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CONSIDERATIONS IN THE MODELLING OF SEAFLOOR ACOUSTIC BACKSCATTER

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Abstract

The modelling of acoustic backscatter has long been of interest to the US Navy because the application of these models offers the possibility of remote characterization of the seafloor. Basic scattering mechanisms and empirical studies of seafloor backscatter are reviewed in this paper. The Rayleigh criterion offers a means of classifying a rough surface. The Rayleigh parameter, a measure of vertical roughness, and the Rayleigh reflection coefficient, a measure of reflection loss between boundaries, are reviewed. The task of modelling the scattering from a surface with two scales of roughness is approached using a combination of two scattering approximations, one valid for small-scale roughness and one valid for large-scale roughness. The method of small perturbation is used for small-scale roughness, and the method of tangent plane, or Kirchoff approximation, is used for large-scale roughness.

1 Introduction

This paper reviews the factors involved with the modelling of seafloor acoustic backscatter. Backscattering of sound from the seafloor has long been of practical importance in sonar work because in many cases it acts as the dominant masking agent of the reverberation against which a sonar target must be detected. In other cases, backscatter measurements offer a means of remotely characterizing properties of the seafloor. It is therefore important to know the dependence of backscattered reverberation on grazing angle, frequency, bottom type, and bottom roughness [1]. These four factors are primary considerations in the modelling of seafloor backscatter. Many empirical studies [2, 3, 4, 5, 6, 7, 8, 9, 1, 10, 11] of backscatter, given various frequencies, grazing angles, and bottom types, have been conducted in efforts to gain insight to the physical processes involved with backscatter. Attempts have been made to relate the statistical properties of backscattered signals to independently observed geological characteristics of the seafloor. Changes in bottom type and roughness structure have been found to correlate with the acoustic backscattered signal.

The problem of modelling seafloor acoustic backscatter is one of modelling the sound scattering from a randomly rough surface. All rough surfaces can be conveniently divided into two classes: surfaces with exactly given profiles and surfaces with random irregularities. Surfaces with random irregularities occur throughout nature, and the seafloor bottom is a prime example. Such a surface is not known in exact detail, and even if it were known in exact detail at every point and every instant in time, anything other than a statistical solution would be too specific to be of much value. The class of rough surfaces with periodic roughness irregularities presents the case where a non-statistical approach is possible. This class of rough surfaces was the first to be considered due to the greater simplicity of the non-statistical approach. It is useful to study surfaces with periodic roughness even though they do not occur as commonly as do randomly rough surfaces because the theory for periodically rough surfaces is general enough to give some indication as to the behavior of randomly rough surfaces [12]. Lord Rayleigh [13] first treated a problem of scattering of waves from a periodically rough surface, where he considered normal incidence of sound waves onto a sinusoidal surface. Rayleigh's work is now considered classic in the field.

The modelling of the ocean bottom is further complicated by the fact that the bottom possesses two scales of roughness. That is, the ocean bottom consists of both large and small scale irregularities (Fig. 1), giving it a rather broad spatial spectrum. The Rayleigh parameter, discussed in section 5, determines the scale of roughness.

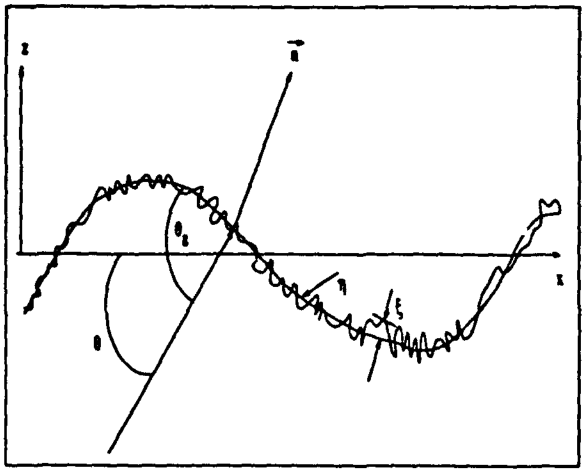

Figure 1: Small and large scale components of a rough surface [19].

