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High-Resolution, Three-Dimensional Measurements of Low-Frequency Sound Propagation in Shallow Water

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Abstract: An overview is presented of the Model Mapping Experiment (MOMAX), in which both fixed and moving source configurations were used to transmit several pure tones in the frequency range 50 – 300 Hz in shallow water. The magnitudes and phases of these signals were recorded on several freely drifting buoys, each containing a hydrophone, GPS and acoustic navigation, and radio telemetry. High-resolution, three-dimensional measurements of the sound field were made out to ranges of 10 km and illustrate the influence of the laterally varying seabed in both the space and wavenumber domains. In addition, the phases of the measured signals show a remarkably high level of stability and regularity which can be exploited to make accurate estimates of the relative source/receiver speed from measurements of the time rate-of-change of the phase. [Work supported by ONR.]

INTRODUCTION

MOMAX was conducted aboard the R/V Endeavor during the period 21 March – 3 April 1997. A series of eight experiments was carried out in the East Coast STRATAFORM/SWARM area off the New Jersey coast in about 70 m of water. Three drifting buoys (each equipped with a hydrophone, GPS and acoustic navigation, and radio telemetry) received signals at ranges of up to 10 km from sources deployed in one of two configurations: (1) an NRL J15-3 source suspended from the ship (drifting or underway) at a depth of 30 m and transmitting pure tones at 50, 75, 125, and 175 Hz (cf. Fig. 1); and (2) a Webb source moored 1 m above the bottom and radiating pure tones at 200 and 300 Hz. In both cases, the nominal source level was 170 dB re 1μPa @ 1 m. In addition to the acoustic measurements, the following environmental data were recorded: (1) 3 – 6 kHz chirp sonar subbottom data along every buoy and source track; (2) numerous CTD casts throughout the region; and (3) Seamon temperature logger data at several depths on each drifter buoy and on the Webb source mooring.

EXPERIMENTAL RESULTS

An examination of the measurements indicates that the data are of very high quality and offer great promise for high-resolution characterization of the low-frequency acoustic field in shallow water. An example of the magnitude and phase versus source/receiver range of the 50 Hz pressure field received on one of the buoys (Shemp) in Experiment 2 is shown in Fig. 2. In this experiment, both source and receiver were drifting at about 1/2 kt. The application of kinematic moving-base-station differential processing to the ship and buoy GPS positions, each with absolute accuracy of about 100 m, permits the determination of the relative range between source and receiver to an accuracy of less than 1 m.

A striking feature in Fig. 2 is the remarkable stability and regularity of the phase, even though the magnitude reflects a complex bimodal (perhaps trimodal) interference pattern. This phase behavior occurs also at the higher frequencies and higher source/receiver speeds (up to 3 kts) measured in the experiment. A preliminary calculation indicates that the phase is dominated by the term $k_0 r$, where r =source/receiver range, $k_0 = \omega/c_0$, ω =frequency, and $c_0 = 1500$ m/s. This simple phase model appears to be effective even in a complex multipath environment with complicated sound velocity profiles in the water column and bottom. This model enables us to make accurate estimates of the relative source/receiver speed from measurements of the time rate-of-change of the phase in Experiment 2.

Finally, the precision navigation permits the creation of a two-dimensional, synthetic aperture planar array for frequencies up to several hundred Hz. The pressure field data measured on the array were transformed into the wavenumber domain, where the lateral variability of the waveguide manifests itself in the spatially evolving spectral content of the modal field.

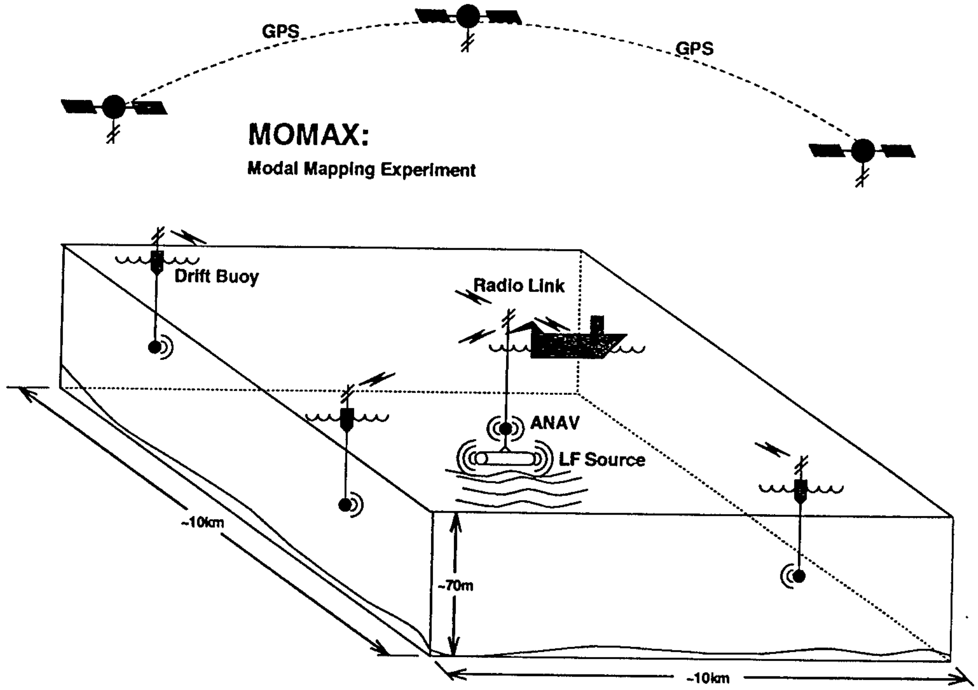

Figure 1: MOMAX experimental configuration.

