fairly low. In the discussion of the (first) multipath power in Section 4.2, we noted that Channel A had periods with signal enhancement. From Figures 52 through 54, for Channel A, one sees that in time periods with signal enhancement, a fairly low third component was detected. Such a low second-multipath component was not detected on Channel B since the signal-to-noise ratio is limited to about 14 dB.

It may be justified to assume that whenever the second multipath power drops 10 dB under the power value of the first multipath, its contribution is negligible. We can try to extend the validity of the "two-ray model" with the data presented in Figures 52 through 54 and Table 3.

The following percentages of time represent second-multipath power values larger than -10 dB (from Figures 52 through 54)

	Channel A	Channel B
March 22-23	82%	75%
August 29	93%	85%
August 30	92%	75%

By multiplying these percentage values with the statistics of three-component impulse responses (seventh and ninth columns in Table 3), we find that under the assumption made, a two-ray (i.e., one multipath) model is adequate for:

	Channel A	Channel B
March 22-23	96.63%	95.8%
August 29	94.32%	92.7%
August 30	95%	97.37%

or for an average time of 95.3% of the time.

Other qualitative representations of the relation between the first multipath power and the second multipath power are given in Figures 55 and 56. These are scattergrams of one multipath power versus the second but this time the second and first multipath relative powers are both measured relative to the direct signal peak power.

Since by definition $a_1 \geq a_2$ (Figure 48), all the data in Figures 55 and 56 lie on or under a 45° line. Only three-component impulse response data are plotted so that one can get the feeling of data scatter or concentration from

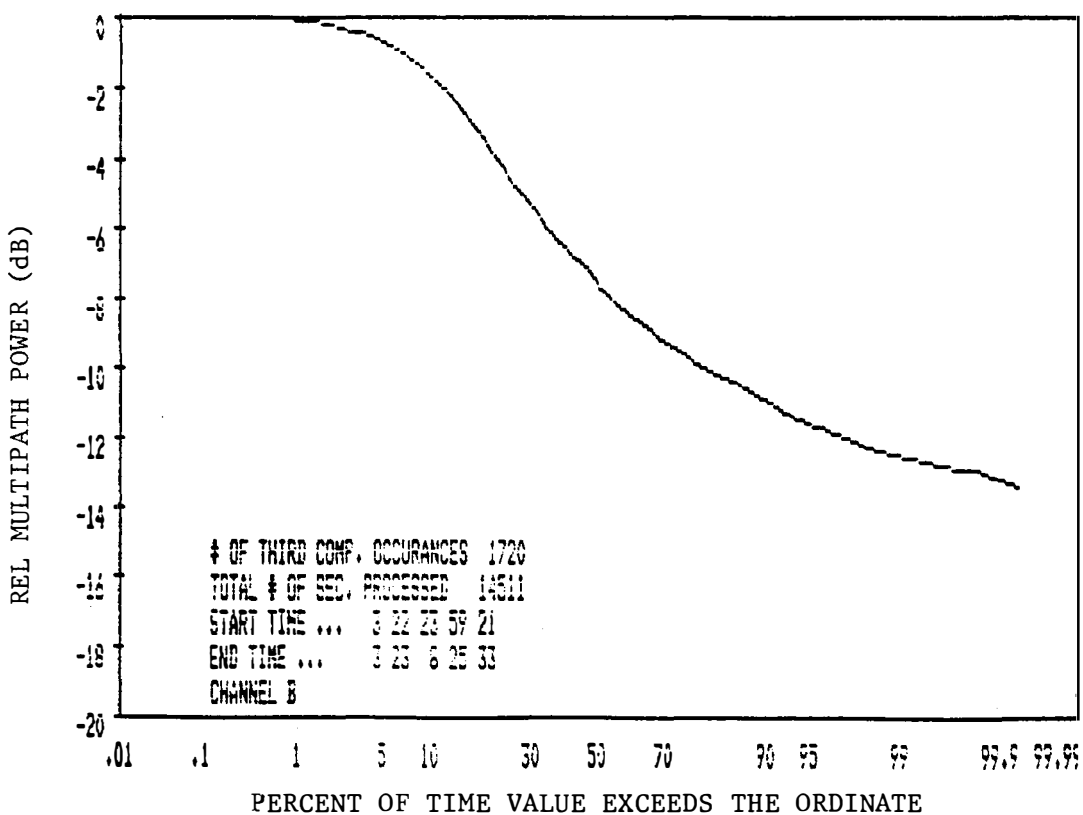
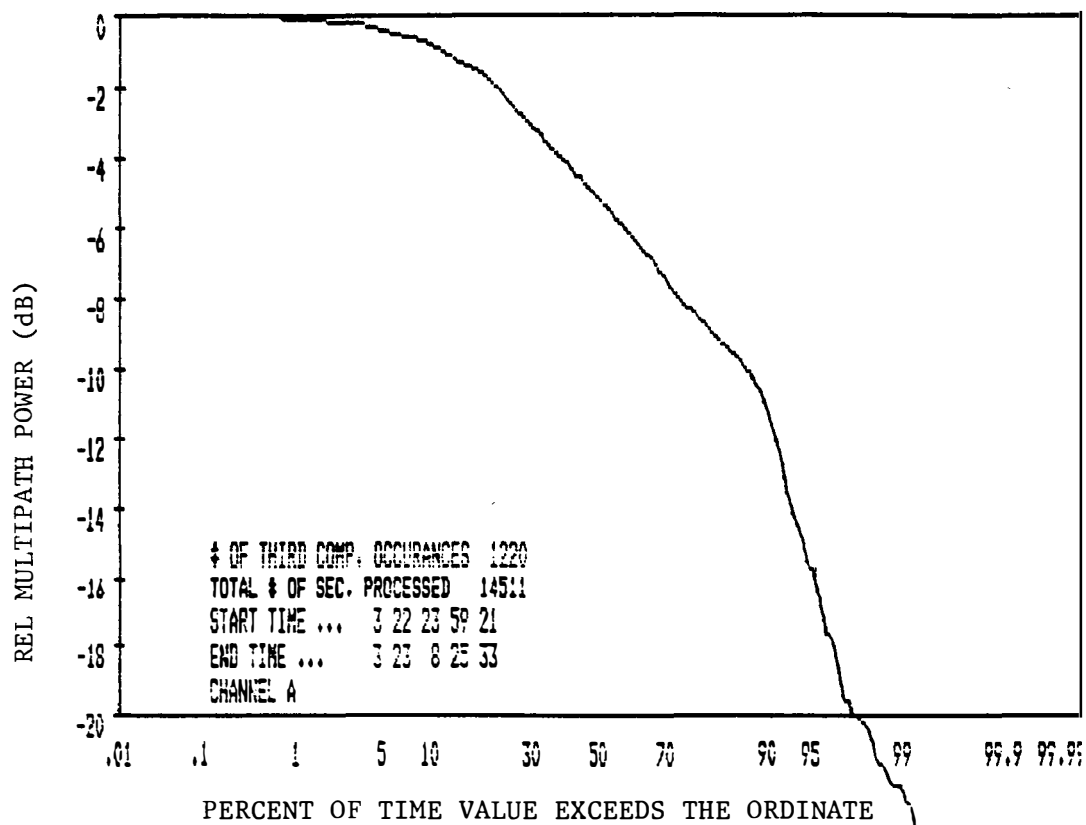


