EFFECTS OF SHIP MOTION ON ACOUSTIC REMOTE SENSING

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Ship motion affects quality of acoustic data collected by various acoustic remote-sensing systems used for bottom and fisheries surveying. The angular position of an acoustic beam changes in time from its nominal position vertical to sea surface. This motion affects the acoustic returns from the bottom and other targets by changing their intensity and arrival times. In this paper we illustrate these effects on bottom returns obtained using single beam sonar.

INTRODUCTION

The acoustical monitoring of bottom and biological resources is usually undertaken through acoustic systems mounted on a moving ship. The angular movements of the echosounder transducer beam (pitch, roll, yaw) strongly influence the intensity and shape of acoustical returns (echoes). A sample of a bottom backscattering signal obtained in heavy weather (5° in the Beaufort wind scale) with an ELAC LAZ 4700 echosounder and conical beam with beamwidth of 16° at 30 kHz is shown in the echogram in Figure 1. The ship is moving with a constant velocity over a flat, homogenous bottom and the echogram shown covers a time period of 223 seconds using a pinging rate of 112 pings/min. We can clearly see higher intensity patches corresponding to a near vertical beam position interleaved with low intensity patches corresponding to an angular beam tilt reaching 15°.

One method to avoid such distortions and to produce quality data is to obtain returns only from near vertical transmissions. This can be accomplished by monitoring transducer motions and by initiating the transmissions only at proper instances. Alternately, transmissions may be conducted at a constant pinging rate, but only returns from near vertical transmissions are selected for further analysis. It might be also possible to make such selection based on certain properties (like symmetry) of the returns characteristic of vertical incidence.

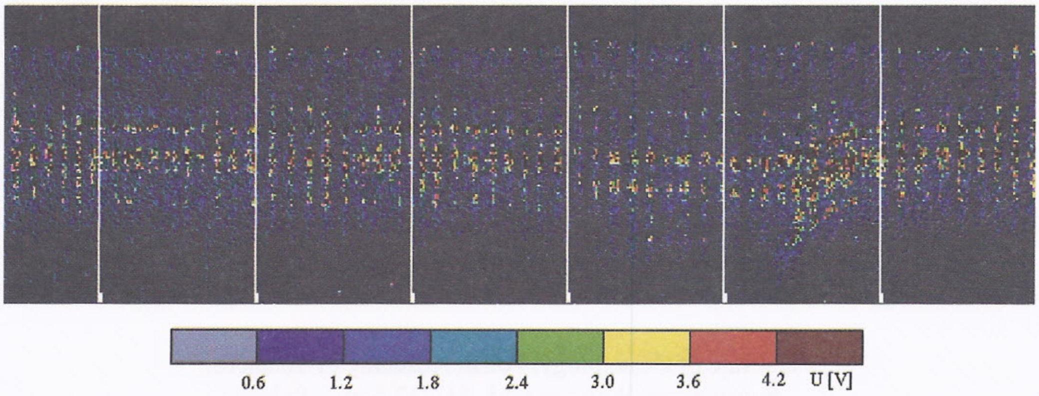

Figure 1. The echogram of bottom backscattering signal recorded in heavy weather (5°B)

The latter method does not require transducer motion sensing and is applicable also to sloping bottoms.

The object of this paper is to examine the influence of a swaying acoustical beam on the level of bottom backscattering strength.

1. THE GEOMETRY OF A SWAYING VESSEL

The movement of a swaying vessel can be described by angles of rotation in a Cartesian coordinate system XYZ. The rotation around the X-axis is named roll (r); around the Y-axis, pitch (p); and around the Z-axis, yaw, as shown in Figure 2. Vertical movement of a ship with respect to the bottom (heave) is not considered in this paper.

