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Variability in normal-incidence acoustic response in shallow-water marine sediments

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ABSTRACT

Lateral variations in mass properties of sediments (grain density, porosity, and composition) occur at many spatial scales in all types of sediments. Sediment bulk properties determine elasticity and density and, therefore, the degree of acoustic response. Variations in properties and processes limit the potential of using acoustic response to differentiate sediment types. Small changes in one or more properties can produce a wide variation in the acoustic response, and empirical curve fitting most often serves as models for these relationships. Sedimentary data and acoustic variability at 30 and 50 kHz from three sites in the Mississippi Sound (Lambert et al., 2002) have been further analyzed and compared for the available Shepard sediment classes. Initial observations revealed trends in acoustic variability based on sediment classification. Clustering techniques were used to estimate the central tendency of the sparse set of geoacoustic measurements based on selected combinations of geotechnical parameters. The group-averaged sediment properties (geotechnical, granulometric, and geoacoustical) partially correlate with the acoustic coefficient of variation of the normal-incidence ping-ensemble 50 kHz response. Changes in acoustic fluctuations at 30 and 50 kHz strongly correlate with water content and compositional variations, and are consistent with volume variability and scattering.

1. Introduction

Acoustics provide a remotely sensed assessment of the sea floor that can be correlated to important geophysical/geotechnical properties. An international conference on sea floor classification broadly centered on two topics (Anderson et al., 2008): (1) the standardization of instruments and methods and (2) the measurement of variability in sea floor attributes that determine the natural variability of the sea floor at different spatial scales. Issues include sensor calibration and sea floor classification. Acoustic response from the sea floor provides only broad sediment classifications, and the relationship between acoustic returns and sediment type and structure is not fully understood. In addition, climate change occurs at variable rates and affects surficial sediment processes. For example, changes in coastal erosion that transport and deposit sediments occur along all continental margins, and changes in benthic environments affect the economic and aquaculture potential. Some formerly unnavigable Arctic areas are becoming navigable, while other navigable environments are deepening and becoming capable of supporting larger vessels. Harbors, especially those located within estuaries, are requiring significant dredging. Coastal storms are changing in frequency and intensity and can create bottom obstructions and navigational hazards. There is a greater need for regular survey mapping of these new and changing bottom terrains for safety of navigation, ecological concerns, and mineral resource management.

Marine sediments are commonly classified by grain size and often show considerable variability in their properties. Phoon and Kulhawy (1999) serve as reference for sediment variability. In their view, total variation in sediment properties includes (1) inherent geotechnical variability, (2) measurement error, and (3) transformation uncertainty. Inherent variability results from the geologic processes that occur through time to produce and continually modify the marine sediment. These processes include erosion, deposition, resuspension, and geochemical (early diagenesis). Inherent variability also includes geophysical (mass-physical, hydrologic, skeletal, and mineralogical) properties and biological processes (bioturbation, shell breakage, and burrow stabilization), all of which may have interactions with one or more of the other properties (Potter et al., 1980; Lindholm, 1987). Measurement error is introduced by the analytical process used to obtain and

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analyze the data. Transformation uncertainty occurs when measurements are transformed into geotechnical properties using empirical correlation or other models and may be increased by variability of the acoustic response.

This paper examines relationship(s) between measured geotechnical parameters and the variation in acoustic response, specifically the coefficient of variation (CoV) of an ensemble of acoustic ping amplitudes, to determine if variability in the sediment properties of different sediment classes can be discerned in acoustic variability at 30 and 50 kHz. The unknown inherent geotechnical variability helps establish the scale of acoustic fluctuation and a lower-bound for transformation uncertainty. The complex relationship between the sediment bulk properties, local spatial inhomogeneity, grain size distribution, and the acoustic variability has led to semi-empirical correlations of sediment type and acoustic properties for normal incidence geometries, for example Lambert et al. (1993). We seek additional correlative delineation of sediment properties from the acoustic variability (as represented by the CoV). As a normalized measure of deviation, CoV will be used to compare sediment property variations with acoustic variations and to determine if variability in sediment properties of different sediment classes is discernible in acoustic variability at 30 and 50 kHz. If valuable information is available from the acoustic variability, it may impact bottom sediment surveys, particularly transect speed and area coverage.

Inherent variability in geophysical properties of shallow water marine sediments occurs over a continuum of spatial scales (both laterally and vertically). Active sonar systems operating in littoral regions contend with sediment variability in the geophysical and geotechnical properties of the sea floor. Holland (2002) observed significant geoacoustic and acoustic variability within individual regions and marked similarity between regions. The lateral boundaries between distinct sedimentary units may or may not be abrupt, while depth layer boundaries are usually clearly identifiable. Acoustic variability within distinct sedimentary units arises from geometric factors (sonar geometry and variability in layer thicknesses and sea floor slope and roughness), geophysical/geoacoustic variability (grain and density macrostructure and porosity), bathymetry, and acoustic scattering.

