MODELING BISTATIC SURFACE SCATTERING STRENGTH INCLUDING A FORWARD SCATTERING LOBE WITH SHADOWING EFFECTS

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Abstract

Both the rough air-sea interface and entrapped air bubbles due to wave breaking scatter sound in all directions and contribute to so-called reverberation in active sonar. There are monostatic sonar systems where the source and receiver are at the same position, bistatic sonar systems where the source and receiver are separated, and multistatic sonar systems involving multiple sources and receivers at different positions. In monostatic situation, reverberation is mainly due to backscattering. In bistatic and multistatic situation, forward and out-of-plane scattering are significant contributors. The empirical Chapman-Harris formula is often used to predict surface backscattering strength in monostatic sonar. To better predict reverberation due to the sea surface in bistatic or multistatic sonar, a three-dimensional scattering formula that includes a forward scattering lobe will be desirable. Following the approach of earlier work, in this paper the separable form of backscattering models are extended by including an expression of forward scattering lobe obtained under the Kirchhoff approximation, taking into account shadowing effects. Comparison with another more sophisticated model shows that shadowing corrections are important at low grazing angles. The formula obtained here is simple and includes scattering effects from both the roughness of the sea surfaces and the sub-surface bubbles. It may be useful for modelling multistatic surface reverberations.

Introduction

Wind generates rough sea surfaces. Wave breaking under strong winds also produces entrained air-bubbles below the sea surface. Both roughness of the sea surfaces and the trapped air bubbles scatter sound from sonar and lead to surface reverberation.

Scattering occurs out-of-plane as well as within the vertical plane containing the source and receiver. Modelling active sonar reverberation from the sea surface requires assessment of the surface scattering strength, which is defined as the ratio in dB of the intensity of the scattered sound by a unit surface area referenced to a unit distance to the incident plane wave intensity. For monostatic sonar where the transmitter and receiver are co-located, the reverberation is mainly due to backscattering. For multistatic sonar where multiple transmitters and receivers are spatially distributed, there are additional contributions to the received reverberation from forward and out-of-plane scattering.

The empirical Chapman-Harris formula [1] of surface scattering strength is often used for modelling monostatic sonar performance and its separable form used for modelling multistatic configurations. However, to more accurately predict reverberation in multistatic ASW sonar systems, formulas for three-dimensional scattering are still desirable. Gauss and Fialkowski (2000) [2] presented a semi-empirical surface scattering strength (SESSS) model that combines incoherently scattering from the rough air-sea interface with scattering from the bubble clouds.

This work follows the approach in Ellis and Crowe (1991) [3] and Caruthers and Novarini (1993) [4] where backscattering models are extended by using the so-called separable approximation, and then combined with a term obtained under the Kirchhoff approximation for facet scattering to obtain a three-dimensional scattering function. We further modify the Kirchhoff facet term using the shadowing factor in Torrance and Sparrow (1967) [5] and compare the results with those of Gauss and Fialkowski (2000) [2].

Due to the empirical nature of the backscattering models, the expression obtained here includes the effects of both the roughness of the sea surfaces and the sub-surface bubbles. The formula is simple to use in multistatic active sonar performance models.

Chapman-Harris Backscattering Model

Based on measurements using explosives, Chapman-Harris (1962)[1] give the following empirical fit to measured surface backscattering strength (BS) for wind speeds 0-30 knots and frequencies 400 to 6400 Hz,

$$\begin{aligned} BS_{\mathrm{CH}} &= 3.3\beta\log_{10}(\theta/30) - 42.4\log_{10}\beta + 2.6 \\ \beta &= 107(Uf^{1/3})^{-0.58} \end{aligned} \tag{1}$$

Where θ is grazing angle in degrees, U is wind speed in m/s, and f is frequency in Hz.

