SCATTERING AND REFLECTION OF ACOUSTIC WAVES AT THE BOTTOM AND SURFACE OF THE OCEAN

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ABSTRACT:

The final report is a summary of our study of the effect of roughness of the sea floor on marine geophysical measurements. We show comparisons of our scattering experiments and theory, scattering characteristics of the sea floor, sonographs of ice grooves on the bottom of Lake Superior, and the roughness of the sea floor in the basin west of Spain. Abstracts of the publications (11 papers, 2 contributions to symposium volumes, and 4 research reports) are in the appendix.

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PREFACE

Long before I left the Columbia University Hudson Laboratories, I learned that the major problems in underwater sound were due to the rough boundaries and the inhomogeneities within the ocean. Many of my thoughts are in the last chapters of Ocean Acoustics.(1) When we were writing the book, we were close to that state of the art. We knew that only the most powerful theoretical techniques could make significant advances in the acoustics in the ocean. This book and my review paper, "Acoustic transmission between arrays in a noisy ocean", set forth a theory of optimum acoustic systems. We made guesses as to the ways in which inhomogeneities enter the formulation, and these guesses certainly are subject to considerable testing. Our assumptions concerning the inhomogeneities do not limit the generality and power of the theoretical formulations.

On coming to the University of Wisconsin and joining the Department of Geology and Geophysics, I concentrated on the interaction of sound at the bottom of the ocean. Rona and I had made measurements of thin layers on a flat bottom using sonobuoy reflection profiles.(2) We had difficulty interpreting sonobuoy data, and this we ascribed to roughness of the bottom. Deep towed instruments have shown the presence of many features which are not resolved by surface instruments.(3) I became interested in the roughness of the sea floor, the relation of the roughness to geological processes, and ways of estimating its roughness. The need for better measurements of the roughness of the sea floor and the need for better acoustic theory had been reinforced by my efforts to apply the results of the Marine Geophysical Survey to the prediction of sonobuoy performance. We did not have the theory needed to predict the signal scattered to a hydrophone from an omnidirectional source when the bottom was acoustically rough. Even if we had the theory, the roughness of the bottom and its spatial correlation function were, at best, gross estimates.

My purpose has been: to develop and test a scattering theory, to use side scanning sonar data for the spatial character of the roughness, and to apply the theory to marine geophysical data.

C. S. C.

I. Proposed Research: Long Range Scientific Objectives

The research is to develop methods of relating reflectivity and roughness of the sea floor to its geophysical and geological description. Geological processes shape the sea floor and are manifested in the rms roughness, spatial spectrum of the roughness, the layering, and physical properties of the sediments. These properties can be used, as acoustical theory is developed, to predict the performance of underwater communication and sonar systems in areas where the sound interacts with the sea floor. Laboratory acoustic experiments are to test critical assumptions in the theory. As we become skilled in the interpetation of reflection and scattering data, we will use the large store of existing echo-sounding and seismic profile data in the delineation of the geophysical (acoustical) properties of the sea floor.

II. Introduction

We chose to study the interaction of sound signals at roughened sea surfaces and sea floors. I believed that it was a difficult problem and made a three-pronged attack. Accordingly, we started research on the nature of sea floor roughness, scattering of sound at rough boundaries, and ways to use arrays of transducers to achieve higher spatial resolution of signals scattered at the sea floor. We have achieved the long-range scientific objective of that research.

Many papers have been published as a result of this study, and three students have used part of it for their Ph.D. research.(4,5,6) Since the research is broad, I have organized the final report to give a brief synopsis of the acoustical and marine geophysical research. Abstracts of papers and technical reports are given in the appendix.

III. Scattering of Sound at a Rough Surface.

An understanding of the sound scattering phenomena is the key to using sound to study the sea floor. Eckart's theory of sound scattering has formed the basis of our research.(7) His 1953 paper is very elegant and direct. He used the Helmholtz integral and a statistical procedure for injecting the randomly rough surface into the sound scattering problem. To obtain simple formulas, Eckart made four simplifying approximations:

1) He used the Kirchhoff approximation (signals are reflected as if the local area is a plane surface),
2) He let the slopes be so small that they could be ignored,
3) The incident wave front on the surface is a plane wave,
4) He estimated the scattering of sound at very short sound wavelengths λ relative to the rms roughness σ ($k\sigma \gg 1$, where $k = 2\pi/\lambda$) by one procedure and the scattering at long wavelengths of sound, $k\sigma \ll 1$, by another. Neither procedure can be used in the middle region, $k\sigma \simeq 1$.

We mention that Eckart derived a coherent reflection coefficient which only depended upon the Kirchhoff approximation.

For the following reasons, we believed that the effects of the simplifying approximations had to be measured for the theory to be of practical value in sea floor studies:

1) The errors due to the Helmholtz integral and the Kirchhoff approximation can be tested by experiment.
2) Factors for inclusion of the slopes of the rough surface have been

derived. On the basis of the acoustical studies which were made under Professors R. T. Beyer and A. O. Williams of Brown University, we believed that the errors due to the first and second approximations were small.(8,9)

3) Practically all marine acoustic measurements were made using systems having rather large beamwidths. Thus, the wave front is nearly spherical over the illuminated area.

4) We expect $k\sigma$ to range over all values and the restriction to a limited class of spatial correlation functions of the surface (Gaussian) needs to be removed.

