A Sediment Imaging System Using Acoustic Tomographic Techniques

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Abstract:

An acoustic imaging system has been developed to characterize both horizontal and vertical variability of the sound speed structure of the sediment. The system consists of an array of needle-like probes, approximately 1 meter in length, that may be easily pressed into the sediment. Each probe contains a 20 element line array of acoustic transducers. Acoustic travel time is precisely measured between all combinations of transducers, thus creating a well saturated web of raypaths through the imaging volume. By using inversion techniques, this data may be used to create an image of the sound speed structure of the sediment within the array. The sound speed structure may then be used to determine various material properties of the sample.

This paper presents a detailed description of the system that was developed at Woods Hole Oceanographic Institution in 1996. The transducer design, electronics design and mechanical design issues will be discussed. Data will be presented from sea trials performed in 1996, when the system was first tested in Woods Hole, MA.

I. Introduction

Understanding of the three-dimensional variability of acoustical, geological, and mechanical properties of sediments is of crucial importance in various underwater remote sensing, object detection, surveying, and sediment type classification problems. Sediment volume inhomogeneity on the centimeter scale has a major impact on the design and application of high-frequency sonars, especially when operated in shallow waters. Yet there is little information available on such inhomogeneities due to limitations on measurement techniques. A systematic method of acquiring such data in situ with ground truth information and a dependable way of analyzing and interpreting the data sets do not exist. To address this need, in the past two years under the support of the ONR Ocean Acoustics program, Woods Hole Oceanographic Institution has developed an instrument designed for in-situ sediment classification and imaging, using acoustic tomographic techniques. This instrument is capable of mapping the horizontal and vertical variability of the sound speed structure in a one square meter slice of sediment. The sound speed structure may then be used to determine various material properties of the sample. This paper provides a brief description of the instrument, and presents data taken during the initial field trials in November, 1996.

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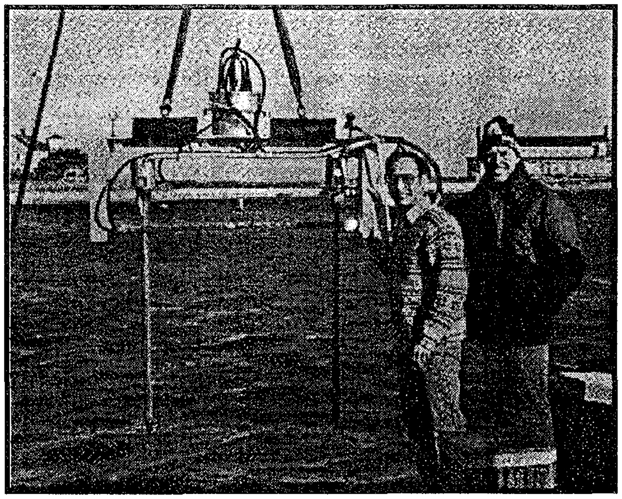

Figure 1: Sediment Imaging Probe System

II. System Description

The in-situ sediment acoustic imaging system consists of an array of needle-like probes which may be pressed into the sediment, where each probe is a vertical line array of acoustic transducers. The current system consists of three identical probes attached to a sturdy frame, and connected to a subsea electronics pressure housing. Two probes are

