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Application of a modified time delay spectrometry technique in modeling of underwater acoustic propagation.

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NAVAL POSTGRADUATE SCHOOL
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APPLICATION OF A MODIFIED TIME DELAY SPECTROMETRY TECHNIQUE IN MODELING OF UNDERWATER ACOUSTIC PROPAGATION

by

Louis L. Prudhomme

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Thesis Advisor: O.B. Wilson, Jr.

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Application of a Modified Time Delay Spectrometry Technique in Modeling of Underwater Acoustic Propagation

by

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B.S., Tulane University, 1980

Submitted in Partial fulfillment of the
requirements for the degree of

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ABSTRACT

The analysis of sound propagating by multiple paths in an ocean at short ranges has been conducted using a Modified Time Delay Spectrometry (TDS) technique. In this version of TDS, a source driven by a linear FM slide and an HP3561A Dynamic Signal Analyzer are used to measure the amplitude as a function of frequency of signals traveling by different paths and having different arrival times. Two sets of data from the acoustic test ranges at the Naval Undersea Weapons Engineering Station were analyzed for different environmental conditions to determine the relative amplitudes of the directly propagating and surface reflected signals. Comparisons with simple rough surface scattering theory showed reasonable agreement. Results and control software are presented and discussed. Recommendations for future applications are made.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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Finally, to my most staunch supporter whose love extended to helping me type my thesis, my wife Lynette.

I. INTRODUCTION

A. BACKGROUND

The Naval Undersea Warfare Engineering Station (NUWES) in Keyport, Washington, performs measurements on torpedo radiated noise as part of the test and proofing process of torpedoes. From these measurements torpedo radiated noise baselines are established, torpedoes are accepted or rejected on the basis of meeting established radiated noise criteria, and design improvements in noise reduction can be evaluated. For these reasons, it is important that sound transmission loss between the source, the torpedo, and the receiver, a system called the Noise Recording System (NRS), be accurately modeled. The current model, based on empirical data, appears to be satisfactory under normal conditions. However, under unusually rough surface conditions scattering effects may disturb the measurement.

A limited number of experiments and theoretical studies have been conducted by Naval Postgraduate School (NPS) Students and Faculty to determine the significance of rough surface reflection in the multipath acoustic transmission loss problem. Brekke [Ref. 1] developed a computer-controlled FFT-based dynamic signal analyzer variation of a technique called Time Delay Spectrometry (TDS) to measure the separate contributions of multipath propagation.

TDS, originally developed by Richard C. Heyser in 1967 [Ref. 2], utilizes a transmitted Linear Frequency Modulated (LFM) pulse or "swept tone" with constant amplitude. A frequency tracking spectrum analyzer uses the difference in arrival times to discriminate between the acoustic signal traveling by a direct path and those signals traveling by reflected paths.

In a thesis at NPS, LT Ward [Ref. 3] outlined the multipath problem including environmental considerations for the NUWES test ranges at Dabob Bay and Nanoose. Further, he generated a computer model for predicting transmission loss under varying sea states. This model has not yet been verified experimentally. However, TDS may now make this possible.

B. OBJECTIVES

The objective of this thesis is to apply the modified TDS multipath measurement system to measure the effect of surface roughness on propagation loss as a function of frequency and compare the results with theory. The problem, theory, and special considerations will be presented first, followed by a description of the TDS systems. Analysis of data taken at the test range at Nanoose will then be presented including a brief discussion of the variability of the results. Results, conclusions and suggestions for future research will also be discussed.

II. PROBLEM DESCRIPTION AND CONSIDERATIONS

A. THE MULTIPATH PROBLEM

For the measurement of radiated noise, during part of the test run, the torpedo passes by a vertical array of three calibrated omnidirectional hydrophones. Maximum horizontal range between the torpedo and array is less than 1000 yards. Torpedo and hydrophone arrays are at approximately mid water depths. Water depth is typically about 600 feet in Dabob Bay and about 1200 feet at the Nanoose range. Transmission loss due to absorption can be neglected since geometrical spreading losses are between 40 and 60 dB greater than absorption at these ranges at sound frequencies of interest between 50 Hz and 30 kHz.

Since the tests are conducted in relatively shallow water, acoustic reflection from the boundaries can make significant contributions to the total acoustic intensity at the receiver. Therefore, in order to model the multipath problem adequately, geometry, boundary conditions, and environmental effects must be considered.

1. Assumptions

It is assumed that the acoustic signal is of small amplitude and that sound propagation can be described by the linear inhomogeneous wave equation. Thus the water channel acts as a linear filter. It is also assumed that the water column containing the source and the receiver is homogeneous. The bottom is considered to be flat and horizontal.

2. Multipath Geometry

Figure 2.1 depicts simple multipath geometry. According to the approach developed in Albers [Ref. 4:pp. 49-51] and presented by Ward [Ref. 3:pp. 87-88] and Brekke [Ref. 1:pp. 25-27], the acoustic signal at the receiver is the sum of source signals traveling the direct path and the contributions of "image" sources traveling various reflected paths.

Following Brekke's notation [Ref. 1:p. 27], the source depth is ZS and the receiver depth is ZR. The horizontal separation between source and receiver is R and the channel depth is H. In terms of these quantities, the direct path distance (XR), the surface reflected path distance (XSR) and bottom reflected path distance (XBR) are given by:

$$XR = [R^2 + (ZR - ZS)^2]^{1/2} \quad , \qquad (2\text{-}1)$$

$$XSR = [R^2 + (ZR + ZS)^2]^{1/2} \quad , \qquad (2\text{-}2)$$

and

$$XBR = [R^2 + (2H - ZR - ZS)^2]^{1/2} \quad . \qquad (2\text{-}3)$$

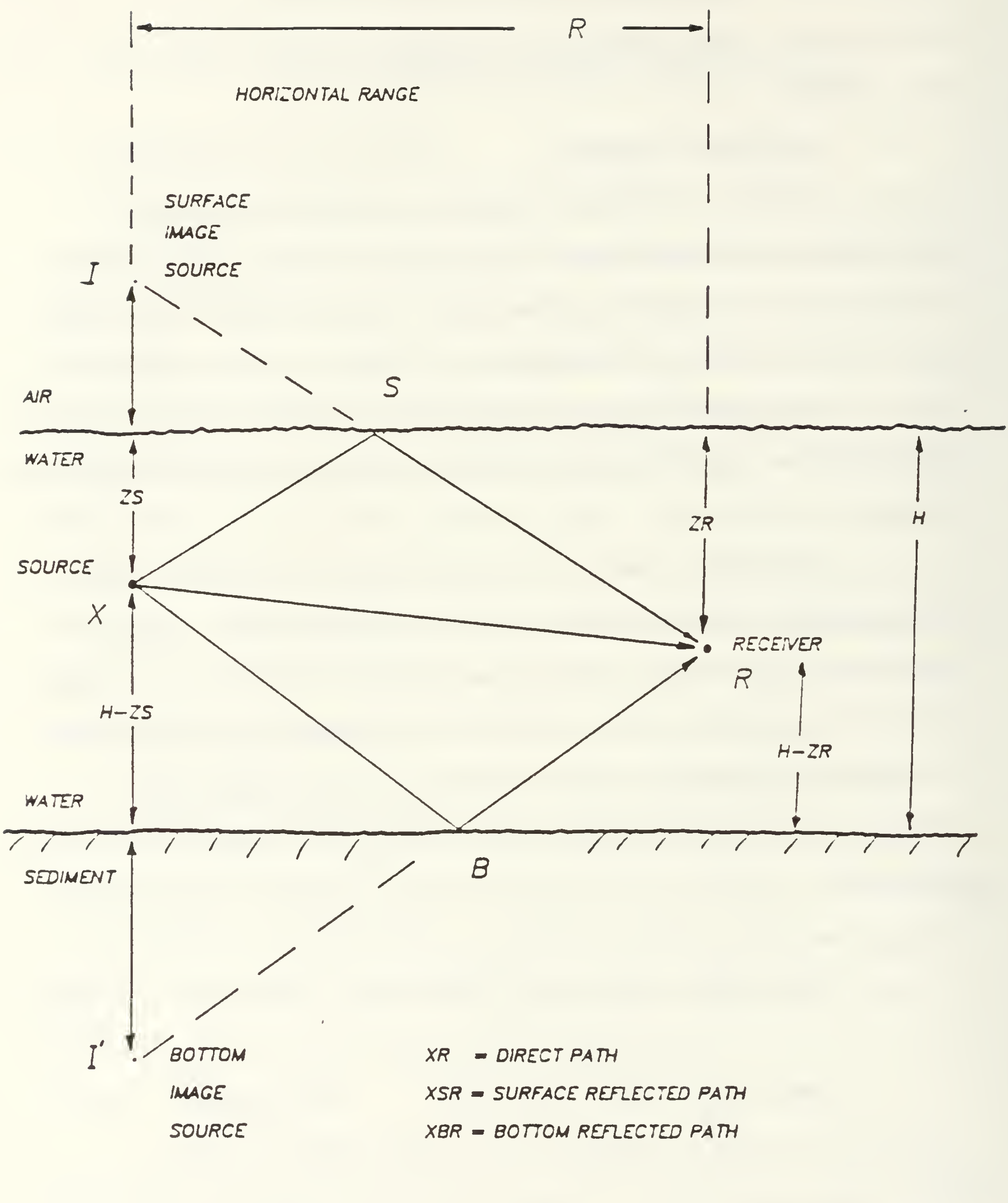


Figure 2.1 Simple Multipath Geometry
(Extracted from Ref. 1]

For periodic signals, the contributions of the image sources must be considered with respect to both relative phase and amplitude. The phases of the reflected signals are shifted with respect to the directly propagating signal by an amount proportional to the difference in propagation path. Additionally the surface reflected signal undergoes a complete phase reversal at reflection. The delayed arrival times, for a given sound velocity c, are computed as follows:

Surface time delay is $$t_s = \frac{XSR - XR}{c} \qquad (2\text{-}4)$$

Bottom time delay is $$t_b = \frac{XBR - XR}{c} \qquad (2\text{-}5)$$

and the time delay between arrivals of surface and bottom reflected sounds, or inter-reflected time delay t_r, is

$$t_r = \frac{XSR - XBR}{c} \quad . \qquad (2\text{-}6)$$

Assuming an omnidirectional source radiating simple harmonic waves, the acoustic pressure wave function at a range r is given by:

$$P = (A/r)\ \exp j(\omega t - kr) \qquad (2\text{-}7)$$

where A is the pressure amplitude at unit distance, k is the wave number (ω/c), and is the angular frequency [Ref. 5:

p. 112]. The acoustic pressure at the receiver due to the signal arriving via the direct path is given by:

$$P_d = (A/XR) \exp j[\omega t-(k\{XR\})] \tag{2-8}$$

The contribution of the surface "image" is given by:

$$P_s = -R_s (A/XSR) \exp j[\omega t-(k\{XSR\})] \tag{2-9}$$

where Rs is the coefficient of reflection for the surface [Ref. 3:p. 90]. Similarly, the contribution due to bottom reflection is given by:

$$P_b = R_b (A/XSR) \exp j[\omega t-(k\{XBR\})] \tag{2-10}$$

where R_b is the coefficient of reflection for the bottom. It is possible that R_b may have an additional phase term determined by the nature of the water-bottom composition and the angle of incidence [Ref. 3:p. 90]. Assuming that the direct and reflected waves are coherent one finds the total acoustic pressure at the receiver is the sum of several contributions:

$$P_{tot} = P_d + P_s + P_b \,. \tag{2-11}$$

Equation (2-11) can be rewritten as:

$$P_{tot} = M P_d \tag{2-12}$$

where

$$\mathbf{M} = [1 - \frac{XR}{XSR} R_s \exp(j\omega t_s) + \frac{XR}{XBR} R_b \exp(j\omega t_b)] \quad . \qquad (2\text{-}13)$$

Ward [Ref. 3:p. 91] defines this factor as the "Multipath effect."