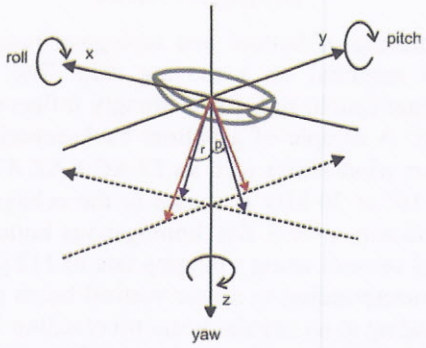

Figure 2. Roll, pitch and yaw of a swaying vessel

The intensity of the sea bottom echo signal is dependent on the incidence angle as determined by the angular position of an acoustic beam. For reflections from an isotropic bottom and symmetric conical acoustic beam, pitch and roll angles are the only factors influencing the backscattered signal. In this case the acoustic beam incidence angle θ is related to pitch and roll angles as:

$$tan^2(\theta) = tan^2(r) + tan^2(p)\ , \tag{1}$$

where r (roll) and p (pitch) are the angles of beam rotation.

2. THE BOTTOM BACKSCATTERING STRENGTH

The model of the backscattering coefficient m_{bs} was adopted from Novarini and Caruthers [2]. The coefficient is the sum of three parts:

$$m_{bs} = m_f + m_\mu + m_v\ , \tag{2}$$

where m_f represents the scattering contributions from fine-scale components of the bottom surface, m_μ is the contribution from microscale roughness and m_v is the contribution from the volume of bottom sediment.

The backscattering coefficient m_f is the product of a coherent reflection coefficient M and the factor F describing the fine-scale slopes of the bottom facets:

$$m_f = M(k, \sigma_\mu, K_p) \cdot F(\delta_f, \theta), \tag{3}$$

where k is the wavenumber, σ_μ is the rms height of the fine-scale roughness, and K_p is the attenuation factor for compressional waves, $F(\cdot)$ is the contribution of the fine-scale slopes, and δ_f is the rms slope of the fine-scale bottom surface facets.

The backscattering coefficient m_μ is related to scattering at microscale roughness of the bottom surface. The equation for coefficient m_μ was derived on the basis of Bragg scattering theory [1]:

$$m_\mu = \pi^{-2} R_0^2 k^4 \cos^4\theta \cdot W\left(\frac{k}{\pi}\sin\theta\right), \tag{4}$$

where R_0 is the Rayleigh reflection coefficient (dependent on angle of incidence and bottom sediment attenuation) and W is the power spectra describing sea floor roughness.

The backscattering coefficient m_v is the volume scattering coefficient defined as:

$$m_v = \mu_v(m_0) \cdot V(\theta - \alpha_{f0}), \tag{5}$$

where μ_v is a surface scattering constant attributed to volume scattering and $V(\theta - \alpha_{f0})$ is a functional form dependent on the angle of incidence θ and on α_{f0}, the mean-squared angle of the slope of the fine-scale bottom surface. The logarithmic measure of the backscattering coefficient (bottom backscattering strength BBS) is defined as [3]:

$$\mathrm{BBS} = 10\log_{10}(m_{bs}). \tag{6}$$

The frequency and angular dependencies of BBS were computed for three types of sediments: silt, clay and sand. The roughness and acoustical parameters of chosen sediments are presented in Table 1.

Table 1. The sediment parameters used in model computation [1].

sediment	c [m/s]	ρ [kg/m^3]	K_p [dB/(m/kHz)]	a	b	δ_f [deg]	σ_μ [m]	m_0
silt	1510	1700	0.1	1.2×10^{-3}	1.95	2.2	0.04	6.0×10^{-5}
clay	1510	1700	0.1	2×10^{-3}	1.95	2.0	0.06	2.2×10^{-6}
sand	1784	2000	0.7	2.8×10^{-3}	1.90	3.0	0.03	4.0×10^{-4}

a and b are constants describing bottom surface power spectra ($W = a^2 K^{-2b}$); and m_0 , the scattering cross section per unit volume. The acoustical parameters of silt and clay are similar but roughness parameters are different.

An example of angular dependencies of BBS and its three components is shown in Figure 3.

