SIGNAL PROCESSING FOR WIDE-BEAM NORMAL INCIDENCE SEDIMENT CLASSIFICATION

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1. INTRODUCTION

The acoustic reflection coefficient is a parameter that can be used to classify ocean sediments. It is essentially a plane wave concept. In practice, it is approximated by a narrow beam spherical wave. Generally, the narrower the beam the better the approximation. Typically, beamwidths less than 10° are considered acceptable. This paper is a quantitative study of the effects of beamwidth on the determination of ocean sediment acoustic reflection coefficients. In this respect the title is a little misleading because this is really a precursor to the development of signal processing techniques. Expressions for the coherent and incoherent components of the acoustic signal are described, without complete derivations. The results for two representative cases, a sand and a mud bottom, are shown. The effect of beamwidth on the echo-to-reverberation ratio, of the surface reflection and of subbottom interfaces, is illustrated. The feasibility of compensating for poor directivity by decreasing the height of the sonar above the bottom is examined and found to be limited. It is concluded that signal processing efforts should be directed towards increasing directivity.

2. THEORY

A number of theoretical models of ocean sediment scattering already exist. Early work by Eckart[1] models the scattering of plane waves on a rough surface. According to Eckart, the echo from a rough surface is reduced relative to that from a smooth surface by $8.68(k\sigma)^2$ decibels, where k is the wavenumber and σ the r.m.s. surface roughness. Stanton[2,3] has shown a relationship between the probability density function of the echo level and the r.m.s. roughness. These models are essentially plane wave models. It is implicitly assumed that, in practice, the behavior of a narrow beam signal will adequately approximate that of a plane wave. Using the plane wave approximation, LeBlanc, Schock and Panda[4] and Lambert[5] have studied the correlation between the acoustic data and sediment geology. A quantitative analysis of the effect of sonar beamwidth and height above bottom on the quality of the acoustic data would lead to a better understanding of sediment classification performance of practical systems.

The hypothesis is that sonar height and beamwidth have an effect on the signal-to-reverberation level, where signal is defined as the coherent reflection from the sediment surface and subbottom interfaces, and reverberation is defined as the incoherent scattered signal due to sediment surface roughness and sediment volume inhomogeneities.

The problem is illustrated in Fig. 1. Consider a sonar at a height h above the bottom. The signal consists of a reflection of intensity I_r from the water sediment interface, and one or more additional reflections I_i from subbottom interfaces, which arrive at discrete intervals after the transmission. The reverberation consists of sediment surface I_s and volume I_v scattering components. At any instant, the insonified surface and volume regions are bounded between the surfaces of two approximately spherical surfaces separated by half a pulse length ($c\tau/2$), where c is the sound speed and τ is the pulse duration.

Given a source intensity at unit distance of I_o, the echo from the sediment interface at time t is given by,

$$I_o(t) = I_o \frac{|R_o|^2 e^{-4\alpha h}}{(2h)^2} e^{-2k^2\sigma^2} \quad , \; 2h/c < t < \tau + 2h/c \; ;$$

$$= 0 \, , \qquad \text{otherwise} \qquad (1)$$

where τ is the pulse length, k is wave number in water, R_o is the reflection coefficient at normal incidence, α the attenuation coefficient in water, and σ the r.m.s. surface roughness. The echo from a smooth subbottom layer of equal reflectivity is given by

$$I_i(t) = I_o \frac{|V_o|^4 |R_o|^2 e^{-4\alpha h - 4\alpha_s d_i}}{(2h + 2d_i)^2} e^{-2(k - k_s)^2\sigma^2} \, , \; 2(h/c + d_i/c_s) < t < \tau + 2(h/c + d_i/c_s) \; ;$$

$$= 0 \, , \qquad \text{otherwise} \qquad (2)$$

where k_s, c_s and α_s refer to the wavenumber, sound speed and attenuation coefficient in the sediment, d_i is the depth of the interface below the surface, and $|V_o|^2$ the energy transmission coefficient through the surface at normal incidence.

Assuming the volume scattering cross section per unit volume σ_v to be constant, the volume scattering term is an integral of the contributions over the insonified volume. With reference to Fig.1, the volume scattering element at range r and time t is given by,

$$dI_v(t,r) = I_o \left|\phi(\theta)\right|^4 \frac{|V|^4 \sigma_v \, e^{-\alpha_s c_s t - 2(\alpha - \alpha_s c_s/c)\sqrt{h^2+r^2}}}{(ct/2)^2} 2\pi r \, dr \, dt \; , \quad \frac{\sqrt{h^2+r^2}}{c} < t \; ;$$

$$= 0 \, , \; \text{otherwise} \qquad (3)$$

where the incidence angle θ is defined as $\theta = \arctan(r/h)$, $\phi(\theta)$ is the directivity function of the transducer, and $|V|^2$ the energy transmission coefficient through the surface.