If the phases of the signals are incoherent, the intensity of the combined signals is the sum of the intensities of the separate signals, and is given by:

$$I_{tot} = I_d + I_s + I_b \quad . \qquad (2\text{-}14)$$

Equation (2-14) can then be rewritten as:

$$I_{tot} = M_I \, I_d \quad , \qquad (2\text{-}15)$$

where

$$M_I = [1 + I_s/I_d + I_b/I_d] \quad . \qquad (2\text{-}16)$$

Equation (2-16) is defined as the Intensity Multipath coefficient. The surface reflection intensity, I_s, is determined by the condition of the surface.

The reflection coefficients, R_s and R_b, are determined by the physical properties of the boundaries. R_b is small at both ranges [Refs. 1, 3] and should be considered significant only when either source or receiver is located near the bottom. For purposes of this research R_b is assumed to be negligible. The surface is assumed to provide no mechanism for absorbing acoustic energy and, since the specific acoustic impedance of air is small compared to that of seawater [Ref 5:p. 127], the energy in an acoustic signal incident at the surface is assumed to be perfectly reflected or scattered back into the water.

3. Surface Reflection

Urick [Ref. 6:p. 128] describes the sea surface as "both a reflector and a scatterer of sound and has a profound effect on propagation . . . where source and receiver lie at shallow depth." Surface "roughness," defined in terms of signal wavelength, determines the nature of the acoustic signal after interaction with the surface. Urick defines the Rayleigh parameter, $kH \sin \theta$, as the criterion for acoustic "roughness," where k is the wave number (ω/c), H is the rms wave height (peak to trough) and is the grazing angle [Ref. 6:p. 129]. When $kH \sin \theta >> 1$, the reflection process is called scattering and the sea surface randomly scatters all the energy from an incident acoustic signal. For $kH \sin \theta << 1$, the surface behaves as an acoustic mirror and the reflected wave is completely coherent with the incident wave [Refs. 3, 5, 6].

The vertical elevation of the sea surface is a time-variant random process and is usually modeled statistically.

A relatively good first approximation of the probability distribution of the surface wave height [Ref. 3:p. 66], particularly when $kH \sin \theta < 1$ [Ref. 7:p. 344], is the stationary Gaussian process. According to developments of Beckmann and Spizzichino [Ref. 8:pp. 73-74], the mean time average scattering coefficient $\langle q \rangle$ for a normally distributed surface is given by:

$$\langle q \rangle = X(k_z)\, q_o \tag{2-17}$$

where q_o is unity (smooth surface), $X(k_z)$ is the spatial Fourier transform of the surface probability density function or "characteristic function," and k_z is the wave propagation vector for the acoustic signal. The characteristic function for a Gaussian distribution is given by:

$$X(k_z) = \exp\left(-\sigma^2 k_z^2/2\right) \tag{2-18}$$

where σ is the mean-to-peak rms wave height. The propagation vector, k_z, for the case where the reflected angle Φ_r is equal to the incident angle Φ_i, is given by:

$$k_z = 2k \cos \Phi_i \quad . \tag{2-19}$$

The term k_z is equivalent to the Rayleigh parameter. Beckmann and Spizzichino define it as $g^{1/2}$ and use it as a measure of surface roughness [Ref. 8:p. 82]. Using the definition of g and Equation (2-15), the mean time average scattering coefficient of Equation (2-13) becomes:

$$<q> = \exp(-g/2) \quad . \qquad (2-20$$

The power reflection coefficient, R_π , is the ratio of acoustic energy scattered by a rough surface to the energy scattered by a smooth surface (unity) [Ref. 3:p. 68] and is defined by the expression:

$$R_\pi = <qq^*> = \exp(-4k^2 \sigma^2 \cos^2 \Phi_i) \quad . \qquad (2-21)$$

The surface amplitude reflection coefficient, R_s, is then given by [Ref. 3:p. 63]:

$$R_s = R_\pi^{1/2} = \exp(-2k^2 \sigma^2 \cos^2 \Phi_i) \quad . \qquad (2-22)$$

Based on experimental determinations, Clay and Medwin [Ref. 7:p. 344], show that for values of $g^{1/2}/2$ greater than unity, Equation (2-19) tends to under-estimate the true value of R_s. They cite shadowing effects and variation in actual wave shapes as reasons for these differences.

If it assumed that there is negligible bottom reflection, the multipath term of equation (2-12) becomes:

$$\mathbf{M_S} = [1 - \frac{XR}{XSR} R_s \exp(-j\omega t_s)] \quad . \tag{2-23}$$

The sound pressure level at the receiver due to sound travelling by the direct path is given by:

$$SPL_D = SPL_M - 10 \log_{10} |M_S|^2 \ , \tag{2-24}$$

where

$$SPL_M = 20 \log_{10} |\mathbf{P_{tot}}| \ . \tag{2-25}$$

Equation (2-22) is the total sound pressure level at the receiver.

4. Environmental Considerations

Brekke [Ref. 1] and Ward [Ref. 3] include extensive environmental data for both NUWES test ranges. The key environmental variable affecting multipath propagation is extreme variation in the sound velocity profile (SVP). There is the possibility of strong negative gradients occurring above 100 ft in depth. The resulting refraction may reduce delay time between the signal traveling the direct path and reflected paths so that they may not be discernible [Ref. 1:pp. 27-37] or may affect the actual angle of incidence at the surface.

B. TDS CONSIDERATIONS

An analytical discussion of the modified TDS technique is presented by Brekke [Ref. 1:pp. 16-24]. The points of the verification to be considered here are the linear sweep or LFM pulse and the response of the HP3561A Dynamic Signal Analyzer.

1. The LFM Pulse

Figure 2.2 represents the LFM pulse in the time domain. The amplitude of the signal is constant and for convenience is assigned a value of unity. The frequency range F is the difference between the start frequency f_1 and the stop frequency f_2. The carrier frequency f_c is defined as the average of f_2 and f_1. The sweep has a period of T seconds before it repeats. In terms of these parameters, the instantaneous voltage of the LFM pulse can be determined as a function of time in the expression [Ref. 1:p. 17]:

$$X(t) = \cos[(\pi(F/T)t^2 - \pi Ft + 2\pi f_c t] \quad . \qquad (2\text{-}26)$$

The phase of the signal is:

$$\phi(t) = \pi(F/T)t^2 + 2\pi f_1 t \quad . \qquad (2\text{-}27)$$

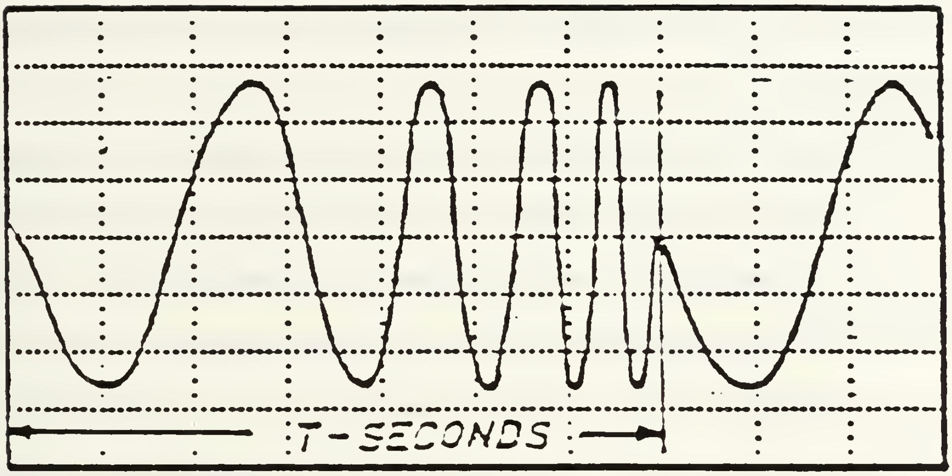


Figure 2.2: The LFM Pulse
(Extracted from Ref. 1)

The instantaneous frequency f_i is obtained by taking the derivative with respect to time of Equation (2-27) and dividing by 2π:

$$f_i = (F/T)t + f_1 \ . \tag{2-28}$$

The sweep rate (S) is defined as the derivative with respect to time of Equation (2-28):

$$S = F/T \ . \tag{2-29}$$

In the context of multipath propagation, the instantaneous frequency of the signal propagating by the direct path differs in frequency from the reflected signals by an amount equal to the sweep rate, S, times the delayed arrival time of the reflected signal given in Equations (2-4) and (2-5).

2. Response of the HP3561A Dynamic Signal Analyzer

In the current experimental configuration, the LFM pulse is applied to a broad band-width projector. The acoustic wave propagates by one or more paths through the water to a hydrophone. The electrical signal from the hydrophone is recorded in analog form on magnetic tape. The recorded signal is subsequently analyzed using the HP3561 Dynamic Signal Analyzer. The measurements are based on a 1024 point FFT algorithm. The displayed spectrum contains 400 bins. Frequency resolution of the analyzer is determined by the selected frequency span F of the analyzer in terms of the bin separation b:

$$b = F/400 \ \text{Hz} . \qquad (2\text{-}30)$$

For a frequency span of 5 kHz, the corresponding frequency resolution is 12.5 Hz. The time record length, the observation time t_{obs} during which the analyzer receives data from the signal, is given by:

$$t_{obs} = 1/b \ \text{sec} . \qquad (2\text{-}31)$$

This is the minimum amount of time required by the analyzer to obtain sufficient samples to carry out the FFT algorithm. The energy contained in each of the 400 bins is calculated and made available for display by the analyzer during the observation time. In most operating modes, the HP3561A displays only the most recent time record data. In Time Capture mode, however, the analyzer acquires and stores data contained in 40 contiguous time records. Time Capture will be discussed in more detail in the next chapter.

