High-Resolution Characterization of Seafloor Sediments for Modeling Acoustic Backscatter

Thomas H. Orsi[†], Michael E. Duncan[†], Anthony P. Lyons[‡], Kevin B. Briggs[§],
Michael D. Richardson[§] and Aubrey L. Anderson[*]

[†]Planning Systems Incorporated
115 Christian Lane
Slidell, LA, U.S.A.
Email: torsi@psislidell.com; mduncan@psislidell.com

[‡]SACLANT Undersea Research Centre
Viale San Bartolomeo 400
19138 La Spezia, ITALY
Email: lyons@saclantc.nato.int

[§]Naval Research Laboratory
Stennis Space Center, MS, U.S.A.
Email: kbriggs@zephyr.nrlssc.navy.mil; miker@zephyr.nrlssc.navy.mil

[*]Department of Oceanography
Texas A&M University
College Station, TX, U.S.A.
Email: aanderson@ocean.tamu.edu

Abstract

Quantitative information on fine-scale sediment inhomogeneity is extremely scarce and sorely needed for developing realistic volume scattering models. To address this deficiency, we present a novel approach for sediment core characterization, X-ray computed tomography (CT). By providing a means to construct extremely fine-scale density profiles and to quantify volume inhomogeneities in two- and three-dimensions, CT analyses can assist efforts in characterizing benthic processes and result in more accurate inputs for modeling acoustic backscatter.

1. Introduction

At the high frequencies used by many sonar systems, the spatial structure of the sediment's physical properties plays a key role in determining the scattering characteristics of the seafloor. This spatial heterogeneity, however, is exceedingly complex with three-dimensional characteristics that have largely defied measurement by traditional methods. Aside from the fact that rather coarse laboratory sample intervals are necessary to obtain statistically reliable values (on the order of a few centimeters), the physical property measurement is usually an integrated value in which some spatial information is lost. As a result, quantitative information on near-surface fine-scale sediment inhomogeneity is lacking, particularly at spatial scales used in the development of realistic volume scattering models. To address this lack of information, we present a novel approach to sediment core characterization, X-ray computed tomography (CT). We have found CT to be a powerful analytical technique for characterizing sediment cores: it is non-destructive and quantitative, has sub-millimeter resolution, and permits two- and three-dimensional visualization of sediment structure [1, 2]. We begin by briefly discussing the physics and mechanics of CT and CT scanners. We then describe several CT applications useful for high-frequency acoustic modeling.

2. CT Principles and Approach

Non-destructive testing techniques have been used for decades in geotechnical engineering, geology, and soil science to examine the internal structure of rock and sediment samples. X-radiography, one of the more common of these techniques, is based on the differential transmission loss of radiation through a substance. The technique remains popular because it is rapid, non-destructive, and provides information concerning density variations within a sample. Despite its popularity, several problems arise when using X-ray transmission images for quantitative purposes: (1) a large proportion of available information is lost when three-dimensional structures are superimposed on two-dimensional photographic film; (2) the ability to record and/or display small differences (1-2%) in radiation transmission is limited because of film non-uniformities; and (3) much of the detected radiation is scattered "out-of-plane" from within the specimen [3, 4]. Thus, X-radiography is of limited value for our purposes.

X-ray computed tomography (CT) is a medical technique developed during the early 1970's to generate cross-sectional X-ray images of the brain [5]. Also called computer-assisted tomography or CAT scanning, CT is a method of reconstructing detailed cross-sectional images of a sample from a series of projections taken at angular increments about the object. Although CT is similar to conventional radiography, it differs in several key ways [3]: (1) there is no superimposing of structures due to the geometry of the apparatus and characteristics of the radiation beam; (2) contribution of scatter to the detected signal is minimized through the use of a finely collimated X-ray beam; (3) high signal-to-noise detectors used in CT scanners permit the recording of attenuation differences as small as 0.1%; and (4) sophisticated image reconstruction algorithms solve for X-ray attenuation of a local volume element independent of the surrounding media.