The total volume scattering component as a function of time t is given by,

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$$I_v(t) = \int_{t}^{t+\tau} \int_0^{\infty} dI_v(t_1,r)\, dt_1\, dr \tag{4}$$

For a circular transducer of radius a, the directivity function is given by,

$$\phi(\theta) = \cos^2(\theta/2)\, \frac{J_1(ka \sin\theta)}{ka \sin\theta} \tag{5}$$

The model for the surface scattered component is not quite as simple, because the scattering cross section per unit area σ_s is known to be dependent on the angle of incidence. It may vary significantly over the range of the anticipated angles. The roughness scattering model for ocean sediments by Jackson, Winebrenner and Ishimaru[6] and Mourad and Jackson[7], based on the composite roughness scattering theory for sea surface scattering by McDaniel and Gorman[8], is the most current. The composite roughness scattering theory is applicable only at incidence angles greater than 30°. At normal and near normal incidence, the Kirchoff theory is used. The gap between the two theories is filled by interpolation. Since this study is particularly sensitive to the backscattering from the range of angles that often fall between these two theories, a more unified theory is needed.

With reference to Fig. 2, the elemental pressure due to surface roughness scattering may be expressed as,

$$dp_s(x,y,t) = \frac{jk\rho c\, R(\theta)\, \phi(\theta)\, \cos(\theta) e^{(jk - \alpha)ct - (k\sigma \cos(\theta))^2} (e^{-2jkz\cos(\theta)} - 1)}{2\pi(x^2+y^2+h^2)}\, dx\, dy\,, \quad (t+\tau)c > 2\sqrt{x^2+y^2+h^2} > tc$$

$$= 0\ , \text{ otherwise} \tag{6}$$

where the surface height z is a stochastic function of horizontal position (x,y). The total pressure is expressed as,

$$p_s(t) = \int_S dp_s(x,y,t)\, dxdy \tag{7}$$

where S represents the insonified region in the x-y plane at time t, defined by

$$(t+\tau)c > 2\sqrt{x^2+y^2+h^2} > tc\ .$$

The intensity is given by the ensemble average <..> of the pressure magnitude squared,

$$I_s(t) = \langle | p_s(t) |^2 \rangle / \rho c \qquad (8)$$

3. RESULTS

Two types of sediment were modeled, a sand and a mud sediment. They were modeled after the sediments analyzed by Briggs[9]. The sediment parameter values used in this study are listed in Table 1. A 10 kHz sonar with a 1 ms pulse length was modeled. Five sonar beamwidths were tried, ranging from 1.5° to 23.4°, labeled a through e, as listed in Table 2.

Table 1. Modeled sediment parameters

		SAND	MUD
Roughness	m, r.m.s.	0.017	0.004
Wavenumber spectrum slope	dB/decade	-35	-35
Reflection coefficient	-	0.3	0.1
Volume scattering cross section to attenuation ratio	dB^{-1}	0.002	0.004
Attenuation	dB/m/kHz	0.5	0.1
Sound speed	m/s	1700	1500

Table 2. Sonar beamwidths modeled

SONAR	TRANSDUCER RADIUS m	-3 dB BEAMWIDTH
a	0.2	23.4°
b	0.4	11.6°
c	0.8	5.8°
d	1.6	2.9°
e	3.2	1.5°

The computed signal to reverberation (S/R) ratio of a sonar at a height of 100m over the mud bottom is shown in Fig. 3. It is seen that the S/R increases with beamwidth in a linear manner. This is a benign bottom. Even with a 23.4° beamwidth, an echo from a subbottom interface at a depth of 5 m will have a S/R ratio of 10 dB. The maximum S/R is achieved, not at the surface, but at a depth of about 1m. It appears that the S/R is depressed by surface backscatter in the top 1 m.

The corresponding result for sand is shown in Fig. 4. It is seen that a surface echo S/R in excess of 10 dB is only achievable at the narrowest beamwidth. Due the strong surface backscatter, the surface echo S/R is depressed by about 20 dB relative to the return from an interface of the same reflectivity at a depth of 1 m. At a minimum S/R of 10 dB, penetration depth at the narrowest beamwidth is no greater than 4 m.

