On acoustic scattering by a shell-covered seafloor

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Acoustic scattering by the seafloor is sometimes influenced, if not dominated, by the presence of discrete volumetric objects such as shells. A series of measurements of target strength of a type of benthic shelled animal and associated scattering modeling have recently been completed (Stanton *et al.*, ''Acoustic scattering by benthic and planktonic shelled animals,'' J. Acoust. Soc. Am., this issue). The results of that study are used herein to estimate the scattering by the seafloor with a covering of shells at high acoustic frequencies. A simple formulation is derived that expresses the area scattering strength of the seafloor in terms of the average reduced target strength or material properties of the discrete scatterers and their packing factor (where the reduced target strength is the target strength normalized by the geometric cross section of the scatterers and the averaging is done over orientation and/or a narrow range of size or frequency). The formula shows that, to first order, the backscattering at high acoustic frequencies by a layer of shells (or other discrete bodies such as rocks) depends principally upon material properties of the objects and packing factor and is independent of size and acoustic frequency. Estimates of area scattering strength using this formula and measured values of the target strength of shelled bodies from Stanton *et al.* (this issue) are close to or consistent with observed area scattering strengths due to shell-covered seafloors published in other papers. [S0001-4966(00)02702-8]

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INTRODUCTION

Acoustic scattering by the seafloor has long been studied in order to either predict the performance of sonar systems or to use sound to quantitatively map the seafloor. The scattering is influenced by the roughness of the interfaces between the water and bottom and subbottom layers as well as inhomogeneities (Medwin and Clay, 1998; Ogilvy, 1991; Urick, 1983; Jackson *et al.*, 1986a, b; Jackson and Briggs, 1992; Jackson and Ivakin, 1998; Stanic *et al.*, 1989; Tang *et al.*, 1994, 1995; Richardson and Briggs, 1996; Ivakin, 1998). There are both continuously varying inhomogeneities and discrete ones. Rocks, shells, and gas pockets are among the discrete inhomogeneities.

There is evidence that the presence of shells on the seafloor can influence, if not dominate, the scattering (Jackson *et al.*, 1986b; Stanic *et al.*, 1989; Zhang, 1996). Descriptions to date of the effects of the scattering by beds of shells have generally involved incorporating the shells as part of the continuously rough seafloor. This approach can produce reasonable estimates of the scattering provided that the bed of shells resembles a single-valued featureless surface. For other conditions, the discrete or volumetric nature of the shells can result in a multi-valued surface (e.g., a spherical shell lying on an interface is described by a multi-valued function). Scattering effects specific to a multi-valued surface may be important in the estimates for both dense and sparse distributions. Accounting for the discrete nature of scattering by shell-covered seafloors has been limited, in part, by the general lack of information on the scattering characteristics of individual shells (Zhang, 1996).

Recently, an extensive set of measurements of target strength has been performed on the scattering by a type of benthic shelled animal (Stanton *et al.*, 2000). This substantial data set served as a basis for a target strength model of the animals for a wide range of sizes and acoustical frequencies. In this paper, the model and data are used to estimate the levels of acoustic scattering at high acoustic frequencies that may be expected from a seafloor that is covered with shells. A simple approximate formula for scattering by a layer of discrete scatterers is derived in order that the estimates be made. A comparison of the estimate using the target strength data is made with seafloor scattering data presented in Jackson *et al.* (1986b) and Stanic *et al.* (1989).

I. TARGET STRENGTH MEASUREMENTS OF BENTHIC SHELLED ANIMALS

In a recent study, the scattering characteristics of periwinkles (*Littorina littorea*), a type of benthic shelled animal, were studied (Stanton *et al.*, 2000). Measurements of backscattering were made in free space—i.e., the animals were away from any boundaries. The backscattering was measured over parts or all of the range 24 kHz to 1 MHz for 0- to 360-degrees orientation in as small as 1-degree increments. The length of the six animals ranged from 6 to 14 mm. Discrete (narrow-band) frequencies were used over most of the frequency range and broadband signals were used at the higher frequencies. Both the spectral and temporal (pulse compression) characteristics of the data were examined and served, in part, as the basis of scattering modeling.