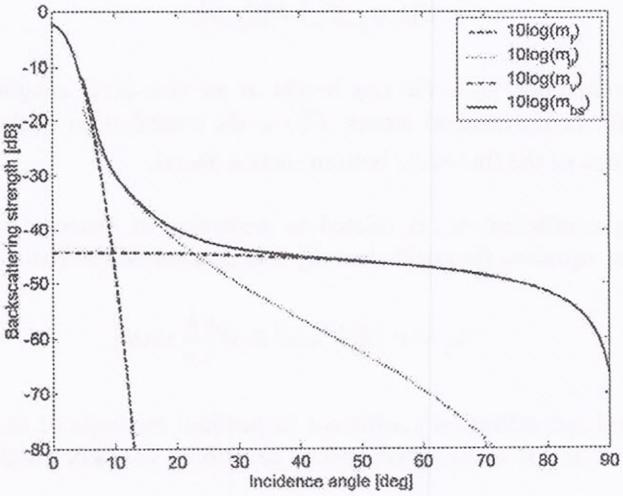

Figure 3. Angular dependency of BBS and its three components for silt at frequency 30 kHz

The computation was made for silt (for parameters as in Table 1) and a frequency of 30 kHz. For angles of incidence close to zero (vertical position of the beam), fine-scale scattering at the rough surface m_f plays a dominant role. The Bragg theory is not valid for this case [2]. For this reason, for angles less than 5° we do not take into account the microscale component m_μ in calculating BBS. This leads to a slight "mismatch" in the BBS curve at 5°. For angles of incidence exceeding 10°, the volume and microscale (Bragg) scattering is dominant. For large values of angle of incidence, volume scattering is dominant.

Figures 4a, 4b and 4c represent the frequency-angular dependencies of BBS for three types of sediments: silt, clay and sand. Left graphs show BBS as a function of frequency changing from 1 to 100 kHz; the right graphs correspond to three chosen frequencies 1, 30 and 100 kHz.