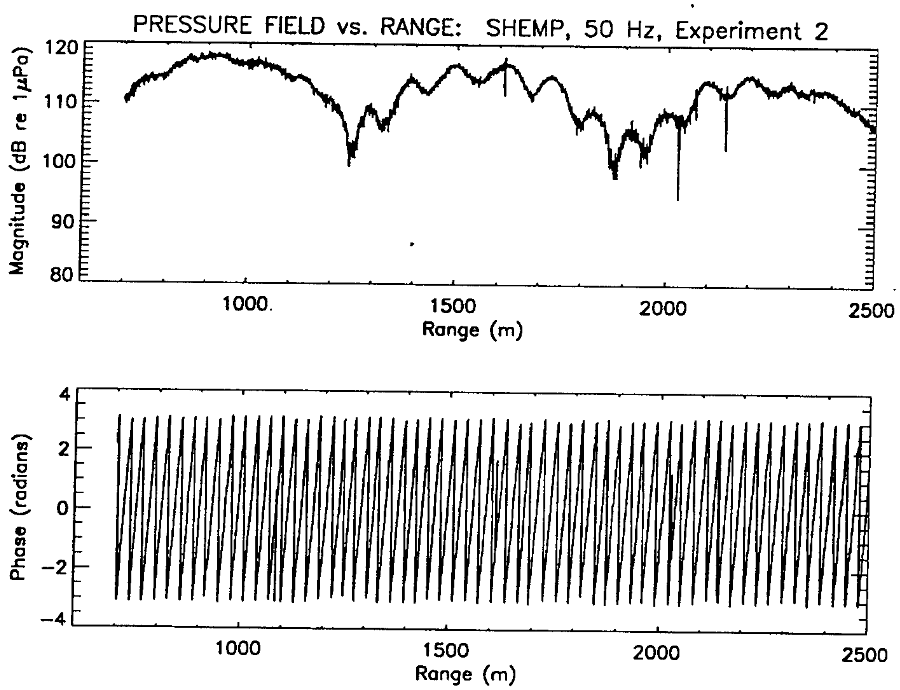

Figure 2: Pressure magnitude and phase versus source/receiver range at 50 Hz.

MOMAX: Modal Mapping in a Complex Shallow Water Environment

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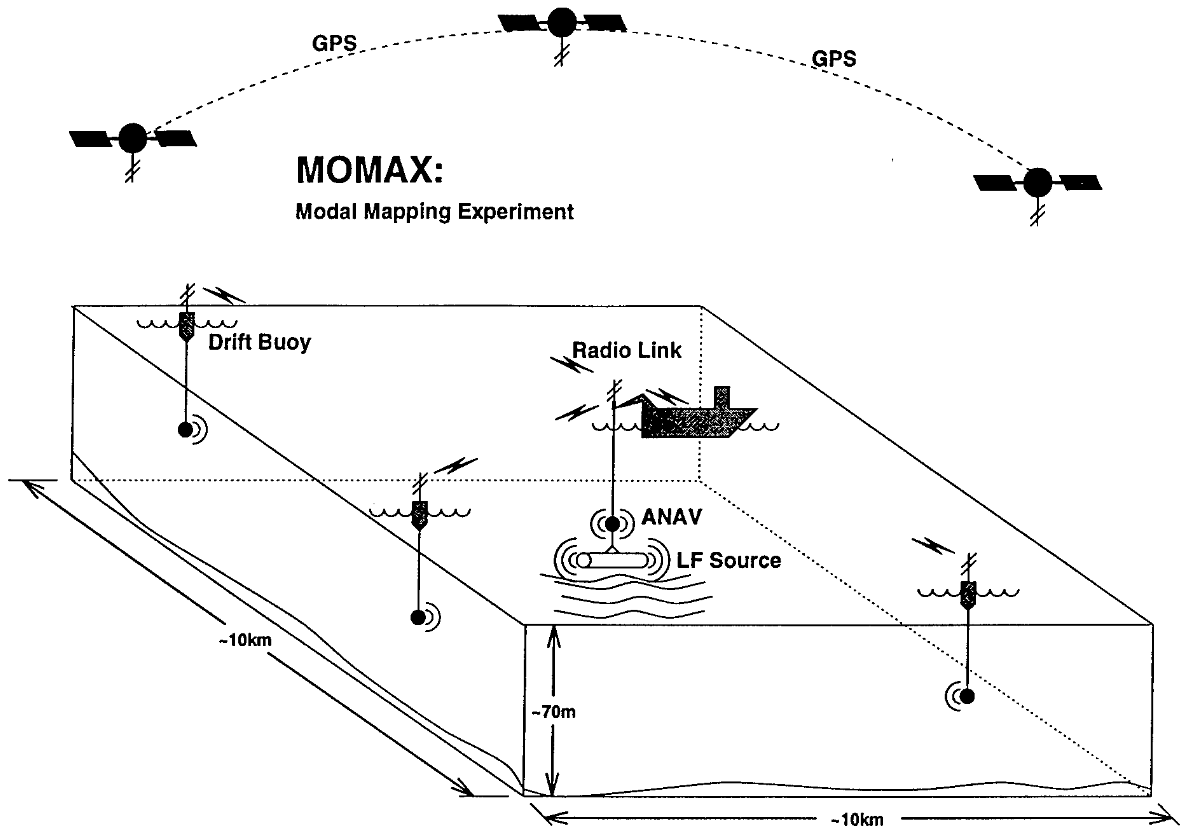

Figure 1: Sketch representation of MOMAX experimental layout

1 Introduction

This document is intended as an overview of the modal mapping experiment (MOMAX: MOdal MApping eXperiment) carried out in the general vicinity of the East Coast *STRATAFORM* site off the coast of New Jersey in March of 1997. The general strategy behind MOMAX is to use freely drifting buoys with suspended hydrophones to map out the acoustic normal mode field generated in a shallow water environment by a single acoustic source. The Experiment Overview section describes experimental layout and environment, and the general techniques and events associated with the experiment cruise. The MOMAX Data section discusses the nature, quantity, and quality of the data collected during the cruise. The Data Processing and Analysis section explores the theory and technique implemented in the reduction, merging, and scientific analysis of the MOMAX data sets.

2 Experiment Overview

2.1 The Layout

Figure 1 represents the basic layout of the MOMAX cruise experiment. A modal field was established in a shallow-water waveguide environment using a low frequency sound source suspended from the R/V Endeavor to an approximate mid-column water depth. During certain experiment runs the sound source was moored near the bottom of the water column. The sound source was driven at several different frequencies simultaneously, ranging from 50 Hz to 300 Hz. Freely drifting buoys with attached hydrophones suspended at an approximate mid-water column depth were used to sample the generated acoustic modal field over the two-dimensional plane defined by the hydrophone suspension

