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Statistical Characterization of Seafloor Roughness

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(Invited Paper)

Abstract—The topography of the seabed can strongly affect underwater sound propagation in the ocean. ~~In this regard,~~ seafloor features fall into ~~three~~ overlapping categories according to size: large features that block propagation, intermediate features that act primarily as sloping bottoms, and small-scale features that act as scatterers. In this paper, statistical parameters of bottom topography for the latter two categories ~~are presented.~~ Spatial wavenumber spectra of ocean bottom and subbottom roughness are determined from narrow-beamwidth echosounding and seismic reflection profiling. The spectra are compared to the expression $P(K) = CK^{-b}$, where $P(K)$ is the power spectral density, C is a proportionality constant, K is the wavenumber, and b is a constant that characterizes the class of roughness. The parameter b is often assumed to be 3; however, ~~the present~~ study shows that b can range from about 1 to 5. Topographic samples were found to have probability density functions which were both non-Gaussian and Gaussian. It is suggested that a first-order roughness data base include band-limited ~~root mean square~~ (RMS) roughness; K_1 and K_2 (the wavenumbers of the estimate); b; sediment type; physiographic province, water depth, and location.

INTRODUCTION

SEAFLOOR ROUGHNESS is an important factor in acoustic propagation. Properties of roughness are not only a means for studying seafloor geology [14], [16], but also provide a method for seafloor classification [5]. This paper deals with a quantitative description of seafloor topography for use in acoustic problems. First, various types of roughness parameters that have been used as input to acoustical models are reviewed. Then estimates of seafloor and subbottom roughness obtained from stabilized narrow-beam echosoundings are presented. These data, along with data presented from the literature, can provide interim estimates of roughness parameters until an extensive roughness data base is established. Finally, the form of a first-order seafloor roughness data base is suggested.

SEAFLOOR TOPOGRAPHY AND UNDERWATER ACOUSTICS

The interaction of sound with the seafloor depends upon bottom density, sound attenuation, sound velocity, and interface roughness. The density, sound velocity, and attenuation of the seafloor have been estimated and included in data bases for use in acoustic modeling. Examples of this are the "geoacoustic models" of Hamilton [8] based on 1) *in situ* and laboratory measurements on sediments, 2) seismic experiments, and 3) acoustic experiments.

The effect of seafloor topography on underwater sound propagation is a function of experimental geometry and frequency. Topographic features fall into three overlapping size categories: 1) large features that block propagation, 2) intermediate sized features that primarily act as sloping bottoms, and 3) small-scale features that act as scatterers. Only topography of the first, and to some extent the second categories, is readily available for use in acoustic modeling.

Deterministic Data Bases

Topographic features of the seafloor of the first and second categories given above may be described deterministically and input into range-dependent acoustic propagation models such as Parabolic Equation [22] and GRASS [4]. Topographic data are usually obtained from bathymetric charts or data bases such as SYNBABS, a computerized bathymetric data base and software system that synthesizes great-circle bathymetric profiles from average depth in 1/12 degree cells [23].

Recently developed single-interaction scattering models, such as Facet Ensemble ([13], [18]) require input of a high-resolution topographic profile. Such profiles are difficult to obtain on a global scale, but a data base to support such modeling might consist of a series of profiles from areas in which there is uniform small-scale roughness (roughness provinces). The data base could be either a part of, or separate from, the statistical data bases described below.

Statistical Data Bases

Intermediate-scale and small-scale features cause scattering of sound and errors in range and bearing estimates [11]. Different statistical parameters of roughness are required for different scattering theories. Eckart [6] has shown the spatial wavenumber spectrum to be an important factor in the scattering of sound from a randomly rough surface. Clay *et al.* [3] showed that the coherent component of the specularly scattered sound is sensitive to the probability density function (PDF) of the displacements of the rough surface. For the case of a Gaussian PDF, Eckart [6] showed that the coherent component of sound reduces to a simple expression involving the Root Mean Square (RMS) roughness of the surface. There have been suggestions that the seafloor roughness PDF's tend to be approximately Gaussian [15].