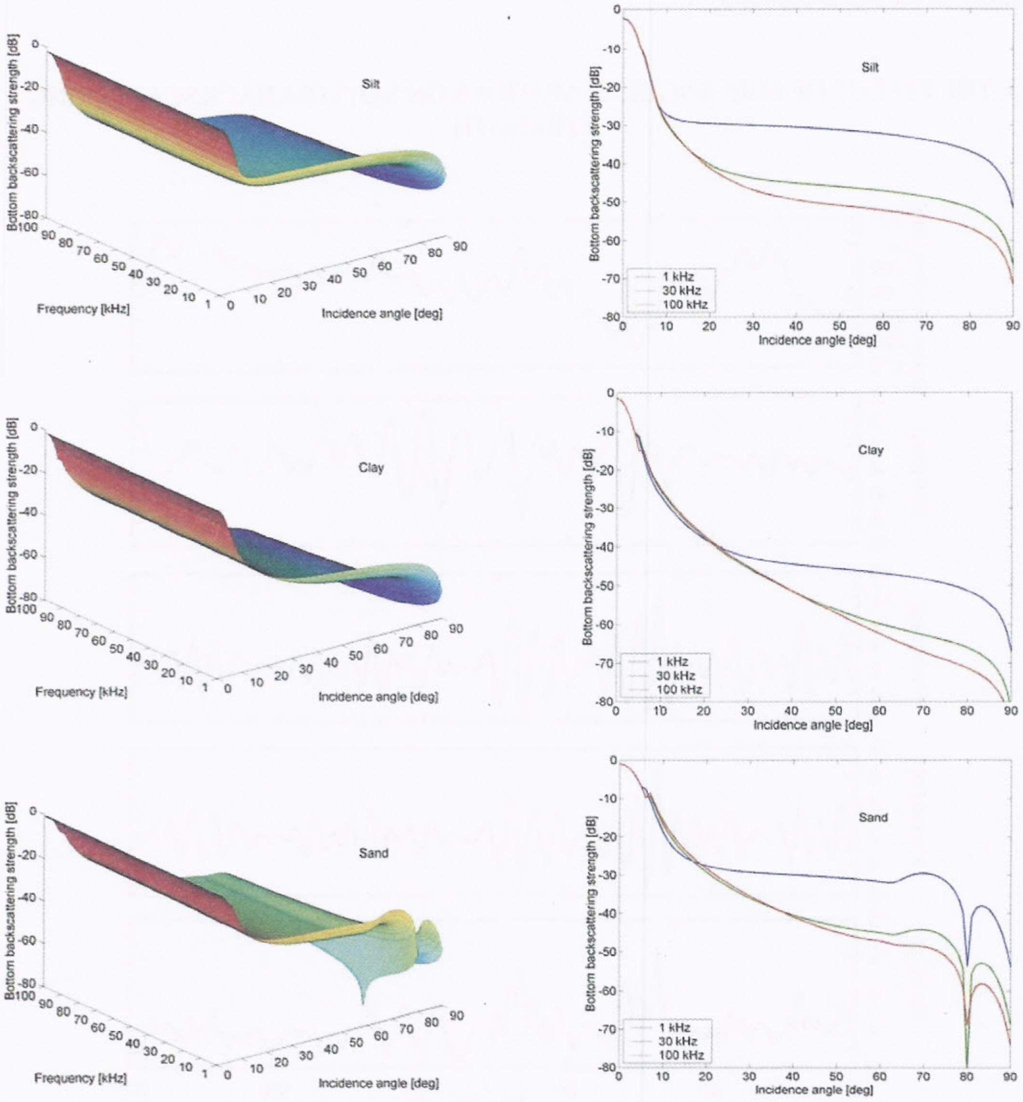

Figure 4. Frequency-angular dependencies of BBS for three types of sediments: a) silt, b) clay and c) sand

The level of BBS is independent of frequency and incidence angle up to 8o for silt and 4o and 6o for clay and sand, respectively. An increase of frequency and incidence angles over the value mentioned above causes a decrease in the BBS level. For sandy sediment (Figure 4c) and an 80o angle of incidence, there is a sharp dip of BBS value. The dip is noted near the vicinity of the critical angle in the reflection of the acoustical wave from the bottom. In the case where attenuation is absent, the energy of the acoustical wave is reflected totally for angles of incidence greater than critical. In our model we compute wave reflection for attenuating sediments and, therefore, above the critical angle of incidence part of the acoustic energy is transmitted into the bottom. This fact is reflected in the increasing BBS in the vicinity of the dip to the right.

3. THE EFFECT OF SHIP ANGULAR MOTIONS ON BOTTOM BACKSCATTERING STRENGTH

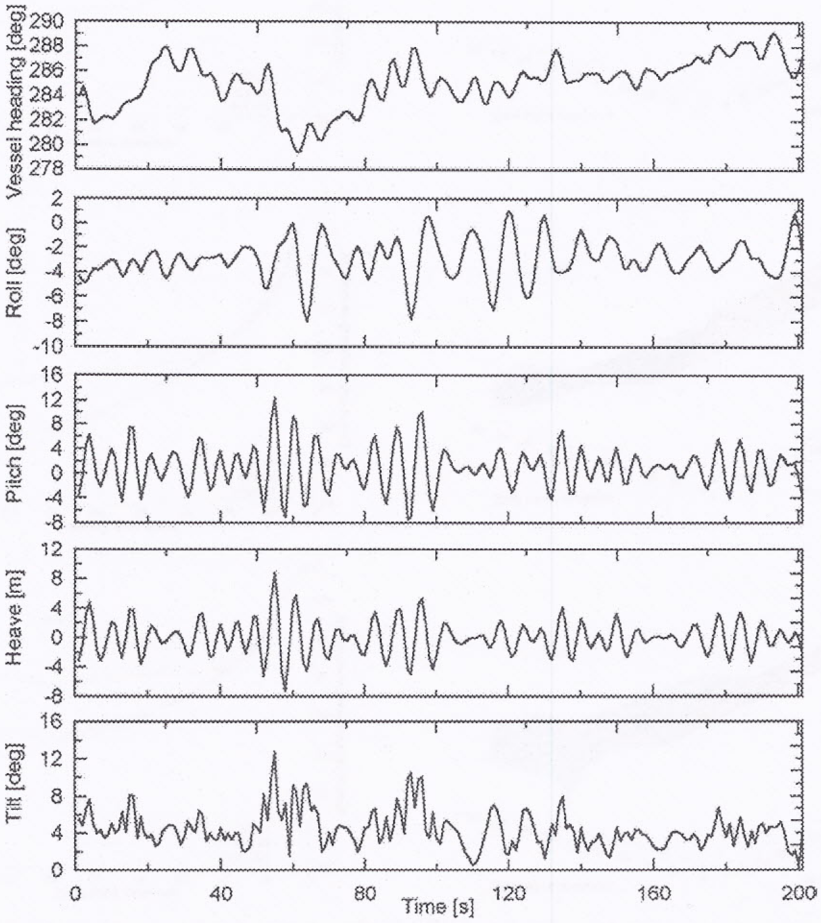

Figure 5. 200-second record of vessel heading, roll, pitch, heave and tilt of acoustic beam