The medical community quickly demonstrated the diagnostic power of CT in their analysis of body tissues and in the detection of tumors. Industrial and scientific applications that soon followed have studied an amazing diversity of materials, ranging from tomatoes and trees, mummies and fossils, concrete and meteorites, to rock and ice. Applications more relevant to marine geoacoustics include those of soil scientists and agricultural engineers who have used CT to examine soil bulk density, water content, macroporosity, and water-plant root interactions [6]. Vinegar and others [7] pioneered its use in the characterization of oil reservoir rock cores and flow processes. As a result CT studies are common in the petroleum industry. In contrast, CT applications to technical problems in marine geology and geotechnical engineering have thus far been more limited in scope [see Ref. 1], although each has demonstrated convincingly the utility of CT. Interestingly, the geoacoustic modeling community is only beginning to appreciate the power of CT data and its potential benefit for model development in high-frequency acoustics.

For CT analysis, a sample is centered within a circular gantry which supports the X-ray source and a bank of detectors. Depending on the generation (i.e., style) of the scanner, either the source and detectors rotate together around the sample in a circular path, or the source rotates about a stationary detector bank, measuring X-ray attenuation along multiple ray paths through the sample. Each source-detector location provides a line integral measurement of X-ray attenuation, called a ray sum. Ray sums are generally made over a span of locations $>180^\circ$ and then combined and transformed via a computer interface into a two-dimensional "map" of attenuation coefficients using a filtered back-projection reconstruction algorithm. The data, in the form of a numerical matrix generally 256 x 256 or 512 x 512 elements in size, can be viewed on a dedicated video monitor where pixel brightness (or color) is proportional to the associated X-ray attenuation value for that element. Alternatively, as we have done, the stored digital data can be output for further analysis on a workstation using standard image processing techniques.

3. CT Applications

We have used CT techniques to characterize cores from various environments and sediment types, including: (1) gassy lacustrine muds from central Texas [8]; (2) high-porosity (and commonly gassy) muds of Eckernförde Bay, western Baltic Sea [9]; (3) sandy shell hash of the Louisiana continental shelf [10]; (4) fine to medium quartz sands off Panama City, FL [11, 12]; and (5) sandy calcareous muds off Marquesas Keys and Dry Tortugas, FL [13, 14]. Currently, we are using CT to examine bioturbated muds off Orcas Island, WA, and heterogeneous sediments at the California STRATAFORM site. In the following, we discuss two CT applications relevant to the development of realistic acoustic backscatter models: (1) the transformation of CT numbers to equivalent sediment bulk density for deriving high-resolution density profiles of the seafloor; and (2) characterization of sediment volume inhomogeneities, such as those found in gassy, shell-bearing, and/or bioturbated seafloor sediments.

3.1 Construction of High-Resolution Density Profiles

Among geoacoustic parameters, bulk density often exhibits strong gradients in the upper 30 cm of the seafloor [11]. While these high-gradient layers are relatively thin compared to low-frequency wavelengths, they can be very important at higher frequencies (10-100 kHz). This is due to the fact that at shorter wavelengths the interaction of these layers with a sonar signal may lead to a frequency-dependent acoustic impedance profile. The effects of the density profile on high-frequency reflection and transmission of acoustic energy, as well as, on surface and volume scattering strengths have a direct impact on the detection of buried objects, classification of bottom/subbottom types, and determination of propagation loss.

With respect to geoacoustics, one of the more advantageous characteristics of CT is its strong linear dependency on sediment density (Figure 1A). Historically, the most common way of determining the seafloor density structure has been through laboratory analysis of "undisturbed" sediments obtained either by divers or by subsampling box cores. To determine its density structure, a sediment core is transported to the laboratory (or any processing area) where the material is either extruded or collected after splitting the core liner. This material is weighed wet, dried, then reweighed to determine its bulk density (assuming an average grain density). However, much information regarding the variability of the sediment is lost due to the integrated nature of the measurement. In contrast, Figure 1B shows a high-resolution density profile constructed using

CT images. Construction of these logs is made by incrementing the sample through the scan plane using a positioning table. Quantitative analysis is then conducted on an image-by-image basis using a "fixed" region-of-interest (ROI). These high-resolution profiles can be used for a variety of geoacoustic purposes, such as constraining the maximum scattering response correlation length as a function of frequency. For example, Lyons [12] examined the finely layered sediments of Eckernförde Bay, western Baltic Sea, and concluded that for frequencies greater than about 10 kHz, sampling intervals should be less than 1 cm. (This interval is smaller than the measurement interval normally used when making seafloor core measurements.) Instead, Lyons used the CT profiles (2-mm vertical scale) to estimate correlation lengths of 0.5 cm and 0.7 cm and variances ranging from ~10^{-4} to 10^{-5} for Eckernförde sediments. We emphasize that to detect correlation lengths this small requires sampling resolutions of at least 2.5 mm, a value that cannot be obtained with traditional sampling methods.