The consequence of these relations is that the delayed arrival times given by Equations (2-4) and (2-5) must be greater than t_{obs} in order to resolve the directly propagating and reflected signals [Ref. 1:p. 48]. For delay arrival times less than t_{obs}, the difference between the instantaneous frequencies of the direct and reflected signals is less than the resolution of the analyzer and thus, the energy of both direct and reflected signals are contained in the same bins.

The possibility of energy leaking into an adjacent bin and creating additional measurement errors is reduced by using a "window function" feature on the HP3561A. The result of using a window function is a minimum bandwidth separation, f_band, given by [Ref. 1:p. 48]:

$$f\_band = C \times F \quad , \qquad (2\text{-}32)$$

where C, a constant determined by the window function selected, is expressed in terms of the frequency span. For a Hanning window, C is 0.00375. Thus, if the selected frequency is 5 kHz, the resulting f_band is 18.75 Hz. So, in order to resolve the direct and reflected signals, it is necessary to insure that the delayed arrival times are sufficient to maintain the minimum bandwidth separation. This is accomplished by setting a lower bound on the sweep rate, S_m, given by [Ref. 1:p. 49]:

$$Sm > f\_band/t\_delay \,, \qquad (2\text{-}33)$$

where t_delay is given by Equations (2-4) through (2-6). For surface reflection, t_delay = t_s.

III. TDS MULTIPATH MEASUREMENT SYSTEM

The TDS Multipath Measurement System is comprised of two major subsystems [Ref. 1:p. 39]:

(1) Range and test configuration

(2) Data processing system.

The range and test configuration described here is specific to the data used in this research. The test format was developed by John G. Burwell of the Acoustics Division, NUWES, Keyport, and has been implemented by Keyport personnel in previous TDS research. The data processing system presented by Brekke [Ref. 1:pp. 42-61] has been modified. A description of the hardware configuration is provided here. The software used is a slightly modified version of the TDS software documented by Brekke [Ref. 1]. The key features of the TDS programs will be discussed here and software modifications will be documented.

A. RANGE AND TEST CONFIGURATION

The data used in this study were obtained at the NUWES range at Nanoose, Canada, in February 1986. The acoustic projector for the test was the Sonar Acoustic Test System (SATS). The receiver was the Noise Recording System (NRS) with three calibrated hydrophones at depths of 330 ft., 390 ft., and 430 ft. Horizontal separation between SATS and NRS was approximately 300 yds. Wave heights were estimated at 1 to 2 ft peak-to-peak at the time of the measurements.

The test signal was a linear sweep from 50 Hz to 30 kHz. Three tests were conducted with sweep periods of 1 second, 2 seconds and 4 seconds. Thirty sweeps were transmitted for each test.

The sound signals arriving at each of the NRS hydrophones were recorded on separate channels of a magnetic tape recorder.

B. THE DATA PROCESSING SYSTEM

1. Hardware

The equipment configuration used is shown in Figure 3.1a. It is essentially the same as that used by Brekke [Ref. 1:p. 42-43], with an HP thinkjet printer replacing the HP2671G printer. For the routine tests, the graphics and printing requirements could be satisfied using the HP thinkjet as shown in Figure 3.1b.

The measurements of the signal are carried out by the HP3561A Dynamic Signal Analyzer on the recorded signal under computer control. Previously, triggering the Dynamic Signal Analyzer was done using a 1 pulse-per-second signal derived from the output of the time code generator [Ref. 1]. This was not possible, since the period of the LFM pulses for two of the tests exceed 1 second. To accommodate the longer sweep periods, the trigger signal of an HP3314A

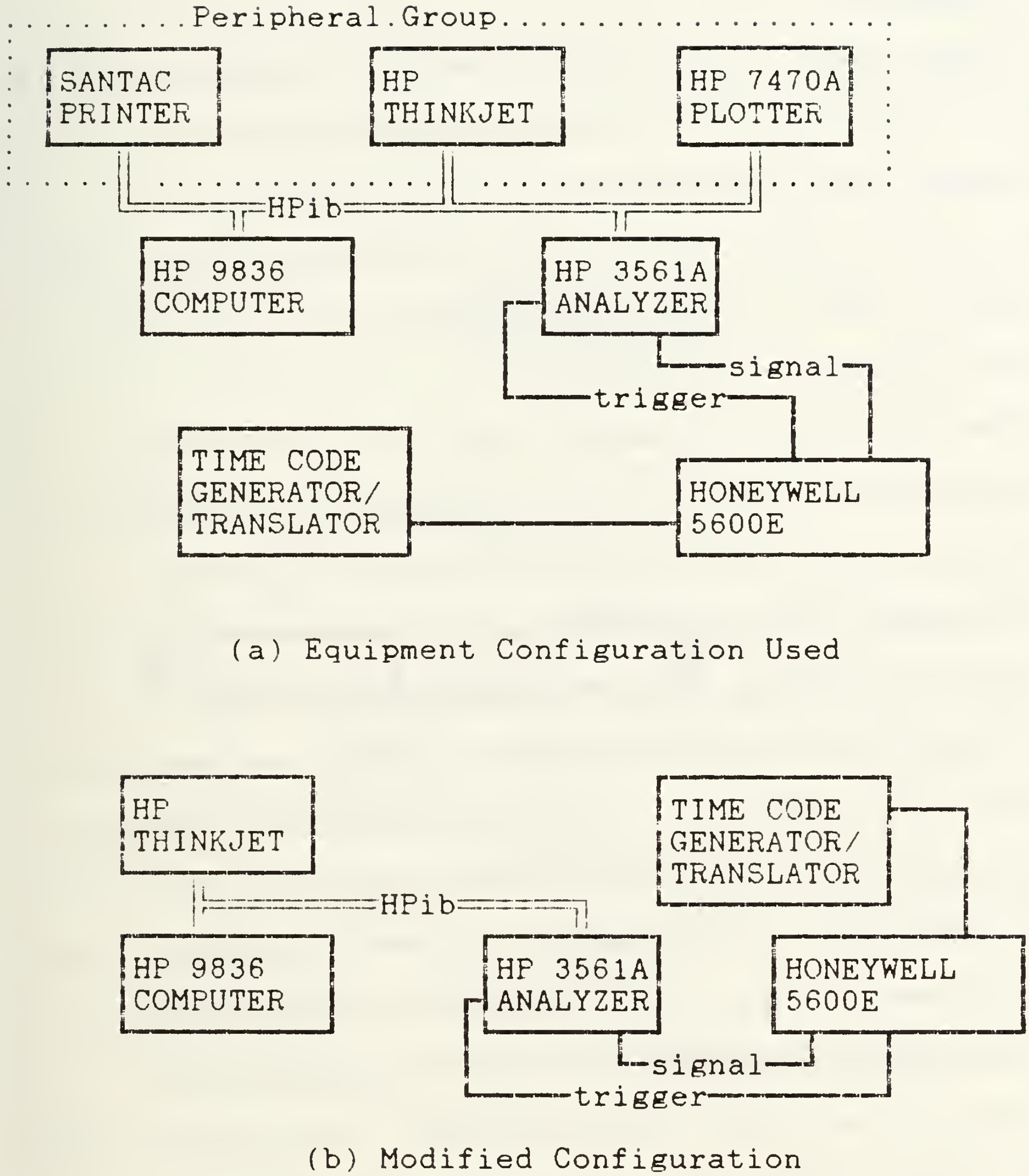


Figure 3.1 TDS Hardware

Arbitrary Function Generator was set to 4 seconds and recorded on the edge track of the data tape.

2. Software

Brekke [Ref. 1] provides a detailed documentation of the TDS_1 program. Here, a general discussion of the capabilities of the TDS software will be presented with emphasis placed on the features used in this research. The modifications used in the current version 3C of the TDS_1 program will also be documented.

The original TDS program, TDS_1, was designed to control the HP3561A Dynamic Signal Analyzer in performing TDS Multipath Measurements. It is written in HP Basic program language 2.0 with extension AP2_1. The program is structured in a modular design illustrated in Figure 3.2. It was designed to analyze a series of LFM pulses sweeping from 500 HZ to 20 kHz with a repetition period of 1 second. The Set_analyzer subprogram in version_1 set the HP3561A to measure an LFM pulse corresponding to these parameters. In order to accommodate the sweep rates and sweep periods for the new data described in part A of this chapter, the program required some small modifications. The set analyzer subprogram which services all the major subprograms was altered to allow an operator interactively to select the frequency span, start frequency and trigger method of the analyzer prior to starting any analysis.

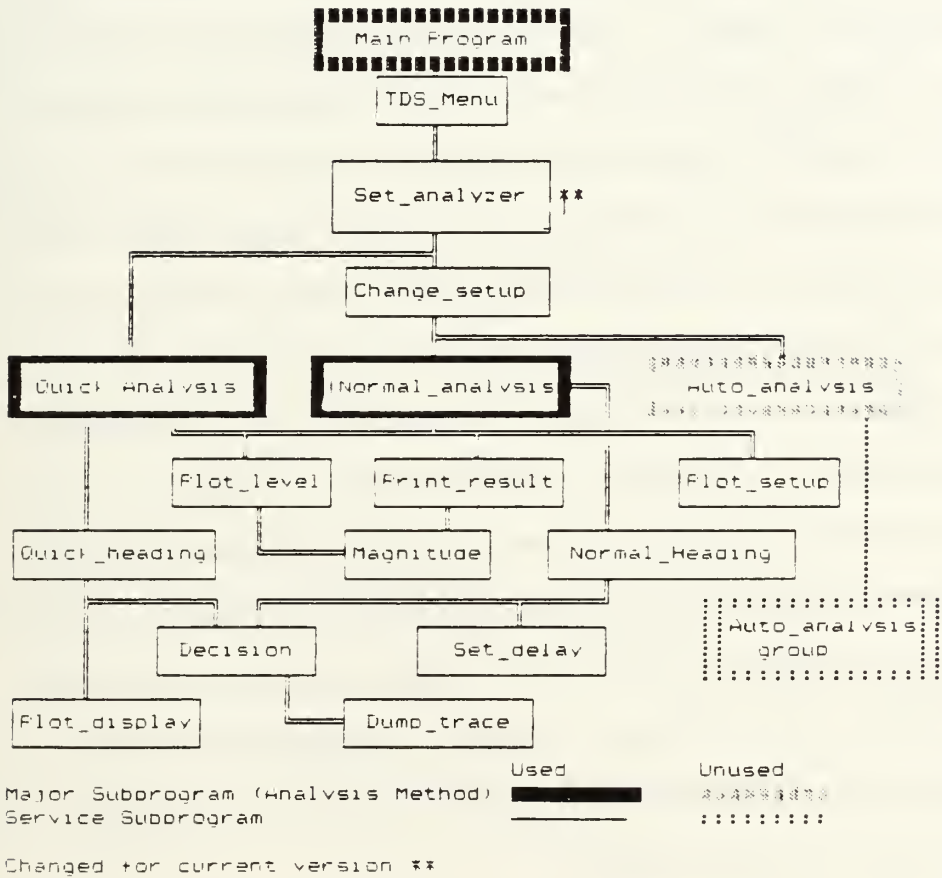


Figure 3.2 Structure of the TDS_1 Program

The signal is analyzed by one of three methods: Quick_Analysis, Normal_Analysis, and Auto_Analysis. Referring to Figure 3.2, one sees that these three methods form the three major subprograms of TDS_1. These analysis methods are discussed in the following paragraphs.