Ship motion changes the angular position of an acoustic beam in time from its nominal position vertical to the sea surface and this affects the acoustic echo signal. Knowledge of the angular-frequency BBS dependence can be sufficient to recognize the influence of a swaying acoustic beam on the BBS level.

We computed this effect utilizing pitch and roll data collected on board r/v Miller Freeman while surveying the southeastern Bering Sea on March 2-3, 2001. From the 29-hour record of the pitch, roll and heave we chose a one-hour record and used it for computations. Figure 5 is an example of a 200 second record of vessel heading, roll, pitch, heave and tilt of acoustic beam calculated from Equation 1.The average value of roll shown in Figure 5 is negative because the vessel was tilted towards one board. The tilt of the acoustical beam reaches a value of 13°.

Figures 6a and 6b show the results of computations of BBS and its components as a function of the varying-in-time tilt of the acoustic beam. The upper group of graphs (6a) were obtained for frequency of 1 kHz of incidence wave and the lower one (6b) for 30 kHz. The values of roughness and volume scattering coefficients are presented in the consecutive second, third and fourth graphs of Figure 6 a and b. The blue lines on the graphs correspond to silt, green lines to clay and red lines to sand. The fluctuations in BBS and its components are closely related to values of tilt, which do not exceed 14° in this case. The minimum value of BBS is for clay at 30 kHz and is -58.7 dB; for silt the value is -44.3 dB and for sand, -39.3 dB. For the lower frequency of 1 kHz the minimum values of BBS are -43.9 dB for clay, -29.6 dB for silt, and -29.0 dB for sand. There is a large difference between minimum values of BBS for sand and clay: -15.9 dB (at 1 kHz) and -19.4 dB (at 30 kHz). There are smaller differences between mean values of BBS (-1.71dB for clay-sand at 1 kHz and -1.74dB for clay-sand at 30 kHz).

The interruption in microscale roughness backscattering coefficient m_μ is the result of the fact that the Bragg theory is not valid for small angles of incidence. The detailed results of mean, minimal, maximal and standard deviation of BBS values for 1, 30, 100 kHz and three types of sediments are presented in Table 2.

Table 2. The mean, minimum, maximum and standard deviation of BBS for 1, 30, 100 kHz and three types of sediments.

frequency	1000 Hz			30000 Hz			100000 Hz		
sediments	silt	clay	sand	silt	clay	sand	silt	clay	sand
BBS mean [dB]	-8.77	-8.93	-7.19	-8.80	-8.93	-7.22	-8.80	-8.93	-7.22
BBS min [dB]	-29.56	-43.92	-28.99	-44.33	-58.69	-39.32	-49.55	-63.91	-40.48
BBS max [dB]	-2.38	-1.57	-1.05	-2.39	-1.57	-1.06	-2.39	-1.57	-1.06
BBS std [dB]	-9.26	-8.71	-8.32	-9.26	-8.71	-8.32	-9.26	-8.71	-8.32

The influence of swaying of the acoustical beam upon the values of BBS is shown in the histograms presented in Figure 7. The narrowest range of BBS values is for sandy sediments and the broadest range is for clay. The frequency increase moves the values of BBS to only slightly higher values.