At the time that Tolstoy and I were writing Ocean Acoustics, we believed that most of the problems with scattering theory were associated with 2) and 4). In analyzing the results of an experiment in which the fluctuations of reflected sound were measured, I had broken the sea surface into small subareas and applied plane wave theory to each subarea.(10) Since my main interest was in using measurements of coherent reflection coefficients to estimate roughness of the sea floor, I didn't continue work on the sphericity of the wave front.

In the summer of 1968, Professor Medwin and I did a set of sound scattering experiments in his laboratory at the Naval Postgraduate School, Monterey, California. We measured the cross correlation of signals scattered to a pair of hydrophones. To explain our results, I expressed the illuminated area as being the sum of small subareas.(11) This work was published in a pair of papers by Medwin and Clay in 1970.(12,13)

Laboratory experiments had shown that sphericity of the incident wave front had to be included. Professor Horton showed that the Fresnel approximation could be used as an approximation for spherically incident waves.(14) I combined this with my research involving ways to include arbitrary correlation functions of the rough surface. These results were published in "Notes on Ocean Acoustics" in 1971.(15) This study had important but unpleasant results. The scattering function, as it is usually defined, is dependent upon the beamwidth of the sonar which is used to make the measurements. In the specular direction, the bottom loss term in the sonar equation depends upon the beamwidth in addition to the character of the bottom.

G. A. Sandness, a doctoral student who was supported under the ONR contract, did a set of experiments to test the dependence of the scattering function upon beamwidth.(16) The experimental and theoretical scattering functions are shown in Figure 1. We believed that the agreement verified the theoretical approach. In making these measurements, Sandness had developed experimental techniques which enabled him to reduce the fluctuation of measurements of the scattered sound signals to a few percent.

The next step was to study the necessity of including the slope factor. These measurements were made in a backscattering mode to increase the magnitude of slope factor relative to the zero slope approximation. The experimental results were systematically different from the theory. Sandness found that the difference was due to the use of the Fresnel approximation. He suspected that the error was associated with the use of a spherically incident wave front instead of the actual wave front. A very small source radiates a spherical wave front. We were using transducers having 5° beamwidths. In the "far field" the wave front was nearly spherical in the main lobe, but it had different phases in the minor lobes. Surprisingly, the

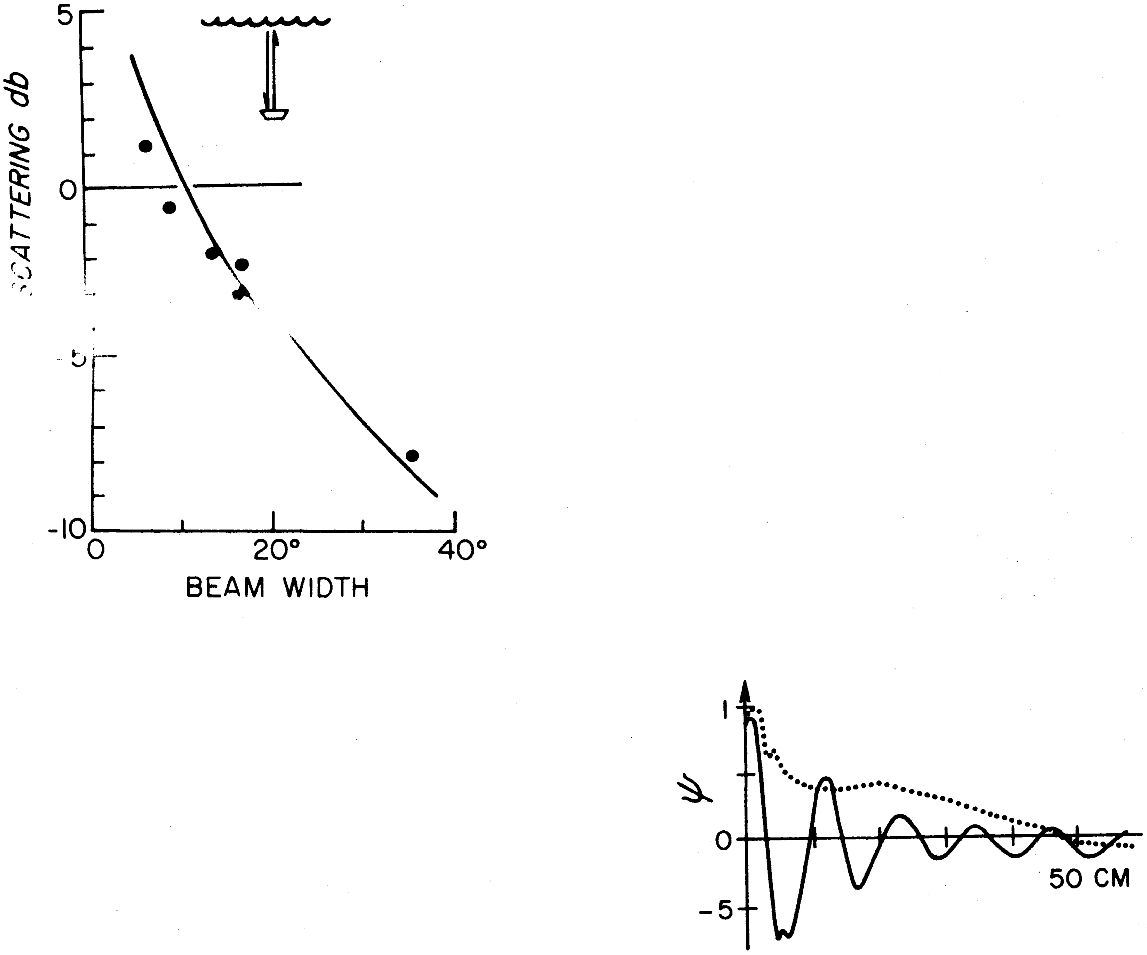


Figure 1. Scattering function. The data were taken at 200 kHz at depths of 50 cm. $\sigma = .14$ cm, $k\sigma = 1.1$. The measurements were made at vertical incidence. The dotted line is the crosswind correlation function, and the solid line is the up-down wind correlation function.