a. Quick_Analysis

In this method the HP3561A is operated in the "Time Capture Mode". The analysis is based on data taken from 40 time records stored in the time buffer of the analyzer memory. Each time record consists of the data processed during one observation time t_{obs}. The total time during which the analyzer processes data is 40 x t_{obs}. Figure 3.3 illustrates the storage of the LFM pulse in the time buffer. The data are displayed as a 3-dimensional magnitude map. Each map consists of 60 traces. The overlap (or increment) processing selected determines the time increment represented by each subsequent trace. For the 20% overlap processing used in the TDS program, each trace represents a 0.2 x t_{obs} increment of the delay time. The analyzer uses 20% new data taken from the subsequent time record for each new trace.

The purpose of the overlap processing is to optimize the useful information displayed by the analyzer. In selecting an appropriate overlap, the sweep rate, the analyzer frequency span, and the frequency span of the LFM pulse must be considered. For example, the 4 second LFM

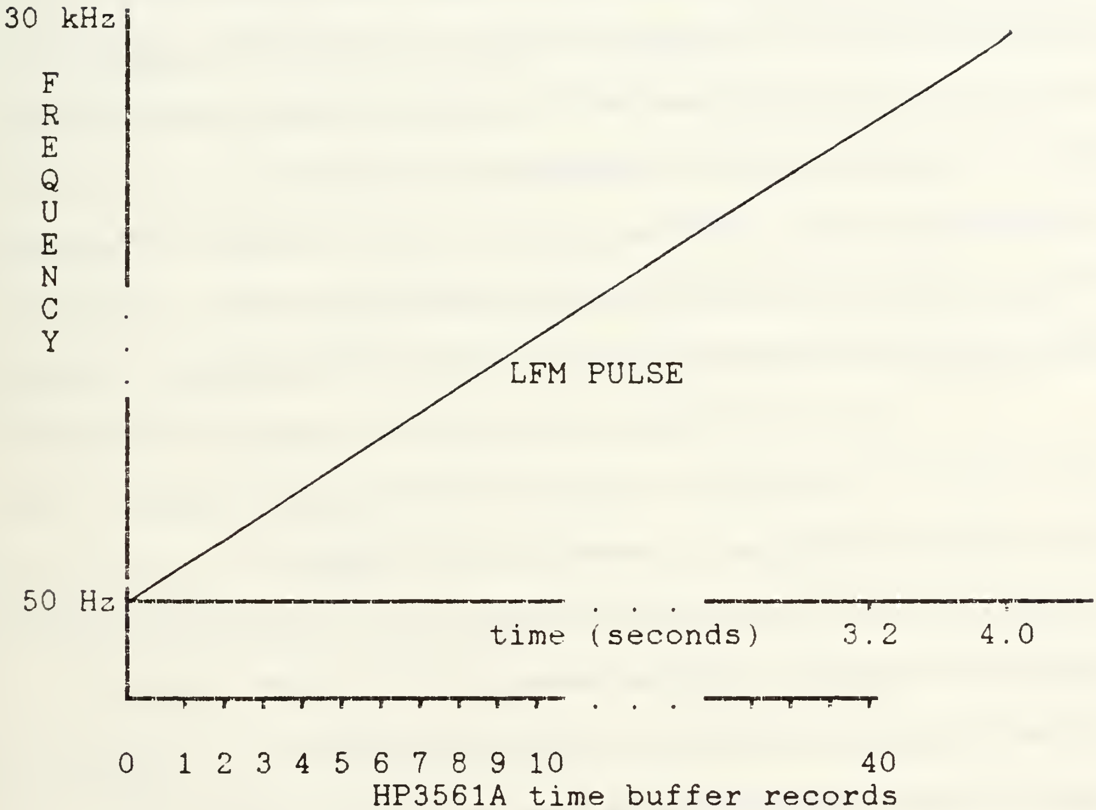


Figure 3.3 Storage of an LFM Pulse in the HP3561A Dynamic Signal Analyzer Time Buffer for a Typical Case

pulse sweeps through a 5-kHz frequency span in approximately 678 ms. The time delay between the direct and reflected signal is about 100 ms. For the 20% overlap processing used in the TDS program each trace represents 0.2 x 80 ms = 16 ms. Thus, the analyzer uses about 50 traces to display direct and reflected signals. If, however, 30% overlap processing is used, each trace then represents 24 ms. In this case only 35 traces are used to display direct and reflected signals, leaving 25 traces displaying no useful data. If 10% overlap processing is selected, each trace represents 8 ms. The number of traces required to display direct and reflected signals is approximately 90 which exceeds the 60 traces that can be displayed by the analyzer.

Quick_Analysis provides the operator a quick overview of a "Spectral Segment" of a single sweep of the signal to be analyzed. A "spectral segment" is the portion of the LFM pulse that can be displayed by the analyzer. If the start frequency of the analyzer is 500 Hz and the frequency span selected is 5 kHz, then only the "segment" of the LFM pulse between these two frequencies can be processed.

From the spectral 3-D map, the arrival times of the "Spectral Segment" for both direct and reflected signals can be determined by adjusting the start_time of the analyzer. The time when the reflected signal vanishes from the "Spectral Segment" should also be determined. These values are used as input parameters for Normal_Analysis and Auto_Analysis. After the determination of the arrival times and "upper limits of the delayed start_time", or time when the reflected signal vanishes, the program displays individually all magnitude maps between these time limits for operator input. The operator selects peaks for direct and reflected signal using the cursor on the Spectrum Analyzer. These values are recorded by the program and are printed out at completion of the analysis.

It should be noted here that Quick_Analysis requires only a single trigger since only one sweep is captured. The requirement for a sequence of synchronous triggers exists when Normal_Analysis or Auto_Analysis will be performed.

b. Normal_Analysis

In this method 8 sweeps are RMS averaged to reduce effects of signal fluctuation and increase signal to noise ratio before making measurements. The measurements are made in a manner similar to those in Quick_Analysis in which the operator must select peak values using the cursor on the HP3561A. The program increments the delay_step after each measurement to measure the frequency bin of the later arrival time. These measurements are repeated for every delay_step in the time interval determined by the Quick_analysis method.

The delay_step should increment each measurement by a frequency larger than the frequency resolution of the analyzer.

c. Auto_analysis

This method automates the measurements performed by Normal_Analysis method. Due to a high noise level at the lower end of the spectrum, the operator's observation was necessary to discriminate between direct and reflected signals. Consequently, the Auto_Analysis method was not used in this study.

d. Analysis Products

Each of the methods produces a table of voltage levels for direct and reflected signals as well as a noise level. The program enables the operator to plot the magnitude of direct and reflected signals as a function of frequency. This requires that all the tabulated frequency values be monotonically increasing. This is not always the case, since often the reflected path peak is recorded at a lower frequency than the previous measurement due to the uneven nature of boundary reflection. Using a longer delay time will reduce this problem, but with the result that fewer samples are recorded.

IV. DATA ANALYSIS

The analysis of a "spectral segment" of LFM pulse with the 4 second period is presented here. Procedures used here are the same for the analysis of any "spectral segment" of any LFM pulse. Multipath problem considerations are discussed with respect to TDS parameters. Measurements made using the Normal_Analysis method are used to determine the effects that surface reflection or scattering have on the acoustic field at the receiver. Measurements by the Quick_Analysis method on several different sweeps are compared to the Normal_Analysis results to estimate the sweep to sweep variability in results.

A. ANALYSIS PARAMETERS

1. Time Delays

The sound velocity profile given in Figure 4.1 is typical for the Nanoose range in February [Ref. 9]. Because the effects of refraction due to this profile are small for horizontal ranges of a few hundred yards, the water column will be assumed to have a constant sound speed of c = 4850 ft/sec. The multipath parameters for the problem are given in Table 1.

The minimum time delay given by Table 1 is 82 ms. The minimum frequency span setting for the HP3561A is 5 kHz corresponding to t_{obs} = 80ms.