Sea floor roughness plays a dominant role above a few kHz. Interference from acoustic arrivals from varying heights due to roughness may obscure the effects of geophysical properties (Brekhovskikh and Lysanov, 1982). Williams et al. (1998) reported that in the first centimeter, the sediment can be unconsolidated and exhibit a significantly higher spatial variability than in the deeper parts of the same sediment. The physical acoustic properties of the upper decimeters of the sea floor are controlled primarily by the layered density gradient of the sediments and volume inhomogeneities. Biological processes (such as cementing grains together into larger pellets) are responsible for creating and changing sediment macrostructure within the upper decimeters of the sea floor (Orsi et al., 1994). These processes can dilate or compact sediments, while hydrodynamic processes tend to hinder cementation.

Signal-to-noise ratio decreases with increasing depth within sediments due to attenuation and scattering. Beam pattern and distance to the sea floor determine the sonar's footprint. As the size of the footprint changes, the number and size of the scatterers may change, as may the signal-to-noise ratio (Penrose et al., 2005). Geophysical sediment variability at scales smaller than the insonified footprint is integrated by acoustic systems. Thus, a multimodal mixture of sediments may not be readily distinguishable from a single type with more uniform acoustic properties. Acoustic echo returns are reported to vary markedly over small time intervals for the same bottom type and are attributed mostly to surface roughness, sensor movements, and environmental variability. Statistics of the acoustic response vary with sediment, geometry, beamwidth, and frequency but are not always consistent (Farwell, 1996; Lyons et al., 2002). Thermal variability in the water column, reflection angles from the bottom facets, shells and debris in the sediment, and bubbles and turbulence at the transducer play a lesser role. Thus, sediment classification with acoustic systems is quantitative but not absolute as classification is strongly a function of system characteristics, geometry, and sediment form and composition.

2. Material and methods

2.1. Variability in normal-incidence acoustic response

Hamilton (2001) noted that ensemble acoustic ping averaging increased signal stability (except over very rough hard surfaces) and proved effective over a wide range of sediment types. Hamilton et al. (1999) suggested that bottom sediments could be classified by acoustic variability. They also considered ensemble ping averaging based on only the one-third highest values for use in classifying rough hard bottom types. Acoustic response from muds can be highly variable due to the aggregations of clay fabric and the inclusion of solid mineral grains, organic material, variable water content, and possibly gas. In noncohesive sandy sediments near normal incidence, acoustic propagation is borne largely by solid grains as indicated by both the grain shearing model (Buckingham, 2000) and Biot theory (Chotiros, 1994).

2.2. Data acquisition, materials, and acoustic methodology

The present work utilizes the data reported by Lambert et al. (2002). They compared the ping ensemble coefficient of variability at 30 kHz and 50 kHz with sediment layers in a well-characterized area off Gulfport, Mississippi. The reader is referred to that paper for site locations, sediment analysis, experimental methodology, specialized equipment, and procedures. Acoustic parameters are specified in Table 1. In summary, a broadband, narrow-beamwidth transducer was mounted on a remote-controlled trolley suspended from a horizontal I-beam. This maintains a constant height above the sea floor as the transducer moves. The horizontal spacing was 0.3 m, slightly less than one-half footprint at the sea floor for 30 kHz. The combination of frequency and beamwidth creates important differences for the two frequencies including the area of insonification and area of overlap as a function of translation, wavelength response, and spatial averaging (Farwell, 1996; Lyons et al., 2002). The ratio of the acoustic wavelengths (50/30 kHz) is 0.6 as is ratio of the footprints at the sea floor and provides a reference for analysis in Section 5. An acoustic coefficient of variation was calculated for each laterally corresponding sample of the pings at ~6 mm depth intervals. The acoustic response is the RMS-averaged, demeaned acoustic amplitude (in arbitrary units) returned to the transmitter/receiver.

Sediment cores are required to calibrate the sediment type to acoustic response and features (Snellen et al., 2011). Sediment cores were collected at lateral locations along each site and analyzed at the Naval Research Laboratory for their granulometric and

Table 1
Pertinent acoustic parameters from Lambert et al. (2002).

Frequency (kHz)	30	50
Bandwidth (kHz)	35	35
Beamwidth (deg)	14.5	8.6
Footprint on sea floor (m)	0.76	0.45
Pulse length (ms)	0.067	0.04