The scattering process of the animals was observed to be quite complex as the echoes were strongly dependent upon both frequency and angle of orientation. For example, at the high frequencies, dominant echoes were observed from the front interface as well as sometimes from the inside of the opercular opening and from circumferential waves (subsonic Lamb waves). Generally, the animals were found to behave approximately as deformed elastic shelled spheres with discontinuities. A ray analysis was able to describe the scattering qualitatively at the higher frequencies for the single ping (single realization) analysis. However, in order to provide quantitative predictions of the scattering, an approximate all-frequency model was used which was based upon the modal series solution to the smooth elastic spherical shell. The solution was averaged over sizes and shell thickness in order to predict echoes from ensembles of randomly oriented shells. Many of the errors associated with the use of the modal series solution were eliminated as a result of the averaging process.

II. A VOLUMETRIC-BASED SEAFLOOR SCATTERING FORMULATION

Modeling of the scattering by a shell-covered seafloor is extremely challenging. A rigorous approach would be to use a formulation combining effects due to all boundaries (surficial roughness, interface roughness between layers, discrete scatterers) as well as smoothly varying inhomogeneities (see, for example, Ivakin, 1998). Such an approach is beyond the scope of this current analysis where the intention is to simply provide an estimate of the contribution of the scattering by the shells under very limited conditions (i.e., a layer on the surface of the seafloor near normal incidence that dominates the scattering).

In this simplified approach, the following assumptions are made:

(1) Scattering by the shell-covered bottom is modeled using only volume scattering considerations.
(2) The shapes of the shells do not deviate significantly from a sphere (i.e., not to be needlelike).
(3) Multiple scattering is neglected as a first approximation for these closely spaced scatterers except when Lambert's law is used to describe angular dependence of seafloor scattering and multiple scattering is implicit.
(4) High-frequency acoustics (i.e., geometric optics) approximations are made:
   (a) For single targets, $k_1 a_{\mathrm{esr}} \gtrsim 1$, where $k_1 (=2\pi/\lambda_1)$ is the acoustic wave number in the surrounding water and λ_1 is the acoustic wavelength. The term a_{esr} is the equivalent spherical radius of the body, which is the radius of a sphere that has the same volume as that of the body.
   (b) For multiple targets, the phases from the individual scatterers are randomly and uniformly distributed over the range 0 to 360 degrees.
(5) The scatterers are randomly oriented so that the ensemble average backscattered cross section, normalized by the geometric cross section, is independent of $k_1 a_{\mathrm{esr}}$ at high $k_1 a_{\mathrm{esr}}$.
(6) The layer is dense enough so that it dominates the scattering.

In order to estimate the effects of the scattering (at best to first order), the floor is considered from a volume scattering viewpoint and is assumed to be a planarlike array of scatterers. Also, the phases of the echoes from the bodies are assumed to be randomly and uniformly distributed over the range 0 to 360 degrees. With this random phase approximation, the signals add incoherently; that is, the average energy from ensembles of the scatterers is equal to the sum of the energy of the individuals.

Although the sizes of shelled bodies present in a given seafloor study are not necessarily known, estimates of the scattering can still be made in the geometric scattering region through use of backscattering cross sections normalized by cross-sectional area of the scatterer. This allows measurements or models of the scattering by an object at one size to be scaled for applications involving objects of other sizes. The objects are required to be of similar shape in order for this scaling to be valid. The backscattering cross section by a given target in the geometric scattering region (i.e., $k_1 a_{\mathrm{esr}} \gtrsim 1$) can be estimated by the formula

$$\langle \sigma_{\mathrm{bs}} \rangle \simeq (\langle \sigma_{\mathrm{bs}}^{(m)} \rangle / \pi a_{\mathrm{esr}}^{(m)^2}) \pi a_{\mathrm{esr}}^2 \quad (k_1 a_{\mathrm{esr}} \gtrsim 1), \tag{1}$$