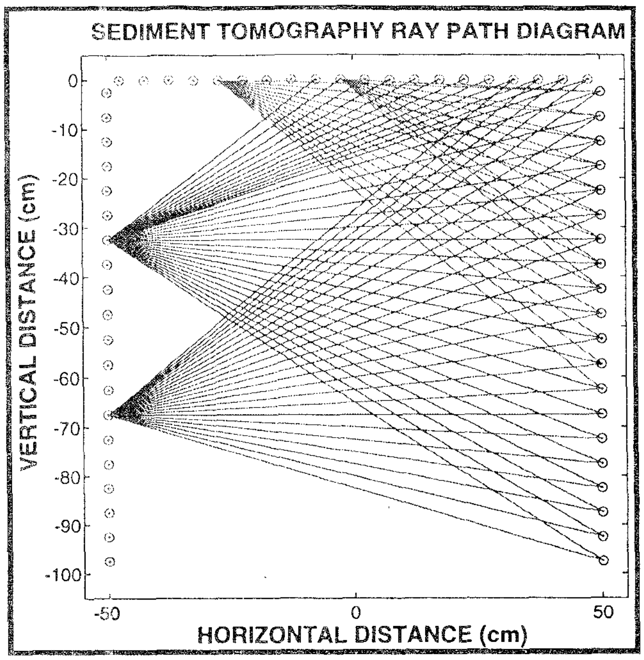

Figure 2: Tomography Raypath Illustration

oriented vertically and pressed into the sediment about 1 meter apart, and the third is oriented horizontally, just above the seafloor, between the two vertical probes (see figure 1). Since these probes are all aligned on a common plane, the current system is capable of only two dimensional imaging. Eventually, more probes may be added to obtain three-dimensional data. Each probe contains 20 acoustic transducers, arranged as a line array with 5 cm spacing. Thus the active area is approximately 1 meter long. Each transducer in every probe is capable of both transmit and receive. An internal multiplexer in the probe is used to select a single transducer so that the number of wires in the cabling is minimized. The probes are connected to the subsea electronics module which contains a transmitter, receiver, and a microcontroller used for the multiplexer control. A multi-conductor cable extends to the surface. This cable connects to a personal computer (PC) via an analog input for data acquisition and a serial port for communication with the subsea microcontroller. A small power supply is the only other surface equipment required to operate the subsea electronics. Individual transducers are selected by the PC software for transmit and receive, and a ping is initiated. All possible raypath combinations between the probes are sequentially interrogated (See Figure 2). The objective is to accurately estimate the travel time from transmit to receive on each ray path. Data is acquired by an analog to digital data acquisition board plugged into the PC. A Windows™ based application program has been written to control the instrument for transducer selection, and to acquire and store the raw SONAR data for all 1200 transmit/receive combinations. Post-processing of the raw acoustic data is done using MATLAB™ script files written to estimate the travel time and, from that, the average sound velocity along each raypath. The resulting set of average sound velocities form the input into the tomography processing algorithm.

The transducers used are free flooded cylinders, with a resonant frequency of 100 kHz with approximately 40 kHz bandwidth. These cylinders have a torroidal beam pattern, and therefore are oriented with their longitudinal axes perpendicular to that of the probe itself, so that their beam patterns are aligned with the imaging plane. The elements are potted in polyurethane, suspended between two high strength steel stiffening bars. The diameter of the probe is 3.8 cm (1.5 inches), expanded slightly at the top to accommodate the interface circuitry and connector pigtail. A long, thin printed circuit board extends along the entire length of the probe, outside of one of the steel bars. Also encapsulated in the polyurethane is a stainless steel tube connected to the probe tip in order to allow for the use of a water jet for assistance in penetrating difficult sediment.

The measured system specifications are as follows:

Center frequency: 95 kHz
Bandwidth: approximately 40 kHz
Source Level Output: 170 dB re 1 uP @ 1 meter
Receiver Sensitivity: -210 dB re 1 v/uP

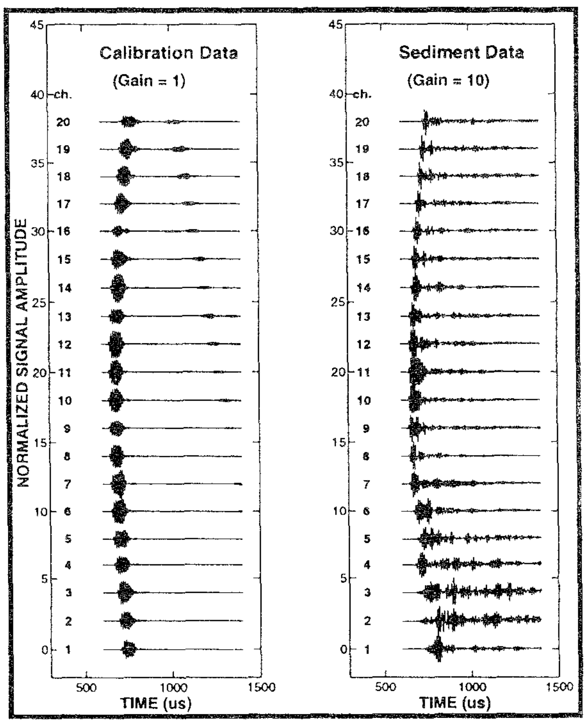

Figure 3: Raw Data from Sediment Imaging Probe System

Equivalent input noise: 40 dB re 1 uP / sqrt(Hz)
Beam Pattern: Torroidal in the vertical plane. Approximately 45° horizontally.

These specifications are sufficient to provide at least 120 dB of dynamic range between the peak signal and the 1 Hz bandwidth noise level. This high SNR, combined with processing gains realized when using wide band signals such as chirps, allows for data collection over a wide range of attenuation coefficients.

The resolution of the imaging system is about 5-10 cm for a sound speed fluctuation of 1-2%.

III. System Trials

The system development took place in FY's 95 and 96 under ONR support. Extensive tank testing was performed to compare candidate transducer designs, as well as to perform system testing prior to field trials. These trials were performed in local waters near WHOI utilizing the coastal research vessel Asterias. The temperature was in the 20s, with light snow and 24 knot wind. Diver support was used to observe the penetration capabilities of the probes and to alert the surface crew in the event of problems. The probe system worked flawlessly, and penetration into the sediment was easy for this muddy site, even without the use of the water jets for assistance.

The direct arrivals provided the travel time information to be used in sediment sound speed and attenuation imaging. Figure 3 shows a comparison of the received waveforms in clear water versus those in the sediment. The unexpected strong reverberant arrivals indicate a high degree of scattering, making it difficult to estimate the arrival time accurately. Some initial results of the sound speed structure are shown in figure 4.