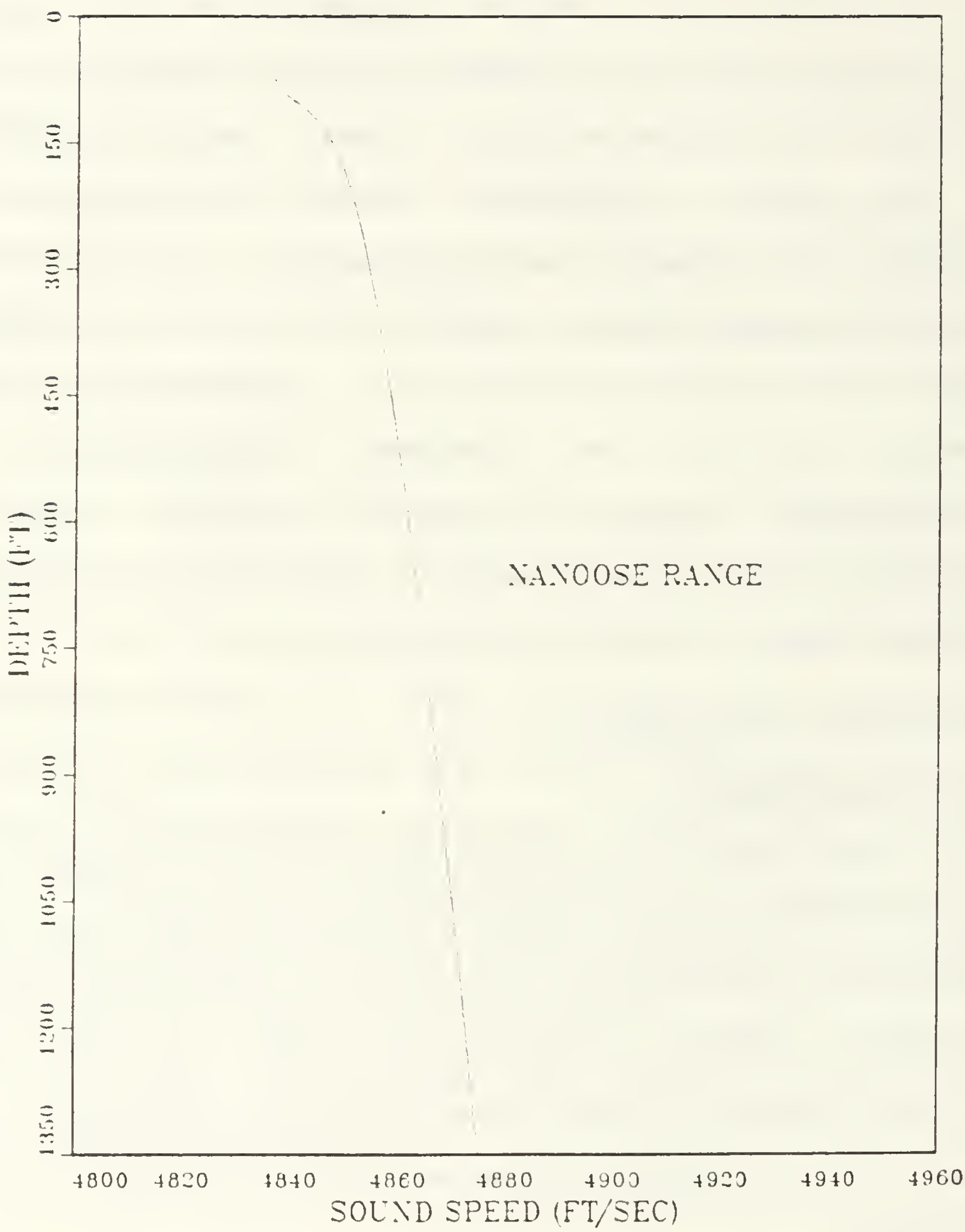


Figure 4.1: Sound Velocity Profile (Nanoose-February)

TABLE 1

DISTANCES AND TIME DELAYS

RCVR (depth)	XR (yds)	XSR (yds)	t_s (ms)
upper (330)	100 yds	233 yds	82 ms
middle (390)	104 yds	251 yds	91 ms
lower (430)	210 yds	266 yds	96.4 ms

Source depth: 300 ft

Horizontal Range: 100 yds (300 ft)

c = 4850 ft/sec.

2. The Rayleigh Reflection Coefficient

Assuming transmission loss to be due to only spherical divergence, the sound pressure level at the receiver due to the direct signal is given by:

$$SPL_S = SPL[P(1)] - 20 \log XR \quad (4\text{-}1)$$

The sound pressure level due to a surface reflected signal is assumed to be given by:

$$SPL_R = SPL\ [P(1)] - 20 \log XSR + 10 \log (R_s) \quad (4\text{-}2)$$

P(1) is the sound pressure at unit distance from the source. Subtracting (4-2) from (4-1) yields:

$$10 \log R_s = SPL_D - SPL_R + 20 \log (XSR/XR) \quad . \qquad (4-3)$$

If all terms on the right hand side of (4-3) are known, then a value for R_s can be determined. Using equation (2-21), one can solve for the mean-to-peak wave height. For six sweeps analyzed using the Quick_analysis method, these calculations gave an average value for σ of 0.54 ft at frequencies less than 1200 Hz. The standard deviation at these frequencies was on the order of 0.05 ft. At frequencies above 1200 Hz, the calculated values for σ decreased.

These results are consistent with data given by Clay and Medwin [Ref. 7:p. 344]. Since the wave heights were estimated between 1 and 2 ft, 0.54 feet for σ seems to be reasonable. So for the data used here, the measurements made by the Modified TDS Measurement System appear to be valid.

3. Selecting Analyzer Settings

Since the minimum time delay is 82 ms (Table 1), the maximum observation time t_{obs} which permits the HP3561A to resolve the direct and reflected signals is 80 ms. This corresponds to a 5-kHz spans on the analyzer. As pointed out in Chapter II, choosing the maximum observation time gives the best frequency resolution on the analyzer.

Figure 4.2 is the 3-D map output of Quick_Analysis. The start frequency selected here is 500 Hz. Ideally, each 5-kHz span in the sweep would be examined successively.

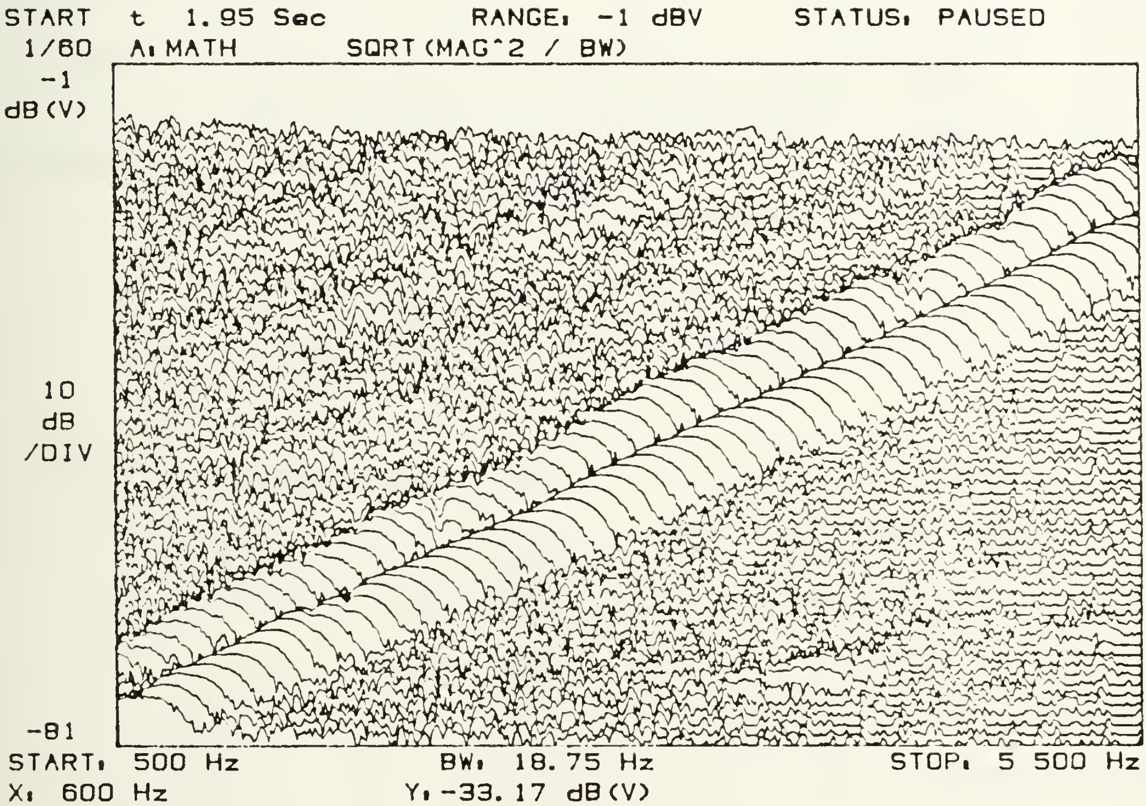


Figure 4.2: Quick_Analysis 3-D Spectral Map

B. MEASUREMENTS

The received Acoustic Level RL(f) at the face of the hydrophone is given by [Ref, 1:p. 74]:

$$RL(f) = ML(f) - CAL(f) - HS(f) + IL(f) - 47 - AG$$

where:

ML(f) is measured level in (dB re 1V)

CAL(f) is measured level of the calibration signal

HS(f) is hydrophone sensitivity

IL(f) is calibration insertion loss

AG is the Auto Gain of the Amplifier.

The levels ML(f) for these measurements are provided in outputs from the TDS_1 program in Appendix B. For selected frequencies used in this thesis, HS(f) and IL(f) are found in Table 2. These values are from the calibration records for the equipment provided by NUWES. The values for AG and CAL(f) used here are +40dB and 0dB. Since $kH \sin\theta$ is approximately unity at 1.2 kHz, some assumptions about signal reflection at the surface can be made. For $f < 1.2$ kHz, the effect of specular reflection from the surface is determined by Equation (2-22). The upper and lower bounds of the acoustic pressure at the receiver are given by:

TABLE 2

HYDROPHONE SENSITIVITIES AND INSERTION LOSSES*

Selected Frequency	Upper HS	Upper IL	Center HS	Center IL	Lower HS	Lower IL
1 kHz	-181.6	-20.0	-182.0	-20.1	-182.2	-20.1
2 kHz	-181.0	-20.0	-181.5	-20.1	-181.0	-20.1
3 kHz	-181.2	-20.0	-182.1	-20.1	-181.7	-20.2
4 kHz	-182.4	-20.0	-182.4	-20.2	-182.3	-20.2
5 kHz	-182.3	-20.1	-182.0	-20.2	-182.3	-20.3

*Data provided by NUWES

$$P_{max} = P_D(1 + \frac{XR}{XSR} R_s) \qquad (4-4)$$

and

$$P_{min} = P_D(1 - \frac{XR}{XSR} R_s) \ . \qquad (4-5)$$

For f > 1.2 kHz, the effect of scattering and incoherent addition from the surface on the average acoustic intensity at the receiver is given by Equation (2-15) where:

$$M_I = [1 + I_s/I_d] \ . \qquad (4-6)$$

The ratio I_s/I_r is equal to the ratio of measured levels of both direct and reflected signal. Since the

Normal_Analysis method uses data averaged over several sweeps, these values should be used to calculate M_I.

Multipath coefficients determined for the selected frequencies in Table 2 are displayed in Table 3.