Figure 52. Distributions of second multipath relative power for Channels A and B for March 22 and 23.

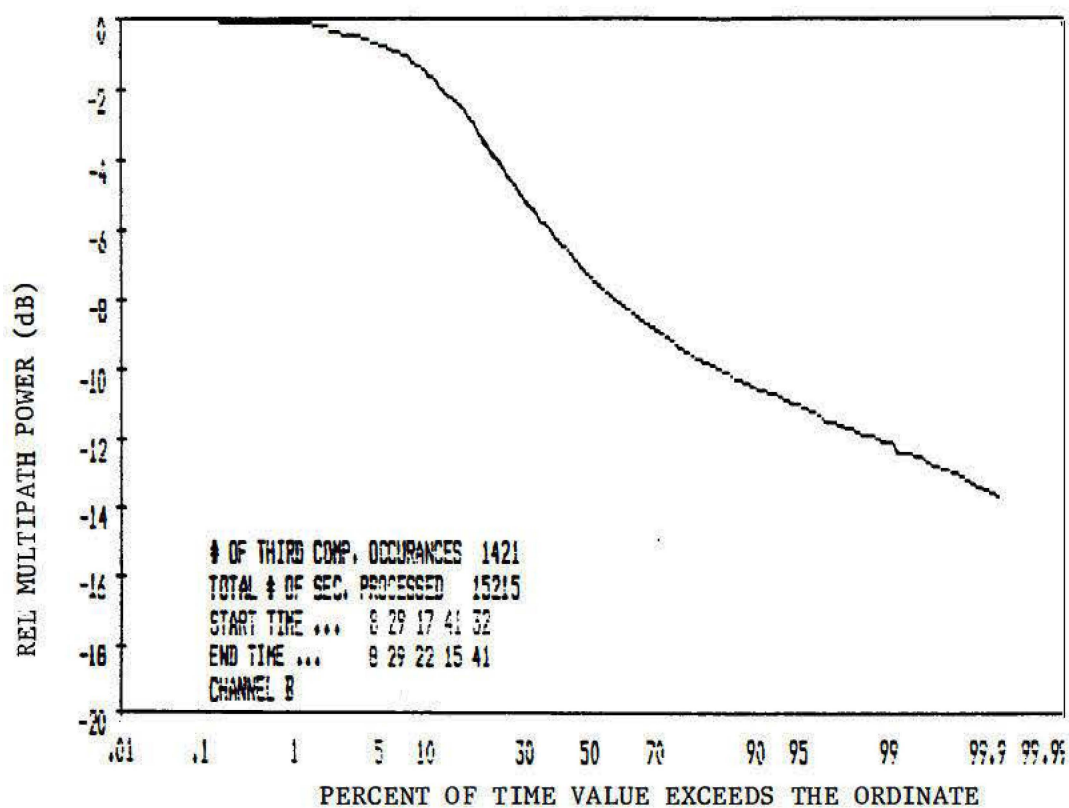
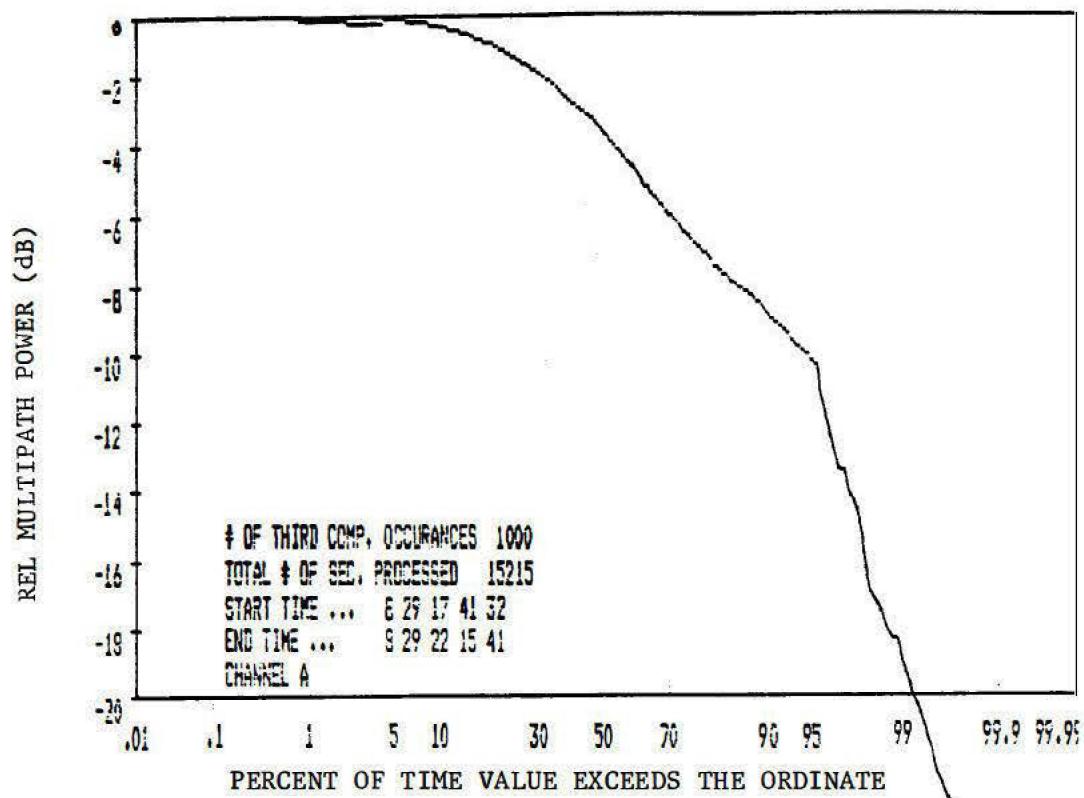