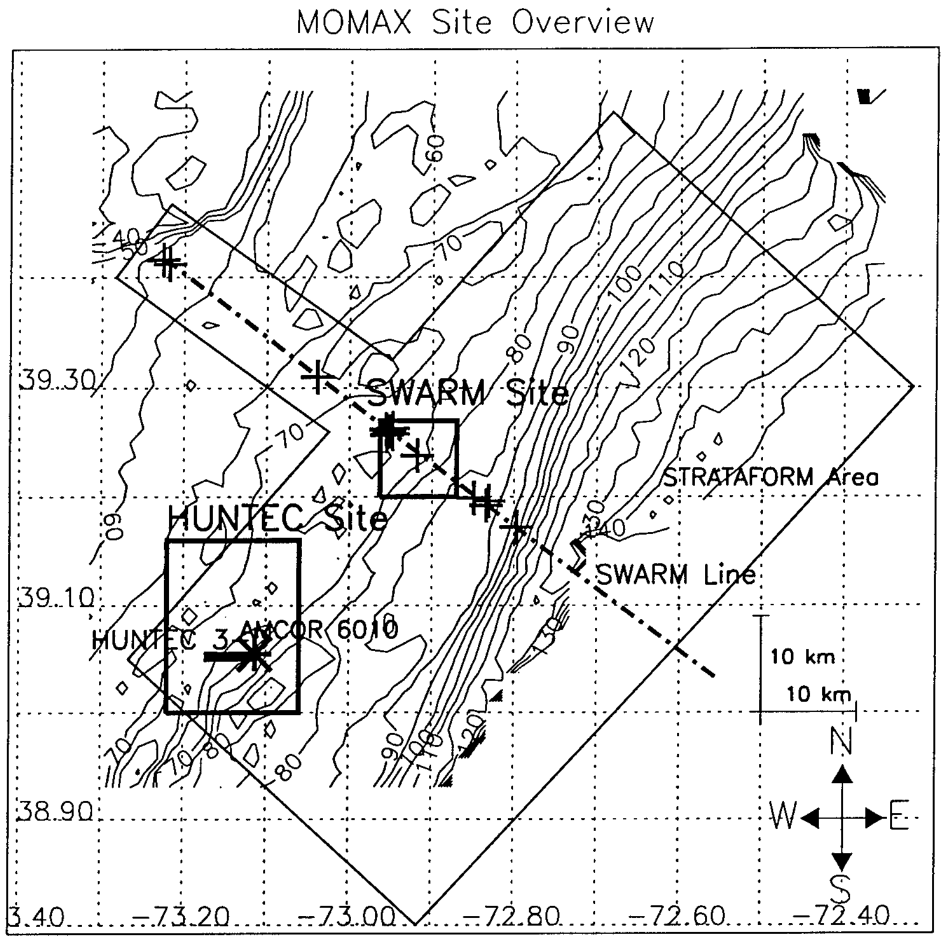

Figure 2: MOMAX Experiment Site

depth. Buoy spatial locations were tracked using GPS receivers attached to each buoy and to the ship. High frequency acoustical transponders were used at the locations of each hydrophone and the acoustic source to aid in the determination of the hydrophones relative to the surface buoys. Data were broadcast directly in real time from the buoys to the ship for recording via a radio telemetric link.

2.2 The Environment

Figure 2 shows a geographic and bathymetric representation of the MOMAX experiment site. The two areas used during the MOMAX experiment have been labeled the HUNTEC Site and the SWARM Site in association with previous studies carried out in those locations. The larger shaded region is a well surveyed area known as the East Coast Strataform Site.

2.3 Acoustic Sources

The two acoustic sources used during the various experimental run were an NRL J-15-3 towed acoustic source and a Webb Research organ pipe type moored acoustic source. The sources were implemented on separate runs. The J-15-3 source was used to generate 4 frequencies of 50 Hz, 75 Hz, 125 Hz, and 175 Hz simultaneously. The J-15-3 was driven so as to produce a total acoustic power

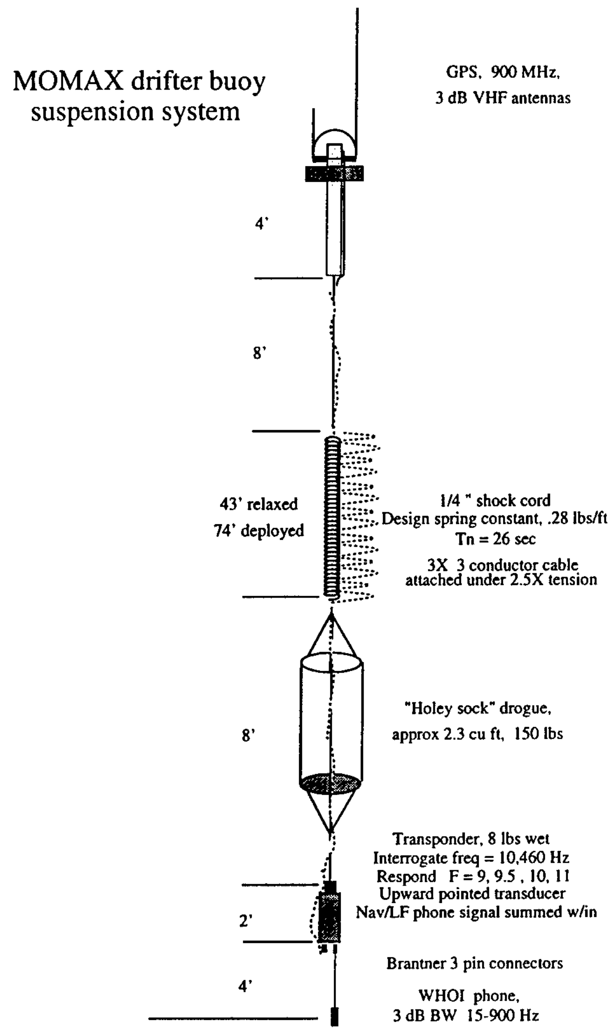

Figure 3: MOMAX drifter buoy suspension system

power level of approximately 173 dB re 1μPa @ 1 m. The Webb source generated 2 frequencies of 200.0 Hz and 299.7601918 Hz simultaneously.

2.4 Hydrophone Buoys

Figure 3 shows a diagram of the various components making up the hydrophone buoy system. The GPS receiver, the radio telemetry hardware, and the associated antennae are located above the floatation part of the buoy shown at the top of the figure. A hydrophone and a transponder are attached at the bottom of the buoy system and a combination shock cord and drogue are used between the floatation level and the water column monitoring level to dampen vertical motions associated with surface waves.

