SEABED VOLUME SCATTER DEPENDENCE ON DIFFICULT-TO-MEASURE PARAMETERS

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Backscatter from the seabed can, for certain sediment types, frequencies and angles, be dominated by volume scatter from within the seabed. In the frequencies above about 100kHz, the penetration is small and gross layering within the seabed is not of concern. However, the scatter from the volume at these shallow depths is determined by the inhomogeneities in the sediment properties, in particular their correlation structure. The sensitivity of the backscatter to the spatial correlation structure of the scatterers is highlighted in this paper.

INTRODUCTION

The scatter of sound from the seabed can be divided by frequency and angle range and by nature of the seabed. Scatter occurs when there are departures in local properties from average values. The main contrast is of course between seawater and the seabed. This is usually seen as a discontinuous change in the product of sound speed and density. The roughness of this interface together with the ρc contrast cause scatter. The roughness is on all scales but the important scales are those which occur within the relevant sonar footprint. Within the seabed there are departures from uniformity, again on all scales, the important ones being related to both footprint and penetration depth. The penetration of acoustic waves into the seabed is usually measured in wavelengths. Absorption effects are in the order of 0.1 to 0.5 dB per wavelength of travel. Thus in the lower kHz frequency range the penetration in metres into the seabed is significant and the layering structure becomes increasingly important. Such structures naturally give rise to frequency selective behaviour. It is not the intention here to discuss the frequency dependence of scatter due to layering effects; the emphasis is directed towards mine hunting frequencies. That is 100kHz and above for proud mines. As mine hunting involves low grazing angles of incidence, penetration of sound into the seabed is further restricted by critical angle effects. In order to insonify buried mines, frequencies in the lower kHz range are required. At the low grazing angles relevant to this activity, layer effects are not significant in general.

Below 100kHz the modeling of acoustic backscatter from the seabed is well established. Provided the seabed parameters are available there is reasonable agreement between theory and experiment. In the case of soft seabeds the volume scatter from within the seabed is accounted for by an adjustable parameter. In a similar way that the seabed interface roughness spectrum influences the frequency dependence of the interface scatter, so the correlation structure of the scatterers within the seabed volume determine the volume backscatter from soft sea beds. Gradients in seabed properties near the interface with the water can cause surprisingly high frequency dependent volume scatter from soft seabeds especially as the frequencies exceed 100kHz.

1. FREQUENCY DEPENDENCE OF SEA-BED BACKSCATTER

In 1964 a now classic paper[1] appeared, addressing the frequency and grazing angle dependence of seabed scatter in the frequency range of interest here. Conclusions were drawn that for most of measurements in soft sediments the backscatter tends to increase with frequency, but at a slow rate with the proviso that scattering patches are comparable to the wavelengths involved.

In Lyons et al (1994)[2] a good description of the state of interface scatter is given. Lyons' modeling work builds on the Jackson composite roughness model and the work of Hines to include specific scatter mechanisms. Lyons also addresses the presence of sub-bottom interfaces as his work is to be compared to 6 .5kHz Gloria data. Included in the many parameters needed are the vertical and horizontal correlation lengths of the density fluctuations in the sediment. The vertical correlation values are relatively easily available from cores but the horizontal correlation values were left as a free parameter. He concludes that the model of Jackson et al (1986)[3] with the addition of scattering from sub-bottom interfaces and scattering from random inhomogeneous continuums adequately agrees with the Gloria 6.5kHz data that was available.

The work of Jackson and others is summarised in the same year (1994) in the first issue of the APL-UW Handbook[4]. Chapter IV deals specifically with scatter from the seabed based on the composite roughness model. For detailed background to the composite roughness model some of the many references included[4] therein are quoted here[5,6,7,8,9]. The report defines nine generic sea bottom types and presents tables of scattering strengths for these as a function of angle, and frequency (10kHz-100kHz). The statistics of backscatter are absent from the model although the relation of pulse length to feature scale affects the statistics of the backscatter. If the bandwidth is large the pulse will tend to see the features and produce event like returns leading to more time spent at extreme amplitudes. For long pulses many features are seen and the Rayleigh like behaviour occurs due to large enough number of scatterers[10].