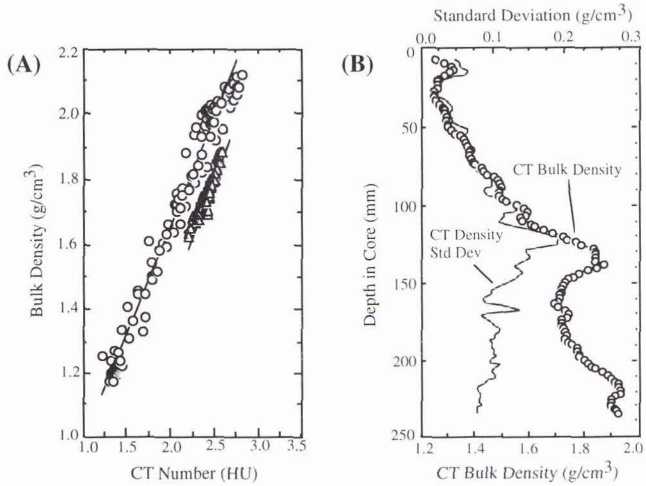

Figure 1. Transformation of CT numbers to sediment bulk density. (A) Empirical correlation. Circles—terrigenous marine sediments (i.e., those with low calcium carbonate content) taken in Eckernförde Bay, Germany; Panama City, FL; and the Louisiana continental shelf ($R^2 = 0.979$). Triangles—carbonate sediments from Marquesas Key, south Florida. (B) Typical high-resolution CT profile (Core 250-BS-BC; Eckernförde Bay, Germany) derived image-by-image.

In another study, we examined the impact of a thin layer of varying density on high-frequency reflection, forward loss, and backscattering of acoustic plane waves from the seafloor [11]. A functional form for density stratification was determined by examining a number of high-resolution CT density profiles, and a solution based on these general profiles was used to estimate the reflection coefficient. The influence of the density profile on reflection loss and backscatter was then calculated using the estimated reflection coefficient. Parameter values used in simulations were also obtained from the CT scans of the cores, as well as from the literature. We found that inclusion of a density profile adds a strong frequency dependence to estimates of the reflection coefficient and forward loss, and the largest effect on total scattering strength is near normal incidence where returns are dominated by interface scattering. The effect of the density profile on the strength of acoustic returns suggests that care should be exercised when using high-frequency systems for measuring sediment properties, especially near-normal incidence.

3.2 Characterization of Volume Inhomogeneities

A complete description of backscattering from the seafloor must include three components: (1) scattering from random discrete scatterers; (2) scattering from random continua; and (3) scattering from rough surfaces. Of the three components, discrete scatterers, such as bubbles, buried shells, and marine organisms (and/or their burrows) are the least understood in terms of their effect on acoustic propagation. This is due in large part to the lack of an appropriate analytical technique for quantifying these features. As we show next, X-ray CT is uniquely suited for quantitative volume descriptions at spatial scales directly relevant for modeling high-frequency acoustic backscatter (i.e., much smaller than 1 cm^3).

3.2.1 Gassy Sediments

It was our interest in characterizing gas bubbles in seafloor sediments that lead to our initial use of CT. In one of our first investigations, Orsi and Anderson [8] obtained a sediment core from Camp Creek Lake, a naturally gassy, man-made lake near College Station, TX (Figure 2). The primary accomplishment of this study was a conclusive demonstration that CT could indeed image, and be used to quantify, bubble characteristics in sediments because of the great density contrast between free gas and the sediment matrix. Bubbles in the studied lake sediment were large, in agreement with the macrobubble model proposed by Wheeler [15] and with earlier visual observations made by Anderson and Hampton [16]. Interestingly, the bubbles deform the sediment matrix to create cavities as they grow, changing shape in a sequence from spheres to ellipses to amorphous "blobs" with increasing size. The increasing departure from sphericity with increasing size results as the bubble overcomes the restraining strength of the sediment and develops in a manner generally dictated by larger scale sedimentary structures. Most important, however, is that the results stressed caution when developing models of gassy sediments, emphasizing that the traditional assumption of tiny spherical bubbles within pores distributed uniformly throughout a volume of sediment may not always be accurate. In fact, our CT analysis revealed that individual sedimentary gas bubbles can grow quite large and possess a multitude of shapes.