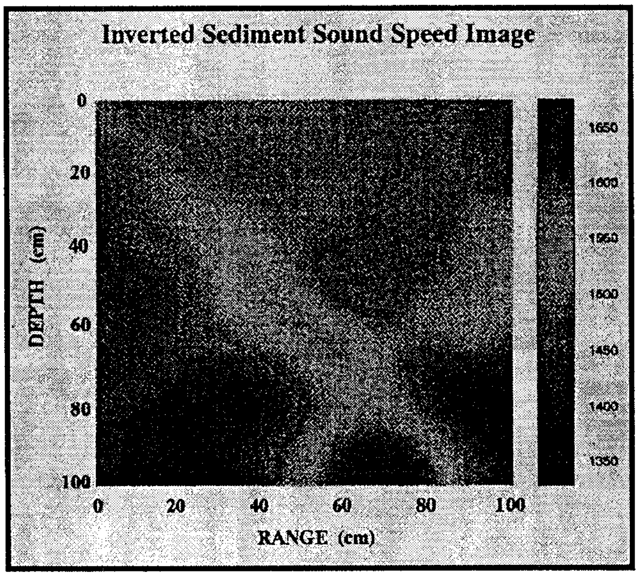

Figure 4: Tomographic Image of Sediment Sound Speed Structure

IV. Data Processing and Inversion

1200 arrival times were determined from 1200 transmit/receive combinations via a post-processing program including automated matched filter processing.

For high SNR (> 40 dB), arrival time corresponding to each ray path was picked automatically while for lower SNR, arrival time was picked in a semi-automatic mode, or interactive mode. 30 pings were acquired for each ray path, the typical standard deviations of the arrival time were less than 50 ns.

An iterative Damped Least Square linear inversion algorithm was then used to generate the sound speed image based on the arrival time inputs (Menke, 1984, Bregman, et al., 1989):

$$\mathbf{s}^{(l+1)} = \mathbf{s}^{(l)} + [\mathbf{R}_{(l)}^T + \lambda \mathbf{I}]^{-1} \ \mathbf{R}_{(l)}^T \ [\mathbf{t} - \mathbf{R}_{(l)} \mathbf{s}^{(l)}]$$

where **s** and **t** are vectors of the slowness and the measured arrival time, respectively, **R** is the kernel matrix whose element is the distance within the ith inversion cell for the jth ray. Superscript T stands for matrix transpose and l for the lth iteration. λ is the damping coefficient and **I** is a unit matrix.

To compensate the uncertainty of transducer positions due to possible probe bending, the transducer positions were assumed to have a small amount of deviation from their original positions when the probes were not bent and were treated as unknowns in inversion (Dyer and Worthington, 1988). To incorporate position errors, the kernel **R** is replaced by **K** and the slowness **s** is replaced by **m**,

$$\mathbf{K} = [\mathbf{R} \ \mathbf{P}_x \ \mathbf{P}_z] \quad \text{and} \quad \mathbf{m} = [\mathbf{s}^T \ \mathbf{x}^T \ \mathbf{z}^T]^T$$

where:

$$P_{x_{ij}} = \frac{\partial t_i}{\partial x_j} \ , \quad P_{z_{ij}} = \frac{\partial t_i}{\partial z_j}$$

and:

$$\mathbf{x}^T = [x_1, x_2, \ldots\ldots x_n]^T \ , \quad \mathbf{z}^T = [z_1, z_2, \ldots\ldots z_n]^T$$

are coordinates of the transducers in the inversion plane (X-Z plane), where n is the number of transducers.

The inversion region was divided into 20 x 20 mesh grids with each being a 5 x 5 cm square cell. The sound speed image obtained from the inversion is shown in Fig. 4. The image shows two dimensional sound speed variability over the range of 1320 m/s to 1680 m/s, within the sampled region.

V. Conclusion

In-situ Sediment Acoustic Imaging can provide 3-dimensional images of the local sediment structure. This development represents the initial step towards a practical tool for oceanographers and acousticians. Because this probe system can measure sound speed and attenuation over two-dimensions and the results are obtained in situ, its advantages over conventional coring techniques are obvious. As a result, in addition to applications to high-frequency acoustics, it has the potential of providing much needed information to geology and geochemistry at a relatively low cost. The probes themselves have been designed so that they may be easily reproduced, with no particularly expensive components.

The major objectives accomplished to date are:

a) The engineering aspects of the system were tested to verify the operational and performance capabilities. Most importantly, the system survived the field trials with no component failures, was easy to deploy and recover, and had sufficient signal to noise ratio to obtain high resolution travel time estimates.

b) An initial data set has been collected to analyze to test the signal processing algorithms. This includes a complete set of "calibration" data, taken by suspending the assembled instrument in mid-water and collecting an entire set of raw data, as well sediment data taken at two different locations.

c) Initial processing of the data has been completed, resulting in a 2-D tomographic image of the sound velocity structure within the probes (see figure 4).

Acknowledgments

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WHOI contribution number: 9509

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