Figure 53. Distributions of second multipath relative power for Channels A and B for August 29.

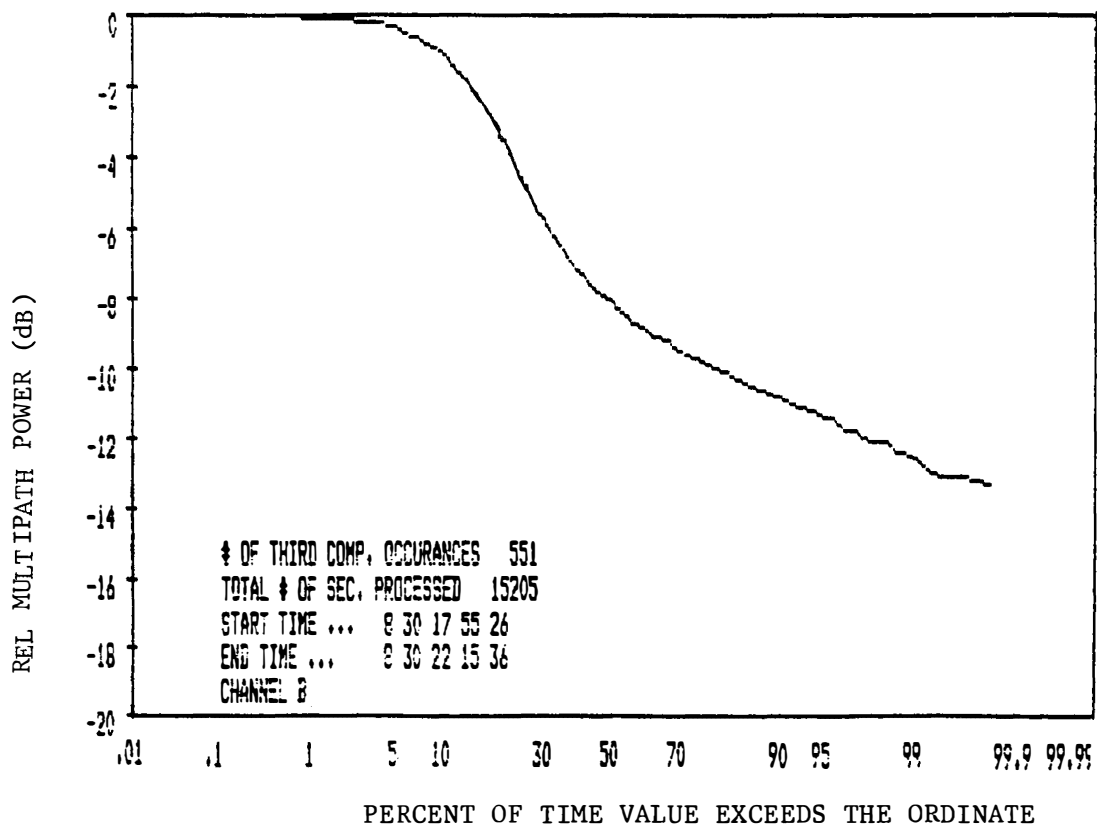
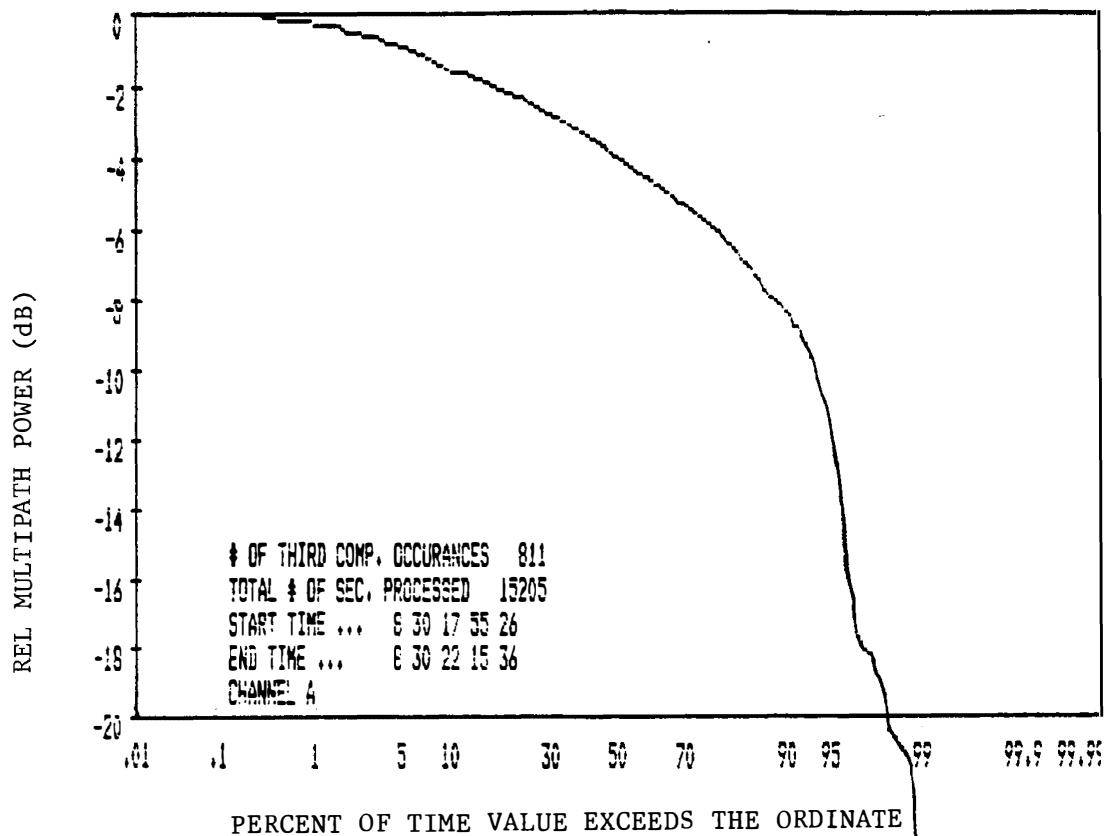