In order to represent spatial wavenumber spectra for areas

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of the seafloor, a simplified model is convenient. Spectra may be approximated by the expression $P(K) = CK^{-b}$, where $P(K)$ is the spatial wavenumber power spectral density, C is a porportionality constant, K is the spatial wavenumber, and b is a constant that is characteristic of the class of roughness (analogous to noise class, e.g., white noise, Brownian noise). Nye [19] has used a dimensional analysis to demonstrate that for the case of $b = 3$, the units of spatial wavenumber power spectral density (meters cubed) cancel and the topography appears to have the same roughness for all scales. An example of the acoustic significance of b is shown by Marsh's [17] theory of scattering from a totally reflecting randomly rough surface. For fixed grazing angle, the backscattering coefficient varies as k^{3-b}, where k is the acoustic wavenumber. Note that for $b = 3$, the backscattering would be independent of acoustic frequency.

Most studies of seafloor topography have been qualitative. A few quantitative studies have dealt with very large-scale topography. For acoustic analysis, statistical parameters relating to the roughness of the acoustic interaction zone are required. In the next sections, the roughness important to acoustic interaction is discussed.

SEAFLOOR ROUGHNESS APPLICABLE TO LOW- AND MEDIUM-FREQUENCY SOUND

The area of interaction for sound reflecting from the seafloor may be estimated by the size of a Fresnel Zone. For 100-Hz sound (acoustic wavelength =15 m) and a 20° grazing angle and with surface source and surface receiver in a 4000-m ocean, the dimensions of the first Fresnel zone calculated by Kerr's [12] method, are 1900 m by 600 m. By the Rayleigh criterion [21], the heights of roughness within the first Fresnel Zone must be greater than about $\lambda/(8 \sin \theta)$, where λ is the acoustic wavelength and θ is the grazing angle, or 5.5 m to appear as a "rough" surface to incident sound. To delineate seafloor features of this scale requires better resolution than conventional wide-beam echosounders can offer; they commonly have a 60° beamwidth, which would imply a 4600-m diameter ensonified area for an ocean depth of 4000 m.

One method of achieving the required solution is to use a stabilized, very narrow-beam echosounder [7]. Data from this type of echosounder were obtained by using the beam of highest resolution of the stabilized 12-kHz multibeam array sonar. Depths obtained from the center beam (normal incidence) were determined to 1 m by precise measurement of the sound travel time. The ensonified area (to the −3 dB point) was less than 90 m in diameter and adjacent samples did not overlap because the sampling interval was about 100 m. Sample series of topographic data were adjusted to a zero mean, and passed through a high pass spatial filter (low cut wavenumber 0.003 m^{-1}). Probability density functions and power density spectra were then computed from the filtered data. A 2048-point discrete Fourier transform with a Hann Window was used to obtain raw spectral estimates. Averages of 10 adjacent estimates were used to produce a smoothed spectral estimate having a resolution of 0.0003 m^{-1} for the band up to 0.03 m^{-1}.

To reduce the effects of system noise, navigational uncertainties, and heave, only data obtained under optimum conditions are used for this study. Aliasing may affect a spectrum if substantial energy occurs at frequencies higher than the spatial sampling frequency (1 sample per 100 m). However, as the beamwidth of the echosounder is not infinitesimally small, the measurement system may act as an antialiasing filter. Other processing effects include bias due to leakage from one band to another. Leakage effects have been minimized by using appropriate windows.

By using the same measurement system, processing, and estimation techniques on a wide range of seafloor types (Table I), first-order estimates of the probability density functions (Fig. 1) and power density spectra (Fig. 2) can be obtained. These functions and the RMS roughness are band-limited parameters, since they pertain to the band of topographic wavenumbers sampled by the measuring system and the high-pass processing filter. The PDF's appear to have both Gaussian and non-Gaussian distribution. The values of b (Table I) were obtained by a logarithmic least-square fit of each power spectrum for those values that were above measurement system noise (Fig. 2). These b values, which vary from about 1 to 5, have a greater variation than that reported by other investigators. Nye [19] concluded that spatial wavenumber spectra of widely different types of land topography have the approximate form corresponding to $b = 3$, even though the values of C are greatly different. Marsh [17] compiled power spectra of nine topographic surfaces, including four sea bottoms which followed the form corresponding to $b = 3$. The lake-bottom spectrum reported by Horton *et al.* [10] has the form $b = 0$. Bell [1] calculated spectra for North Pacific abyssal hills from numerous sources including deep-tow echosounding data and found that b varies from 2.0 to 2.5 for wavelengths less than 10 km and that b was about 1.0 for longer wavelengths. The wide range in b for the seafloor is not unexpected, since there are many unrelated processes that act to form the relief. This is in contrast to the constant value of $b = 3$ for the equilibrium range of wavenumber spectra of fully developed wind-blown sea surfaces [20], where roughness results from a single mechansim. One characteristic of all seafloor power spectra for vitually all scales of topography is that b is rarely less than 1, indicating that the power is concentrated in the longer wavelengths. This suggests that features that are tall relative to their horizontal dimensions are rare. Such features would tend to be unstable and short-lived in the ocean environment.