A comment is made in the report[4] that data suggests that the top few-centimetre-layer has significant gradients in its porosity hence in its density, with weaker gradients in sound speed and attenuation. Long wavelength waves do not see the gradient but short wavelength waves see only it, which has implications for the frequency dependence. The APL-UW model does not include this. Currently some significant progress is being made in this area by Pouliquen[11,12].

2. VOLUME DEPENDENCE

Volume scatter from within the seabed is important in softer sediments at high frequencies over a significant range of grazing angles. This is evidenced by the analysis of data from Jackson et al [3,8].

In the composite roughness model[4] the volume scatter coefficient is treated as a single parameter whose value is adjustable to bring experiment into coincidence with theory. This is advantageous from the point of view of lack of knowledge of the seabed parameters; in essence it may be seen as an approach to measuring the volume scatter coefficient. As it is, the number of parameters required by the composite roughness model is six. To describe the sediment volume scatter coefficient, assuming its origin lies in the spatial porosity variations, would require an extra three parameters at least. These are the variance of the porosity fluctuations and the horizontal and vertical correlation lengths of these fluctuations. Such quantities are hard to measure even in a research environment.

The contribution of volume scatter to the overall seabed backscatter[3,8] can be significant. There are more examples from the recent literature[11,12] in which the role of the measured gradient in seabed properties close to the interface together with actual measurements of porosity variance and correlation structure are examined.

The opportunities for frequency dependencies to emerge from seabed volume scatter are several. The scatterers lie within a medium whose acoustic attenuation is frequency dependent. They also lie beneath a refracting interface for which the refractive index is complex due both to the presence of absorption and in some instances due to the existence of a critical angle[13]. The existence of a gradient in properties together with the correlation structure of the scatterers introduces frequency dependence. The correlation lengths can be quite different in the vertical and horizontal directions due to sediment depositional factors.

There are several references[11,14,15,16,17] in which specific expressions for the equivalent surface scatter coefficient due to volume scatter are presented. These mainly differ is how the effect of a refracting interface on spreading loss is introduced particularly near critical angles.

The backscatter coefficient due to volume scatter, expressed as an equivalent surface scatter is[18]

$$m_s = \frac{|T_{01}|^4 m_v}{m^2} \int_0^\infty \frac{\exp(4\mathrm{real}(\mathrm{i}k_1 \cos\theta_1 z))}{|A(z)|} dz \qquad (1)$$

The quantities are defined in the Appendix. (The quantity A contains the observer height h above the interface. For the examples presented below, the value of m_s is effectively independent of h for h>50 wavelengths) and the volume scatter coefficient is

$$m_v = 2\pi k_1{}^4 Q G_p(2k_1) \qquad (2)$$

It is mainly through the power spectrum G of the porosity fluctuations that the different dependencies on frequency emerge. For example if the porosity structure is isotropic with an exponential correlation function with correlation length a, then

$$G(2k_1) = \frac{1}{16\pi^2 k_1{}^4 a} \qquad (3)$$

However, if the porosity structure is anisotropic with an exponential correlation function which has correlation lengths a and b, different in the horizontal and vertical directions then

$$G(2k_1) = \frac{1}{2\pi^2 k_1} \frac{a}{\left(1 + 4k_1{}^2 a^2 \cos^2\theta_1\right)} \frac{b^2}{\left(1 + 4k_1^2 b^2 \sin^2\theta_1\right)^{3/2}} \qquad (4)$$

These expressions for G were derived in[18] but do occur in several places in the literature[11,14]. The vertical correlation structure is available from cores but few[11,15] direct measurements of correlation lengths have been made.