Figure 54. Distributions for second multipath relative power for Channels A and B for August 30.

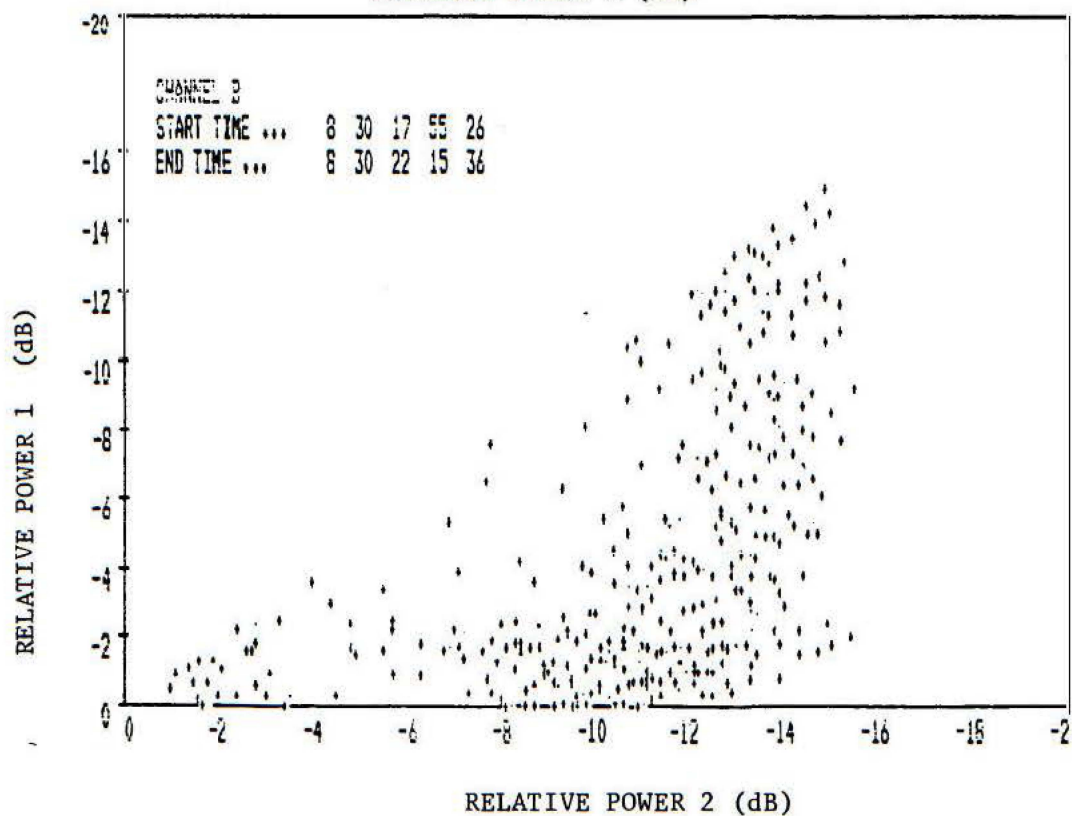
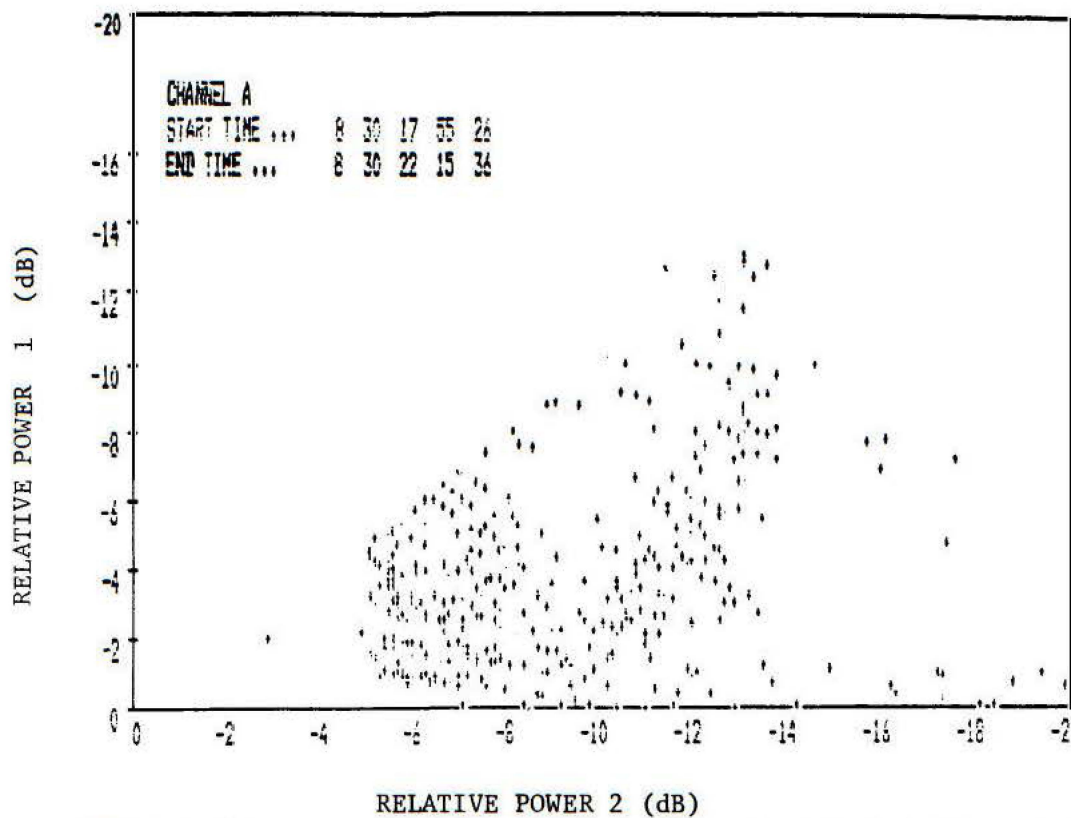


Figure 55. Scattergrams of relative multipath power for the first multipath component versus the second multipath component for Channels A and B on August 30. Power for each component is relative to the direct signal power.