RMS roughness estimates determined in this study (Table I) are consistent with those found by Clay and Leong [2]. Further, physiographic provinces appear to be characterized by certain ranges of RMS roughness. However, there is no apparent relationship in these data between b and RMS roughness or b and physiographic province. It appears that additional studies with much larger, higher resolution data sets are required to determine if there are relationships between b and seafloor type.

If roughness spectra can be approximated by the exponential expression, a statistical data base might include parameters such as band-limited RMS roughness; K_1 and K_2 wavenumber bounds of the estimate; b; sediment type; water depth; physio-

TABLE I
RMS ROUGHNESS AND SPECTRAL SLOPE PARAMETER b OF BAND-LIMITED TOPOGRAPHY

Physiographic Province	Ocean	Band-limited RMS (Meters)	b
Rise	Atlantic	3.7	3.2
Continental Slope	Atlantic	6.4	2.2
Seamount	Atlantic	3.6	2.1
Abyssal Plain	Atlantic	<1.3	-
Abyssal Plain	Atlantic	<1.5	-
Rise	Norwegian Sea	<1.1	-
Abyssal Hills	Pacific	3.4	4.9
Continental Shelf	Norwegian Sea	2.5	2.0
Marginal Plateau	Norwegian Sea	1.9	1.9
Abyssal Hills	Pacific	2.5	4.2
Continental Rise	Mediterranean	<1.4	-
Continental Rise	Norwegian Sea	<1.2	-
Marginal Plateau	Norwegian Sea	2.1	1.5
Abyssal Hills	Pacific	2.3	2.2
Continental Rise	Mediterranean	<1.0	-
Basin	Norwegian Sea	5.4	1.8
Basaltic Interface*	Atlantic (av. of 50)	259±74	1.8±.4
Basaltic Interface*	Pacific (av. of 50)	99±36	1.6±.4

Spatial wavenumbers are 0.003 to 0.03 m^{-1} except those denoted by *, where spatial wavenumbers are 0.00006 to 0.003 m^{-1}. In cases where the roughness is less than the resolution of the measuring system, the upper limit of RMS roughness is given and b is not estimated.

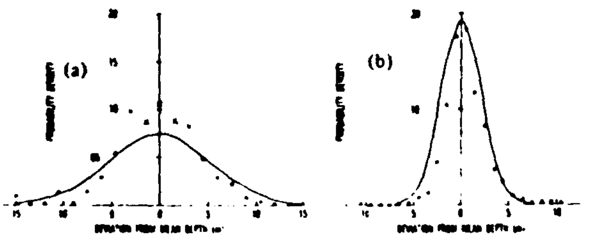

Fig. 1. Probability density function of ocean bottom topography. The solid lines represent the Gaussian PDF of topography filtered by a high-pass spatial filter, wavenumber = 0.003 m^{-1}. (a) Norwegian Sea–Basin, (b) Norwegian Sea–Marginal Plateau.

Fig. 2. Spatial wavenumber power spectral density of seafloor topography. The solid lines represent the logarithmic regression for spectral values that are above the measurement noise. (a) Norwegian Sea Basin, (b) Norwegian Sea Marginal Plateau.

graph province, and geographic location. The RMS roughness for other frequency/wavenumber bands could be estimated from the exponential expression. Further work is required to determine if such a relatively simple data base can adequately represent bottom roughness.

SEAFLOOR ROUGHNESS APPLICABLE TO VERY LOW-FREQUENCY SOUND

At very low frequencies (less than 20 Hz), acoustic wavelengths are long (greater than 75 m), the effective attenuation low, and the Fresnel zone size large (dimensions proportional to $f^{-1/2}$). A significant amount of very low-frequency energy can pass through the water-sediment interface and interact with the subbottom. Whether the water-sediment interface or a subbottom interface is the principal scattering surface will depend on experimental geometry, roughness of the interfaces, acoustic wavelength, sediment thickness, sediment density, and the sound attenuation and sound velocity in the sediment. For large areas of the world's oceans, the principal subbottom interface for VLF sound is the sediment-basalt interface.