difficulty was due to the use of the Fresnel approximation in calculating the reflection at the smooth surface. Sandness had been using the reflection from the smooth surface to calibrate the system, and the error due to the Fresnel approximation entered the calibration procedure.

Since the Fresnel approximation was suspect along with boundary conditions, Sandness did a numerical integration of the Helmholtz integral for the rough surface. The result was in excellent agreement with experimental measurements, Figure 2. We now had a standard against which to test theoretical approximations. The results are:(17)

1) The slope of the surface needs to be included.
2) The amplitude and phase of the incident sound signal are needed to calculate the reflection from a smooth surface.
3) When the surface is very rough, $k\sigma\cos\theta > 1$, the phase of the incident sound signal becomes less important, and Fresnel approximation can be used.

While the numerical studies were being made, I derived theoretical equations which were applicable to Sandness's experiments.(18) The Fresnel approximation, Gaussian approximation for the main lobe of the beam, and slope factor as given in Ocean Acoustics, p. 197-99, were used for numerical calculations.(1) The comparison of the approximate theory and experimental measurements are shown in Figure 3.

On the basis of our experiments and for errors at the few percent level, I summarize the status of sound scattering theory as follow:

1) The Helmholtz integral and Kirchhoff approximation can be used.
2) The slope factor should be included. For incident and scattering angles greater than 45°, shadowing effects are important, and our