3. EXAMPLE PREDICTIONS AND DISCUSSION

In order to emphasise the sensitivity of m_s to the correlation structure an example is given in Figure 1 using experimental data from Porto Vernere and Punta della Mariella[11], a soft sediment areas where volume scatter is expected to dominate. Plots are given for backscatter coefficients as functions of frequency and angle. The difference in assuming isotropic and anisotropic exponential correlation structure can be remarkable.

For the isotropic case, the correlation function is taken as exponential and given by

$$B(\tau) = \exp\left(-\left|\sqrt{x^2+y^2+z^2}\right|/a\right) \qquad (5)$$

whilst for the anisotropic case the correlation function is exponential in orthogonal directions

$$B(\tau) = \exp\left(-\left|\sqrt{x^2+y^2}\right|/a\right)\exp\left(-|z|/b\right) \qquad (6)$$

In the plots the values of the correlation lengths a and b are equal as detailed in Table (1). If a=b then why are the results so different between the isotropic and anisotropic cases? The images presented in Figure 2 are designed to help the understanding. Here simulated plots of porosity sections of the seabed are shown together with the corresponding power spectrum G(k). Although the differences in the porosity sections when a=b is visually slight the power spectra G are quite different, and it is G that, for a fixed correlation length a(=b) and a given k, determines the differences in the angular dependence of the backscatter. For example if |k| is small there is no great difference between the spectra over angle but for larger |k| there is an increase in emphasis of backscatter both at small angles of incidence and also at large angles of incidence. The frequency dependence of backscatter due to volume scatter as predicted by equation (1) for the isotropic correlation function is, as seen in Figure(1), modest and not a noticeable function of angle above critical angle. However, when the anisotropic correlation function is assumed, even with a=b, the frequency dependence can be strong and can even reverse its trend as a function of angle. The increase in the power spectrum for the anisotropic case at grazing angles for higher values of |k| combats the sharp reduction as the critical angle is passed.

