

High-Frequency Sound Interaction in Ocean Sediments: Modeling Environmental Controls

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LONG-TERM GOALS

The goal of the High-Frequency Acoustics Departmental Research Initiative (DRI) is to develop accurate models for high-frequency acoustic penetration into, propagation within, and scattering from shallow-water ocean sediments. This project will provide the statistical characterization of surficial sediment properties that is required to test, compare, and validate these physical acoustic models. The emphasis of the first experiments is testing the various acoustic models proposed to account for the anomalous penetration of high-frequency energy at subcritical angles in sand. These experiments should also improve our general understanding of high-frequency acoustic bottom scattering and frequency-dependent acoustic propagation within sediments. Additional objectives of this project are to understand and model the complex interactions among environmental processes, sediment structure, properties, and behavior. We (with other DRI investigators) will document the effects of biological, geological, biogeochemical, and hydrodynamic processes on the spatial and temporal distribution of sediment physical, geotechnical and geoacoustic properties at the experimental site and develop predictive empirical and physical models of the relationships among those properties. These models allow portability of high-frequency bottom interaction models to sites of naval interest.

OBJECTIVES

The objectives for the current year were to conduct surveys of the proposed sites for the SAX99 experiment (October-November 1999), provide preliminary seafloor physical and geoacoustic property data required for high-frequency acoustic simulations, and develop and perfect measurement techniques for upcoming SAX99 experiments.

APPROACH AND RESULTS

Site Surveys: The purpose of the site surveys was to select a large (at least 600 x 600 m) uniform site with the required environmental characteristics (uniform, well-sorted, fine-medium sand without significant layering to a depth of at least 2 meters) for the SAX99 experiments planned for the coastal waters of the northwestern Florida shelf in October-November 1999 and to provide average values of seafloor properties for pre-experimental acoustic simulations. As part of a study of sediment geoacoustic properties of the Florida continental shelf aboard the R/V Seward Johnson (August 16-September 6, 1998) a potential experimental site off Panama City, Florida was characterized before

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and after the passage of Hurricane Earl. A 3.5-km by 5-km rectangle centered at 30° 07.23'N; 85° 47.54'W was sampled using normal-incidence echo sounding, side-scan sonar, bottom photography with stereo and video cameras, grab samples, in-situ probes for characterizing seafloor geoaoustic and physical properties, sediment bubble collectors, low-frequency seismic studies, water column measurements, ambient noise measurements, diver cores, and diver observations. Most of the surficial sediment within the survey rectangle was fine to medium sand. Depth ranged between 15-18 meters with a uniform acoustic backscatter strength throughout most of the area. Sound speed and attenuation (1700-1800 m/s; 0.25 dB/m/kHz), shear speed (100-125 m/s), porosity (35-40 %), and bulk density (2000-2060 kg/m³) were typical for well sorted fine-to-medium sands. Occasional lenses of muddy sand were found in the short (20 cm) core samples. Seafloor bottom roughness was of low relief (amplitude of 2-3 cm), isotropic, and presumably controlled by sediment reworking by benthic fauna. Very few larger epifaunal organisms, such as sand dollars that might contribute to discrete scattering from the seafloor, were observed. No gas bubbles were found in the sediments. In short, the site seem to meet the criteria set forth by the acoustical requirements, with the possible exception of the rare lenses of mud within the sediment. After the passage of Hurricane Earl, roughness had changed and a thin (0-20 cm) layer of mud covered the proposed site. As a result of these changes in the seafloor the backscatter strength was greatly reduced. The increased roughness (sand ripples with a period of 50-75 cm and amplitude of 15-20 cm) was a direct result of 9-meter gravity waves that came ashore off Panama City. The layer of mud resulted from the outwash from St Andrews Bay after Hurricane Earl past the area. Subsequent collection of sediments with vibracores (18-20 March 1999; Nancy Dewitt, USGS) at the Panama City site found numerous near-surface shell layers and mud lens, as well as a deeper mud facies from a drowned late-Pleistocene back-bay estuarine environment. This deeper sediment heterogeneity was also detected in the analysis of low-frequency surface wave data. The combination of drowned mud layers, near surface shell beds, and mud flaser lens at the proposed Panama City site suggested a second site should be found.