The effect of sonar height was examined. If height has a significant effect then it should be possible to equalize the performance of different beamwidths by adjusting the height. It was found that in the case of mud, the height above bottom made only a marginal impact on S/R, because the reverberation was mainly due to volume scattering. The differences were so small that it is not worth showing. Therefore, in the case of a mud sediment, height above bottom has negligible effect on performance and cannot compensate for a beamwidth that is too wide. In the case of sand, the height appeared to have a significant impact on S/R. The heights were adjusted for the five sonar beamwidths to achieve a S/R of approximately 10 dB at a depth of 2 m. The results are shown in Fig. 5. It is seen that the S/R does not simply scale linearly with height. Each sonar is affected in a different way, but some improvement in the S/R of a wide beam sonar may be achieved by getting closer to the bottom.

4. CONCLUSION

It was found that a narrow beam is necessary to achieve penetration and realize high S/R ratios for detecting the sediment surface and subbottom interfaces. In the case of mud, height above bottom was found to have little effect on S/R. In the case of sand, due to the dominance of the surface backscatter, the height above bottom has a significant effect and detection performance is generally increased by working closer to the bottom. This result shows that signal processing methods to improve performance should be directed towards increasing the directivity of the sonar.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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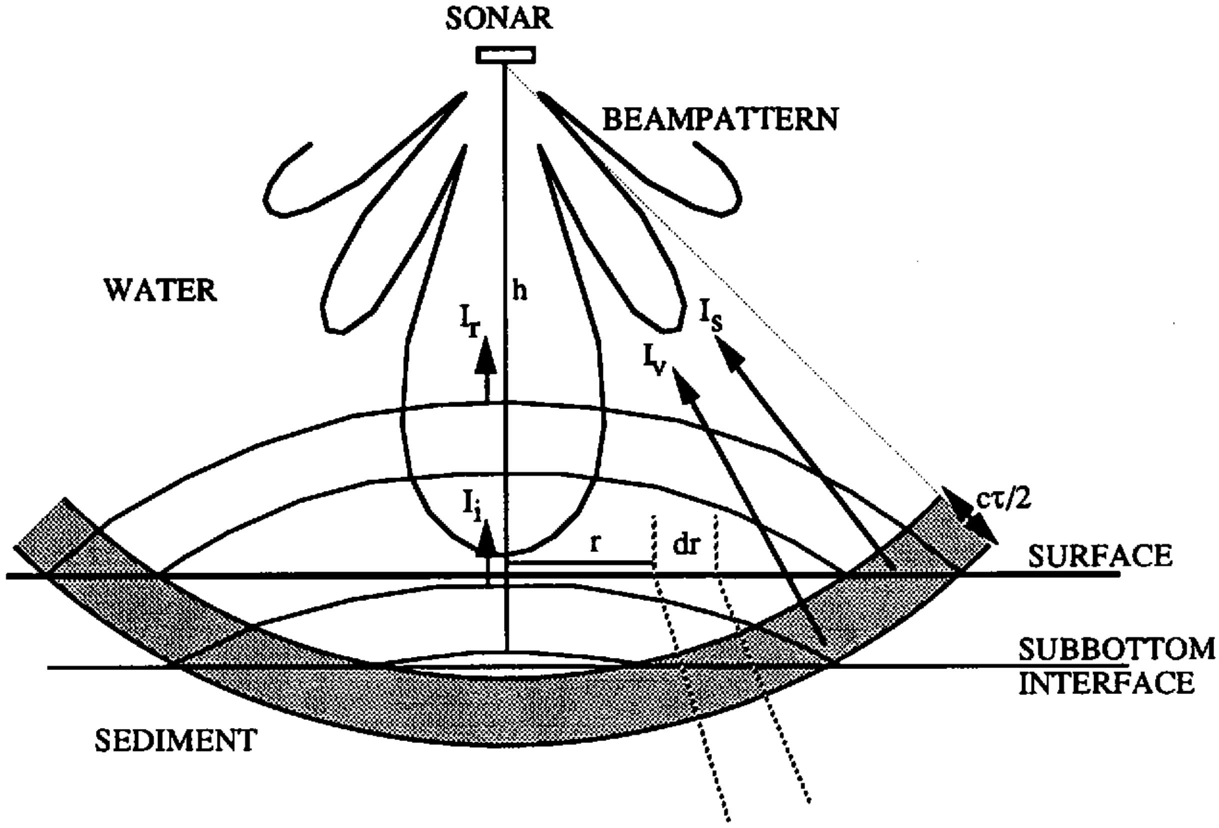