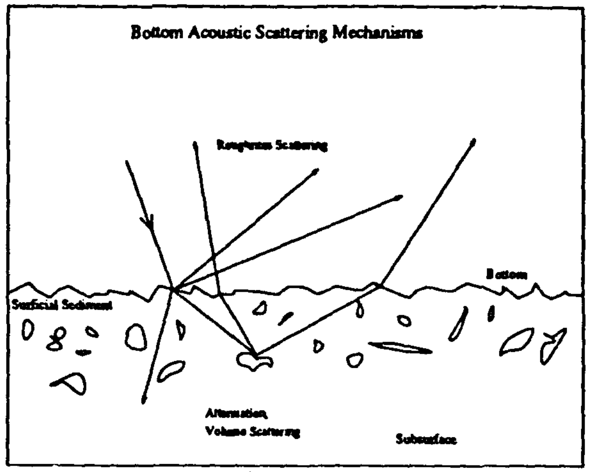

Figure 2: Bottom Scattering Mechanisms [18].

The modelling of wave scattering from this type of surface is based on the primary assumption that the surface roughness can be divided into two components, a small-scale component and and large-scale component. We will discuss these as well as other considerations in the following sections. First, though, we will review the basic scattering mechanisms.

2 Scattering Mechanisms

The sea bottom acts as an effective reflector and scatterer of sound; it redistributes a portion of the sound acoustic energy incident upon it to the ocean above. Early studies of sea-bottom reverberation investigated its dependence on such parameters as bottom type, bottom roughness, frequency, and grazing angle. It is common to relate the bottom scattering strength to bottom type, even though it is realized that particle size is only an indirect indicator of acoustic scattering. Sediment type serves as a first cut means in classifying the bottom in terms of acoustic backscattering. Not all acoustic energy is necessarily redistributed to the ocean above; a portion of the acoustic energy incident upon the bottom may be transmitted into the subsurface, so bottom type must affect the division of energy between the water above and the earth below. The transmission of acoustic energy into the earth creates another effect, called "volume scattering." Here, each sedimentary particle can be thought of as a scatterer of sound, so a portion of the return from the bottom is produced by this volume scattering within the sediment itself. The reradiation of sound that has penetrated the bottom may be an important process to consider at low frequencies and high grazing angles, where reflection and scattering from subsurface layers may occur. At high frequencies there is little penetration into the sediment of the seabed so volume scattering would be negligible, and the principal characteristics of the bottom return would remain to be given by discontinuity of acoustic properties occuring at the bottom itself [14].

The types of scattering depicted in Fig. 2 are scattering due to interface roughness and scattering from within the sediment volume itself. Models have been developed to describe both types of processes. The relative importance of these two processes is not well established. Jackson and Briggs [11] published a study on the roles played by interface roughness and sediment volume inhomogeneities. In a previous study, Jackson et al. [15] reported that roughness scattering was dominant for a sandy site surveyed, and sediment volume scattering was dominant for a silty site. This paper will deal with only the considerations used in modelling the scattering from the rough interface. We will now review empirical studies and their implications, and then discuss the factors in modelling sound scattering from a rough surface.

3 Empirical Studies

Empirical studies have been conducted in efforts to relate acoustic backscatter to sediment type, bottom roughness, and dependence on grazing angle and frequency. Many of the empirical studies have served as insight to the physical processes involved in backscatter, and this insight has aided in the development of theoretical models of the backscatter process.

An extensive study of the backscatter process was conducted by Nolle [7] in 1963. Nolle measured the velocity and attenuation of sound waves in water-filled sands and the scattering from a water-sand interface. His analysis predicted limiting behavior of the measured backscatter with respect to particle size and frequency.

In the early 1960's, McKinney and Anderson [1] also made an empirical study of seafloor acoustic backscatter. Data was taken from backscattering of sound from the ocean bottom at sixteen locations. The goal of the study was to compare field data with theoretical predicitons and laboratory results, and to obtain quantitative data on average reverberation levels. This data was given as a function of grazing angle and frequency for mud, sand, and gravel. Backscattering increased with grazing angle according to sin and $\sin^2$, depending on angle and sediment type. McKinney and Anderson concluded that a knowledge of the particle structure of the bottom is helpful in trying to measure reverberation level.