By its empirical nature, the Chapman-Harris model includes scattering effects from both the roughness of the sea-surface and the subsurface bubble clouds. Eq. (1) can be written in linear form,

$$b(\theta) = 10^{2.6}\beta^{-42.4}(\theta/30)^{3.3\beta} \tag{2}$$

Three Dimensional Surface Scattering Function

Following Ellis and Crowe (1991) [3] and Caruthers and Novarini (1993) [4], we extend the Chapman-Harris backscattering formula b(θ) of Eq.(2) to three-dimension by the following formula

$$\begin{aligned} S(\theta_i,\theta_s,\phi) &= [b(\theta_i)b(\theta_s)]^{1/2} + D(\theta_i,\theta_s)F(\Delta\Omega) \\ F(\Delta\Omega) &= (8\pi\delta^2)^{-1}(1+\Delta\Omega)^2 \exp\left(-\frac{\Delta\Omega}{2\delta^2}\right) \\ \Delta\Omega &= (\cos^2\theta_i + \cos^2\theta_s - 2\cos\theta_i\cos\theta_s\cos\phi)/(\sin\theta_i + \sin\theta_s)^2 \end{aligned} \tag{3}$$

Where θ_i, θ_s are the incident and scattered grazing angles, ϕ is the scattered azimuthal angle relative to the incident plane, $\Delta\Omega$ is a measure of the deflection of the scattering angle from the specular angle, δ is the root-mean-squared slope of the rough sea surface, which can be approximated by the empirical expression of Cox and Munk (1954) [6],

$$\delta^2 = 0.003 + 5.12\times10^{-3}U \pm 0.004 \tag{4}$$

The first term $[b(\theta_i)b(\theta_s)]^{1/2}$ in Eq. (3) represents so-called separable approximation to the backscattering model $b(\theta)$, the term $F(\Delta\Omega)$ represents a forward scattering lobe from Gaussian-distributed facets under the Kirchhoff approximation (also called the method of tangent plane approximation)[7] [8], the function $D(\theta_i,\theta_s)$ accounts for shadowing effects on the forward scattering lobe and is discussed below.

The Shadowing Factor

Adjacent facets may obstruct sound incident upon a given facet or the sound reflected by it. This masking and shadowing effect is especially important at low grazing angles. To account for this effect, we adopt the approximate shadowing factor in Torrance and Sparrow (1967) [5],

$$\begin{aligned} D(\theta_i,\theta_s) &= \min\left(1, \frac{2\cos\alpha\sin\theta_s}{\cos\theta_i'}, \frac{2\cos\alpha\sin\theta_i}{\cos\theta_i'}\right) \\ \theta_i' &= (1/2)\cos^{-1}(\sin\theta_i\sin\theta_s - \cos\theta_i\cos\theta_s\cos\phi) \\ \cos\alpha &= \sin\theta_i\cos\theta_i' + \cos\theta_i\sin\theta_i'\cos(\sin^{-1}(\cos\theta_s\sin\phi/\sin 2\theta_i')) \end{aligned} \tag{5}$$

This shadowing factor is derived using the assumption that each facet is one side of a V-groove cavity, and sound rays only reflect once (i.e. multiple scattering is ignored).

For backscattering, $\theta_i = \theta_s, \phi = \pi$, the shadowing factor is unity.

NRL Bistatic Surface Scattering Model

The Semi-Empirical Surface Scattering Strength (SESSS) model of Naval Research Laboratory [2] is based on the incoherent summation of scattering from near surface bubbles and scattering from the rough air-sea interface. Scattering from near surface bubbles is described by a bistatic extension obtained from consideration of convolution of Lloyd-mirror patterns with an empirical void-fraction profile. Scattering from the rough air-sea interface is approximated by Bragg scattering from an isotropic, power-law roughness spectra under the small slope approximation.