A second cruise (8-19 July 1999) aboard the R/V Pelican was used to survey potential SAX99 experimental sites between the Panama City and Fort Walton Beach, Florida. Side Scan sonar and subbottom chirp sonar (Steve Shock, FAU) suggested two areas (the original Panama City site and an area 10 km west of Destin, Florida) might be suitable. The area west of the Destin inlet was centered at 30° 22.75'N; 86° 38.75'W; in 18-20 m water depths, and approximately 2 km off Fort Walton Beach, Florida. Observations made by divers and with underwater video cameras confirmed to suitability of this second site. Roughness at the Fort Walton site (wavelengths 50-80 cm; amplitudes 5-7 cm) was greater than at Panama City (wavelengths 40-80 cm; amplitudes 3 cm) but both were less than roughness measured after the passage of Hurricane Earl. Degradation of the roughness was probably the result of sediment reworking by benthic fauna (fish, crabs, sand dollars, etc.). Surficial sediment sound speed and attenuation (1750-1800 m/s; 0.4 dB/m/kHz), porosity (35-40 %), and bulk density (2000-2100 kg/m³) were similar at the two sites. Subsequent collection of sediments with vibracores (24-28 August 1999; Nancy Dewitt, USGS) at both the Panama City and Fort Walton Beach sites confirmed the suitability of the later site. Vibracores within a small area (1 km²), large enough for the SAX99 experiment, at the Fort Walton site contained a surficial layer (170 to 270 cm) of well sorted fine to medium sand. Sediment from these cores contained less than 5% shell material and satisfied the other DRI requirements. Based on data collected from the two NRL site survey cruises and the two USGS vibracoring cruise, a 500 m² area in 20 meters water depth, 2 km off Fort Walton Beach was chosen for SAX99 experiment. Data on seafloor physical and geoaoustic property as well as bottom roughness was provided high-frequency acoustic modelers for simulations.

Development of measurement techniques: In order to compare the predictions of penetration of high-frequency acoustic energy into sediments based on current hypotheses to actual data, seafloor roughness and spatial variability of sediment physical and geoacoustic properties must be characterized. In the past, the lack of adequate sediment characterization has allowed acoustic modelers to choose values for seafloor properties that are in concordance with their hypothesized penetration mechanism. Our objectives are to provide statistical characterization of seafloor, which eliminates this subjective option.

Based on an evaluation of acoustic modeling requirements, values of the following sediment properties are required to evaluate acoustic penetration models.

- Sediment grain properties: grain size distribution, shape and surface texture, grain density, bulk modulus, organic matter composition, and mineralogy
- Water properties: density, bulk modulus, viscosity, compressional speed all calculated from pore water temperature, salinity and pressure
- Porometry: calculated porosity, tortuosity, pore size distribution, pore shape, pore throat size, grain contacts, permeability
- Bulk density, porosity, permeability, percent organic matter
- Frame bulk and shear modulus
- Frame bulk and shear log decrement
- Shear and compressional speed and attenuation
- 2-D seafloor roughness spectrum (spatial and temporal variations)
- Bubble size, distribution, and volume

All sediment properties do not require the same level of measurement effort. For several properties, physical handbook determination is adequate (e.g., pore water density, bulk modulus, viscosity, and sound speed can be accurately determined from pore water temperature, salinity and pressure). Laboratory determination of sediment grain size properties from diver cores is adequate, although variability and vertical gradients should be statistically quantified. Other properties such as geoacoustic (shear and compressional wave speed and attenuation) properties, seafloor roughness, and bubble characterization need to be measured in situ. Frame bulk and shear moduli and log decrements can be estimated from sediment geoacoustic properties or measured under laboratory conditions. Based on model requirements, mean values, range, statistical variability, vertical gradients, and statistical characterization of two- and three-dimensional spatial variability of a subset of sediment properties are also required. Measurement scales required to statistically characterize the heterogeneity of sediment properties such as bulk density, compressional wave speed and attenuation, and bottom roughness depend on acoustic measurement frequency. Measurement requirements are approximately a quarter of an acoustic wavelength, or as small as 1 cm for penetration experiments, and as small as 1 mm for scattering experiments. Most measurements can be made with existing technology, but development of specialized new techniques is required for certain measurements (e.g., resin impregnation for the porometry measurements; new techniques to measure grain bulk modulus and frame modulus; techniques to measure the 3D spatial heterogeneity of geoacoustic and physical properties).

3-D Volume Inhomogeneity Measurements (Kevin Briggs and Peter Jackson): From measurements of sediment volume inhomogeneities in three dimensions, correlation lengths in x , y , and z dimensions can be calculated in order to model the acoustic scattering from the sea floor. Inductive measurement of electrical resistivity is an in-situ, non-intrusive technique that will image porosity and density of

sand sediments without sediment disturbance. The Sediment Resistivity Array Imaging System is currently being fabricated to operate with the aid of divers, and is derived from experience with previous version used to measure 2-dimensional electrical resistivity in sediment slabs. This system has 1024 independent electrodes arranged in a rectangular array (32 x 32) with 5-mm spacing. By varying the geometry of the electrical field generated between transmitting and receiving electrodes, sediment depths to 8-cm are examined for electrical resistivity. The system is diver-deployed and, through communication with the surface where the data are logged, can be moved to various locations on the sea floor including contiguous segments for the purpose of creating a mosaic of a larger area. From these data, 3-D images are created from which correlation lengths are resolved and density spectra estimated. Such measurements are used as inputs to the composite roughness model.