In the late 1960's, Wong and Chesterman [3] conducted a study of backscattering at grazing angles between .4 and 8 degrees using a frequency of 48 kHz at 12 locations in the inshore waters of Hong Kong. Their study showed that backscatter strength increases by about 25dB as the bottom type changes from silt and sand to rock. Data obtained from this study suggests that backscatter depends on both bottom type and bottom roughness, though it is difficult to discern which factor is dominant, especially because bottom roughness and its sediment type are seldom completely independent. Wong and Chesterman conclude that a knowledge of the percentage of sand and the effective bottom roughness is helpful in estimation of seafloor backscatter.

In the early 1970's, Hamilton [16] conducted a study of sound velocity and attenuation measurements in the seafloor off of San Diego for frequencies between 3.5 and 100 kHz. The sediment type for this region ranged from coarse sand to clayey silt. One objective of the study was development of a method to predict attenuation in marine sediments given frequency and common physical properties such as grain size. Hamilton also investigated the relationships between frequency, velocity, attenuation, and other physical properties. Hamilton's measurements are still in current use in backscatter models.

More recent acoustic backscattering measurements were made by Boehme et al. [8] in 1984 in efforts to provide data at low grazing angles from which backscatter strength values could be extracted. These measurements were taken near San Diego and the data was analyzed to determine the mean value and standard deviation of bottom backscattering strength per square meter as a function of grazing angle, insonified area, transmit signal type, and frequency. Lambert's rule held true fairly well in estimation of the bottom backscattering strength as a function of grazing angle for all frequencies and pulse types used. Boehme et al. reported a frequency dependence consistant with that reported by McKinney and Anderson [1].

Also in the mid-1980's Jackson et al. [10] made bottom backscatter measurements at six shallow-water sites for frequencies ranging from 20-85kHz. Bottom types ranged from silt to sand to gravel. This study was motivated by the fact that even though a number of high-frequency bottom backscattering studies had been reported, the physical properties of backscattering were still not well understood. So, backscatter measurements were made as well as measurements of the physical properties of the seabed. Bottom samples were taken at all experimental sites. This study showed a slight frequency dependence, and scattering strength generally decreased with grazing angle.

The physical backscatter data gathered has served to provide an idea as to the physical processes involved in seafloor acoustic backscatter, but these are still not well understood. Quoting Jackson et al.,

> Until the various bottom scattering mechanisms are understood, one cannot hope to understand the observed frequency and grazing angle dependence, or to take full advantage of backscatter strength measurement as a remote sensing tool. Study of these mechanisms requires a combination of experiment and physical modeling. Some general questions arise in this context: Is it possible to develop useful models for high-frequency bottom backscattering, or is the seabed so complicated and so variable as to defy all but the crudest modeling efforts? If useful models can be developed, which parameters (grain size, porosity, roughness, etc.) are sufficient to determine the high-frequency scattering properties? [10].

Empirical studies have provided insight to the physical processes involved in seafloor backscatter, though it is questionable whether a useful physical model is feasible. We will now investigate common factors considered in modelling the scattering of sound from a rough surface.

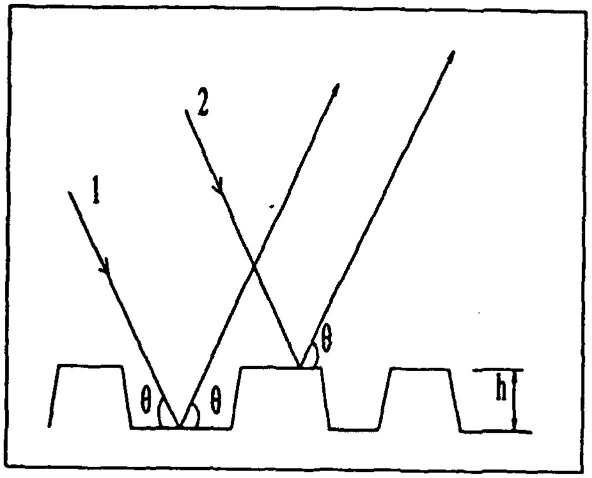

Figure 3: Derivation of the Rayleigh criterion [15].

4 Scattering from Rough Surfaces

The first consideration in the modelling of sound scattering from a rough surface is the determination of what classifies a rough surface. That is, for what values of wavelength, angle of incidence, and surface roughness, does specular reflection become diffuse scattering?