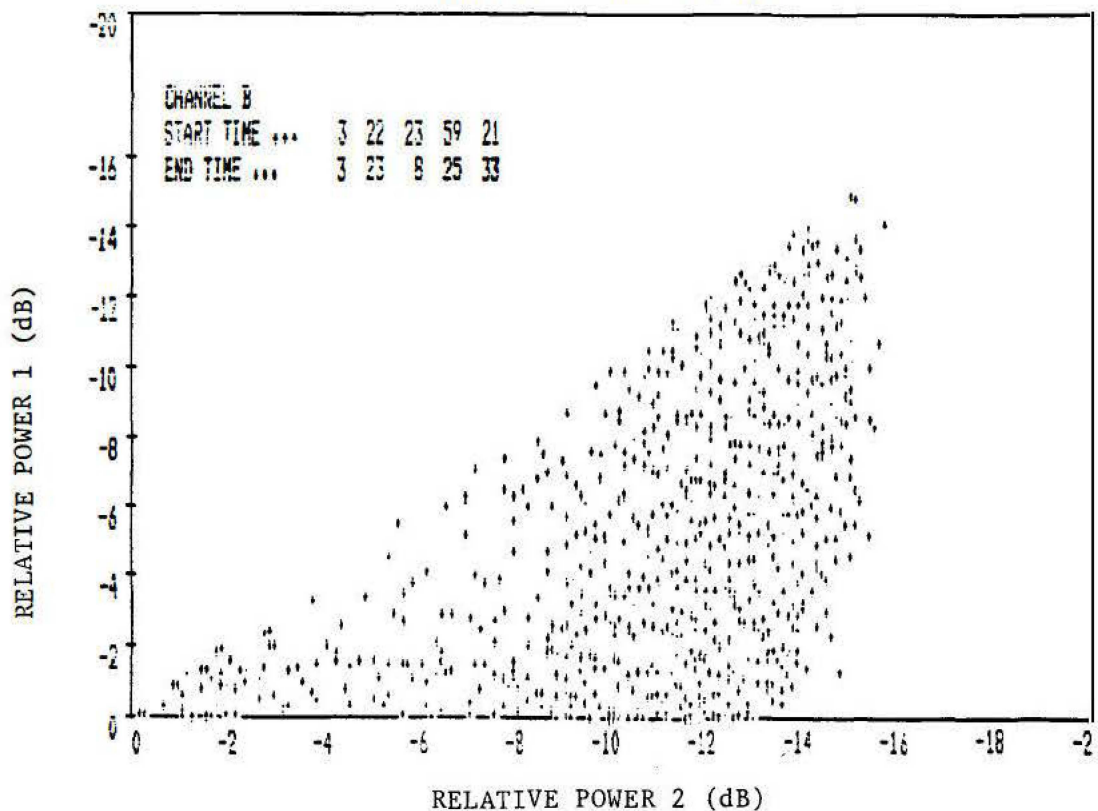
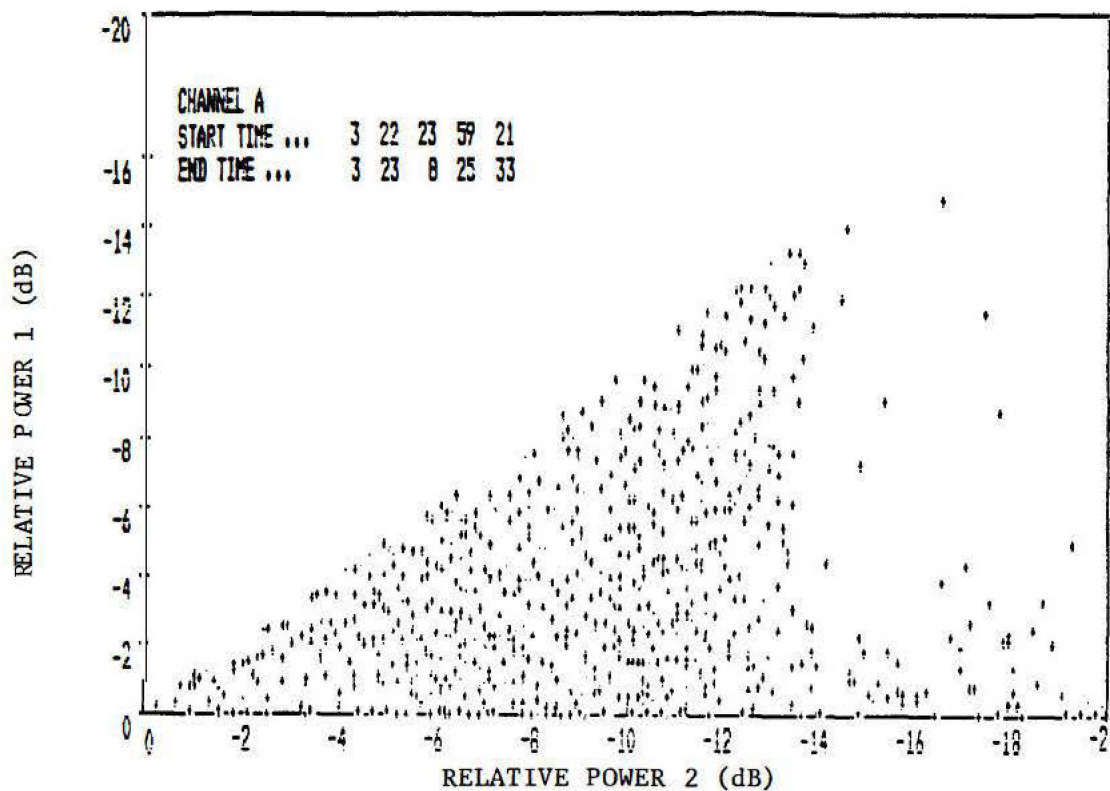


Figure 56. Scattergrams of relative multipath power for the first multipath component versus the second multipath component for Channels A and B on March 22 and 23. Power for each component is relative to the direct signal power.

such a scattergrams. Two scattergrams, one for the "March data" and one for the "August data" are presented. It is seen that for the particular examples selected, the second multipath power for the "March data" has more sample points and larger variability than the second multipath power for the "August data."

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

The project was launched to evaluate and analyze multipath data collected during the ITS Point Mugu channel probe experiments. The project was divided into two major phases, namely the development of the analysis software and the analysis and evaluation of the data itself. At the end of the first phase, two unpublished internal reports were completed that describe the software that was developed. It also explains the logic behind the various computer programs and supplies an operating guide for the MASP. In the course of the second stage, large amounts of data were processed and analyzed. A large variety of analyses cross-sections were performed on the data. The results of that analysis constitute the substance of this report. Some of the analysis schemes and the results shown here have not been published in the literature before. A new complete view of multipath static and dynamic statistics is provided here together with interpretations and applications.

The following general multipath statistics were analyzed and their cumulative distributions presented: multipath delay, multipath power, and multipath phase. Special cases of "nonminimum phase" were detected and their delay and power distributions were calculated. Possible statistical relations were tested between multipath delay and power. Impulse response width was analyzed. Dynamic properties of multipath were analyzed and main results presented. This included the rate of change in multipath's power, delay, phase, and rates of collapse and development of multipath. Furthermore, the durations of "nonminimum phase" impulse response were calculated. A theoretical in-band amplitude slope was calculated, and an experimental in-band amplitude slope diversity switch was programmed and its distributions were calculated.