Results

Backscattering

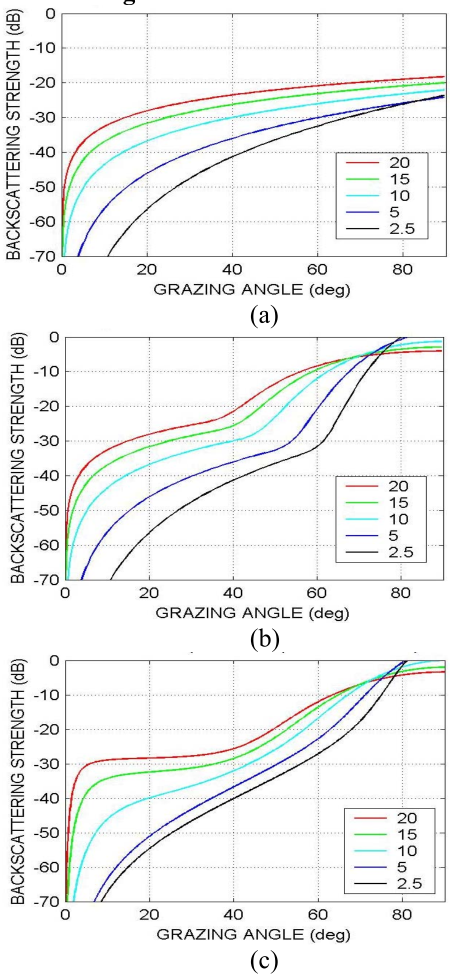


Fig. 1. Surface backscattering strength at 1500 Hz for wind speeds from 2.5 m/s to 20 m/s. (a) Chapman-Harris model (b) Chapman-Harris model plus Kirchhoff facet scattering, (c) SESSS model of NRL.

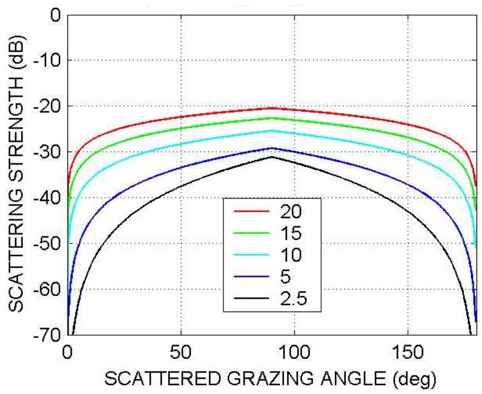
Fig. 1 show results of comparison of the surface backscattering strength for wind speeds from 2.5 m/s to 20 m/s at an acoustic frequency of 1500 Hz. At low grazing angles, scattering from bubble-clouds dominates when wave breaking is significant. At high grazing angles, scattering is mainly due to the surface roughness.

We can see that the Chapman-Harris model plus the diffuse scattering lobe is closer to the results from the SESSS model of NRL. However, there are appreciable differences between the two.

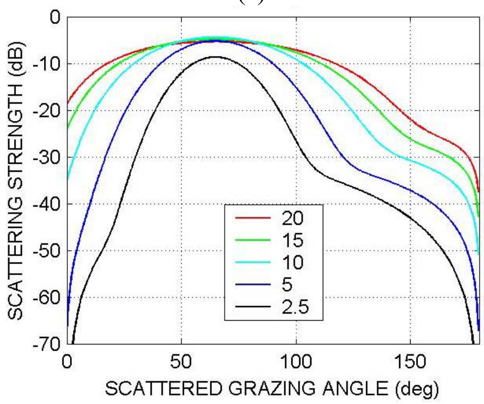
We note that the empirical parameters in the semi-empirical SESSS model and the original Chapman-Harris model are fitted using different data sets. It may be possible to obtain better agreements between the Chapman-Harris model with Kirchhoff scattering lobe and the SESSS model if the empirical parameters of the original Chapman-Harris model were re-fitted using the same data set as that used for the SESSS model.

Bistatic Scattering

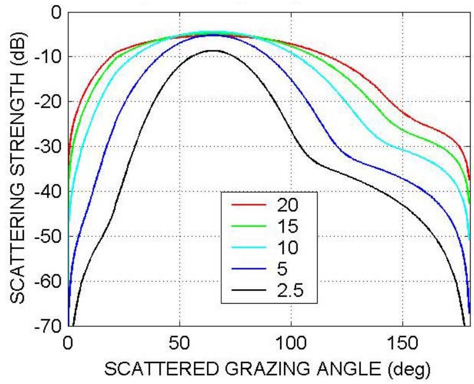
Fig. 2 shows results of comparison of the BISTATIC surface scattering strength for wind speeds from 2.5 m/s to 20 m/s at an acoustic frequency of 1500 Hz. We can see that the shadowing factor improved the agreement at low grazing angles between the Chapman-Harris model with forward scattering lobe and the SESSS model.