2.5 Cruise Overview

Figure 4 is a chart showing a temporal overview of the various experiments carried out over the 8 operational days of the MOMAX cruise. The top of the chart shows a time line covering the 8 days of experiments labeled with the appropriate year day number. The experiment row shows the

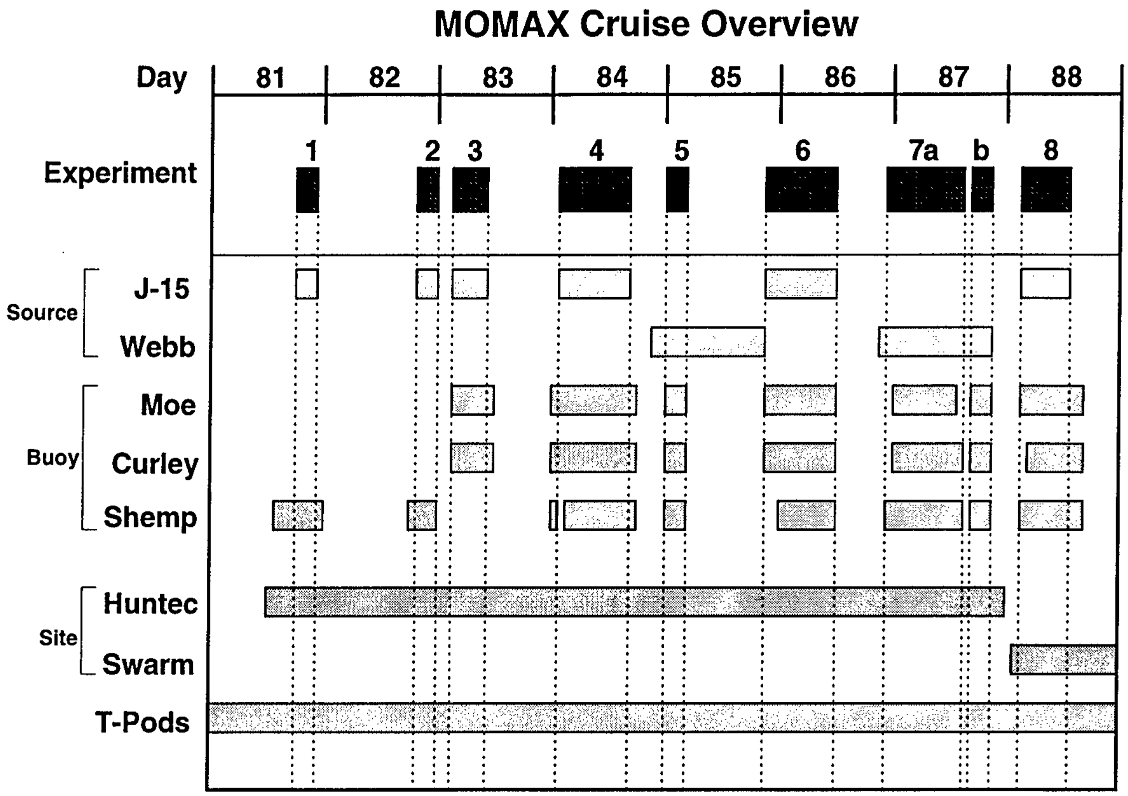

Figure 4: Temporal overview of 8 operation days of MOMAX cruise

experiment label designation for each of the 9 experiments, with the shaded box width below each label showing the approximate time and duration of the experiment. The remainder of the chart follows a similar format, showing the operation times of the acoustic sources, the deployment times of the buoys, and the sites of the experiments. The T-pods are solid state temperature sensors placed at various levels on the buoy suspension lines and source suspension lines and were continuously operational.

3 Momax Data

3.1 Low Frequency

Low-frequency acoustic data sampled by the suspended hydrophones were collected and stored during each experiment run. The acoustic signal measured at a hydrophone was mixed into a radio signal and broadcast back to a VHF receiver onboard ship. The acoustic signal was extracted from the radio signal, band passed for a low frequency band covering the source driven frequencies, sampled at 3255.208333 Hz, and stored on an Exabyte tape.

3.2 High Frequency

The buoy and source network was rigged with an acoustical ranging system of transponders to determine the relative buoy-to-buoy distances and source-to-buoy distances. Every 30 seconds, a 10.5 kHz pulse of 12 millisecond duration was transmitted from a transponder attached near the acoustic source. Each buoy was correspondingly equipped with a transponder that responded to this interrogation ping with a similar ping of different, but known, frequency (9.0 kHz, 9.5 kHz, and 11.5

kHz for the three buoys). Measurement of the source-to-buoy and buoy-to-buoy ping travel times permits the determination of the associated ranges. Note that this provides enough information to determine the polygon shape defined by the 4 point system (1 fixed source and 3 buoys), but gives no information on the angular orientation of the polygon. The associated high-frequency signals were mixed onto the carrier radio signals and transmitted to the VHF receiver at the ship. The acoustic signal for the high-frequency ranging pulses was extracted in similar manner (ie., appropriate higher frequency band pass), sampled at 40 kHz, and stored on an Exabyte tape.

4 Data Processing and Analysis

4.1 Low-Frequency Demodulation

The harmonic signals associated with the multiple driven source frequencies were extracted from the recorded signal by demodulation in the frequency domain. These low-frequency signals resulting from the hydrophone measurements may be modeled as a superposition of a finite number of propagating sinusoidal signals having the general form:

$$f(t) = \sum_{i=1}^{N} A_i \cos(2\pi f_i t + \phi_i). \tag{1}$$

Here there is an index i associated with each of the signals, A_i and ϕ_i being the magnitude and phase, respectively, of the sinusoidal signal of frequency f_i. Thus, the signal for the earlier mentioned J-15 acoustic source is represented by:

$$\begin{aligned} f(t) \quad = \quad & A_{50}\cos(2\pi 50t + \phi_{50}) + \\ & A_{75}\cos(2\pi 75t + \phi_{75}) + \\ & A_{125}\cos(2\pi 125t + \phi_{125}) + \\ & A_{175}\cos(2\pi 175t + \phi_{175}). \end{aligned} \tag{2}$$

As the magnitude and phase of each of the signals sinusoidal components is desired, it is necessary to demodulate the signal with respect to each of the tone frequencies. This process is facilitated by transforming the signal to the frequency domain and picking off the magnitude and phase values appropriate to the chosen frequencies. The signal, $f(t)$, is transformed using the Fourier transform pair defined below:

$$F(\omega) \quad = \quad \int_{-\infty}^{\infty} f(t) e^{i\omega t} dt \tag{3}$$

$$f(t) \quad = \quad \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{-i\omega t} d\omega. \tag{4}$$