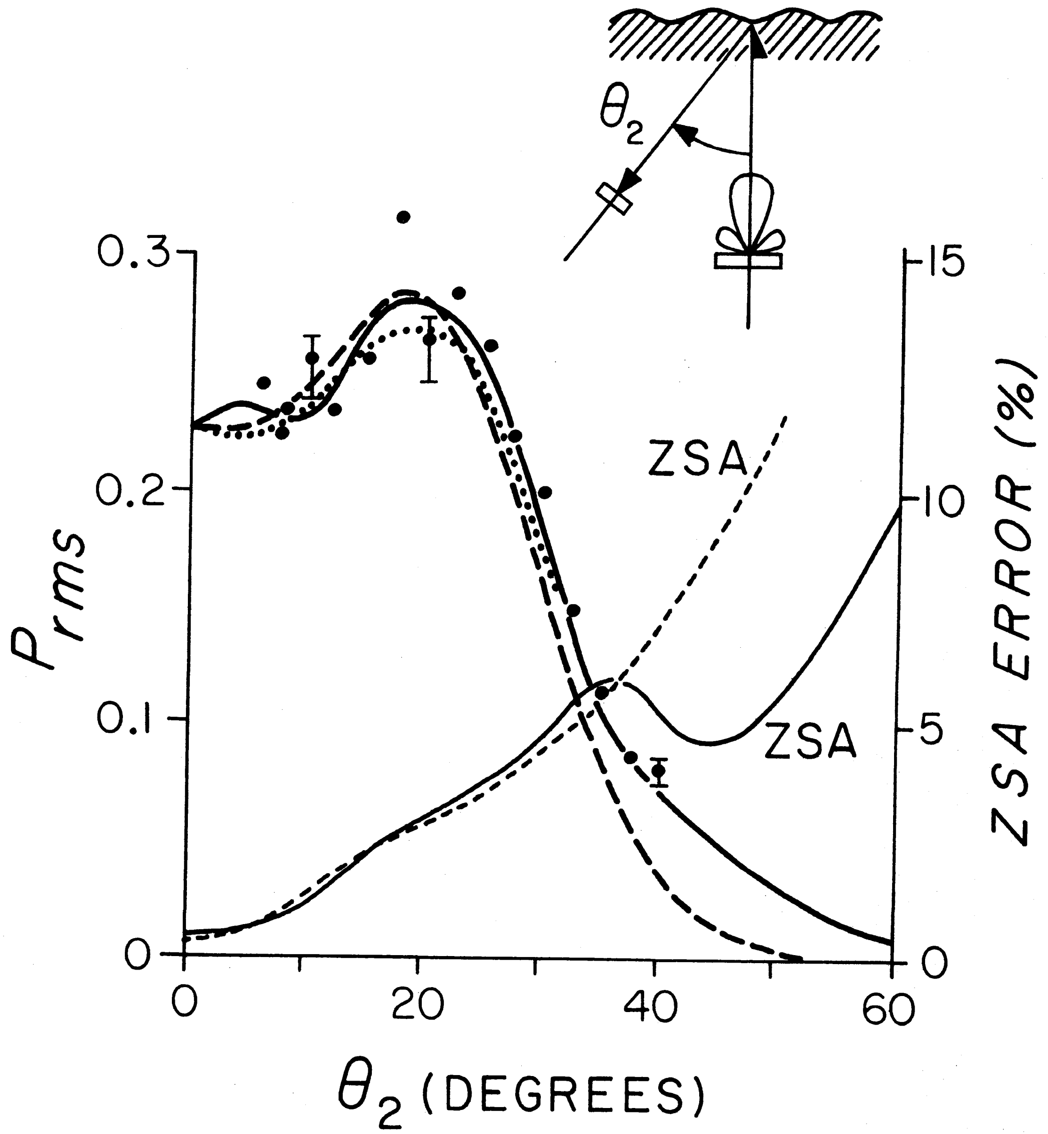


Figure 2. scattered sound at 200 kHz. The rms scattered pressure and the error of zero slope approximation (the curves labeled ZSA) are shown. The solid and dotted curves were computed numerically; the dashed curves are from an analytical solution using a Gaussian beam, and the circles are measured values. The sound is vertically incident and scattered hydrophone at θ_2. The beamwidth of the transducer, null to null, was 16°. R was approximately 50 cm. The surface was sinusoidally corrugated and had a wave length of 7.8 cm and σ of 0.21 cm. $k\sigma$ was 1.83. Based upon Sandness (1973).

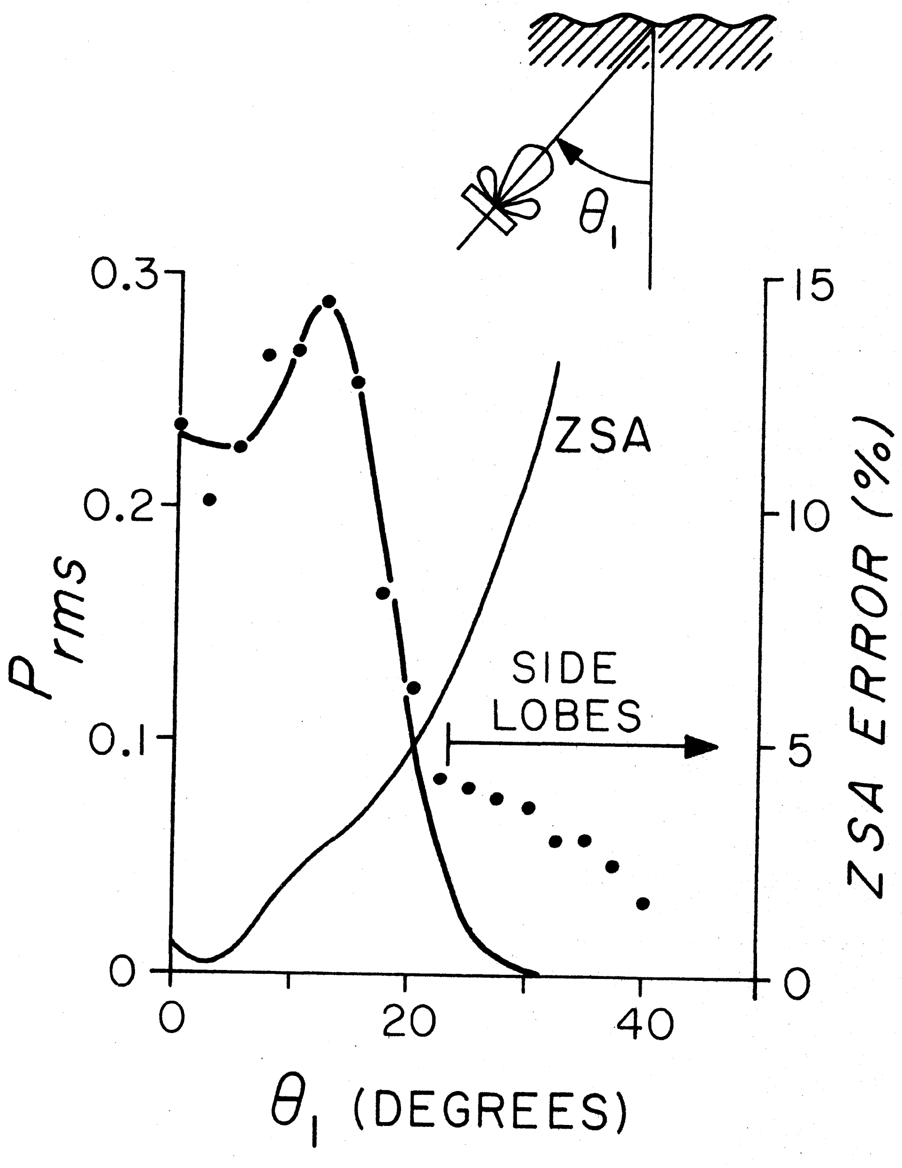


Figure 3. 200 kHz backscattered sound. The rms scattered pressure and error of the zero slope approximation, ZSA for backscattering are shown. The curves are from the analytical solution. The circles are measured values. The side lobes were ignored in the analytical computation. Sandness attributed the scattered sound for $\theta_1 > 20°$ to the side lobes of the transducer. From the geometry, a portion of the side lobe was forward scattered to the receiver at an angle of incidence of about 12° for $\theta_1 > 20°$. R is approximately 50 cm. The surface is the same as for Figure 2. Based upon Sandness (1973).

results do not apply.

3) The sphericity, amplitude, and phase of the incident wave must be included. The spatial correlation distances of the roughness relative to the dimensions of the first Fresnel zone are very important.
4) Scattering functions have been derived for arbitrary spatial correlation functions and all values of $k\sigma$.
5) The coherent reflection coefficient and the probability density function (PDF) of the rough surface are related by the Fourier transformation and quite independent of the measuring system. If the surface is shadowed, the PDF is modified.(19)
6) Scattering functions and bottom losses depend upon the geometry of the measurement and the measuring system in addition to the bottom.