TABLE 3

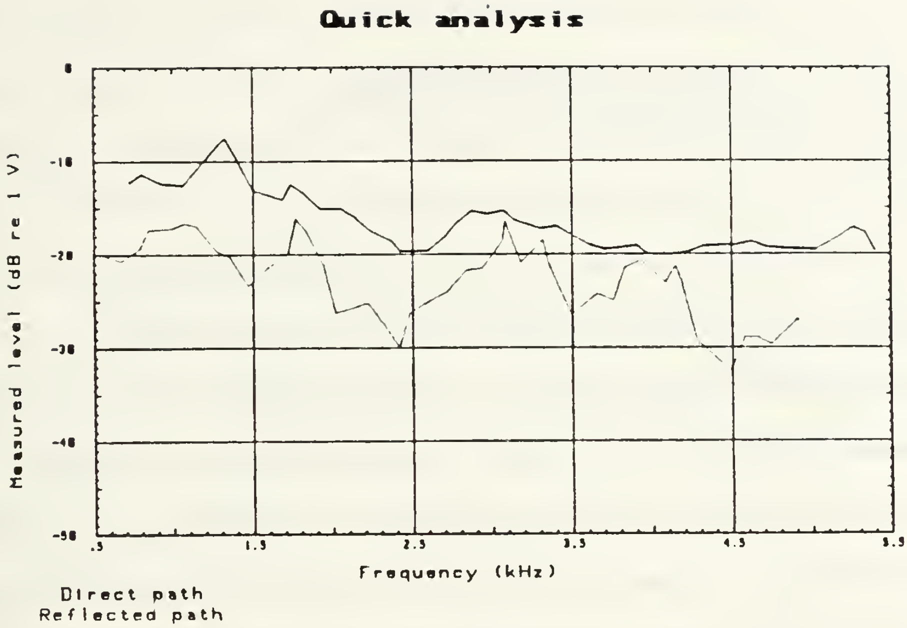
MULTIPATH COEFFICIENTS AT SELECTED FREQUENCIES

f kHz	type	Coefficient
1	coherent (M_S)	0.58 to 1.42
2	incoherent (M_I)	1.53
3	incoherent (M_I)	1.17
4	incoherent (M_I)	1.17
5	incoherent (M_I)	1.18

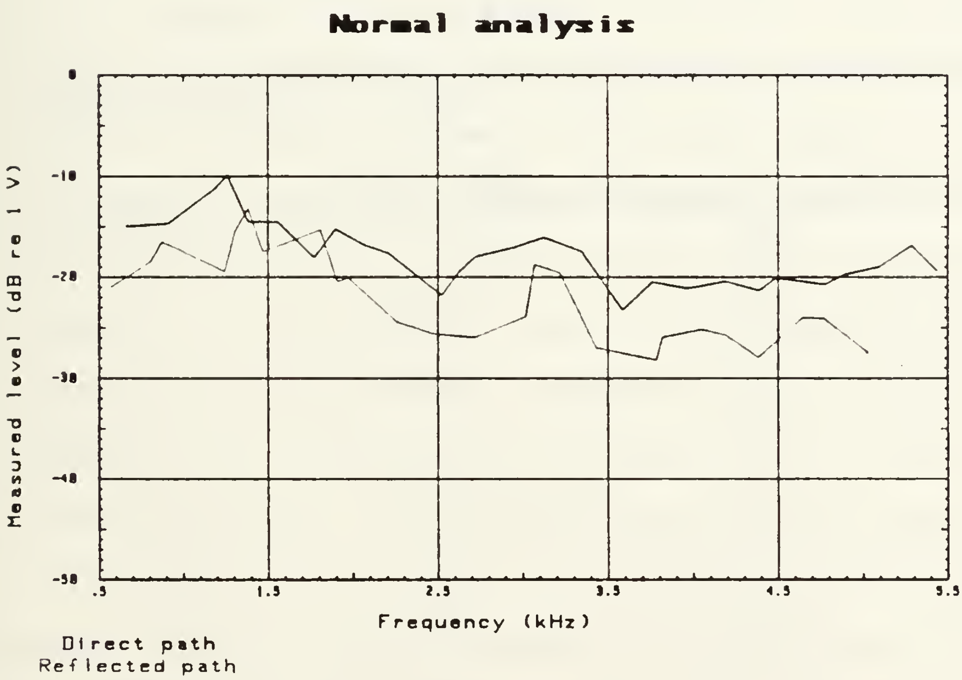
C. VARIABILITY OF RESULTS

Figure 4.3 shows a comparison of the results of Quick_Analysis and Normal_Analysis for the same conditions. Normal_Analysis, as discussed earlier, makes an RMS average of 8 sweeps. In order to check the variability of results Quick_Analysis was performed on six different sweeps. The energy averaged level of the measured band levels is given by:

$$\langle X \rangle = 10 \log_{10} \left[\sum 10^{LVL/10} / N \right] , \qquad (4\text{-}7)$$



(a) Quick_Analysis



(b) Normal_Analysis

FIGURE 4.3: Quick_Analysis and Normal_Analysis Products
(Output from TDS_1 Program)

where LVL is the measured level in a given frequency band and N is the number of measurements. Table 4 gives the mean level <X>, and "normalized" level of the standard deviation, 10 log(S) - <X>, for several frequencies.

The Rayleigh reflection parameter varies from about 1 to 5.5 over the frequency span in the experiment. The energy averaged Quick_Analysis measurements are close to the measurements obtained by the Normal_Analysis method. This indicates that the Normal_Analysis measurements provide a fairly good approximation to the average acoustic energy in each band of the measured signal.

TABLE 4

STATISTICAL COMPARISON OF SURFACE REFLECTED LEVELS

Freq (Hz)	Quick Analysis <X>	(dB re 1V) Normal Analysis	$10\log_{10}(s)-<X>$
1000	-12.6	-12.0	-13.4
1500	-13.9	-14.6	- 3.8
2000	-18.4	-18.3	- 0.25
2500	-25.7	-26.1	- 2.4
3000	-21.2	-21.9	- 1.5
4000	-24.0	-21.5	- 4.0
5000	-24.4	-22.9	- 2.7

V. DISCUSSION AND CONCLUSIONS

A. DISCUSSION

1. Procedure

Two factors which caused the greatest difficulty in analyzing data were the way in which the trigger was set and the choice of the number of sweeps for each data run. As discussed earlier, the Dynamic Signal Analyzer was triggered by signals recorded on the edge track of the data tape. The Honeywell 5600E magnetic tape recorder has a total of 14 channels. This includes 13 data channels and one edge channel, typically used for voice comments. The edge channels can be recorded without disturbing the data recorded on the data channels. The edge tracks, located on the "edge" of the tape, sometimes suffer degradation caused by tape guides on the recorder. The trigger for the HP3314 Arbitrary Function Generator was set to 4 seconds and recorded on the edge track. Several attempts were made to synchronize the trigger with the start of the LFM pulse. The data analyzed in this thesis required approximately 1.9 second trigger delay. For the overlap processing used in the TDS program, only 80 percent of the LFM pulse was processed in Quick_Analysis. Since the trigger was not synchronized to the start of the LFM pulse, 20 percent of the signal between 8 kHz and 12 kHz could not be captured by the analyzer.

The trigger level remained high for approximately 1.7 seconds. This made Quick_Analysis possible for parts of the sweep arriving during times of high trigger. Normal_Analysis was not possible, however, because the analyzer continued to trigger and sample <u>different</u> portions of the LFM pulse.

For further TDS measurements a sharp, short-duration trigger is necessary and should be recorded on tape with the data. The data Brekke used had a one second sweep period which was synchronous with the range time signals. A 1-Hz trigger was derived from the IRIG-B, time code generator translator. If a one second sweep period is maintained, the frequency span of the signal will have to be reduced to accommodate a slower sweep rate. If a slower sweep is used, such as the 4 second sweep used here, the advantage of a larger frequency span is gained. In this case, a trigger signal synchronous with the start of the LFM pulse should be recorded.

The total data time for all three tests was 3.5 minutes, with two minutes the maximum total time for slowest sweep rates. Normal_Analysis requires 8 sweeps to make one measurement. For thirty sweeps, a maximum of 3 measurements can be made before the tape must be rewound, repositioned and started again. For the 5-kHz span used here approximately 42 measurements are required and consequently the rewind process was repeated a minimum of 14 times. With five minutes of data recorded, the rewind process would be repeated only 5 times. Since the rewind process totals about 3 minutes the analysis time would be reduced significantly. An additional benefit is that increased information available from the longer record could be used to determine the variability of the surface reflection. In future tests, the data recorded should be of a longer time at one sweep rate with 5 minutes of data accumulation as a minimum.

2. Software

The modifications made to the TDS_1 program have made it more flexible in making analysis of data. Eliminating a requirement for the plotter shown in Figure 3.1 (b), would streamline the process considerably. Although HP Thinkjet graphic printouts are not as detailed or colorful as the plots of the HP7470A plotter, for perishable measurements the HP Thinkjet products are adequate.

The Quick_Analysis printouts given in Appendix B.1 read in 4 ms increments; this corresponds to 16 ms of time in the Normal_Analysis printouts, Appendix B.2.

The program in current form can be used for routine measurements. Minor modifications need to be implemented for the changes just discussed, but personnel who would use the products and conduct the measurements should determine the final form of the program.

B. CONCLUSIONS

The Modified TDS Measurement System presented by Brekke [Ref. 1] provides useful information about an acoustic signal propagating by direct and surface reflected paths. When the sea surface has some degree of roughness, measurements by this method permit the effect of the surface reflected signal and the direct signal to be considered separately. Further modifications to the measurement system are still required. In its current configuration, the system is cumbersome. The removal of the requirement for a plotter could streamline the analysis for routine tests.

The HP3561A Dynamic Signal Analyzer can perform an energy average of a recorded bandwidth. This technique may be more accurate than the current method of recording only the peak value, particularly for Quick_Analysis. In Normal_Analysis the averaging over 8 sweeps, eliminates most of the variability so there should not be a significant difference between the average of peaks and the energy average. In Quick_Analysis, however, the averaging over the bandwidth would improve the accuracy of measurements, particularly for the reflected signal at higher frequencies. The results obtained here are not conclusive. More data needs to be analyzed. The results reported here were made for a limited frequency range. Results for different sweep rates and frequency spans should be investigated and compared.

In any future tests, more extensive measurements and recording of environmental conditions need to be made. If reflected signals are distinguishable and if more than one is present, the operator may use TDS_1 to compare any of the reflected signals with the directly propagating signal. Future modification to the TDS program should allow for the analysis of more than one reflected signal.

APPENDIX A

RANGE AND TEST DATA

This list provides a guideline of information to be recorded at the range just prior to conducting tests using the Modified TDS Measurement System.