where the quantity in the parentheses represents the average of the backscattering cross section, $\sigma_{\mathrm{bs}}^{(m)}$, measured or modeled in the $k_1 a_{\mathrm{esr}}^{(m)} \gtrsim 1$ region, normalized by the measured/modeled geometric cross section of the body, $\pi a_{\mathrm{esr}}^{(m)^2}$ (this quantity in parentheses corresponds to the measured/modeled reduced target strength defined later). This quantity is an empirical or modeled scaling factor that relates $\langle \sigma_{\mathrm{bs}} \rangle$ to a_{esr}. The brackets $\langle \cdots \rangle$ denote an average over orientation and/or a narrow range of size or frequency so as to remove the dependence of $\sigma_{\mathrm{bs}}^{(m)} / \pi a_{\mathrm{esr}}^{(m)^2}$ upon $k_1 a_{\mathrm{esr}}^{(m)}$ that is related to various (narrow) resonances and directivity: although $\sigma_{\mathrm{bs}}^{(m)} / \pi a_{\mathrm{esr}}^{(m)^2}$ varies rapidly versus $k_1 a_{\mathrm{esr}}^{(m)}$ (and angle of orientation for nonspherical objects) in the geometric scattering region (i.e., $k_1 a_{\mathrm{esr}}^{(m)} \gtrsim 1$), $\langle \sigma_{\mathrm{bs}}^{(m)} \rangle / \pi a_{\mathrm{esr}}^{(m)^2}$ is relatively constant in this region which makes the below estimates convenient.

For a dense solid sphere, the independence of $\langle \sigma_{\mathrm{bs}}^{(m)} \rangle / \pi a_{\mathrm{esr}}^{(m)^2}$ with respect to $k_1 a_{\mathrm{esr}}^{(m)}$ for $k_1 a_{\mathrm{esr}}^{(m)} \gtrsim 1$ is apparent by examining the component of $\sigma_{\mathrm{bs}}^{(m)}$ due to the front interface. This component makes up a significant fraction of the echo for $k_1 a_{\mathrm{esr}}^{(m)} \gtrsim 1$ and is proportional to $a_{\mathrm{esr}}^{(m)^2}$ (and does not depend upon k_1). The total echo will vary with respect to $k_1 a_{\mathrm{esr}}^{(m)}$ due to interferences between different "partial" waves (e.g., circumferential waves). Once averaged over $k_1 a_{\mathrm{esr}}^{(m)}$, the structure due to the interferences is smoothed out and a relatively smooth curve remains that is proportional to $a_{\mathrm{esr}}^{(m)^2}$. This phenomenon has been demonstrated empirically with scattering by a large range of sizes of irregular scatterers and over a large range of frequencies. In a study by Thorne *et al.* (1995), the scattering of irregular solid elastic objects ranging in size (radii) from 50 μ to 2.5 cm were analyzed (the objects included sand grains and rocks) over a frequency range of 40 kHz to 5 MHz. The average echoes, based on an average over orientations, were plotted on the same figure (Fig. 9 of that paper) on a normalized scale. Plotted was form function (on a logarithmic scale) versus $k_1 a_{\mathrm{esr}}^{(m)}$, which is equivalent (to within some constants) to reduced target strength ($\mathrm{RTS}^{(m)}$ defined below) versus $k_1 a_{\mathrm{esr}}^{(m)}$. Also plotted was the exact modal series solution to a smooth sphere, averaged over size. There was little structure in the data and modal-series-based (averaged) solution for $k_1 a_{\mathrm{esr}}^{(m)} \lesssim 1$. In fact, for $k_1 a_{\mathrm{esr}}^{(m)} \lesssim 2$, the data and theory (normalized by $a_{\mathrm{esr}}^{(m)}$) were essentially independent of $k_1 a_{\mathrm{esr}}^{(m)}$. A similar independence (but of k_1 only) was observed in Stanton *et al.* (2000) involving elastic shelled animals, but involving only a single animal. Finally, a study has been published in which the echoes from randomly oriented shrimp were averaged (Stanton *et al.*, 1993). These scatterers are very elongated and possessed a strong directional scattering pattern. However, once averaged over orientation, the scattering was nearly independent of $k_1 a_{\mathrm{ecr}}^{(m)}$ for above about 3 ($a_{\mathrm{ecr}}^{(m)}$ is the equivalent *cylindrical* radius). Although data only involved a narrow range of sizes, the theory showed an independence of average reduced target strength upon $k_1 a_{\mathrm{ecr}}^{(m)}$ for high $k_1 a_{\mathrm{ecr}}^{(m)}$.