Rayleigh developed a method of relating these considerations, as presented by Beckman and Spizzichino [12]. For the two rays (Fig. 3), 1 and 2, incident on a surface with irregularities of height h at grazing angle θ, the path difference between the two rays is given by

$$\Delta r = 2h\sin\theta \quad (1)$$

and the phase difference is then

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta r = \frac{4\pi h}{\lambda}\sin\theta \quad (2)$$

where λ is the acoustic wavelength.

When this phase difference is small, the two rays are almost in phase as they would be in the case of a perfectly smooth surface. As the phase difference increases, the two rays interfere until $\Delta\varphi = \pi$, where they will be in phase opposition and will cancel. The energy must be redistributed in other directions since energy cannot be lost. So, for $\Delta\varphi = 0$, the surface is smooth and produces specular reflection. For $\Delta\varphi = \pi$, the surface scatters diffusely and is therefore rough. Differentiation of a rough surface from a smooth one can be treated by choosing a value half-way between the two cases, $\Delta\varphi = \pi/2$, and substituting this value in for Eq. 2. This gives the relation known as the "Rayleigh criterion." In other words, a surface is considered smooth for

$$h < \frac{\lambda}{8\sin\theta} \quad (3)$$

Other values for $\Delta\varphi$ have been suggested as more realistic. Beckman and Spizzichino note, however, that there is little point in determining an exact dividing line, and that a safer way of expressing the basic idea of the Rayleigh criterion is

$$\frac{4\pi h}{\lambda}\sin\theta \quad (4)$$

and this may be used as a measure of effective surface roughness. The surface will tend to be effectively smooth under only two conditions

$$\frac{h}{\lambda} \to 0 \quad (5)$$

and

$$\theta \to 0 \quad (6)$$

Beckman and Spizzichino also note that the crudity of the Rayleigh criterion is obvious. It is based on simple ray theory and the irregularities of the rough surface are described by a single parameter. In engineering practice, the Rayleigh criterion is still widely used as an approach to rough surface scatter. The Rayleigh criterion is a simple expression that requires only three easily measurable parameters, h, θ and λ. Due to this, the Rayleigh criterion lends itself well to practical use.

The Rayleigh criterion establishes an approximate division between surfaces that may be regarded as rough or smooth but does not establish a quantitative description of the reflection by a rough surface, as we address now. A field scattered by a rough surface should be considered the sum of two components: the specular component and the diffuse component. The existence of these two components is a phenomenon which appears in any type of rough surface, and not just a consequence of a particular model of a rough surface. Reflection off of a smooth surface produces purely specular reflection. Specular reflection is directional and obeys the laws of classical optics. Its phase is coherent and its fluctuations have a relatively small amplitude. In contrast, diffuse scattering has little directivity and its phase is incoherent. Its fluctuations are large in amplitude and are Rayleigh distributed. The existence of specular and diffuse reflections and their properties has been shown in investigations of scattering by rough surfaces, and has been demonstrated experimentally [12]. We have seen that an elementary consideration in the modelling of scattering

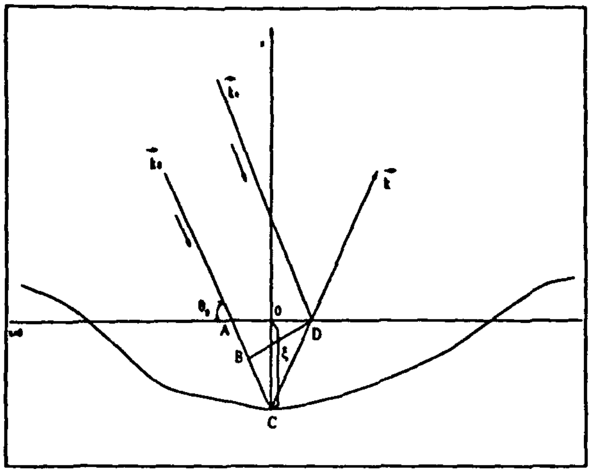

Figure 4: Derivation of the Rayleigh parameter [19].

from a rough surface is establishing the criterion of what classifies a rough surface. We will now consider a means of measuring the degree of roughness of the surface.