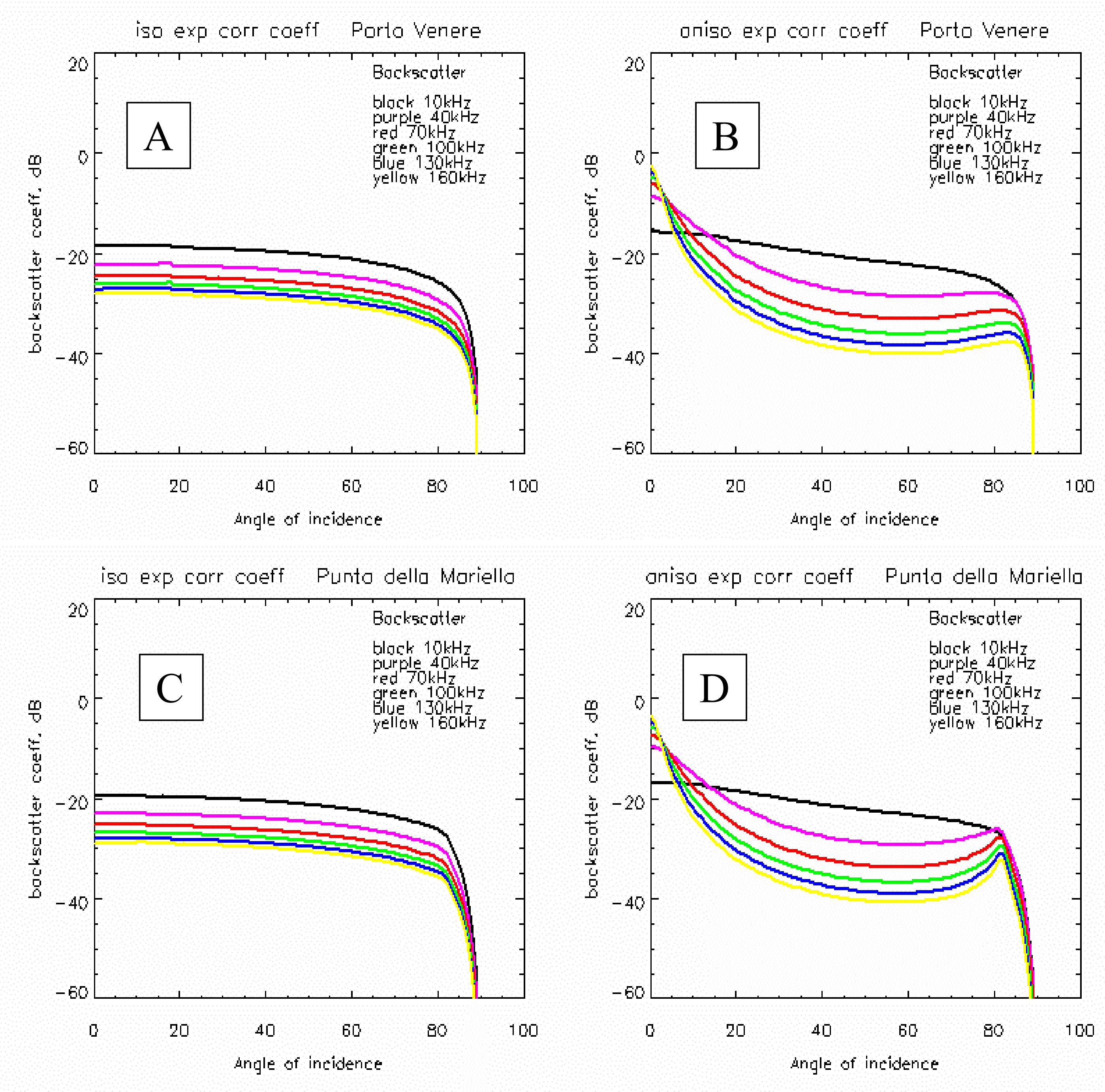

Fig.1 Backscatter coefficient using Equation (1) is plotted versus angle of incidence for frequencies from 10kHz to 160kHz in increments of 30kHz. Data from two sites are used, namely Porto Venere and Punta della Mariella, as listed in Table 1. These are both sites of soft sediments and volume scatter is expected. Measurements[11] have indicated an exponential correlation function for the density fluctuations. In (A) and (C) an isotropic exponential correlation is assumed whereas in (B) and (D) an anisotropic exponential correlation is assumed with a=b. (see equations (5) and (6)) The predictions of backscatter here in (A) and (C) are in good agreement with measurements[11]