For an array of N similarly sized, random-phase scatterers on a section of the seafloor of area A, the ensemble average echo energy is proportional to

$$s_N = N\langle \sigma_{\mathrm{bs}} \rangle. \tag{2}$$

The quantity N is related to the area and packing factor $\mathcal{F}$ as

$$N = (A/\pi a_{\mathrm{esr}}^2)\mathcal{F}, \tag{3}$$

where $\mathcal{F}$, which is equal to the fraction of seafloor covered by the objects, is less than unity and the shape of the body is assumed not to deviate significantly from a sphere (i.e., not to be needlelike so that the equivalent spherical radius can be used here). The area scattering coefficient, which is proportional to the average scattered energy per unit area, is equal to

$$s_A = s_N / A. \tag{4}$$

Inserting the above expressions into Eq. (4) gives

$$s_A = (\langle \sigma_{\mathrm{bs}}^{(m)} \rangle / \pi a_{\mathrm{esr}}^{(m)^2})\mathcal{F}. \tag{5}$$

Expressing this in terms of logarithms for the sonar equation, the area scattering strength on a decibel scale is equal to

$$S_A = 10 \log s_A \tag{6}$$

Applying this to Eq. (5) gives

$$S_A = \langle \mathrm{RTS}^{(m)} \rangle + 10 \log \mathcal{F}, \tag{7}$$

where the average reduced target strength $\langle \mathrm{RTS}^{(m)} \rangle$ is defined by

$$\langle \mathrm{RTS}^{(m)} \rangle \equiv \langle \mathrm{TS}^{(m)} \rangle - 10 \log \pi a_{\mathrm{esr}}^{(m)^2} \tag{8}$$

and the average (free-field) target strength $\langle \mathrm{TS}^{(m)} \rangle$ is defined by

$$\langle \mathrm{TS}^{(m)} \rangle = 10 \log \langle \sigma_{\mathrm{bs}}^{(m)} \rangle. \tag{9}$$

Note that both $\langle \mathrm{TS}^{(m)} \rangle$ and $\langle \mathrm{RTS}^{(m)} \rangle$ here are based on averages of $\sigma_{\mathrm{bs}}^{(m)}$ over orientation and/or a narrow range of size or frequency which makes these averaged forms of $\mathrm{TS}^{(m)}$ and $\mathrm{RTS}^{(m)}$.

Equation (7) is a very interesting result, as it shows that for high $k_1 a_{\mathrm{esr}}$, the area scattering strength from a bed of discrete scatterers can be related to the sum of the average reduced target strength of one scatterer and the packing factor on a decibel scale. Note that it is similar to the first-order scattering term of the predictions by arrays of bosses published in Twersky (1957). Because of the scaling properties of the average reduced target strength, the term $\langle \mathrm{RTS}^{(m)} \rangle$ in Eq. (7) can be determined from a benthic animal of a different size than that in the bed provided that the scattering is in the geometric scattering region and that the animal is morphologically similar.