For simplicity of demonstration, a signal containing only a single harmonic frequency will be considered here. Substituting this single frequency form of $f(t)$ into the above forward Fourier transform, $F(\omega)$, one gets:

$$F(\omega) = \int_{-\infty}^{\infty} \left[A\cos(\omega_o t + \phi) \right] e^{i\omega t} dt. \tag{5}$$

Here ω_o is the driven frequency of the oscillation being extracted. Using the exponential definition of cosine, the above equation may be rearranged to get the form:

$$F(\omega) = \frac{A}{2}\int_{-\infty}^{\infty}[e^{i(\omega_o t+\phi)} + e^{-i(\omega_o t+\phi)}e^{i\omega t}dt. \quad (6)$$

Pulling the phase term out of the integral and using the delta function result of the Fourier transform of a complex exponential, the result reduces to the following simple form:

$$F(\omega) = \pi A[\delta(\omega+\omega_o)e^{i\phi} + \delta(\omega-\omega_o)e^{-i\phi}]. \quad (7)$$

Since $F(\omega)$ is nonzero only under the conditions that $\omega = \pm\omega_o$, it is a simple matter to calculate the Fourier transform over the desired signal and pull off the magnitude and phase for the appropriate values of ω based on the complex number generated by the transform at the given frequency. For the actual implementation of this demodulation technique, a Fast Fourier Transform (FFT) algorithm from Numerical Recipes in C was used to calculate the complex Fourier transform of a real signal. Thus the complex number pair associated with the desired carrier frequency was then picked off and used to calculate the magnitude and phase of the particular sinusoidal component. The frequency domain method of demodulation was chosen both for the multiple frequency capability of working in Fourier space and the efficiency of the FFT algorithm.

This technique is demonstrated in figure 5, which shows the time series over about 1.25 seconds of the recorded low-frequency acoustic signal and the magnitude of its associated Fourier transform. The localized peaks in the magnitude are clearly visible at the 50 Hz, 75 Hz, 125Hz, and 175 Hz frequencies used to drive the J-15-3 source. Determination of these peak values and their associated phases, or an equivalent complex representation, constitutes a single demodulated complex pressure data point for each frequency, centered on the time window chosen. The phase points determined by this method must be further adjusted to account for phase accumulation taking place before the time of the demodulation window chosen. Figure 6 shows a sample of this demodulation procedure for the 50 Hz signal for a particularly smooth section of drift path for one of the buoys. The magnitude panel reveals the characteristic interference pattern associated with shallow water acoustic modes. The phase shows remarkable stability as it accumulates over range. Note the reversal in phase accumulation as range separation starts to decrease near the end of the time series. The buoy range was determined from the GPS data collected at the buoy and on the ship.

4.2 Pressure Field Measurement Calibration

Each hydrophone suspended below the drifting buoys is calibrated such that a pressure fluctuation of 1μPa at the hydrophone results in a -160 dBV rms voltage signal. There is also a 6 dB net gain incorporated in the summation hardware. Thus, the following equation may be used to convert the demodulated voltage signal magnitude to an acoustic pressure magnitude with units of dB relative to 1 μPa at 1 meter:

$$Pressure[dB] = 20LOG_{10}(|V|) + 160 - 6. \quad (8)$$

In the above equation $|V|$ is the magnitude of the demodulated voltage signal.

4.3 Spatial Pressure Field

As the GPS receivers on the buoys actually determine latitude and longitude values, it is reasonably straightforward to map a demodulated acoustic signal onto the two-dimensional drift path of a buoy, provided the times of the GPS measurements and the sampled acoustic signal are well known. Figure 7 shows the magnitude of the 50 Hz signal over a single buoy's drift path relative to the ship. This mapping was generated by interpolating the GPS determined spatial coordinates onto the temporal