The theory, in Fresnel approximation, is in Hampton, ed., Physics of Sound in Marine Sediments, p. 373-446 (1974).

IV. Scattering Characteristics of Features on the Sea Floor.

Reverberation measurements have been used for many years to measure the scattering characteristics of the sea floor. When reverberation measurements are made using systems having very low directionality, the sound scattered by all unresolved features is lumped into a gross average scattering function. To apply the results of low resolution measurements to the prediction of the performance of a high resolution system, one assumes that the roughness is statistically homogeneous. That is, within the physiographic province, all sub-areas have the same r.m.s. roughness and spatial correlation functions. On the basis of side-scanning sonar records, it is fair to say that the hypothesis has limited applicability. Since the roughness is not statistically homogeneous, it is important to identify scattering features and to relate them to geological processes.

In 1968, the side-scanning sonar was the most practical high resolution system for measurement of the backscattering of sound of the bottom. Measurements were made using 30, 45, and 200 kHz, sonars. Because of an accident, our sonar studies were made in Lake Superior, north of the Keweenaw Peninsula. A research aircraft of the National Center for Atmospheric Research was lost in the fall of 1969. John Berkson of our laboratory assisted in the search and interpreted the side-scanning sonar records. The search ship also carried underwater television and divers. Shore-based transits were used for navigation. They surveyed about 50 km^2 north of Freda, Michigan. This enabled us to correlate sonar data with ground truth.

Berkson found part of the area to be sandy and relatively smooth. The backscatter here was uniform. A large pipe was found but apparently the aircraft wasn't in this area.(4) Elsewhere the bottom was quite variable, having boulders, patches of gravel, and outcrops. If the aircraft were in the rough areas it would have been extremely difficult to find it. To process the sonar records, Berkson first reduced the 19-inch graphic records photographically and then removed the lateral distortion.(20) The corrected records were assembled in a mosaic. A tracing of the mosaic is shown in Figure 4.(4, 21) The 1969 survey is the region designated as A where water depths were less than 60 m. Scattering features are: sand having small ripples, patches of boulders and gravel, and outcrops. These features have the appearance of submerged beaches.

The following year, we extended the sonar survey north into Region B and water depths greater than 60 m, Figure 4. We found a marked change in the topography, and the sonar records were spectacular. After correction for distortion, the records showed that the bottom was covered by an intersecting network of grooves, Figure 5. The widths ranged from 5 to 75 m, and some grooves had lengths to about 2 km. From echo sounding records, the depths were of the order of 5 m. A tracing of the mosaic of the records is shown in Figure 6.(21) R. J. Wold, University of Wisconsin, Milwaukee, told us that his seismic profiler data did not show grooves on the bed rock beneath the sediments.

G. A. Sandness, of our laboratory, suggested that the submerged points of icebergs could cut grooves like the ones we found. He used a water and "Crisco" model to show how the points dragging on the bottom could cut about