For a very simple case of scattering by a dense solid sphere (smooth round rock), the average backscattering cross section can be approximated in the high $k_1 a_{\mathrm{esr}}^{(m)}$ region as

$$\langle \sigma_{\mathrm{bs}}^{(m)} \rangle = \tfrac{1}{4} a_{\mathrm{esr}}^{(m)^2} \mathcal{R}_{12}^2, \tag{10}$$

where $\mathcal{R}_{12}$ is the reflection coefficient $[\mathcal{R}_{12} = (gh-1)/(gh+1)$, where g and h are the mass density and sound speed of the object, respectively, normalized by the corresponding quantities for the surrounding water]. This term represents the echo from the front interface which makes up much of the total echo [see, for example, Eq. (16) of Marston, 1988].

Inserting Eq. (10) into Eq. (7) gives

$$S_A = 10 \log(\mathcal{R}_{12}^2 / 4\pi) + 10 \log \mathcal{F}, \tag{11}$$

where now the expression for scattering strength has been reduced to depending only on the material properties and packing factor.

These simple equations, Eqs. (7) and (11), show that the acoustic scattering by arrays of random phase scatterers, such as on the seafloor, can be reduced to being related to the reflective properties of the scattering, $\mathcal{R}$ (or more generally, normalized cross section) and the packing factor. This formula is made simple, in part, because of the fact that the cross-sectional area dependence of the scattering was cancelled out in the calculation of number per unit area. Of course, the above formula is a very crude approximation and, at best, only applies near normal incidence. For shallow (near horizontal) grazing angles, shadowing effects will become important. Also, for all angles, scattering by the surrounding substrate seafloor material plays a role. Nonetheless, the above formulas can be useful for certain estimates.

In order to extend the results to other angles, the seafloor scattering is assumed to obey Lambert's law. In this approximate approach, the area scattering strength is expressed as

$$S_A(\theta_g) = 10 \log \mu + 10 \log \sin^2 \theta_g, \tag{12}$$

where θ_g is the grazing angle ($\theta_g = 90$ degrees is normal incidence) and $10 \log \mu$ is the scattering strength at normal incidence (Urick, 1983). This formula has proven to be useful in studies of scattering by the seafloor. For example, Stanic *et al.* (1989) showed that the scattering has followed this angular dependence for 5 degrees $\leqslant \theta_g \leqslant 30$ degrees. For accurate predictions over a wider range of angles and conditions, other approaches are required (see, for example, Jackson *et al.*, 1986a; Gensane, 1989; Ivakin, 1998). Equating the expressions for S_A in Eqs. (7) and (11) to the term $10 \log \mu$, Eq. (12) becomes

$$S_A(\theta_g) = \langle \mathrm{RTS}^{(m)} \rangle + 10 \log \mathcal{F} + 10 \log \sin^2 \theta_g, \tag{13}$$

$$S_A(\theta_g) = 10 \log(\mathcal{R}_{12}^2/4\pi) + 10 \log \mathcal{F} + 10 \log \sin^2 \theta_g, \tag{14}$$

respectively.

These formulas estimate the scattering as a function of grazing angle, in terms of the average reduced target strength of an individual target [Eq. (13)] or material properties [Eq. (14)] and the packing factor of the targets.

III. COMPARISON WITH SEAFLOOR SCATTERING DATA

There have been very few controlled experiments involving acoustic backscattering by the seafloor in regions where there is a significant presence of shells. Two such studies were published by Jackson *et al.* (1986a, b) and Stanic *et al.* (1989). In the Jackson *et al.* (1986a, b) studies, the acoustic scattering by the seafloor was measured as a function of grazing angle, acoustic frequency, and seafloor type. One of the seafloor types involved a bottom material that consisted of very fine sand with a dense covering of live shellfish. The scattering by the bed that contained the shellfish was elevated relative to the section of seafloor that contained sandy silt and no shellfish, indicating that the shellfish played a significant role in the scattering. In the studies by Stanic *et al.* (1989), the studies were focused entirely on a region where the seafloor was covered with shells and the acoustic scattering was measured as a function of grazing angle and acoustic frequency. Characterization of the shells was made possible through the use of samples collected at the site.