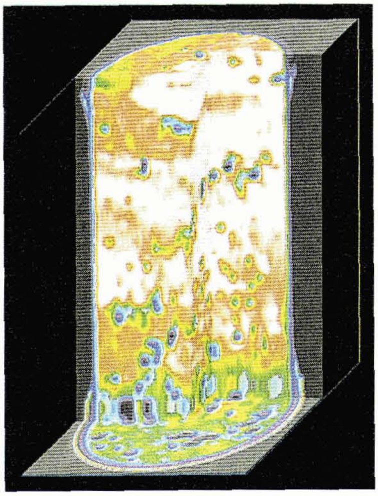

Figure 2. Volume rendering of a gassy Camp Creek core. The core is 1-ft long (30.5 cm) and is oriented properly, i.e., the top of the core and top of image is the lake bottom. This composite image is consists of 147 horizontal CT slices (2-mm thick). Note the gas bubbles (dark) and the general increase (lighter shades) in density with depth in the core.

Since our initial study, CT research into the nature and geometry of gas bubbles has advanced considerably [e.g., 17, 18], and has furthered the development of acoustic backscattering models for gassy sediments. The high downcore resolution of CT data has provided detailed descriptions of depth-dependent bubble fields within the sediment. CT information has enabled computation of discrete bubble scattering cross sections *versus* frequency which has formed the basis of a "thick layer" bubble scattering model described by Lyons et al. [19]. This model accounts for two-way propagation loss through a depth-dependent bubble distribution. Model results have shown that bottom loss predictions produced by "thin layer" or integrated bubble profiles may underestimate actual values by as much as 10 dB depending on frequency and bubble size distribution.

3.2.2 Shelly and Coarse-Grained Sediments

Of the common sediment types in shallow-water environments, sands and shell-bearing material are two of the more difficult types to characterize geotechnically. The main problem with studying these sediments is obtaining representative "undisturbed" samples for testing, due to their lack of cohesion and/or to the presence of shells. Besides identifying regions of disturbance, CT analysis of these sediments can also be used to investigate seemingly anomalous physical property values or to pin-point regions where laboratory measurements may be unknowingly in error. Figure 3 is one such example, which shows the occurrence of considerable intratest porosity in sediments collected off Marquesas Keys, Florida [13, 14]. Intratest porosity is common in shelly sediments where it serves to increase sediment porosity and decrease sediment density, due to the addition of water and/or slurry trapped within the interior of the buried shells. Another difficult-to-detect artifact, common in density profiles of sands, is shown in Figure 4. The high laboratory densities in the upper centimeters of Core CBBL 490-PC-DC are inaccurate and attributable to sediment dewatering that occurred unknowingly during laboratory sampling. They are easily corrected, however, using CT information since the approach is non-destructive and conducted before taking physical samples.

Figure 3. Identification of intratest porosity in shelly sediments using X-ray CT (CBBL 89-2-KW-DC, Marquesas Keys [13]). Note the intratest porosity as indicated by the dark regions contained within the interior of the two gastrapod shells. Also note the considerable hetereogeneity resulting from the shell fragments and calcified burrow (circular feature located in the center of the image). For scale, this image is 10 cm per side.

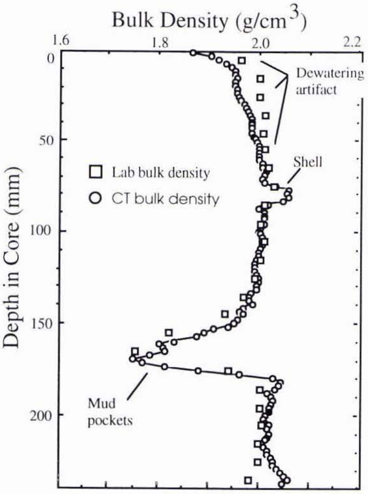

Figure 4. Detection and correction of a dewatering artifact in a density profile of sandy Panama City sediments (Core CBBL 490-PC-DC). Note the dewatering zone in the lab density profile, influence of a shell on the CT density profile, and interval of mud pockets detected by both methods.