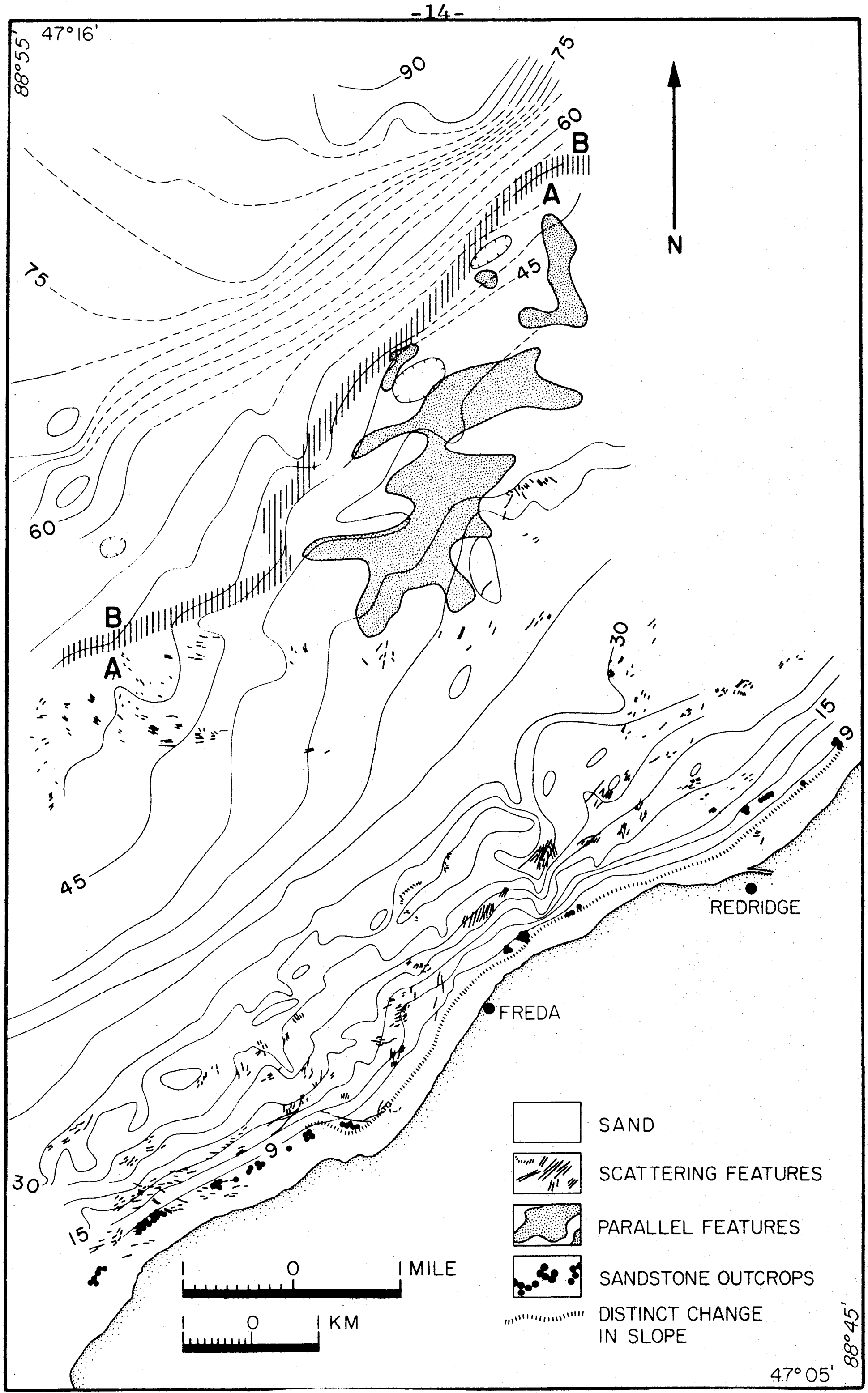


Figure 4. Bathymetry and character of Lake Superior floor in Regions I and II. Bathymetry based on echosoundings ~450 m apart; character of lake bottom based on interpretation of sonar mosaics; scattering features probably patches of boulder gravel. Contour interval, 3 m.

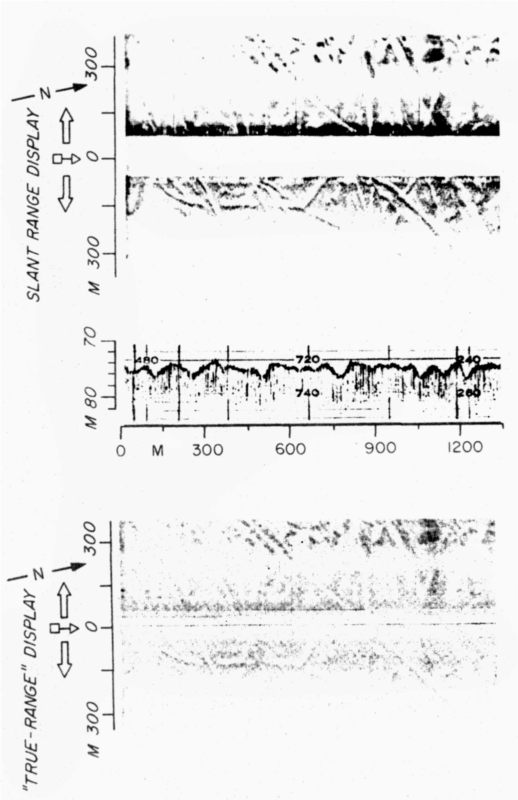


Figure 5. Grooves of Zone B. Original sonograph in slant-range display shown at bottom. "True-range" sonograph (bottom) has been corrected for lateral-scale and slant-range distortion. Continuity of grooves crossing ship's trace now more apparent: lighter zone in left channel of sonograph caused by interference lobe involving rays reflecting off ship's hull and rays taking the direct path. Echogram in center.