Finally, we have analyzed the special cases of two-multipath component impulse responses while presenting values for the percentage times when such responses occur.

7.2 Conclusions

Two periods of the experiment were selected for analysis and evaluation--one period was in the month of March 1984 and the second one in August 1984. During the "March period," the acquisition system monitored 28 percent and for the "August data" 96 percent of the experiment time. This indicates that in the summer the over-water propagation path selected had degraded error performance and considerable multipath.

Average median multipath relative power level for Channel A is -4 dB below direct signal level and -9.2 dB below direct signal level for Channel B. Multipath delay distributions tend to be normally distributed with typical median delay levels of 6 to 12 ns for Channel A and 12 to 21 ns for Channel B. Longer delay levels were measured on Channel B.

For one particular test on August 30, we were able to associate a sharp deviation of the delay distribution with multipath activity and long periods of error burst measured on the receivers. Two mathematical expressions found in the literature for maximum delay for a given path geometry and antenna beamwidth (Ruthroff, 1971; Hubbard, 1984) were tested on the data.

Ruthroff's formula appeared to give a loose upper bound, while Hubbard's formula came closer to the median values of Channel A delays and below Channel B median delays. An attempt was made to find a statistical dependence between multipath delays and power (Figure 20) but the correlation appears to be negligible. Using the distributions for multipath delay and power, plus the delay versus power scattergrams, we conclude that the Channel B antenna was tilted upward, resulting in longer delays and usually with lower power. The two multipath component data to be mentioned later supports these contentions.

Some interesting results were found while analyzing the "nonminimum phase" impulse responses. For the "March data" between 11 and 44 percent of recorded impulse responses showed nonminimum phase while for the "August data" 7 to 59 percent had that characteristic. Assuming that all "nonminimum phase" cases were recorded and by using Tables 2 and 3, we find the following statistics of "nonminimum phase" existence relative to total experiment duration:

	<u>Channel A</u> (percent)	<u>Channel B</u> (percent)
March 22	12.3	10
March 23	18	15.7
March 24	7.3	2.6
August 29 (1)	42	25
August 29 (2)	42	28
August 30	16.8	4

These are very large time percentages with "nonminimum phase." According to Allen's (1984) notes, a "nonminimum phase" case is hard to correct when detecting data symbols in the receiver. It is possible that the occurrence rate of error bursts, especially in the summer, may be due to this phenomenon. Multipath delay distributions are normally distributed. Evaluation of the behavior of the nonminimum phase responses in time revealed that for 30 percent of the time the duration of the phenomena was equal or smaller to 1 s. The largest periods of such consecutive responses were 24 s in March and up to 55 s in August.

The rate of change in multipath power was found to be typically median levels of 4 dB/s on both channels. The highest values recorded on Channel A were 27 dB/s and some 14 dB/s on Channel B. It was concluded that high rates of change on Channel A are due to signal enhancement on that channel. Median levels for rate-of-change in delays are 4 ns/s for Channel A and 2 to 7 ns/s for Channel B. Highest values calculated were 22 ns/s for Channel A and 32 ns/s for Channel B.

Typical median values for rate of change in phase are 0.3 to 2 rad/s. When calculating the duration of collapse and development of multipath it was found that development periods are always shorter than the collapse periods. Median values for development and collapse are 4 s. The largest collapse values were 140 s in August and 63 s in March. The impulse response width statistics showed that for very long time periods (about 99 percent of the time), the impulse response width for the -10 dB level is significantly higher than the theoretical impulse response width for a nonmultipath impulse response. It is concluded that impulse response broadening is due to reflection from low atmospheric layers or the sea. This conclusion is based on the fact that at the operating frequency of 8.6 GHz, no atmospheric dispersion can broaden the direct-ray signal to such an extent.

Theoretical calculations of worst-case, in-band amplitude slope were based on the "two-ray" model. The measured delay and power spreads were used to

establish propagation path quality. Since only theoretical worst-case, in-band amplitude slopes were calculated, one should be cautious in contrasting this data with Barnett's (1979) conclusions that slopes greater than 0.2 dB/MHz will cause receiver performance degradations in excess of $BER = 10^{-3}$.

An in-band amplitude slope diversity switch was programmed and its output distributions show that Channel B had smaller in-band amplitude slopes for most of the time. Median "switch" amplitude slopes are around 0.05 dB/MHz and the largest "switch slopes" calculated were 0.8 dB/MHz.

In the course of analyzing impulse responses with two multipath components, it was found that such responses exist for 2.1 to 11.3 percent of the time (see Table 3). It was concluded that a two-ray model (one multipath) is quite adequate to describe the propagation path for Channels A and B for as much as 95 percent of the time.

The thrust of this conclusion is that a "three-ray model" should be used to describe fully the channels' transfer functions. Various assumptions were used by Rummler (1979) to postulate a requirement that the delays between the first two paths be sufficiently small, in order to solve signal ambiguity problems. Another approach to the multipath effect has been presented here. The results of this report are based on analysis of real measurements of multipath delays and powers. Rummler's delay requirements appear nonsupported by the first and second multipath delay distributions reported here.

7.3 Recommendations

After the work reported here, one is lead to two sets of recommendations:

- (i) Recommendations concerning the experimental system and
- (ii) Recommendations for future development of the analysis system and further modeling work on data.

