THE DEVELOPMENT OF A DIVER DEPLOYED X-RAY ATTENUATION MEASUREMENT (XRAM) DEVICE TO MEASURE THE DENSITY GRADIENT IN SITU

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The value for the reflection coefficient from a sand/water interface can have a significant impact in the modeling of the acoustics of shallow water communications, anti-submarine signal processing and buried mine detection. However, depth dependent density can have a considerable influence on the measured value for the reflection coefficient, particularly at high frequencies. Therefore, an accurate in situ measurement of the bulk density of the transition layer is critical to the interpretation of reflection data. Previously, bulk density measurements were either taken from scans of cores which disrupted the natural grain assembly or conductivity probes in which the density is measured indirectly. For this study, a novel means of directly determining the density gradient in situ using x-ray attenuation was developed. The system is small, lightweight and diver deployed allowing a greater flexibility in density measurements. Calibration measurements of materials with varying densities as well as laboratory measurements of the transition layer of a sand/water interface will be presented. Issues involved with the applicability of the current device and future developments will be discussed. [Work supported by ONR, Ocean Acoustics]

1 Introduction

Accurate measurement and interpretation of the reflection coefficient from the ocean bottom is important in a diverse range of applications spanning communications, signal processing, buried mine detection and inversion for sediment properties. The importance of obtaining an accurate reflection coefficient value is magnified in littoral environments where multiple-bounce interactions with the sediment layer are possible.

One complicating factor in interpreting sand/water reflection coefficients is the presence of depth-dependent density gradients in the sediment. Kimura and Tsurumi showed that, at high frequencies (~150 kHz) and low angles of incidence, a 12 dB difference was observed between the reflection coefficient generated from a model assuming uniform density and two models in which the density varied exponentially with depth [1]. Therefore, a method to measure these density gradients accurately could have a major impact on the interpretation of measured reflection coefficient data.

Several methods have been proposed to measure sediment density gradients. In the
interest of preserving sediment structure, it is preferable to take measurements in situ. The In-situ Measurement of Porosity (IMP) device developed at the University of Washington measures a 3D matrix of electrical conductivity as a function of depth [2]. These measurements can be mapped to density. Unfortunately, conductivity can also be affected by other sediment parameters such as tortuosity which can complicate data analysis. In addition, the device itself is too large for diver deployment and requires engineering support.

In this paper a novel means of obtaining sediment density gradient measurements in situ using a diver-deployed X-Ray Attenuation Measurement (XRAM) device is presented. The system is small, light and requires only ten minutes per site to measure density in the top six inches of the sediment. Therefore, a single diver can make a rapid assessment of the statistical variation of sediment density over an area of the ocean bottom.

2 Background

2.1 The X-Ray Attenuation Measurement (XRAM) device

A picture and diagram of the XRAM device are shown below in Figure 1.

![XRAM picture and diagram](image.png)

Figure 1. XRAM picture and diagram

The entire device is approximately twenty inches high including a six-inch long sediment
probe and is slightly buoyant in water. The small size and low weight of the XRAM make it
easy for a single diver to maneuver. Its cylindrical body contains a PC-104 stack running
LabView, the x-ray source, a preamplifier for the x-ray detector, and the system batteries
which supply power for up to 4 hours before requiring a recharge. The source state, detector
position and data acquisition are under computer control and, after acquisition, the data can be
transferred via wireless link to a second computer for analysis.

A computer-controllable cold-cathode source was chosen so that it would be
non-radiating when not in use. The source emits x-rays at energies ranging from
approximately 5 keV to 30 keV with maximum emission at 10 keV. Physically, the source is
about seven inches long and emits photons in a 120 degree cone which illuminates the entire
sediment probe. The source was selected for its compact size, low heat dissipation and
reasonable price. The size and heat dissipation issues are important for making a compact
underwater device. The price makes it affordable. The x-ray detector was chosen so that it also
had maximum efficiency at 10 keV. Physically, the detector has a 1 cm$^2$ cross-section and fits
easily into the sediment probe.

2.2 Model Equations

A theoretical model of x-ray absorption in sediment was developed for comparison with data
acquired with the XRAM. The most basic model of x-ray attenuation in an absorbing media
makes the following assumptions [3,5]:

1. The beam of emitted x-rays is perfectly collimated.
2. The x-rays are monoenergetic of energy $E$ and initial intensity $I_0$
3. The x-rays traverse an absorber of mass thickness $x$ before striking a detector of
   perfect efficiency at energy $E$

If the above conditions are satisfied the intensity of the x-ray at any point in the absorber
attenuates according to a simple exponential law given by

$$I = I_0 e^{-\mu/\rho},$$

where $\mu/\rho$ is the mass attenuation coefficient for the absorbing medium. However, the XRAM
violates these conditions. Therefore, the model must be adjusted to account for spherical
spreading, the broadband nature of the source and the different path lengths to each point on
the detector. A $1/r^2$ spherical spreading law is used to account for the non-collimated source.
Integration is also performed across the detector face and through the energy spectrum. With
these adjustments the model equation becomes

$$I = \frac{1}{r^2} \int_0^\infty \int_{A_x} I_0(E)D(E)e^{-\mu x(A)} dA dE,$$

where $I_0(E)$ and $D(E)$ are the energy dependent source spectrum and detector efficiencies, $x(A)$
is the mass thickness for each point on the detector face, and $A_d$ is the surface area of the detector. Given the density and depth-dependent porosity of an attenuating material, the mass thickness can be calculated for each detector position on the sediment probe. Values of the mass attenuation coefficient ($\mu/\rho$) for various materials were obtained from NIST [4]. For example, the mass attenuation coefficient for water is plotted in Figure 4 on a log-log scale.