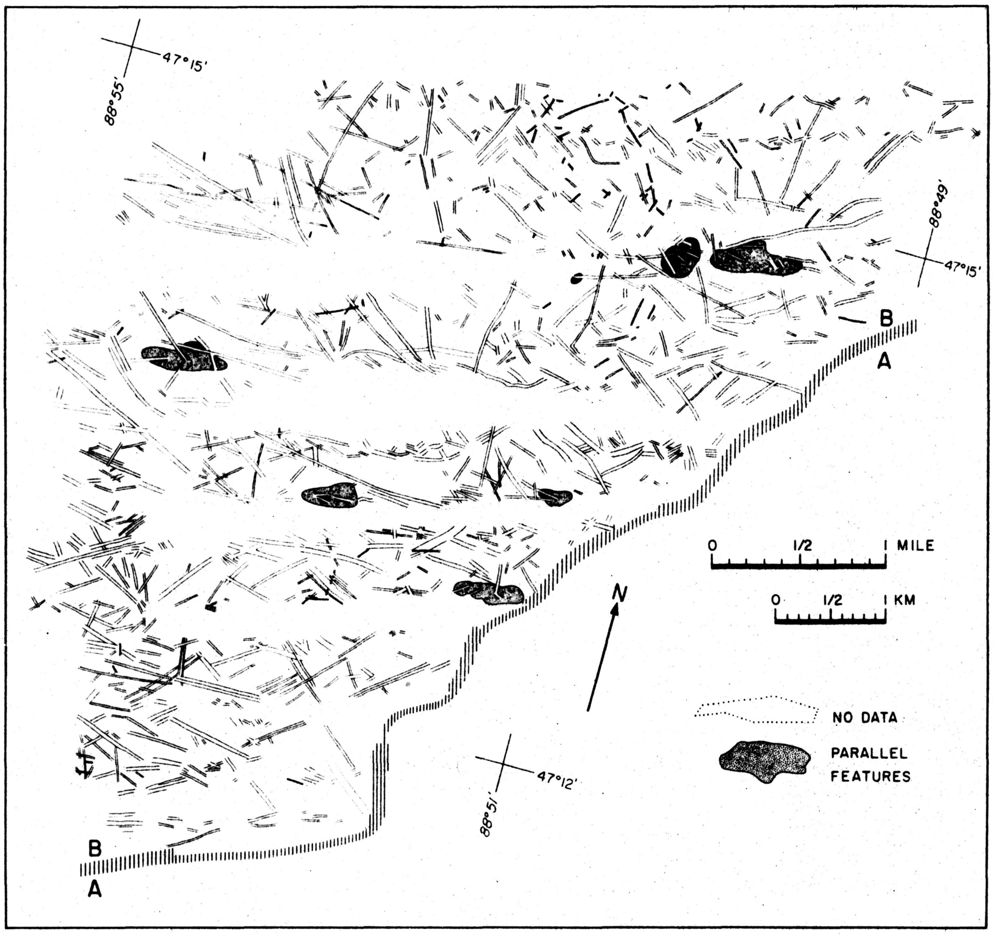


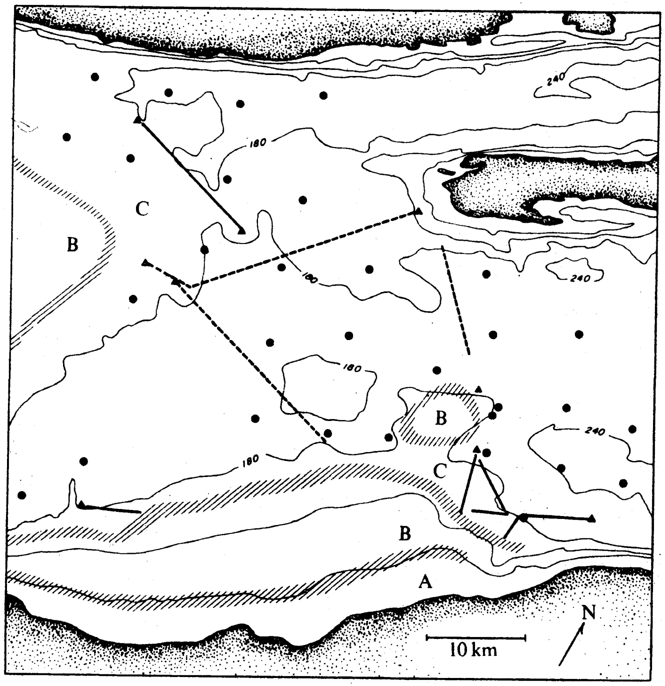
Figure 6. Grooves of Region II. Plot constructed from sonar mosaic. Side-scan sonar maps ribbon of bottom about 450 m to each side of ship's track; Region II surveyed with parallel tracks approximately 510 m apart. When maximum ranges of adjacent sonar records do not touch or overlap, no-data regions result.

the same depth of groove even though the water depth varied. On the basis of glacial history, we believe that the most recent grooves were cut about 10,000 years ago. Recently, sonographs showing groove features have been obtained in the Arctic Ocean.(22)

Berkson identified another physiographic zone which he called "C", Figure 7a.(4) High resolution echo soundings were taken in the area, and these showed the presence of many thin beds. V-shaped troughs occur extensively on the echograms (Figure 7b). Sonographs of the bottom were made using a Kelvin-Hughes transit sonar (46 kHz). As shown in Figure 8, these polygonal features have the appearance of large mud cracks. John Sanders of Barnard College suggested that a syneresis type of process might be the cause.(23) During syneresis, water is expelled during the gelling of the colloidal system. The resulting shrinkage of the sedimentary layer yields syneresis cracks. These appear as polygons, cones, and pits on the records. Large-scale subaerial dessication polygons have been reported. We are unaware of syneresis explanations for similar large-scale submarine features.

V. Delineation of the Geophysical Properties of the Sea Floor.

Our purpose in this part of the work was to combine sound scattering theory and echo soundings of an area to make quantitative estimates of the roughness of the sea floor. As viewed by means of a sonar on a surface ship, features on the sea floor fall into two gross regions: features that are resolved by the sonar system and features that are not. The minimum dimensions of resolvable features is dependent upon the beam width sonar system and the water depth. In our study area, most of the



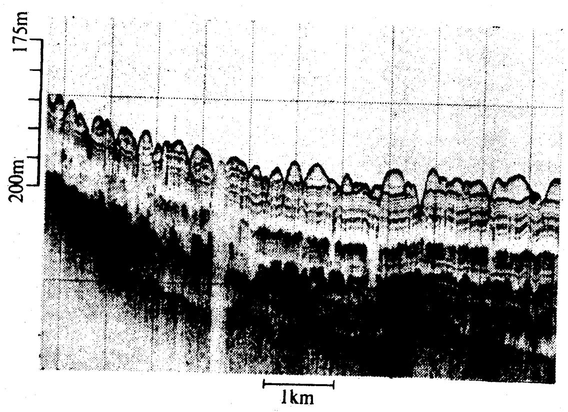


Figure 7b. Sub-bottom profile of valleys.

Figure 7a. Lake Superior area of investigation. ——, Side-scan sonar and vertical echosounding profile; ---, sub-bottom profile; O, Carnegie core; △, bottom sample. A, B and C, Physiographic zones of Berkson and Clay[1]. Contour interval 60 m.