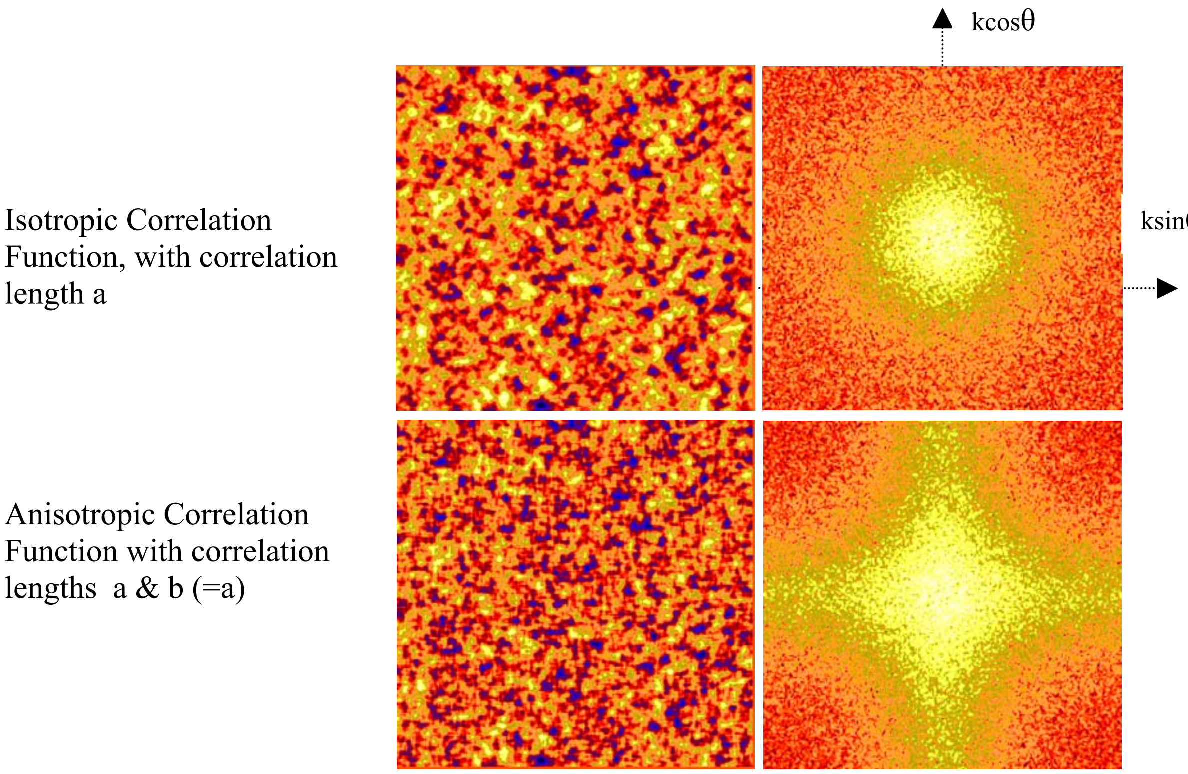

Fig.2 On the left are simulated vertical sections of spatial porosity images in which the porosity variations are correlated with either an isotropic exponential function or with an anisotropic exponential correlation function. On the right are the corresponding power spectra

4. CONCLUSIONS

The contribution of volume scatter to the overall seabed backscatter is recognized as potentially significant, particularly for soft sea beds in mid range angles. However unlike the interface roughness, the power spectra for the spatial distribution of scatter centres is difficult to measure and there is little information at the scale demanded of mine hunting sonar frequencies. Recent evidence[11,12] supports the isotropic exponential model. However, as demonstrated in this report, small changes in the spatial structure of the scatterers leads to significantly different behaviour both with angle and frequency. As a speculation it seems that at the small penetration depths which pertain at the higher MCM frequencies, bioturbation may well ensure that the isotropic distribution is more likely. At the lower kilohertz frequencies employed for buried mine hunting, the anisotropic effects of depositional modes may well play an increasing role.

	Porto Venere (11)	Punta della Mariella (11)
Water density, kg/m^3	1000	1000
Water velocity, m/s	1495	1515
Seabed density kg/m^3	1500	1700
Seabed velocity m/s	1490	1530
Attenuation db/wavelength	0.066	0.14
dc/dP m/s	*-570*	*-570*
dρ/dP kg /m^3	*-1440*	*-1440*
Porosity variance ΔP^2	0.002	0.0039
$Q/\Delta P^2$	*1.8*	*1.5*
Vertical correlation m	0.02	0.0075
Horiz correlation m	0.02	0.0075
Start freq kHz	120	120
Finnish freq kHz	170	170
Increment freq kHz	10	10
Start graz angle deg	5	5
Finish grazing angle deg	80	80

$$Q/\Delta P^2 = \frac{1}{c_0}\frac{\partial c}{\partial P} + \frac{1}{\rho}\frac{\partial \rho}{\partial P} \quad \text{where P is porosity}$$

Tab.1 Values used in demonstrating the sensitivity of m_s to correlation structure