Fig. 1. Illustration of the sources of signal and reverberation

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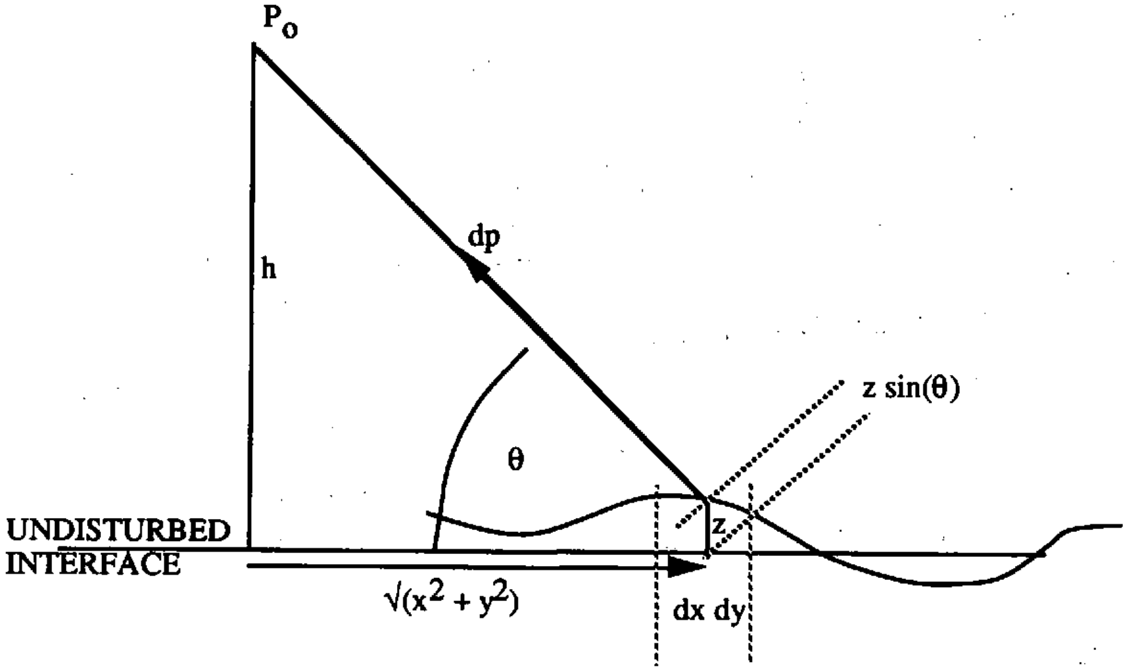


Fig. 2 Surface scattering model

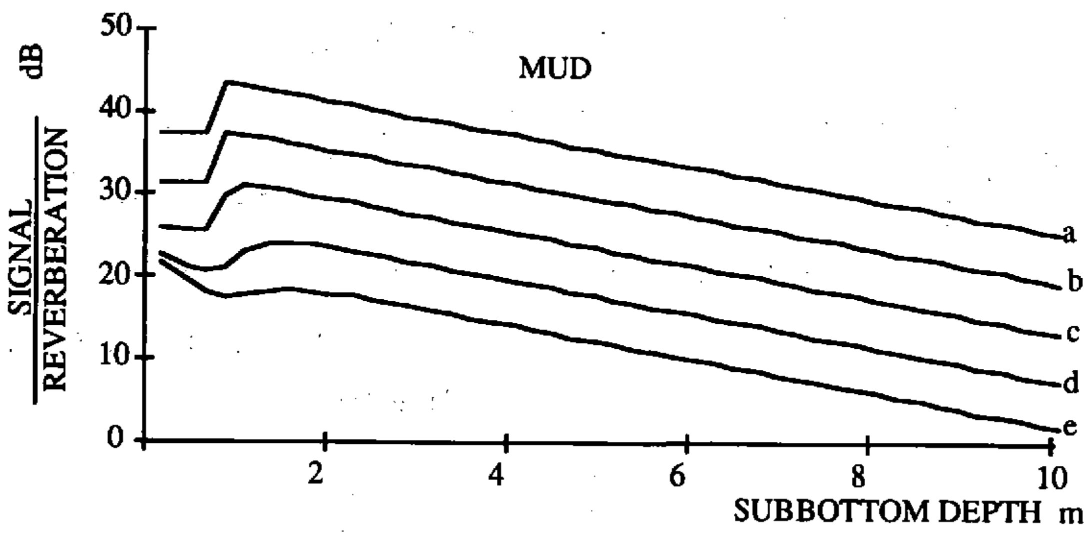


Fig. 3. Estimated S/R as a function penetration depth in mud from a height of 100 m