1. ENVIROMENTAL
   - (a) Wind-Speed and Direction
   - (b) Sound Velocity Profile
   - (c) Wave Heights
2. CONFIGURATION OF TEST
   - (a) Horizontal Ranges Between Source and Receivers
   - (b) Depths of Source and Receiver
   - (c) Range to Nearest Land
   - (d) Water Depth at Test Sight
3. TEST PARAMETERS
   - (a) Calibration Signal
   - (b) Auto Gain Settings
   - (c) LFM Pulse
     - Frequency Span
     - Repetition Period
     - Number of Sweeps
4. CALIBRATION RECORDS FOR RECEIVING EQUIPMENT
   - (a) Hydrophone Sensitivities
   - (b) Insertion Loss Data

APPENDIX B

TABULATED MEASUREMENT RESULTS

NPS: UPPER HYDROPHONE

ANALYIS METHOD: QUICK ANALYSIS

DATE OF ANALYSIS: 12/1/86

RECORDED MAGNITUDE LEVELS (dB re 1V)

DELAY(MS)	DIRECT MAGN	DIRECT FRQ(HZ)	REFL MAGN	REFL FRQ(HZ)	NOISE MAGN
1900	-9.33	500	19.75	0	-51.16
1904	-9.21	563	19.75	0	-49.99
1908	-8.85	662	19.75	0	-49.69
1912	-7.76	750	19.75	0	-49.51
1916	-9.28	875	19.75	0	-48.67
1920	-8.09	1013	19.75	0	-47.57
1924	-8.46	1125	19.75	0	-45.92
1928	-6.39	1238	19.75	0	-43.42
1932	-5.06	1300	-14.91	550	-42.00
1936	-6.35	1363	-14.81	725	-42.92
1940	-9.85	1512	-13.85	787	-44.01
1944	-11.53	1575	-14.13	888	-43.88
1948	-9.96	1725	-12.80	1038	-42.29
1952	-9.93	1800	-10.42	1125	-40.59
1956	-11.89	1913	-8.09	1263	-39.72
1960	-12.27	2050	-7.14	1300	-40.14
1964	-11.24	2113	-9.77	1413	-41.08
1968	-12.70	2263	-10.39	1438	-42.77
1972	-11.76	2325	-17.93	1563	-43.72
1976	-13.69	2438	-14.58	1788	-44.94
1980	-15.24	2513	-11.66	1825	-44.79
1984	-15.29	2675	-13.25	1862	-44.20
1988	-13.84	2775	-15.29	2050	-43.45
1992	-12.60	2875	-15.05	2150	-43.15
1996	-11.92	2963	-13.69	2188	-43.06
2000	-11.79	3075	-15.71	2325	-43.49
2004	-11.76	3138	-21.23	2388	-43.11
2008	-14.02	3250	-20.03	2525	-43.25
2012	-14.14	3375	-21.91	2662	-43.68
2016	-13.78	3463	-22.64	2687	-43.72
2020	-14.54	3550	-19.82	2863	-44.14
2024	-16.51	3650	-20.56	2925	-44.03
2028	-16.61	3775	-20.28	3088	-44.07
2032	-16.57	3863	-19.28	3088	-43.96
2036	-16.46	3950	-21.54	3175	-43.60
2040	-17.92	4050	-22.95	3325	-43.76
2044	-17.19	4188	-20.74	3513	-43.06
2048	-16.93	4288	-19.11	3525	-42.96
2052	-17.07	4375	-25.74	3625	-42.80
2056	-17.51	4475	-18.46	3788	-43.04
2060	-17.06	4588	-19.91	3875	-43.03
2064	-17.76	4675	-21.03	3900	-43.03
2068	-18.31	4763	-20.02	4113	-42.63
2072	-18.96	4913	-21.88	4150	-42.52
2076	-18.96	5012	-24.44	4250	-42.66
2080	-18.49	5150	-25.28	4425	-42.89
2084	-16.71	5262	-24.66	4463	-43.21
2088	-15.13	5313	-21.20	4625	-43.59
2092	-16.02	5388	-23.54	4662	-44.61
2096	-16.85	5500	-25.07	4750	-44.73
2100	-21.43	5500	-27.18	4938	-44.39
2104	19.75	0	-22.31	5038	-45.11
2108	19.75	0	-21.15	5125	-45.06
2112	19.75	0	-20.63	5188	-44.84

NPS: MIDDLE HYDROPHONE

ANALYIS METHOD: QUICK ANALYSIS

DATE OF ANALYSIS: 11/30/86

RECORDED MAGNITUDE LEVELS (dB re 1V)

DELAY(MS)	DIRECT MAGN	DIRECT FRQ(HZ)	REFL MAGN	REFL FRQ(HZ)	NOISE MAGN
1930	-6.60	563	19.75	0	-47.81
1934	-7.00	575	19.75	0	-46.91
1938	-4.90	750	19.75	0	-46.20
1942	-4.90	775	19.75	0	-45.30
1946	-6.52	925	19.75	0	-43.57
1950	-5.85	1075	19.75	0	-41.11
1954	-4.62	1213	-10.46	537	-38.72
1958	-2.35	1275	-11.74	613	-36.62
1962	-2.17	1350	-12.51	775	-36.36
1966	-3.96	1400	-8.80	838	-37.98
1970	-7.69	1575	-10.68	912	-39.35
1974	-7.91	1713	-9.84	1075	-38.47
1978	-7.56	1775	-7.72	1138	-37.48
1982	-7.83	1250	-7.83	1250	-37.80
1986	-11.70	1950	-8.40	1313	-39.74
1990	-10.60	2063	-12.51	1363	-41.76
1994	-12.05	2125	-19.36	1525	-42.98
1998	-14.31	2225	-15.91	1713	-42.82
2002	-18.56	2375	-14.30	1800	-42.52
2006	-17.16	2563	-11.77	1913	-41.81
2010	-14.03	2625	-10.19	1975	-40.39
2014	-11.78	2712	-12.24	2075	-40.37
2018	-9.89	2800	-18.73	2162	-41.09
2022	-9.97	2888	-18.77	2263	-42.49
2026	-11.22	2975	-26.56	2388	-42.87
2030	-12.62	3075	-21.96	2513	-42.76
2034	-14.96	3250	-20.09	2600	-42.19
2038	-12.72	3325	-20.20	2700	-41.66
2042	-12.21	3438	-17.33	2787	-40.95
2046	-12.87	3488	-21.88	2838	-40.82
2050	-14.32	3625	-20.61	3075	-40.81
2054	-13.76	3738	-16.74	3100	-40.84
2058	-13.21	3825	-18.80	3238	-40.11
2062	-14.37	3938	-13.67	3337	-39.70
2066	-13.54	4025	-16.05	3400	-39.76
2070	-12.61	4150	-22.63	3475	-39.78
2074	-12.24	4213	-17.31	3663	-39.95
2078	-11.85	4350	-16.63	3738	-38.92
2082	-12.54	4400	-15.81	3825	-38.12
2086	-12.14	4550	-16.08	3938	-37.79
2090	-12.81	4625	-17.19	4088	-37.49
2094	-12.88	4750	-14.96	4188	-37.41
2098	-13.14	4850	-13.11	4250	-38.29
2102	-13.76	4950	-13.13	4350	-38.96
2106	-13.53	5038	-13.67	4400	-38.23
2110	-12.81	5200	-15.56	4550	-38.56
2114	-12.17	5225	-16.06	4588	-39.12
2118	-15.67	5288	-18.46	4763	-40.04
2122	-15.49	5463	-19.72	4825	-40.48
2126	-17.01	5500	-22.65	5012	-41.58
2130	19.75	0	-20.71	5012	-42.47
2134	-20.61	563	-22.11	5200	-42.59

NPS: LOWER HYDROPHONE

ANALYIS METHOO: QUICK ANALYSIS

OATE OF ANALYSIS: 11/30/86

RECORDEO MAGNITUDE LEVELS (dB re 1V)

OELAY(MS)	OIRECT MAGN	OIRECT FRQ(HZ)	REFL MAGN	REFL FRQ(HZ)	NOISE MAGN
1950	19.75	0	19.75	0	-53.79
1954	-12.32	725	19.75	0	-53.47
1958	-11.40	800	19.75	0	-52.60
1962	-12.43	925	19.75	0	-51.99
1966	-12.62	1063	19.75	0	-50.91
1970	-10.87	1150	19.75	0	-50.04
1974	-8.40	1275	-19.97	537	-48.96
1978	-7.57	1325	-20.77	675	-48.13
1982	-9.42	1388	-19.33	800	-48.85
1986	-13.17	1500	-17.37	850	-49.74
1990	-14.19	1688	-17.16	1000	-49.13
1994	-12.49	1738	-16.64	1075	-48.17
1998	-13.37	1813	-16.99	1150	-48.32
2002	-15.20	1925	-19.58	1275	-49.24
2006	-15.11	2050	-20.34	1363	-49.33
2010	-16.04	2138	-23.41	1475	-49.32
2014	-17.56	2238	-21.40	1600	-49.20
2018	-18.68	2375	-19.95	1725	-49.21
2022	-19.70	2425	-16.20	1775	-49.95
2026	-19.58	2600	-17.47	1837	-49.89
2030	-18.23	2700	-21.19	1950	-49.96
2034	-16.74	2775	-26.30	2025	-49.72
2038	-15.37	2875	-25.22	2225	-49.12
2042	-15.73	2963	-27.51	2325	-49.24
2046	-15.33	3075	-30.01	2425	-49.31
2050	-16.37	3138	-26.34	2487	-48.66
2054	-17.29	3300	-25.28	2588	-48.14
2058	-16.97	3400	-24.01	2725	-47.54
2062	-17.63	3463	-21.72	2850	-47.55
2066	-18.95	3600	-21.47	2950	-47.34
2070	-19.51	3700	-18.51	3075	-46.64
2074	-19.31	3800	-16.43	3088	-46.81
2078	-19.03	3900	-20.92	3188	-47.17
2082	-20.04	3975	-18.47	3325	-47.14
2086	-20.06	4125	-21.14	3362	-47.27
2090	-19.76	4225	-26.53	3500	-47.24
2094	-19.12	4325	-24.27	3663	-46.85
2098	-19.03	4438	-25.00	3763	-46.63
2102	-19.01	4525	-21.41	3838	-46.00
2106	-18.64	4625	-20.66	3938	-45.49
2110	-19.25	4713	-23.11	4088	-45.19
2114	-19.41	4813	-21.31	4150	-45.55
2118	-19.48	4900	-22.86	4188	-46.10
2122	-19.56	5025	-29.27	4288	-46.43
2126	-18.28	5162	-32.61	4500	-46.21
2130	-17.17	5262	-28.85	4588	-46.76
2134	-17.76	5338	-28.89	4662	-47.82
2138	-19.66	5400	-29.68	4750	-48.27
2142	-21.11	5500	-27.05	4913	-48.34
2146	19.75	0	-22.19	5000	-48.96
2150	19.75	0	-19.87	5075	-48.89
2154	19.75	0	-19.65	5188	-48.86
2158	19.75	0	-20.04	5238	-49.20
2162	19.75	0	-23.01	5363	-49.70