T_{01}	Pressure transmission coefficient, water to seabed
m_v	Volume backscatter coefficient
k_1	Wavenumber in seabed
θ_1	Angle of refraction
θ	Angle of incidence
z	Depth into seabed from interface
A	$A = \left(1 + \frac{z}{nh}\frac{\cos\theta}{\cos\theta_1}\right)\left(1 + \frac{z}{nh}\frac{\cos^3\theta}{\cos^3\theta_1}\right)$
Q	$Q/\Delta P^2 = \frac{1}{c}\frac{\partial c}{\partial P} + \frac{1}{\rho}\frac{\partial \rho}{\partial P}$ where P is porosity
m	ρ_1/ρ, density ratio seabed to water
n	c/c_1, sound speed ratio, water to seabed
h	Height of measurement point above seabed

Tab.2 List of symbols

REFERENCES

[1] C.M.McKinney, C.D.Anderson, Measurements of backscattering of sound from the ocean bottom, , J.Acoust. Soc.Amer. **36**,158-163,(1964)

[2] A.P.Lyons, A.L.Anderson, F.,S.Dwan, Acoustic scattering from the seafloor: Modeling and data comparison J.Acoust.Soc.Amer. 95,2441-2451, (1994)

[3] D.R.Jackson, D.P.Winebrenner, A.Ishimaru Application of the composite roughness model to high frequency bottom backscattering, J.Acoust.Soc.Amer. 79,1410-1422,(1986)

[4] High Frequency Ocean Environmental Acoustics Models Handbook, APL-UW Technical Report TR 9407, Oct 1994

[5] D.R.Jackson, D.P.Winebrenner, A.Ishimaru Application of the composite roughness model to high frequency bottom backscattering, , J.Acoust.Soc.Amer.79,1410-1422,(1986)

[6] D.R.Jackson,A.M.Baird, J.J.Crisp, P.A.G.Thomson , High frequency bottom backscatter measurements in shallow water, , J.Acoust.Soc.Amer. 80,1188-1199,(1986)

[7] P.D.Mourad, D.R.Jackson, High frequency sonar equation models for bottom backscatter and forward loss Proc Oceans'89, IEEE NY 1168-1175, (1989)

[8] D.R.Jackson, K.B.Briggs, High frequency bottom backscatter: Roughness versu sediment volume scatterin, , J.Acoust.Soc.Amer. 92, 962-977,(1992)

[9] P.D.Mourad, D.R.Jackson, A model/data comparison for low frequency bottom backscatter J.Acoust.Soc.Amer. 94,344-358, (1993)

[10] V. Lupien, The role of scale structure in scattering from a random rough surface JASA 105, 2187-2202 ,(1999)

[11] E.Pouliquen, A.P.Lyons, N.G.Pace, T.H.Orsi, E.Michelozzi, L.Muzi, P.A.G.Thomson, Backscattering from unconsolidated sediments above 100kHz, Proc 5th ECUA, Lyon, France (2000)

[12] E.Pouliquen, A.P.Lyons, Backscattering from bioturbated sediments at very high frequencies, IEEE Oceanic Eng. 27, 388-402, (2002)

[13] The existence of a critical angle is precluded by the presence of attenuation. The attenuation ensures that all angles of refraction are complex. However it is useful to refer to the critical angle as a dividing angle between regions in which the intensity vector of the refracted wave has a significant vertical component and those regions in which the refracted wave intensity travels mainly parallel to the interface.

[14] M.Gensane Sea-bottom reverberation: the role of volume inhomogeneities of the sediment, , Ocean Reverberation, Ed.D.D.Ellis, 59-64, Kluwer,(1993)

[15] T.Yamamoto, Acoustic scattering in the ocean from velocity and density fluctuations in the sediments, , J.Acoust.Soc.Amer. 99,866-879, (1996)

[16] A.N.Ivakin, High frequency scattering from heterogeneous seabeds, , Proc 5th ECUA Lyon, France 1241-1246, (2000)

[17] P.C.Hines, Theoretical model of acoustic backscatter from a smooth seabed, , J.Acoust.Soc.Amer. 88,324-334, (1990)

[18] N.G.Pace, http://staff.bath.ac.uk/pysngp/ The derivation of the expression may be found here together with the derivation of an equivalent expression for the bistatic scatter coefficient due to volume inhomogeneities.