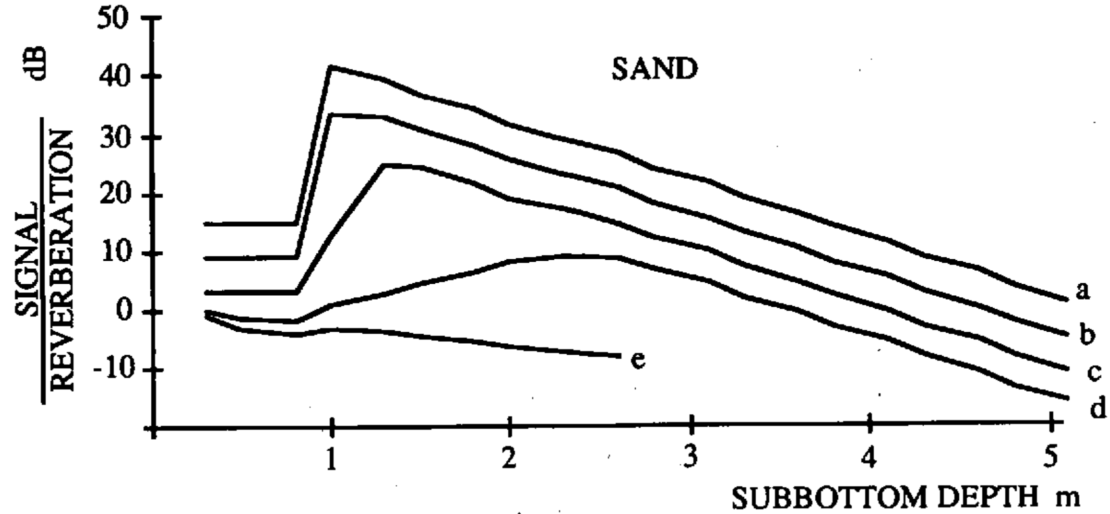
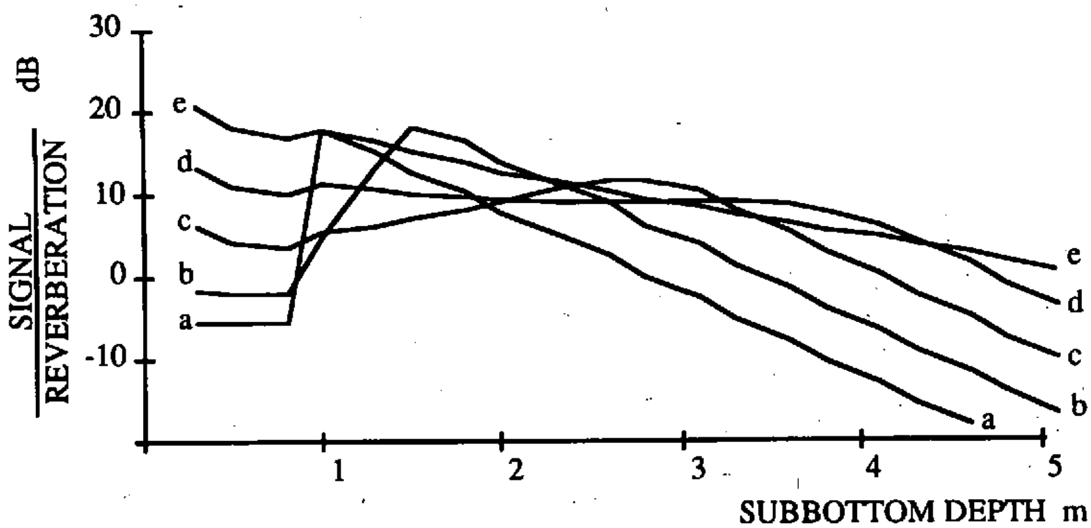


Fig. 4. Estimated S/R as a function penetration depth in sand from a height of 100 m



SONAR	HEIGHT m
a	2
b	40
c	430
d	2500
e	15000

Fig. 5. Estimated S/R as a function of penetration depth in sand after height adjustment for 10 dB S/R at 2 m