3.2.3 Bioturbated Sediments

As attenuation of short wavelengths in sediments is high, properties in the region very close to the water-sediment interface will have a dominant effect on acoustic wave propagation. In this near-surface region, seafloor sediments are frequently highly bioturbated [20] and often display a tiering with depth. This tiering has been thought to explain vertical variations in sediment structure [21, 22]. We have extended this type of analysis to CT density profiles of sediment cores obtained in a variety of shallow-water areas [23]. Our model consists of the following tiers listed in order of increasing subbottom depth (Figure 5):

1. **Mixed layer**—characterized by low bulk densities and high variability due to intense small-scale (meiofaunal, juvenile, and/or small adult macrofaunal) burrowing.
2. **Transitional layer**—characterized by gradually increasing bulk density and high property variability associated with large-scale, but less frequent, mixing by head-down feeding organisms.
3. **Historical layer**—associated with increasing density with a simultaneous decrease in variability resulting from an increase in mechanical compaction and the closing of open burrows and other voids.

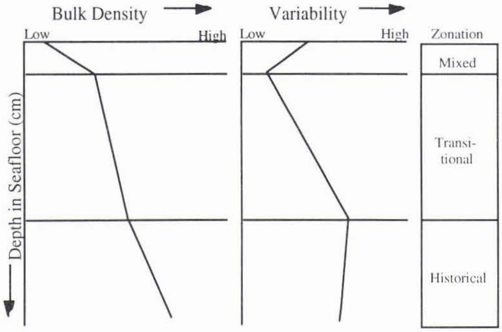

Figure 5. Conceptual CT model of physical property (density) variability in seafloor sediments. "Bulk density" refers to average CT bulk density and "variability" to its standard deviation.

By providing a conceptual framework, the characterization in Figure 5 should assist in modeling physical property variations within the upper decimeters of the seafloor, an important consideration for a variety of scientific and engineering investigations. Figure 6 shows a recently developed representation of the density profile shape for the upper few decimeters of the seafloor based on a smoothed version of the tiered near-surface seafloor structure [11]. Density approaches ρ_s with depth according to the function, $f_\rho = 1 + az$. (We refer to the parameter, a, in this equation as the density profile parameter which is a measure of the thickness of the high density gradients in the combined mixed and transitional layers in Figure 5.) This functional form matches a variety of CT density profiles from Eckernfšrde Bay, the Florida Keys, and Panama City. In these examples, the region of the core profiles which exhibits strong density gradients is the upper 1-5 cm. It is important to note that density data from this region is lacking as it is often disturbed by the coring/sampling process or skipped entirely in a coarse sampling scheme.

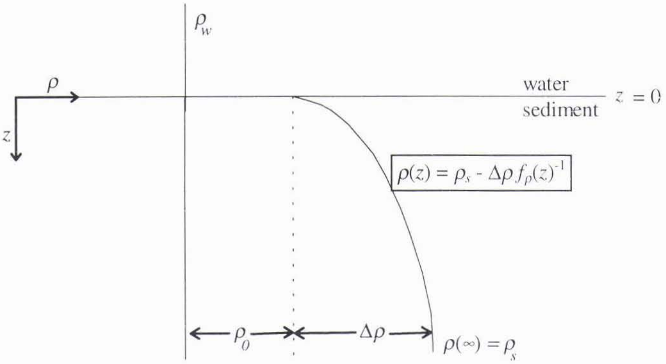

Figure 6. Seabed layering model for density with $f_\rho = 1 + az$ [11].

4. Summary

High frequency sonar systems such as those used in MCM are greatly affected by the small scale density structure of near surface marine sediments. Bioturbation, gas accumulation, and shell material all contribute to the highly variable nature of surficial density profiles. The need to quantify such variability is acute as accurate models of acoustic scattering cannot be developed without a thorough knowledge of relevant environmental factors. Traditional methods of core analysis are typically averages which are insufficient to fully quantify the nature of seafloor inhomogeneities. We have found X-ray CT to be a powerful technique for nondestructive characterization of intact sediment cores. CT methods are capable of obtaining high-resolution, three-dimensional information from which ground truth or model input parameters may be extracted. Methods of analysis have been refined by the medical community and the petroleum industry where CT has been used for several years. The geoacoustic modeling community, however, has yet begun to exploit the richness of CT data. Researchers involved in modeling efforts can, through the use of CT, verify results and gain significant new insight concerning the nature of high-frequency acoustic interaction with the seafloor. Such insight will advance the design of sonar systems and interpretation of sonar data for a variety of applications.

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