5 Rayleigh Parameter

The spectrum of bottom relief of the ocean is very wide, ranging from small "ripple marks" formed by currents on sand to the great mid-oceanic ridges that extend over a thousand kilometers with a height of a few kilometers. The Rayleigh parameter is a measure of the vertical scale of roughness for a surface and is given by

$$P \equiv 2k\varsigma\cos\theta_0 \qquad (7)$$

where k is the wave number of sound, θ_0 is the angle of incidence of the sound wave, and ς is the root-mean-square displacement of the rough surface from its mean level (Fig. 4). For $P \ll 1$ the roughness of the surface is considered *small*. For this case, the surface scatters sound slightly and the main part of the sound energy propogates in the specular direction as a coherent wave. For $P \gg 1$ the surface roughness is *large* and incoherent waves are scattered in all directions.

The physical meaning of the Rayleigh parameter can be treated as follows. Consider the reflections of sound from the rough surface $z = \xi(\mathbf{r}), \mathbf{r} = x, y$ and the phase change along the ray ACD relative to the mean plane $z = 0$. The phase difference is equal to

$$\Delta\varphi = k(BC + CD) = k(2CD - AB) \qquad (8)$$

where

$$CD = \frac{\xi}{\cos\theta_0} \qquad (9)$$

and

$$AB = 2\xi\tan\theta_0\sin\theta_0 \qquad (10)$$

So,

$$\Delta\varphi = 2k\xi\cos\theta_0 \qquad (11)$$

Hence, the Rayleigh parameter P is exactly equal to the root-mean-square of $\Delta\varphi$

$$P = \left[< (\Delta\varphi)^2 >\right]^{\frac{1}{2}} = 2k\varsigma\cos\vartheta_0 \qquad (12)$$

where

$$\varsigma = (< \xi^2 >)^{\frac{1}{2}} \qquad (13)$$

Note that $P \to 0$ if $\frac{\varsigma}{\lambda} \to 0$ or $\vartheta_0 \to \frac{\pi}{2}$. Scattering does not occur and reflection becomes specular in this case [17].

The Rayleigh parameter is a measure of the vertical scale of roughness for a surface and is a primary consideration in many scattering models. We will now examine another common component of many models, the Rayleigh reflection coeffiecient.

6 Rayleigh Reflection Coefficient

The Rayleigh reflection coefficient, R_0, is another common component in many seafloor backscatter models. This component helps account for bottom-reflection loss. Rayleigh derived the reflection loss of incident sound at an angle to a plane boundary between two fluids (Fig. 5). This coefficient relates the intensity of the reflected wave I_r to the intensity of the incident wave I_i

$$R_0^2 = \frac{I_r}{I_i} = \left[\frac{m\sin\theta_1 - (n^2 - \cos^2\theta_1)^{1/2}}{m\sin\theta_1 + (n^2 - \cos^2\theta_1)^{1/2}}\right]^2 \qquad (14)$$

where

$$m = \frac{\rho_2}{\rho_1}, \qquad (15)$$

and

$$n = \frac{c_1}{c_2}. \qquad (16)$$

The reflection loss is then $10\log I_r/I_i$. The values of the sound velocity ratio, c_1/c_2, and the density ratio, ρ_2/ρ_1, are needed to evaluate the Rayleigh reflection coefficient as a function of grazing angle. Brekhovskikh [17] investigates the behavior of loss with the grazing angle for various conditions on m and n. The most common condition found for natural bottoms is that in which a critical angle θ_0 exists

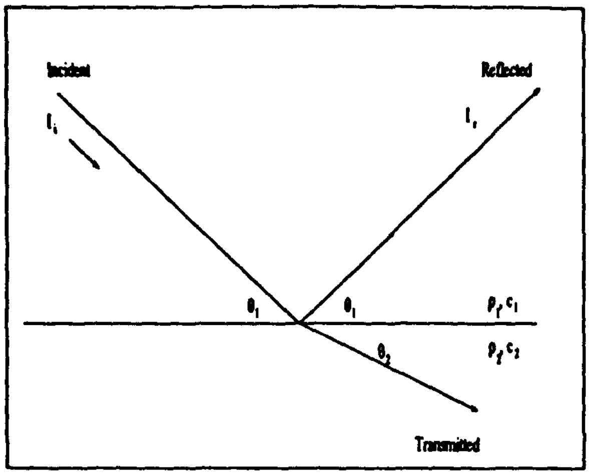

Figure 5: Discontinuity between two mediums, [17].

