Statistical Characterization of Seafloor Roughness

JONATHON M. BERKSON AND J. E. MATTHEWS

(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 \( P(K) = C K^{-b} \), 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

U.S. Government work not protected by U.S. copyright
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
proportionality 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 topog-
raphy 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 wavenum-
ber. Note that for \( b = 3 \), the backscattering would be inde-
pendent 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 \( \lambda \)
is the acoustic wavelength and \( \theta \) 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 com-
monly 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 un-
certainties, and heave, only data obtained under optimum
conditions are used for this study. Aliasing may affect a spec-
trum 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 infinites-
ima l small, the measurement system may act as an antialias-
ing filter. Other processing effects include bias due to leakage
from one band to another. Leakage effects have been mini-
mized 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 sys-
tem 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 sea-
floor 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 wave-
number spectra of fully developed wind-blown sea surfaces
[20], where roughness results from a single mechanism. One
characteristic of all seafloor power spectra for virtually 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 expo-
tential expression, a statistical data base might include parameters
such as band-limited RMS roughness; \( K \), and \( K_2 \) wavenumber
bounds of the estimate; \( b \); sediment type; water depth; physi-
lengths are long (greater than 75 m), the effective attenuation

to determine if such a relatively simple data base can ade-

tory 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 ade-

quately represent bottom roughness.

SEAFLOOR ROUGHNESS APPLICABLE TO VERY

LOW-FREQUENCY SOUND

At very low frequencies (less than 20 Hz), acoustic wave-

lengths 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 wave-
numbers 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 de-
trended 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 30 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 ex-
ponential 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 $\pm$ 74 m for the North Atlantic and 99 $\pm$ 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.
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.

ACKNOWLEDGMENT

We would like to thank the large number of individuals from NORDA and NAVOCEANO who assisted us during this study. We particularly thank J. Gettrust, R. Bennett, R. Wagstaff, and W. Kinney for helpful discussion about the paper.

REFERENCES

[1] T. H. Bell, "Topographically generated internal waves in the open ocean," J. Geophys. Res., vol. 80, pp. 320-327, 1975.
[2] C. S. Clay and W. K. Leong, "Acoustic estimates of the topography and roughness spectrum at the seafloor southwest of the Iberian Peninsula," in Physics of Sound in Sediments, L. Hampton, Ed. New York: Plenum, 1974, pp. 373-442.
[3] C. S. Clay, H. Medwin, and W. M. Wright, "Specularly scattered sound and the probability density function of a rough surface," J. Acoust. Soc. Amer., vol. 53, pp. 1677-1682, 1973.
[4] J. J. Cornyn, "GRASS: A digital-computer ray-tracing and transmission-loss-prediction system, volume 1-overall description," Naval Research Laboratory, Washington, DC, Rep. NNR 7621, 1973.
[5] J. E. Damuth, "Use of high-frequency (3.5-12 kHz) echograms in the study of near-bottom sedimentation processes in the deep-sea: A review," Marine Geology, vol. 38, pp. 51-55, 1980.
[6] C. Eckart, "The scattering of sound from the sea surface," J. Acoust. Soc. Amer., vol. 25, pp. 566-570, 1953.
[7] M. F. Glen, "Introducing an operational multi-beam array sonar," Int. Hydrographic Rev., vol. 47, pp. 35-39, 1970.
[8] E. L. Hamilton, "Geoacoustic modeling of the seafloor," J. Acous. Soc. Amer., vol. 68, no. 5, pp. 1313-1340, 1980.
[9] T. L. Holcombe, "Roughness patterns and seafloor morphology in the North Atlantic Ocean," Ph.D. thesis, Columbia Univ., New York, NY, 1972.
[10] C. W. Horton, A. A. Hoffman, and W. B. Hempkins, "Mathematical analysis of the microstructure of an area of the bottom of Lake Travis, Texas," J. Sci., vol. 14, pp. 131-142, 1962.
[11] A. T. Jacques, "Bottom slope determinations: differences in methods," J. Acous. Soc. Amer., vol. 58, Supplement 1, pp. 29-30, 1975.
[12] D. E. Kerr, "Reflections from the earth's surface," in Propagation of Short Radio Waves (MIT Radiation Laboratory Series, no. 13), D. Kerr, W. Fishback, and H. Goldstein, Eds. New York: McGraw-Hill, pp. 396-444, 1951.
[13] W. A. Kinney, C. S. Clay, and G. A. Sandness, "Scattering from a corrugated surface: Comparison between experiment, Helmholtz-Kirchhoff theory, and the facet-ensemble method," J. Acoust. Soc. Amer., vol. 73, pp. 183-194, 1983.
[14] D. C. Krause, "Interpretation of echo-sounding profiles," Int. Hydrog. Rev., vol. 39, pp. 65-123, 1962.
[15] D. C. Krause, P. J. Grim and H. W. Menard, "Quantitative marine geomorphology of the East Pacific Rise," National Oceanic and Atmospheric Administration, Tech. Rep. ERL 275-AOML, 10, 1973, pp. 1-73.
[16] D. C. Krause and H. W. Menard, "Depth distribution and bathymetric classification of some seafloor profiles, Marine Geol., vol. 3, pp. 169-193, 1965.
[17] H. W. Marsh, "Reflection and scattering of sound by the sea bottom," Part I," AVCO Marine Electronics Office: New London, CN, 1964.
[18] J. C. Novarini and H. Medwin, "Diffraction, reflection, and interference during near-grazing and near-normal ocean surface back-scattering," J. Acoust. Soc. Amer., vol. 64, pp. 260-278, 1978.
[19] J. F. Nye, "A note on the power spectra of sea-ice profiles," in Artic Ice Dynamics Joint Experiment (ALIDEX) Bull., no. 21, pp. 20-21, 1973.
[20] O. M. Phillips, "Dynamics of the upper ocean," New York: Cambridge University Press, 1966.
[21] J. W. S. Rayleigh, The Theory of Sound. 2nd ed. New York: Dover, 1894, reprinted 1945.
[22] F. D. Tappert, "The papabolic approximation method," in Wave Propagation and Underwater Acoustics, J. B. Keller and J. S. Papadakis, Eds. Berlin, West Germany: Springer-Verlag, 1977, pp. 234-287.
[23] R. J. VanWyckhouse, "Synthetic bathymetric profiling system (SYNBAPS)," Naval Oceanographic Office, Washington, DC, Rep. TR-233, 1973.

\* Jonathan M. Berkson received the B.S. degree from the University of Illinois, and the M.S. and Ph.D. degrees in geophysics from the University of Wisconsin in 1969 and 1972.

He was an employee of the University of Wisconsin Geophysical and Polar Research Center, where he worked on problems in processing and interpreting side-scan sonar data and in acoustic techniques for studying the underside of arctic sea ice. He was an employee of the Naval Oceanographic Office, where he worked on problems in acoustic reflection at the seafloor and seafloor roughness. At the Naval Ocean Research and Development Activity he worked on problems in scattering of sound at the seafloor. Since 1983 he has been employed as a...
Senior Research Scientist at the SACLANT ASW Research Centre, La Spezia, Italy, where he is working on problems in interaction of low-frequency sound with the seafloor.

J. E. Matthews received the B.S. degrees in mathematics and geology from the University of Oklahoma in 1960, and the M.S. degree in geophysics from the University of Utah in 1970. He served as a Hydrographic Officer in the U.S. Navy before joining the U.S. Naval Oceanographic Office to work in marine acoustics. Since 1976 he has been with the Naval Ocean Research and Development Activity, where his work is primarily in the area of geoacoustic modeling.