To obtain statistical properties of both the water-sediment and the sediment-basalt interfaces, large-scale roughness data were obtained from seismic reflection records and wide-beam echosounding data from the North Atlantic and North Pacific Oceans. The seismic reflection records provide data for both interfaces. The echosounding records were made in areas of little or no sediment cover. Depths were determined at intervals of 1 km along profiles. The accuracy of these data varied between 5 and 30 m, depending on the seismic recording configuration. The seismic interface depths were then adjusted for a constant sediment velocity layer (1.6 km/s). While these data do not have the resolution of the narrow-bandwidth data mentioned in the previous section, they provide an estimate of roughness in the 0.00006 to 0.003 m^{-1} wavenumber band. The roughness of the smaller wavenumbers of this band is applicable to scattering at the lower frequencies of VLF sound.

Power density spectra and probability density functions were obtained from the digitized data that have been detrended and have had the mean removed. Table I shows estimated large-scale roughness (0.00006 to 0.003 m^{-1} wavenumbers) statistics for the sediment-basalt interface of the North Atlantic and North Pacific Oceans. These estimates, based upon 50 sample profiles from each ocean, yielded mean values of 1.8 and 1.6, respectively, for parameter b. This is consistent with results reported by Bell [1], who found that b for the slope of the North Pacific abyssal hills was 2.0 to 2.5 for wavelengths less than about 40 km with a lower value for longer wavelengths. Bell's results showed a large apparent scatter with only a few data points in the long wavelength range. The standard deviation resulting from fitting the exponential approximation to each power spectrum was 0.4, which is comparable to that found by Bell [1].

The PDF of all samples free of seamounts and fracture zones were found to have a distinct, generally symmetric, central tendency. This is in agreement with the findings of Krause *et al.* [15] for the North Pacific and Holcombe [9] for the North Atlantic.

While the values of b for basalt are similar for both oceans, the average RMS roughness is significantly different (Table I). RMS roughness for the basaltic basement of the two oceans in the spatial wavelength range from 5 to 100 km is estimated to be 259 ± 74 m for the North Atlantic and 99 ± 36 m for the North Pacific Oceans. This analysis excluded the large fracture zones. The uncertainty indicated is one standard deviation of the individual estimates. The means are distinctly different, with the North Atlantic having the higher value. Holcombe [9] has estimated mean relief in the North Atlantic by hand tabulation of peak-to-valley heights and by averaging.

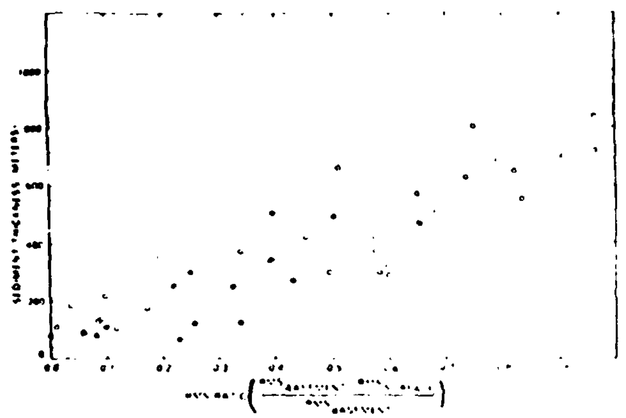

Fig. 3. Total sediment thickness versus ratio of change in RMS roughness to basement RMS roughness.

An approximation comparison of these two results can be made by assuming the topography to be sinusoidal. This assumption yields a conversion of the Holcombe peak-to-peak amplitude to RMS roughness of 244 ± 60 m. The value is in agreement with our data. Increasing sediment cover decreases relief at the water-sediment interface. As shown in Fig. 3, the reduction in RMS roughness is approximately proportional to sediment thickness; however, there is considerable scatter in the data.

CONCLUSION

Statistical properties of seafloor and subbottom interfaces have been calculated for a variety of seafloor types and locations. Conclusions of this study are: 1) the roughness slope parameter b varies from about 1 to 5; 2) while many probability density functions approximate a Gaussian distribution, there are exceptions; 3) the difference between the RMS roughness of the basaltic basement and the overlying sediments is approximately proportional to sediment thickness; and 4) the RMS roughness of the basaltic basement is much larger in the North Atlantic than the North Pacific.

With the increased availability of stabilized multibeam echosounders, there is a potential for developing large data bases of high-resolution seafloor topography statistics. We have suggested that a first-order roughness data base include the following: band-limited RMS, K_1, K_2, b, sediment type, physographic province, water depth, and location. An additional data base might also include actual topographic samples representative of the various seafloor types.

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