NPS: UPPER HYDROPHONE

ANALYIS METHOD: NORMAL ANALYSIS

DATE OF ANALYSIS: 12/1/86

RECORDED MAGNITUDE LEVELS (dB re 1V)

DELAY(MS)	DIRECT MAGN	DIRECT FRQ(HZ)	REFL MAGN	REFL FRQ(HZ)	NOISE MAGN
1900	19.75	0	19.75	0	-47.29
1916	19.75	0	19.75	0	-49.07
1932	-9.14	775	19.75	0	-46.88
1948	-10.98	638	19.75	0	-47.79
1964	-13.94	787	19.75	0	-47.37
1980	-11.66	800	19.75	0	-46.11
1996	-9.63	963	19.75	0	-46.98
2012	19.75	0	19.75	0	-46.98
2028	19.75	0	19.75	0	-46.98
2044	19.75	0	19.75	0	-50.59
2060	-7.81	1388	-13.54	725	-41.32
2076	-10.37	1738	-15.72	1025	-40.88
2092	19.75	0	19.75	0	-40.88
2108	-10.00	1738	-15.14	1063	-40.72
2124	-12.50	2050	-12.39	1325	-38.68
2140	19.75	0	19.75	0	-38.68
2156	-12.03	2088	-9.50	1375	-39.19
2172	-13.90	2350	-13.87	1713	-41.26
2188	19.75	0	19.75	0	-41.26
2204	-13.13	2325	-14.15	1688	-41.00
2220	-16.85	2613	-13.45	1913	-39.81
2236	-14.03	2438	-14.45	1775	-41.69
2252	-15.76	2787	-11.38	1975	-39.08
2268	-13.21	2975	-19.75	2225	-42.37
2284	19.75	0	19.75	0	-42.37
2300	19.75	0	19.75	0	-42.37
2316	19.75	0	19.75	0	-42.37
2332	-15.87	3275	-22.67	2588	-40.30
2348	-17.11	3500	-20.52	2825	-42.85
2364	-15.06	3362	-20.24	2662	-41.32
2380	-17.99	3650	-17.01	2988	-39.05
2396	19.75	0	19.75	0	-39.05
2412	-16.95	3688	-20.10	3000	-41.72
2428	-18.05	3950	-18.58	3225	-38.69
2444	19.75	0	19.75	0	-38.69
2460	-17.19	3975	-18.88	3250	-41.44
2476	-18.27	4263	-29.36	3513	-39.46
2492	19.75	0	19.75	0	-39.46
2508	-17.26	4288	-23.68	3650	-41.00
2524	-25.22	3925	-25.22	3925	-40.76
2540	19.75	0	19.75	0	-40.76
2556	-17.02	4600	-21.30	3900	-39.97
2572	-18.99	4888	-19.34	4188	-38.58
2588	-17.62	4688	-21.09	4012	-39.92
2604	-18.86	4963	-20.25	4238	-39.87
2620	-15.51	5262	-22.99	4538	-40.13
2636	-18.87	5012	-24.54	4288	-40.12
2652	-15.35	5288	-22.95	4563	-40.37
2668	-17.57	5500	-22.17	4850	-41.76
2684	19.75	0	19.75	0	-41.76
2700	-16.64	5475	-24.00	4725	-41.09
2716	19.75	0	-22.76	5062	-40.32
2732	-24.83	575	-25.79	5225	-43.41

NPS: MIDDLE HYDROPHONE

ANALYIS METHOD: NORMAL ANALYSIS

DATE OF ANALYSIS: 12/1/86

RECORDED MAGNITUDE LEVELS (dB re 1V)

DELAY(MS)	DIRECT MAGN	DIRECT FRQ(HZ)	REFL MAGN	REFL FRQ(HZ)	NOISE MAGN
1930	-7.18	500	19.75	0	-43.05
1946	-5.68	750	19.75	0	-40.55
1962	-7.43	963	19.75	0	-37.96
1978	-6.07	787	19.75	0	-42.38
1994	-6.92	1100	19.75	0	-37.34
2010	-2.66	1313	-13.44	750	-34.46
2026	19.75	0	19.75	0	-34.46
2042	-4.24	1388	-11.47	825	-35.67
2058	-11.41	1713	-7.71	1275	-35.05
2074	-8.44	1400	-12.00	912	-35.40
2090	-9.51	1775	-10.34	1213	-33.98
2106	19.75	0	19.75	0	-33.98
2122	-12.61	1862	-10.84	1313	-36.46
2138	-15.45	2150	-14.66	1575	-39.82
2154	-12.28	1988	-7.44	1375	-35.86
2170	-16.65	2238	-14.10	1688	-36.95
2186	-12.23	2138	-12.53	1475	-38.29
2202	-20.14	2450	-12.91	1775	-36.94
2218	-14.61	2737	-23.38	2150	-38.87
2234	-16.73	2550	-14.09	1925	-38.19
2250	-11.35	2800	-19.81	2113	-35.76
2266	-13.70	2963	-30.08	2400	-40.76
2282	-11.45	2787	-18.13	2088	-39.75
2298	-14.29	3050	-30.94	2463	-34.28
2314	-14.28	3325	-24.50	2725	-39.68
2330	-13.08	3050	-26.08	2425	-40.02
2346	-13.65	3337	-27.21	2712	-37.96
2362	-15.95	3563	-21.88	3013	-37.62
2378	-12.60	3387	-22.94	2800	-39.30
2394	-15.89	3738	-25.15	3125	-36.58
2410	-18.46	3925	-18.28	3463	-36.68
2426	-15.35	3775	-21.60	3113	-36.10
2442	-15.15	4037	-17.45	3387	-36.16
2458	-14.81	3850	-16.75	3312	-38.12
2474	-14.23	4150	-20.62	3538	-36.54
2490	-13.49	4425	-17.55	3825	-36.87
2506	-13.19	4238	-18.34	3650	-37.63
2522	-13.81	4475	-21.49	3950	-35.05
2538	-14.54	4725	-19.42	4150	-37.45
2554	-12.97	4538	-17.91	3925	-36.71
2570	-14.72	4813	-19.53	4250	-34.68
2586	-15.36	5062	-20.28	4413	-38.15
2602	-13.83	4850	-17.80	4300	-36.48
2618	-14.22	5188	-17.22	4550	-34.21
2634	-14.23	5012	-17.36	4388	-36.44
2650	-13.65	5238	-18.16	4650	-35.15
2666	-17.83	5500	-22.87	4975	-39.41
2682	-15.08	5262	-18.82	4700	-37.40
2698	-18.71	5500	-22.69	5012	-36.37
2714	-47.10	3300	-22.79	5212	-40.03
2730	-46.87	4163	-23.76	5138	-40.44
2746	-45.35	3288	-24.53	5350	-37.55
2762	19.75	0	-19.77	5188	-39.64

NPST: LOWER HYDROPHONE

ANALYIS METHOD: NORMAL ANALYSIS

DATE OF ANALYSIS: 11/30/86

RECORDED MAGNITUDE LEVELS (dB re 1V)

DELAY(MS)	DIRECT MAGN	DIRECT FRQ(HZ)	REFL MAGN	REFL FRQ(HZ)	NOISE MAGN
1950	-14.98	662	19.75	0	-51.50
1966	-14.68	912	19.75	0	-48.51
1982	-11.24	1188	19.75	0	-48.03
1998	-13.12	975	19.75	0	-50.42
2014	-9.93	1263	-21.03	575	-47.79
2030	-14.56	1388	-18.47	813	-47.43
2046	-9.72	1825	-21.52	675	-47.14
2062	-14.58	1563	-16.53	875	-46.68
2078	-18.08	1775	-19.52	1250	-44.77
2094	-14.41	1700	-20.90	1050	-46.75
2110	-15.23	1900	-15.40	1313	-45.23
2126	19.75	0	19.75	0	-45.23
2142	-16.86	2075	-13.21	1388	-44.71
2158	19.75	0	19.75	0	-44.71
2174	-17.68	2213	-17.51	1475	-46.16
2190	-21.85	2525	-15.29	1813	-46.43
2206	-18.56	2288	-22.28	1700	-44.55
2222	-19.50	2625	-20.51	1913	-46.75
2238	19.75	0	19.75	0	-44.94
2254	-17.98	2725	-20.10	1975	-46.54
2270	-16.99	2963	-24.49	2263	-47.05
2286	-16.51	2825	-23.31	2075	-46.45
2302	-16.05	3125	-25.68	2475	-46.14
2318	-16.32	3050	-27.78	2400	-46.23
2334	-17.49	3350	-26.05	2712	-45.83
2350	-18.22	3250	-29.23	2613	-45.74
2366	-23.30	3588	-23.90	3025	-46.55
2382	-18.01	3450	-26.33	2813	-45.79
2398	-20.50	3763	-18.76	3075	-45.33
2414	-20.27	3650	-22.28	3013	-45.67
2430	-21.14	3963	-19.63	3225	-44.09
2446	-20.07	3838	-21.37	3113	-45.34
2462	-20.42	4188	-27.08	3438	-44.97
2478	-21.12	4063	-23.38	3350	-45.16
2494	-21.38	4388	-28.26	3788	-44.19
2510	19.75	0	19.75	0	-44.19
2526	-20.11	4488	-25.96	3825	-44.24
2542	-20.77	4775	-25.18	4050	-42.58
2558	-19.76	4575	-25.24	3888	-43.69
2574	-19.69	4900	-25.83	4200	-43.90
2590	-20.20	4750	-26.31	4125	-[illegible].22
2606	-18.95	5100	-27.98	4388	-43.82
2622	-20.06	5000	-24.44	4338	-42.88
2638	-16.85	5288	-24.01	4650	-44.05
2654	-17.63	5225	-25.84	4600	-43.46
2670	-19.39	5438	-24.14	4775	-44.95
2686	-20.82	5413	-26.16	4775	-46.11
2702	19.75	0	-27.42	5025	-47.59
2718	19.75	0	-29.21	5188	-47.33
2734	19.75	0	19.75	0	-47.33
2750	19.75	0	-25.72	5188	-46.33
2766	19.75	0	-27.77	5500	-47.66

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c.1 Application of a modified time delay spectrometry technique in modeling of underwater acoustic propagation.