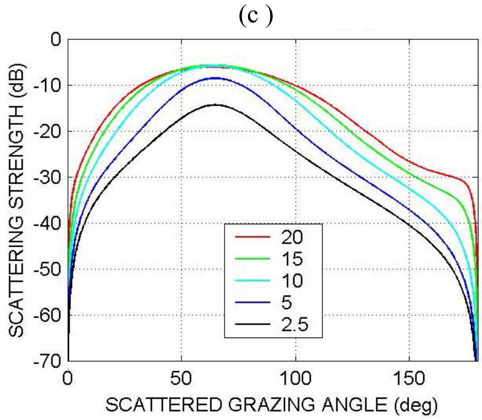
(a)



(b)



(c)



(d)

Fig. 2. Bistatic surface scattering strength versus scattered grazing angle at 1500 Hz for an incident grazing angle of 45 degrees and azimuthal angle of 45 degrees. The different colour lines correspond to wind speeds from 2.5 m/s to 20 m/s. (a) Separable approximations of Chapman-Harris model (b) Separable approximations of Chapman-Harris model plus Kirchhoff facet scattering; (c) Separable approximations of Chapman-Harris model plus Kirchhoff facet scattering with shadowing effects; (d) SESSS model of NRL.

Summary

A simple expression for multistatic surface scattering strength was compared with a semi-empirical NRL model. The expression is based on a combination of separable forms of empirical backscattering models with facet scattering under the Kirchhoff approximation. Geometrical shadowing effects of the facets are accounted for by using a separate loss factor.

Three-dimensional scattering data from carefully controlled measurements are needed to ascertain the accuracy of the expression.

The simple expression is 3-D and includes the effects of both the rough air-sea interface and sub-surface bubbles. It may be useful as a sub-model for modelling reverberation in multistatic sonar.

Future work may include improving the shadowing factor [9] and considering other backscattering models such as those in Ogden and Erskine [10,11,12].

References

[1] R.P. Chapman and J. H. Harris," Surface backscattering strengths measured with explosive sound sources," J. Acoust. Soc. Am. 34, 1592–1597 (1962).

[2] R.C. Gauss and J.M. Fialkowski, "A Broadband Model for Predicting Bistatic Surface Scattering Strengths," in Proceedings of the Fifth European Conference on Underwater Acoustics, edited by M.E. Zakharia et al., 10-13 Jul. 2000, Lyon, France (European Commission, Luxembourg, 2000), Vol. 2, pp. 1165-1170.

[3] Dale D. Ellis and D. Vance Crowe, "Bistatic reverberation calculations using a three-dimensional scattering function," J. Acoust. Soc. Am., Vol. 89, 2207--2214 (1991).

[4] J. W. Caruthers and J.C. Novarini, "Modeling bistatic bottom scattering strength including a forward scattering lobe", IEEE J. Oceanic Eng, 18, 100-107 (1993).

[5] K. Torrance and E. Sparrow, " Theory for off-specular reflection from roughened surfaces," J. Opt. Soc. Am. No.57, pp. 1105-1114, (1967).

[6] C.S. Cox and W.H. Munk, "Statistics of the sea surface derived from sun glitter," J. Marine Res., 13, 198–227, (1954).

[7] L.M. Brekhovskikh and Yu. Lysanov, Fundamentals of Ocean Acoustics, 3rd ed. (Springer-Verlag, Berlin, 2003).

[8] A. Ishimaru, *Wave Propagation and Scattering in Random Media* (Academic, New York, 1978), Vol. 1 &2.

[9] E. I. Thorsos, "The validity of the Kirchhoff approximation for rough surface scattering using a Gaussian roughness spectrum," J. Acoust. Soc. Am. **83**, 78–92 (1988).

[10] P.M. Ogden and F.T. Erskine, "Surface scattering measurements using broadband explosive charges in the Critical Sea Test experiments," J. Acoust. Soc. Am. 95, 746-761 (1994).

[11] P.M. Ogden and F.T. Erskine, "Surface and volume scattering measurements using broadband explosive charges in the Critical Sea Test 7 experiment," J. Acoust. Soc. Am. 96, Pt. 1, 2908-2919 (1994).

[12] M. Nicholas, P.M. Ogden and F.T. Erskine, "Improved empirical descriptions for acoustic surface backscatter in the Ocean", IEEE J. Oceanic Engr., 23, 81-95(1998).