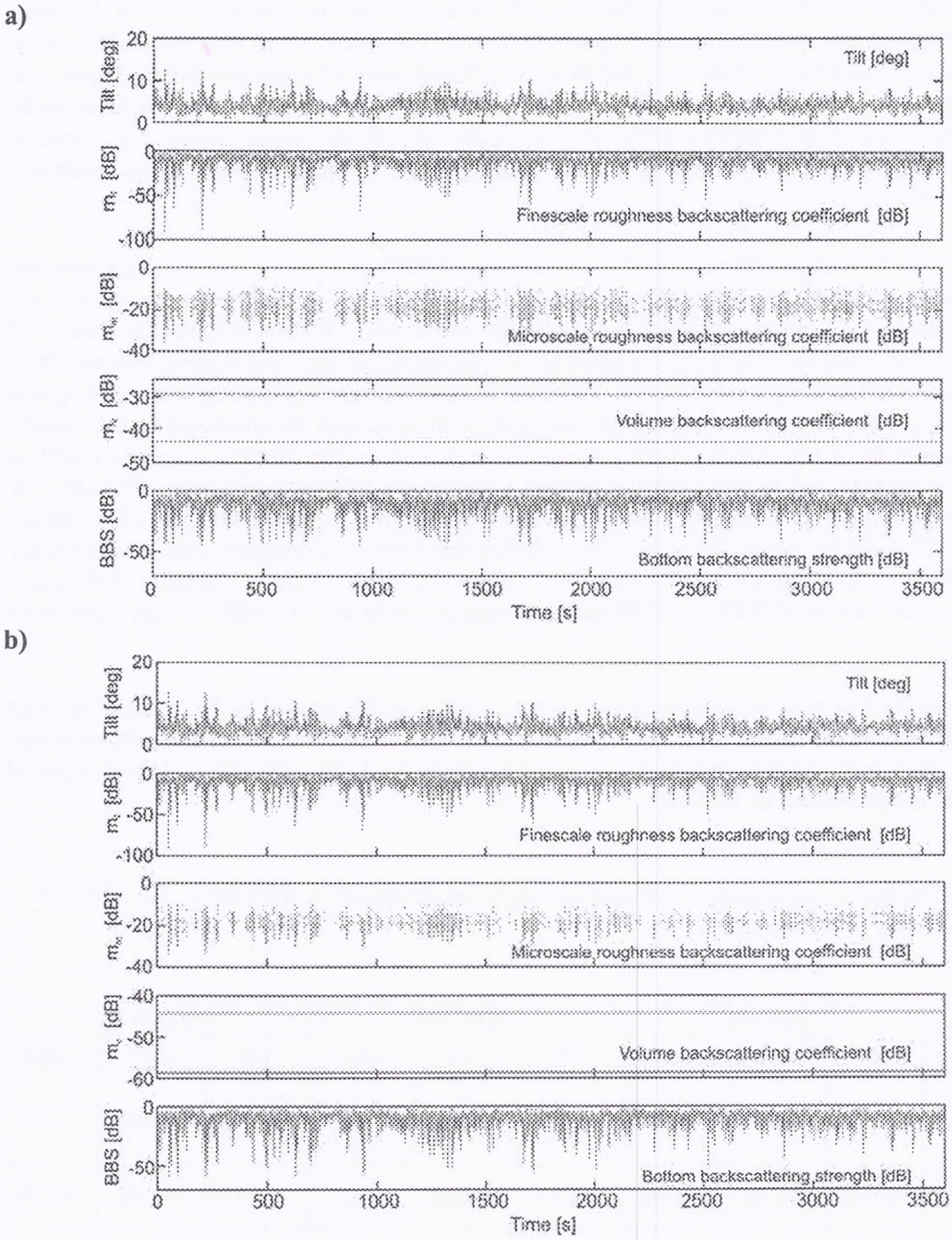

Figure 6. The dependence of BBS and its components (m_f, m_μ and m_v) from tilt of acoustic beam for a) f=1 kHz, b) f=30 kHz. (silt: green line; clay: blue line; sand: red line)