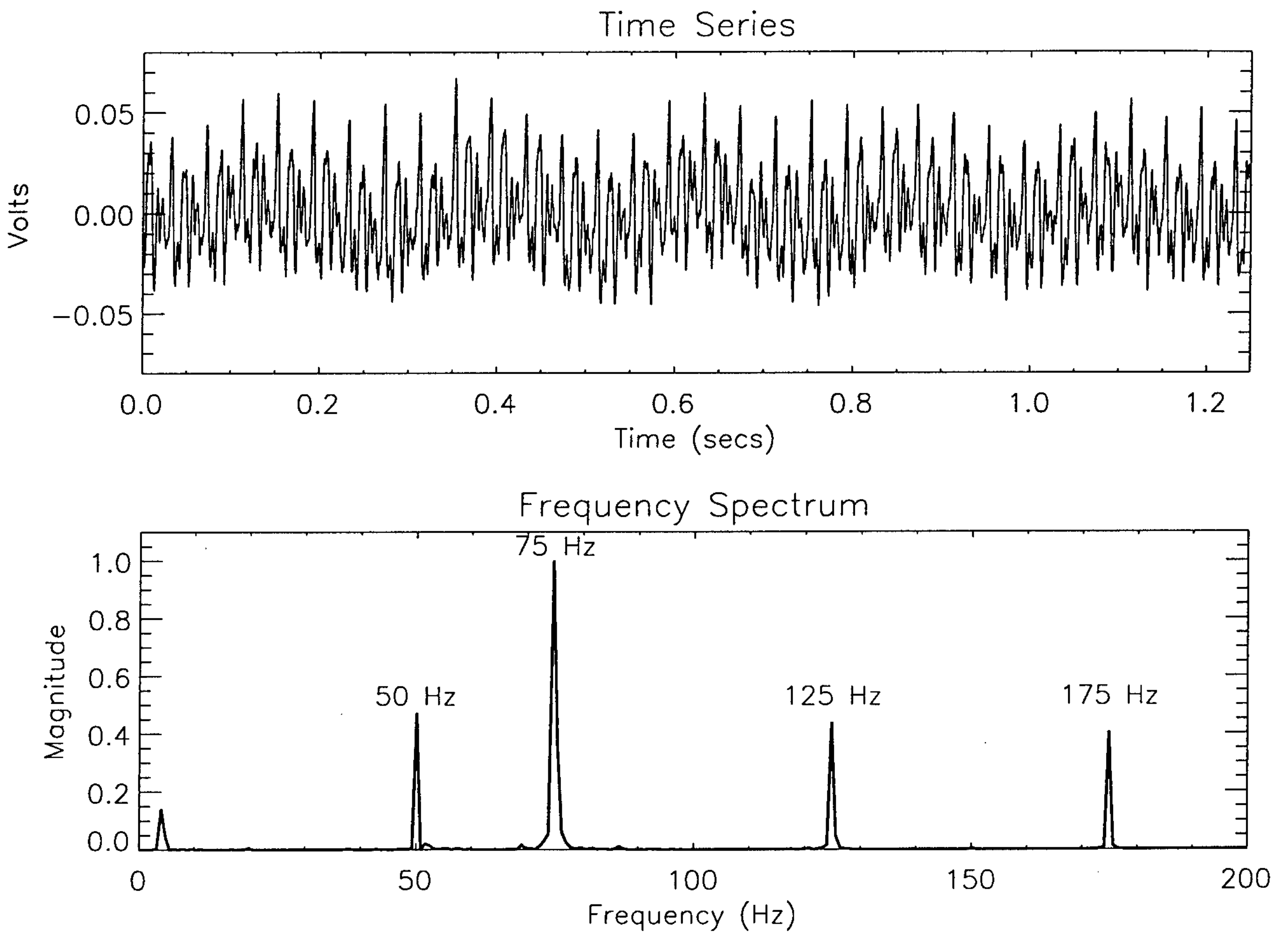

Figure 5: Time series and frequency spectrum based on voltage measurement time series

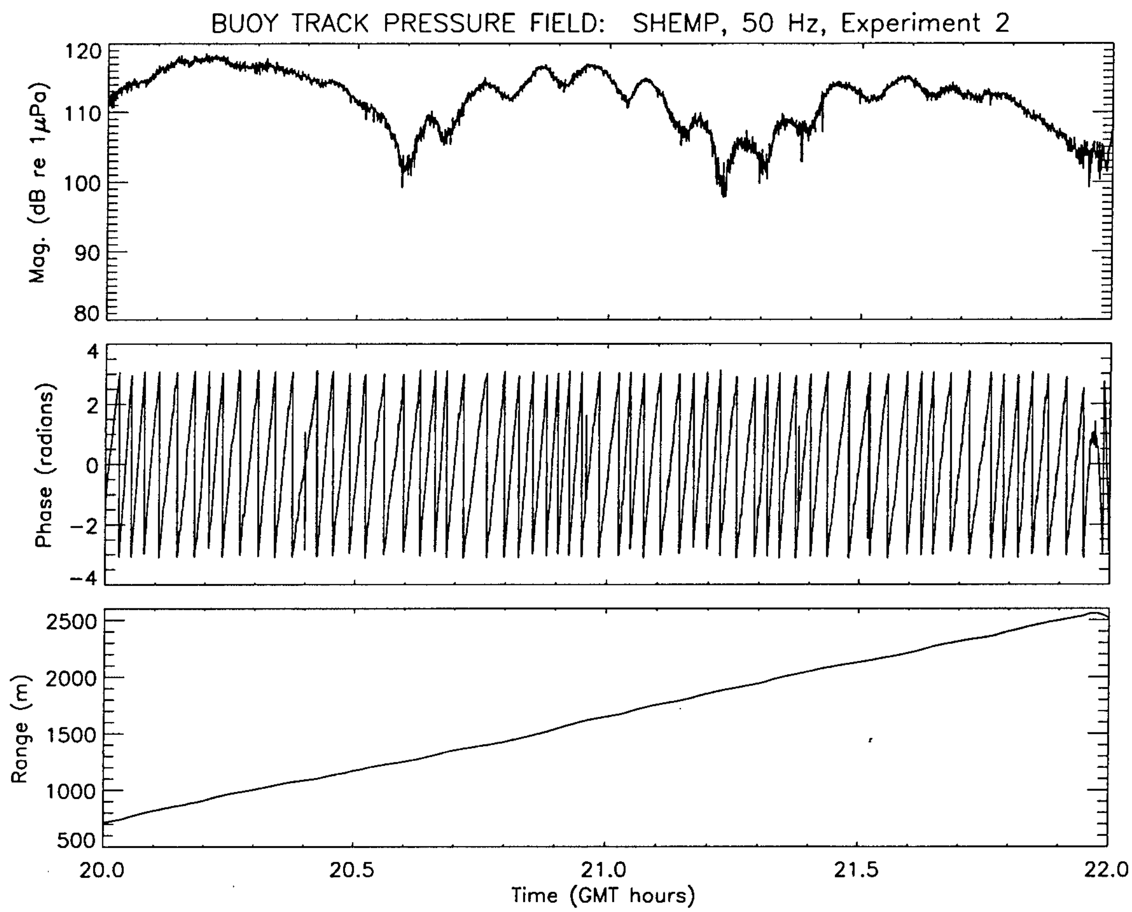

Figure 6: Demodulated 50 Hz time series. The top top two panels show the progression of signal magnitude and phase, while the bottom panel shows buoy range progression relative to the source.