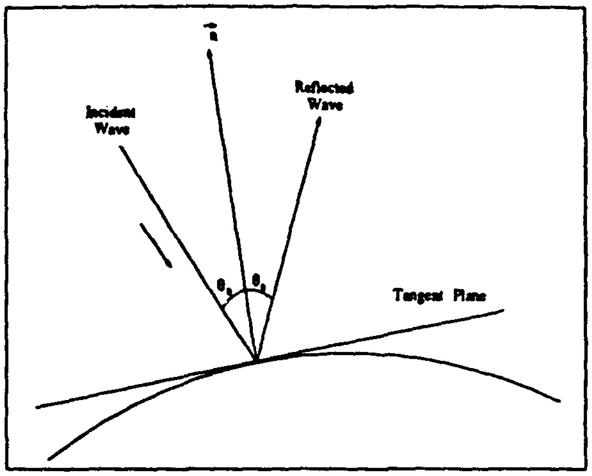

Figure 6: "Local" scattering geometry, [19].

where total reflection occurs (zero loss) at grazing angles less than critical [14]. The Rayleigh reflection coefficient, which accounts for the reflection loss between two mediums, is a common consideration in the modelling of seafloor backscatter. We will now review the effects that small and large-scale roughness components have on modelling considerations.

7 Large and small-scale roughness components

Recall in Fig. 1 the large and small-scale roughness components of the ocean bottom. These differences in irregularities give the ocean bottom a wide spatial spectrum. In modelling such a surface, a combination of two wave scattering approximations are needed: one valid for small-scale roughness and one valid for large-scale roughness. Such a combination is based on the assumption that the surface roughness can in fact be divided into these two components.

The approximation valid for the small-scale roughness is the method of small perturbation (MSP). (See [17] for a detailed description of this method.) The MSP is valid for the case where the rough surface deviates only slightly from a certain mean surface and has sufficiently small slopes. The basic idea behind this theory is that the boundary conditions at a rough surface (See Fig. 4) $z = \xi(\mathbf{r})$ can be transferred to the mean surface by expanding the boundary conditions into a power series of ξ. The sound field in a half-space $z > \xi$ can also be expanded in powers of ξ. The boundary conditions at the mean surface that must be satisfied by the first, second, and higher approximations are then found. This method reduces the problem of wave scattering at a rough surface to the problem of radiation by the distribution of "virtual" sound sources.

The small perturbation method is applicable for the case of a small Rayleigh parameter $P << 1$. The ocean bottom often does not satisfy this condition; the roughness of the bottom is frequently much greater than the sound wavelength. Another method must be used in such cases. The approximation needed for the large-scale roughness component is the method of tangent plane, or Kirchoff approximation. (See [17] for a detailed description of this method.) This approximation is valid for the case where the roughness is sufficiently smooth, though large in contrast to the acoustic wavelength. Under this condition, it is assumed that sound reflection takes place at each point of the surface in the same manner as reflection at an infinite plane tangent to a rough surface at the point considered (Fig. 6). This method yields useful results only for grazing angles close to specular direction.

The combination of these two approximations allows for the modelling of a surface with two scales of roughness. The "two-scale" model is obtained by superimposing the surface with the small displacement $\xi(\mathbf{r})$ upon the smooth, large-scale surface $\eta(\mathbf{r})$. (Fig. 1) [17]. The method of dealing with two-scales of roughness is a primary factor in many seafloor backscatter models.

8 Summary

In modelling backscattering from a rough surface, several key components are considered. We have looked at the case of modelling backscatter from an interface with two-scales of roughness. The first consideration was the classification of a rough surface, established by the Rayleigh criterion. We then reviewed the Rayleigh parameter, which is a common parameter in many seafloor backscatter models and is a measure of vertical roughness. It is used to determine if a small-scale or large-scale scattering approximation is appropriate. The Rayleigh reflection coefficient is another common parameter in many models, and is used to account for reflection loss between boundaries. The task of modelling the scattering from a surface with two scales of roughness can be approached using a combination of two scattering approximations, one valid for small-scale roughness and one valid for large-scale roughness. The validity of the approximations used is a primary concern in the modelling process. Research continues towards developing a physical model for seafloor acoustic backscatter. It has been questioned whether or not such a model is possible, as some researchers suggest that the physical processes involved in backscatter are too complex to accurately model.

9 Acknowledgments

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