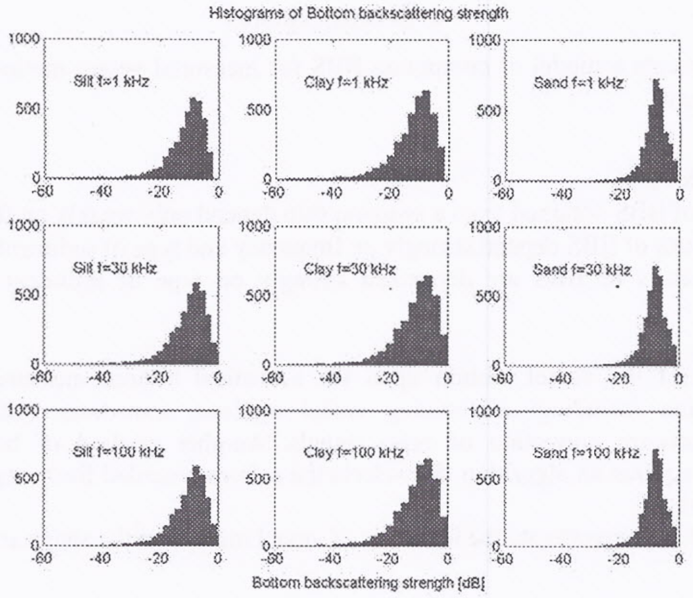

Figure 7. Histograms of BBS for 1kHz, 30 kHz and 100 kHz and three types of sediment

Another form of visualization of the BBS values as given in Table 2 is presented in Figure 8.

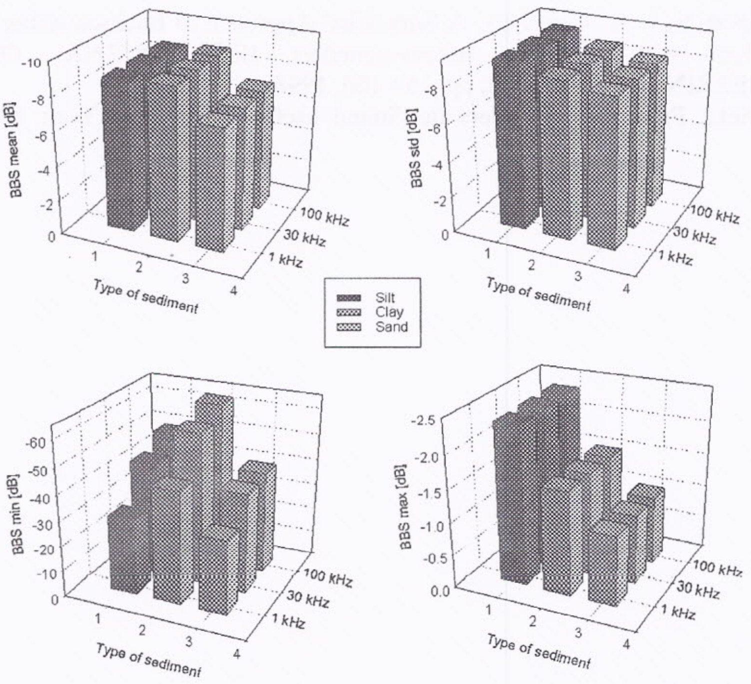

Figure 8. The frequency dependence of minimum, average, maximum and standard deviation values of BBS for three types of sediment

4. CONCLUSIONS

This paper presents a model of computing BBS for measured vessel motion data and three types of sediment.

We conclude that:
- mean values of BBS obtained from a swaying ship depend only weakly on frequency;
- minimum values of BBS depend strongly on frequency and type of sediment;
- maximum values of BBS are dependant strongly on type of sediment and weakly on frequency.

The influence of the vessel motion upon the acoustical bottom measurements calls for corrective action including: minimizing vessel motions, transducer stabilization, beam steering or software correction of echo signals. Another method of bottom surveying improvement requires an algorithm that selects the echoes recorded from angles of incidence close to vertical.
Future research will investigate the influence of vessel motion on the shape and parameters of echo signal.

REFERENCES

1. L. M.Brekovskikh, Yu. P. Lysanov, Fundamentals of Ocean Acoustics, Springer-Verlag, Berlin, 1982.
2. J. C. Novarini, J. W. Caruthers, A Simplified Approach to Backscattering from a Rough Sea Floor with Sediment Inhomogeneities, IEEE JOURNAL OF OCEANIC ENGINEERING, vol. 23, no. 3, pp. 157-166, 1998.
3. R. J. Urick, , Principles of Underwater Sound, McGraw-Hill, New York, 1975.