7.3.1 Experimental System Recommendations

A shift in delay was found when comparing the cophase and quadphase with the Channel B impulse response. These shifts of + or - one sample were detected for 10 to 14 percent of the analyzed impulse responses. It is recommended that Channel A co- and quadphase should be recorded in future experiments.

Several times during the course of the analysis it became obvious that higher sampling frequencies of the impulse response could lead to better resolution of multipath attributes. For example, the inability to measure the correct multipath relative power for high multipath power had an effect on the in-band amplitude slope calculations. It is recommended that the sampling rate be at least double the current sampling rate. Such an improvement will enhance and shorten the multipath detection process within MASP programs FINDPK and HOLDPK.

The following statistics of multipath evaluation and detection use the "derivative" method for detection of hidden multipath. These were extracted from each on the tapes analyzed:

	Total Number of Responses		Total Number Times the Derivative Method Was Used	
	CH-A	CH-B	CH-A	CH-B
Tape #22	12,025	11,201	1,439	1,335
Tape #23	13,525	12,077	1,936	1,971
Tape #24	8,081	8,142	1,719	484
Tape #57	12,373	9,656	2,523	1,516
Tape #58	11,094	9,532	3,096	1,815
Tape #59	10,121	8,932	2,350	373

We conclude that on the average 16 percent of the impulse responses could not be resolved and detected using regular detection schemes. It is recommended that an improvement in the PN probe resolution be made to enhance multipath detection and analysis.

The current computer systems to analyze multipath phenomena are too small in memory capacity and too slow in processing time. The next recommended stages in modeling the Point Mugu data will have to rely on much larger data volume than can be handled by the current system.

7.3.2 Recommendation for Future Analysis and Modeling

Future analysis of large samples of multipath data should proceed and benefit from this work. At the end of this stage of the project, much better understanding of static and dynamic multipath phenomena already exists. Data should be examined and studied for current and further application needs.

It is believed that calculating joint distributions of first and second multipath powers and delays will lead to more conclusive results about the validity of the two-ray multipath model. A model for three multipath components can be deduced from the data if so required. More data from other

experiments (besides Point Mugu) should be analyzed and compared with existing models. It is believed that results obtained using the ITS PN probe are better for modeling purposes than the other existing methods examined by the author.

8. ACKNOWLEDGMENTS

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APPENDIX: MASP PROGRAM LIST

For the ease of use, a complete list of MASP programs is included along with their locations within certain program groups.

A. Programs to evaluate raw data

- | | | |
|----|---|--------------------------------|
| 1. | User oriented pattern recognition -- | HOLDPK, stands alone as HOLDPK |
| 2. | Automatic pattern recognition -- | FINDPK, stands alone as FINDPK |
| 3. | Search raw data for consecutive blocks -- | CHECK; stands alone as CHECK |
| 4. | Response, co and quad of channel B -- | PULSE2, stands alone as PULSE2 |
| 5. | Co-, quad- and phase of channel B -- | ARK, stands alone as ARK |

B. Programs to evaluate processed data: general properties of multipath

- | | | |
|-----|--|--------------------------------|
| 6. | Relative power statistics -- | FADER, number 2 on UTIL2 menu |
| 7. | Delay statistics -- | DELAY, number 3 on UTIL2 menu |
| 8. | Abnormal relative power statistics -- | PSTAT, number 1 on ABNORM menu |
| 9. | Abnormal delay statistics -- | DSTAT, number 2 on ABNORM menu |
| 10. | Statistics of relative phase -- | PHASE, number 1 on PHASER menu |
| 11. | Statistics of impulse response width -- | WIDTH, number 1 on UTIL menu |
| 12. | Scattergram of delay vs. power -- | DELPOW, number 1 on UTIL2 menu |
| 13. | Statistics of delay vs. relative power -- | INTER; stands alone as INTER |
| 14. | Statistics of 2nd multipath power -- | THREEP number 1 on THIRD menu |
| 15. | Statistics of 2nd multipath delay -- | THREED number 2 on THIRD menu |
| 16. | Scattergram of 1st multipath power vs.
2nd multipath power -- | POWER, stands alone as POWER |

C. Programs to evaluate processed data: dynamic properties of multipath

- | | | |
|-----|---|---------------------------------|
| 17. | Statistics of rate of change in delay -- | RATED, number 2 on UTIL menu |
| 18. | Statistics of rate of change in power -- | RAPED, number 3 on UTIL menu |
| 19. | Statistics of rate of change in phase -- | PHRATE, number 2 on PHASER menu |
| 20. | Statistics of multipath life cycle -- | MULTI, stands alone as MULTI |
| 21. | Duration of abnormal multipaths -- | ABSTAT, number 3 on ABNORM menu |
| 22. | Rates of change in delay, phase, and
power vs. elapsed time -- | TIME, stands alone as TIME |

D. Applications

- | | | |
|-----|--|------------------------------|
| 23. | Statistics of in-band amplitude slope -- | SLOPE, stands alone as SLOPE |
|-----|--|------------------------------|

E. Data file statistics

- | | | |
|-----|-------------------------|------------------------------|
| 24. | Data file statistics -- | STATS, stands alone as STATS |
|-----|-------------------------|------------------------------|

F. Utilities

- | | | |
|-----|--|--------------------------------|
| 25. | Combine processed data files -- | LNKFLS, stands alone as LNKFLS |
| 26. | Store processed data file on mag tape -- | TAPWRT, stands alone as TAPWRT |
| 27. | Read processed data file from tape -- | TAPRD, stands alone as TAPRD |

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