High-Resolution Bottom Roughness Measurements (Kevin Briggs and Tony Lyons): Measurement of sediment interface roughness at 0.5-mm spacing over a 2-dimensional area of the sea floor is an essential parameter required to model acoustic scattering from the sea floor. Stereo photogrammetry will be used to make the measurements of relative sediment height at the sea floor. A Photosea 2000M stereo camera will be employed to collect periodic stereo photographs of the sea floor. During the same time frame, a digital stereo camera system developed at SAACLANTCEN, La Spezia, Italy, will be used to take almost identical stereo images. The collocation of the images will enable us to compare the digital system with the calibrated, manually operated stereo comparator in order to calibrate the stereo-correlation calculations created by the Desktop Mapping System (DMS) by R-Wel Inc. The DMS is a low cost software package that facilitates image processing for photogrammetric, remote sensing, and GIS applications using off-the-shelf personal computers. The DMS uses area-based matching to locate the exact points that are the same on each image and is the first personal computer software package that permits the generation of digital elevation models by automated stereo-correlation. The approach to be taken in the field experiment is to depend on the digital images for creating the 2-dimensional power spectra from which model parameters of spectral slope and strength are calculated for predicting backscattering strength.

Quantification of pore and grain parameters in sandy sediments: The objective is to understand and model basic processes that control fluid flow in sandy sediments. A combination of field, lab and modeling techniques are used to measure permeability and to statistically quantify sediment structure and the primary sediment characteristics affecting permeability. Sediment properties such as grain properties (shape, surface morphology, orientation and contacts), pore properties (network, pore size distribution, dimensions, chord lengths, specific surface area, coordination number and tortuosity), and microfabric are measured using standard laboratory techniques as well as petrography and CT-scan imaging of resin impregnated sediment. Techniques have been developed and tested to impregnate sediments collected with cores and impregnate sediments in situ. Direct in situ and laboratory bulk measurements of permeability compare well with model predictions for sediment collected from the proposed Panama City experimental site. We are investing a significant effort in modeling permeability. We have implemented Effective Medium Theory, which involves image analysis techniques to quantify pore factors and tortuosity; and the Kozeny-Carmen Equation, which involves grain factors and tortuosity. We are also investigating the usefulness of Percolation Theory to quantify permeability and tortuosity from CT-scan images of impregnated sediments.

Dynamic measurement of sediment grain compressibility at atmospheric pressure: acoustic applications: Under certain conditions, Wood's equation can be used to predict sound speed in liquid/solid grain suspensions if the bulk moduli and densities of the grains and liquid are known. NRL (Mike Richardson and Kevin Briggs) and APL (Kevin Williams and Eric Thorsos) investigators

developed a technique to measure grain bulk modulus in suspensions where sound speed, fluid density, fluid bulk modulus, grain density, and particle concentrations are known or accurately measured. Estimates of grain bulk moduli made for polystyrene beads suspended in water and glass beads suspended in a heavy liquid provided controls which demonstrated the validity of the suspension technique to estimate values of particle bulk modulus. The measured bulk modulus of sand grains previously collected from the coastal sediments of the northeast Gulf of Mexico was slightly higher than handbook values for polycrystalline quartz (3.6 to 4.0×10^{10} Pa) but given the sensitivity of the techniques and the uncertainties in the measurements is not inconsistent with handbook values. The values, however, are inconsistent with recent high-strain laboratory measurements (0.7×10^{10} Pa) reported by Chotiros and co-workers. Further refinements in the measurement system hold potential to allow direct use of measurements made on individual sediment samples.

Samples of sand collected during the SAX99 experiments will be used to determine the variability of the bulk modulus of sand grains at that site. These data together with values of other sediment physical properties measured at that site will be used to test predictions and implications of the various sediment propagation models that are used to predict scattering from and penetration into seafloor sediments. Sample collection will have no impact on the already proposed sampling strategy.

TRANSITIONS

Work under this program should lead to improved high-frequency models for acoustic penetration into sediments, for scattering from sediments, and for spatial and temporal coherence within sediments. These improvements should have an impact on acoustic modeling detection and classification of buried objects.

RELATED PROJECTS

The proposed work will be accomplished in close cooperation with the Applied Physics Laboratory (APL) University of Washington, the Applied Research Laboratory (ARL) University of Texas, and other ONR investigators. APL and ARL will make acoustical measurements and Naval Research Laboratory (NRL), in collaboration with other ONR investigators, will make environmental measurements critical to understanding and modeling high-frequency acoustic interaction with the seafloor. In addition, NRL Core 6.1 (Sediment Geoacoustics, Mike Richardson PI) is investing considerable effort in the High-Frequency DRI.

PUBLICATIONS

Richardson, M.D., K.L. Williams, K.B. Briggs and E.I. Thorsos. Submitted. Dynamic measurement of sediment grain compressibility at atmospheric pressure: acoustic implications. *Journal of the Acoustical Society of America*.

Richardson, M.D., K.B. Briggs, D.L. Lavoie, L.D. Bibee and others, In preparation. High-frequency sound interaction in ocean sediments: environmental considerations. *IEEE Journal of Oceanic Engineering (Requested paper for special issue)*.

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