The above formulas are now directly applied to the above-mentioned seafloor scattering data. Although the size distribution of the shells was not presented in the Jackson *et al.* (1986a, b) papers, it is assumed for the purpose of this analysis that the scattering by the shells is in the geometric scattering region. For the frequencies of 20 to 50 kHz used in that study, the sizes of the shells would need to be at least about 1 cm long in order to be in the geometric scattering region for the lowest frequency. For the 4-mm- (mean) diam shells observed by Stanic *et al.* (1989), the frequencies need to be about 60 kHz or higher. Also, the shapes of the shells were not documented in either paper. Any differences between the shapes of the shells in the seafloor studies and those used as a basis of modeling the scattering is a potential source of error.

With the assumption that the shells are in the geometric scattering region, the expression given in Eq. (7) for area scattering strength can be used without detailed knowledge of the shell size. As discussed above, since the average reduced target strength in the expression based on an averaged backscattering cross section is relatively independent of size and frequency in the geometric scattering region, it is very convenient for use in this type of application. It is employed simply by using a typical value of the $\langle \mathrm{RTS}^{(m)} \rangle$ from the measurements from Stanton *et al.* (2000) of target strength of the periwinkles in the geometric scattering region. The average value of target strength at high $k_1 a_{\mathrm{esr}}^{(\mathrm{m})}$ of animal No. 97-1 was approximately -55 dB (Fig. 11 of that paper). Using an equivalent spherical radius of the animal to be 2.28 mm, the average reduced target strength of that animal at high $k_1 a_{\mathrm{esr}}^{(m)}$ is approximately -7 dB. Using a packing factor of about 0.8 for closed-packed circles, the estimated area scattering strength for near-normal incidence is -8 dB. This value should be considered an upper bound to the estimate of the scattering by the shells. The presence of shells that have sizes in the Rayleigh scattering region as well as any shadowing effects due to the dense packing of the shells will tend to reduce the estimated value of scattering. Nonetheless, when compared with the values of area scattering strength reported in Figs. 6 and 7 in Jackson *et al.* (1986b) for near-normal incidence, the estimated value of -8 dB lies within the range of observed values which range from about -10 dB to about -2 dB. Figure 21 of Stanic *et al.* (1989) consists of values of $10 \log \mu$ plotted versus frequency that were derived from best fits to data for 5 degrees$\leqslant \theta_g \leqslant$30 degrees. For frequencies above 60 kHz, their values of $10 \log \mu$ range from -22 to -10 dB. Thus, the estimated value of -8 dB using the simplistic discrete-target-based approach overestimates their maximum value of scattering by 2 dB.

IV. DISCUSSION AND CONCLUSION

As a result of recent extensive measurements and modeling of acoustic scattering by shelled animals, an estimate of the contribution of shelled animals to the scattering by a shell-covered seafloor was made possible. The estimate involved a simple formula that was derived herein which related the area scattering strength to the average reduced target strength or simply material properties and packing factor of the objects. The discrete-target-based estimate of scattering due to the presence of a dense covering of shells was close to or consistent with backscattering data from two different shell-covered seafloors. Furthermore, the discrete-target-based formula used in the estimates illustrated that for sufficiently high acoustic frequencies (i.e., in the geometric scattering region), the area scattering strength (at least near normal incidence) is generally independent of size and acoustic frequency and only depends upon material properties and packing factor. This set of dependencies, or lack thereof, is broadly consistent with much of the backscattering data involving the seafloor (shell-covered and otherwise as well as other angles of incidence) which generally show a weak dependence of scattering upon frequency and size of features.

While the measurements and modeling of the scattering by individual shelled animals provided a high-quality basis for the estimates of scattering by a shell-covered seafloor, the estimates were still far from rigorous. Clearly, a rigorous analysis would need to take into account, for example, multiple scattering of the shells, size and shape distribution of the shells, and scattering contributions due to the seafloor substrate. The results of these estimates show promise for incorporating discrete-target-based information into a more general model.

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