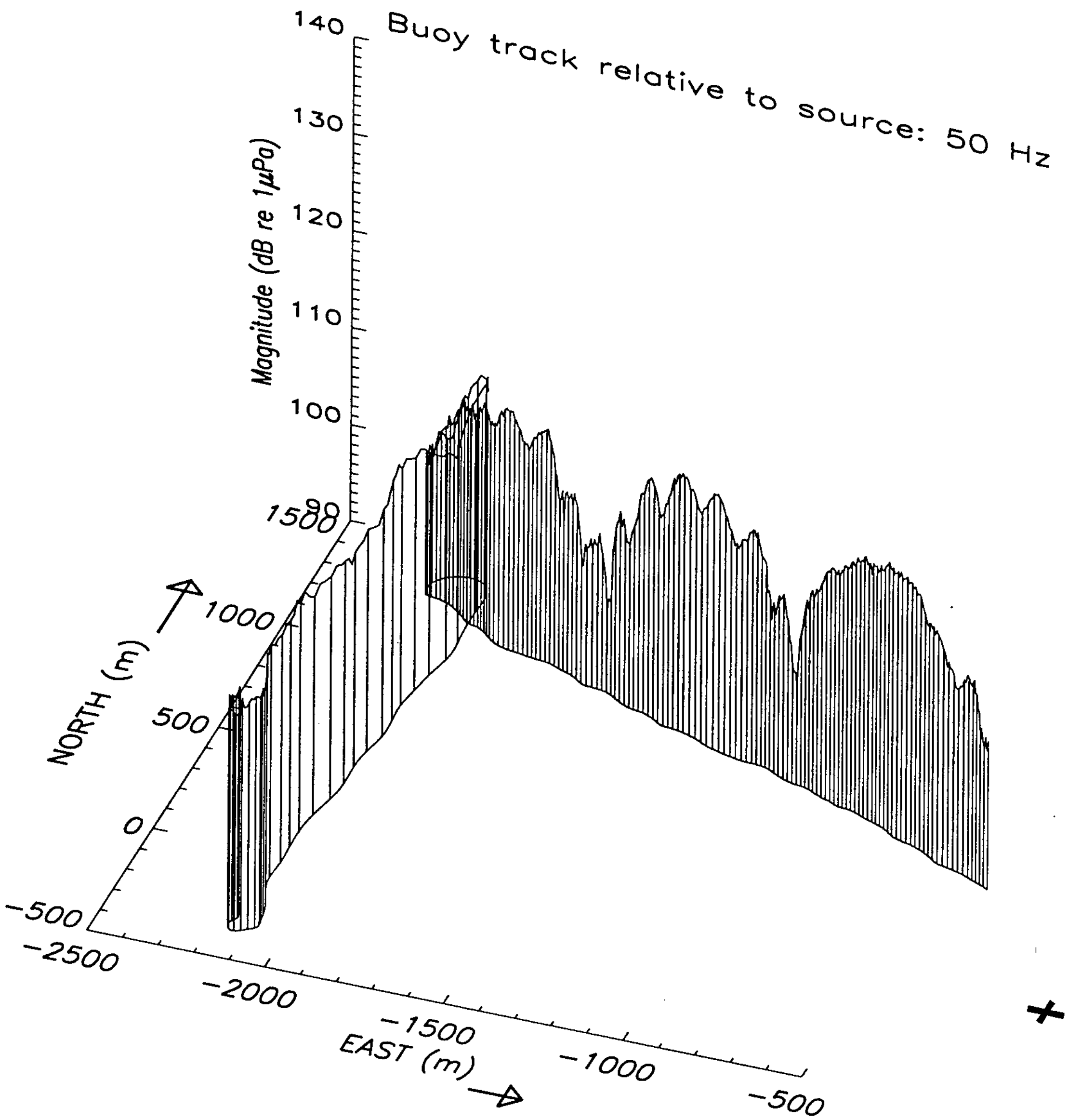

Figure 7: Two-Dimensional mapping of 50 Hz magnitude along buoy drift track.

locations of the 50 Hz signal. The cross, located at coordinates $(0,0)$, indicates the position of the ship and the J-15-3 source. Figure 8 shows a similar mapping for the drift tracks of all three buoys.

Often in wavenumber analysis it is desirable to have the complex acoustic pressure as a function of evenly spaced range. For the case of the two-dimensionally varying buoy drifts seen in this experiment, it is necessary to assume cylindrical symmetry in order to obtain such a function. With this assumption in place, it is simply a problem of interpolation to determine the magnitude and phase of a drifting buoy's signal as a function of range, as seen in Figure 9. In this case, the complex pressure values of the acoustic signal are interpolated onto an evenly incremented line of range. Figure 10 shows the results of such an interpolation onto everly incremented range for a section of the 50 Hz signal shown in Figure 6 and Figure 7.

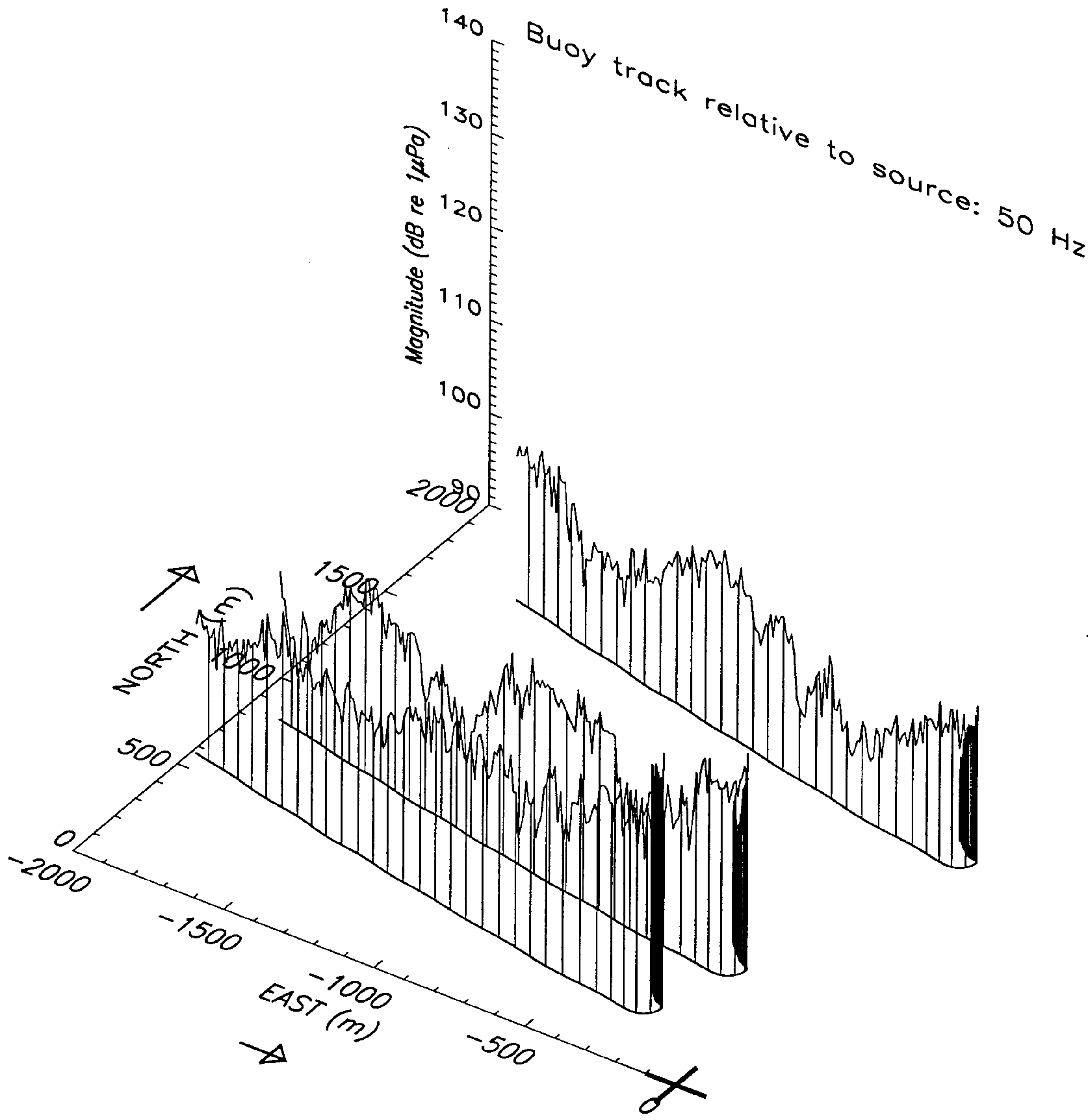

Figure 8: Two-Dimensional mapping of 50 Hz magnitude along buoy drift track for multiple buoys.