3 Data Analysis

3.1 Liquids

To simplify analysis, data were first taken in three liquids and then compared to the model response. The chief simplification afforded by a liquid is that the medium can be assumed to be homogeneous and isotropic which simplifies the calculation of mass thickness. The three measured liquids were

- Water ($\text{H}_2\text{O}$): $\rho = 1 \text{ g/cm}^3$
- Methanol ($\text{CH}_4\text{O}$): $\rho = 0.792 \text{ g/cm}^3$
- Castor oil ($\text{C}_{21}\text{H}_{40}\text{O}_5$): $\rho = 0.956 \text{ g/cm}^3$

Figure 2 shows the detector response plotted with respect to the path length through both water and methanol. A higher detector response corresponds to less attenuation so the higher response in the methanol can be explained by its lower density.

![Figure 2. Attenuation vs. Path Length to Detector for Water and Methanol](image-url)
If a medium with known density (such as water) is used to calibrate the system, the relative density of an unknown attenuating medium can be determined. Also, as illustrated in Figure 3, if the detector response is plotted with respect to the amount of attenuating mass between the source and detector then the system response for water and methanol are identical. In other words, the data for water and methanol indicate that x-ray attenuation is proportional to attenuating mass regardless of the attenuating medium. Using this plot, a unique mapping between attenuating mass and detector output can be made through which the density of the unknown medium can be found. Unfortunately, when attenuation was measured in Castor oil the data did not agree with these conclusions. As the dash-dot curve in Figure 3 shows, the Castor oil data suggest a different dependence on attenuating mass than implied by the water and methanol data.

![Figure 3. Attenuation vs. mass for the three liquids](image)

In order to explain the discrepancies between the methanol/water and Castor oil data, the mechanisms responsible for x-ray attenuation were investigated further.

### 3.2 X-Ray Attenuation Mechanisms

At the energies generated by the XRAM, there are two relevant mechanisms of x-ray absorption: the photoelectric effect and Compton scattering. As can be seen in Figure 4, the mass attenuation data consists of two distinct linear regions which are indicative of the two mechanisms. The photoelectric effect dominates at lower energies. Here the x-ray ejects an inner shell electron which is replaced by an outer shell electron producing a photon of lower
The energy of the x-ray must be greater than the binding energy of the inner shell electron. Compton scattering dominates at higher x-ray energies. In this mechanism, x-rays interact with an outer shell electron which is ejected from the atom. The incident x-ray is scattered in a different direction with a greater energy. Compton scattering is dependent only on the number of atoms in the transmission path. The photoelectric effect is also dependent on molecule size.

Therefore, if density is to be determined independent of material type, the x-ray energy should be in a region dominated by Compton scattering. Unfortunately, as Figure 4 shows, the XRAM source lies in the lower energy region which is dominated by the photoelectric effect. Due to the dependence on molecule size, comparison between attenuating media of grossly different molecular mass will be difficult. From the chemical formulas for the three tested media it is apparent that the molecular mass of Castor oil (C_{21}H_{40}O_{5}) is significantly greater than the mass of either water or methanol (H_{2}O, CH_{4}O). This may explain the discrepancy in the mass to attenuation mapping. However, the molecular weight of sand (SiO_{2}) is on the order of water and methanol. Therefore, reliable analysis could be performed on data taken across a sand/water interface.

![Figure 4. Photoelectric- and Compton-dominated Regions of the X-Ray Spectrum](image)

### 3.3 Sand / Water Interface Data

Data were taken across an interface between water and saturated SiO_{2} beads in order to simulate the conditions of a sand/water interface on the ocean floor. A plastic bucket was filled with water before SiO_{2} beads were slowly poured into the bucket until a 1.5 cm layer of water
remained at the top. In an effort to remove air from the saturated sand, the mixture was then rocked for thirty minutes before inserting the XRAM probe.

Figure 5 shows both the experimental and model responses for the sand/water interface experiment. To model the saturated sand, the best fit was found with a porosity of 0.4 and the location of the interface was modeled as being at 1.7 cm instead of 1.5 cm. This 2 mm shift is probably due to an uneven sand interface or measurement error when the bucket was filled with the SiO$_2$. Agreement between the model and experimental data is nearly perfect up to the interface. After the interface the experimental data is somewhat higher than the model response although it still tracks the general shape of the model. This slight discrepancy can be accounted for by trapped air in the mixture or depth dependent porosity. This effect will be investigated in subsequent publications.

![Figure 5. Model / Experimental Data for a Sand / Water Interface at 1.5 cm](image)

4 Discussion

The X-Ray Attenuation Measurement (XRAM) device is a novel approach to measuring sediment density in situ via x-ray attenuation. X-Ray attenuation can be used to measure density gradients in the first few centimeters of oceanic sediment. These gradients can have a significant effect on reflection coefficients. Data taken in homogeneous liquids suggest that if the attenuation is dominated by the photoelectric effect (as is the case with a low energy x-ray source), the sediment mass attenuation coefficients must be similar to water in order to obtain accurate results. This requirement may be avoided by using a source of higher x-ray energy such that Compton scattering is the dominant attenuation mechanism.

In the sand/water interface experiment, good agreement was obtained between a model
and the experimental data up to the point of the interface and the data disparity after the interface is congruent with expected complicating experimental effects such as trapped air or density gradients. In the near future, further experimental studies will be completed in which the porosity of a suspended sediment is varied so that porosity inversion may be performed.

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References