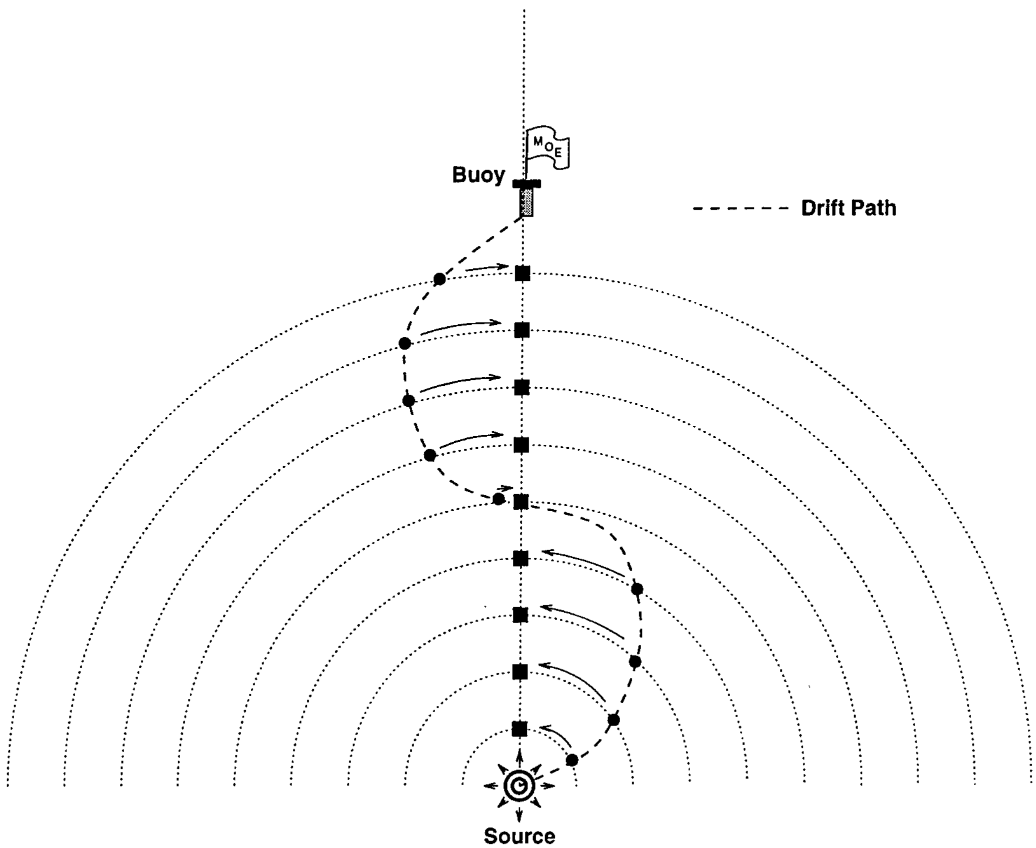

Figure 9: Drift buoy sampled signal is interpolated onto an evenly incremented line of range, under the assumption of cylindrical symmetry.

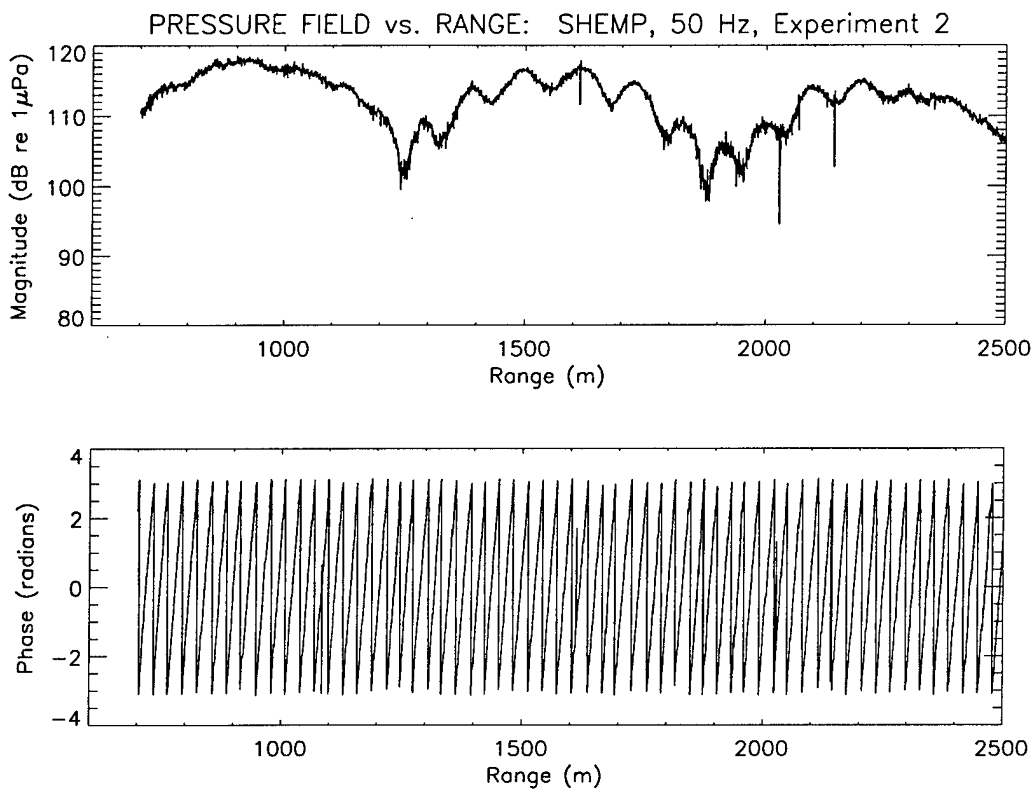

Figure 10: Signal magnitude and phase interpolated onto evenly incremented range line.

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