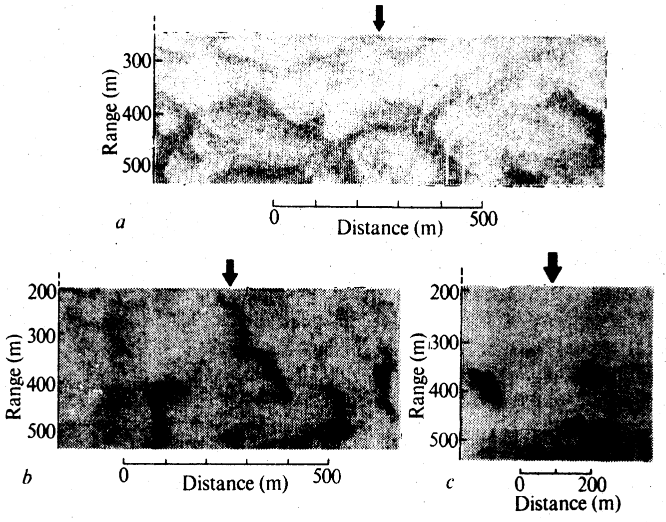
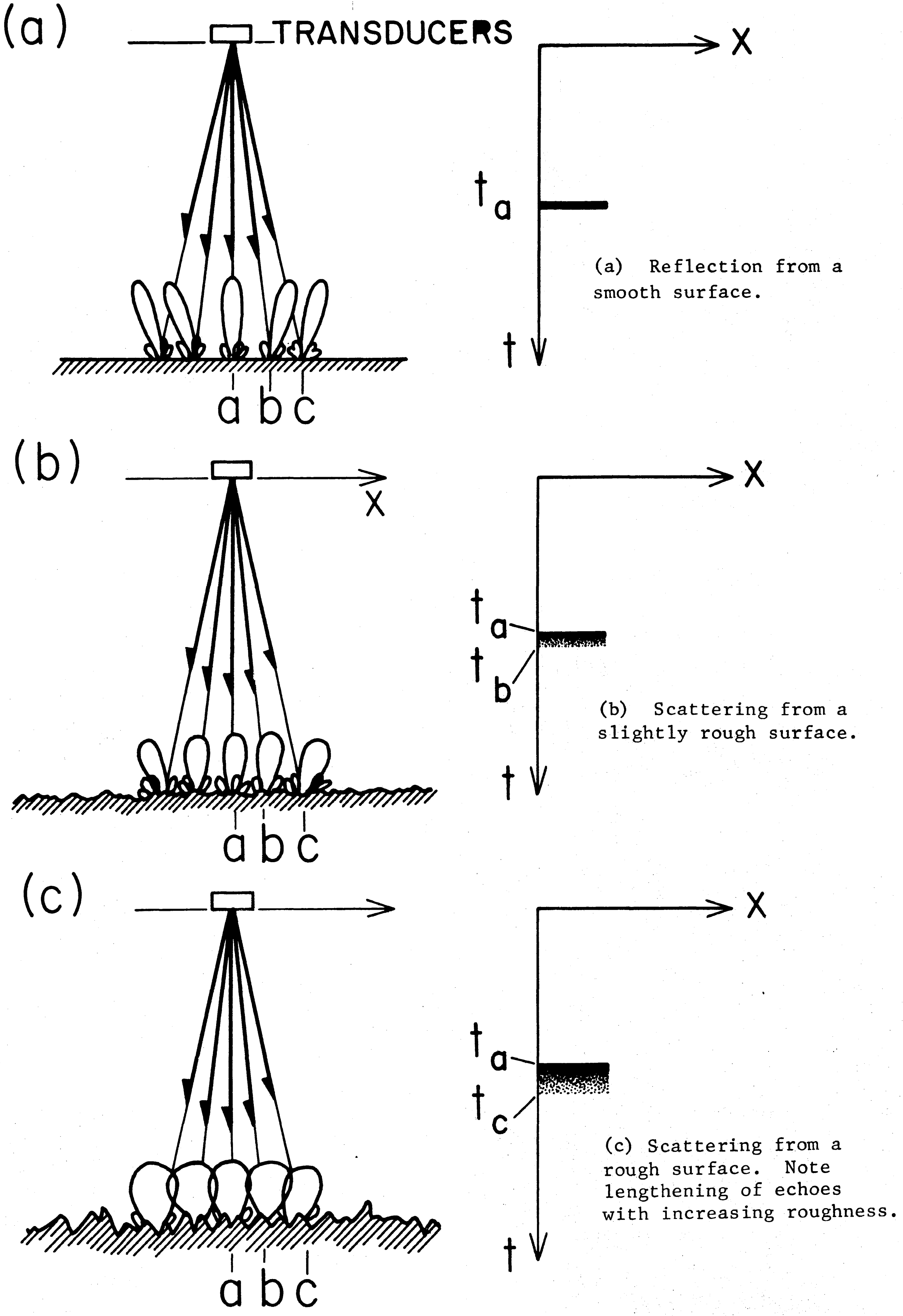


Figure 8. Sonographs of valleys, physiographic zone "C".



(a) Reflection from a smooth surface.

(b) Scattering from a slightly rough surface.

(c) Scattering from a rough surface. Note lengthening of echoes with increasing roughness.

Figure 9. Simplified sketches of scattering of sound at surfaces having different roughness.

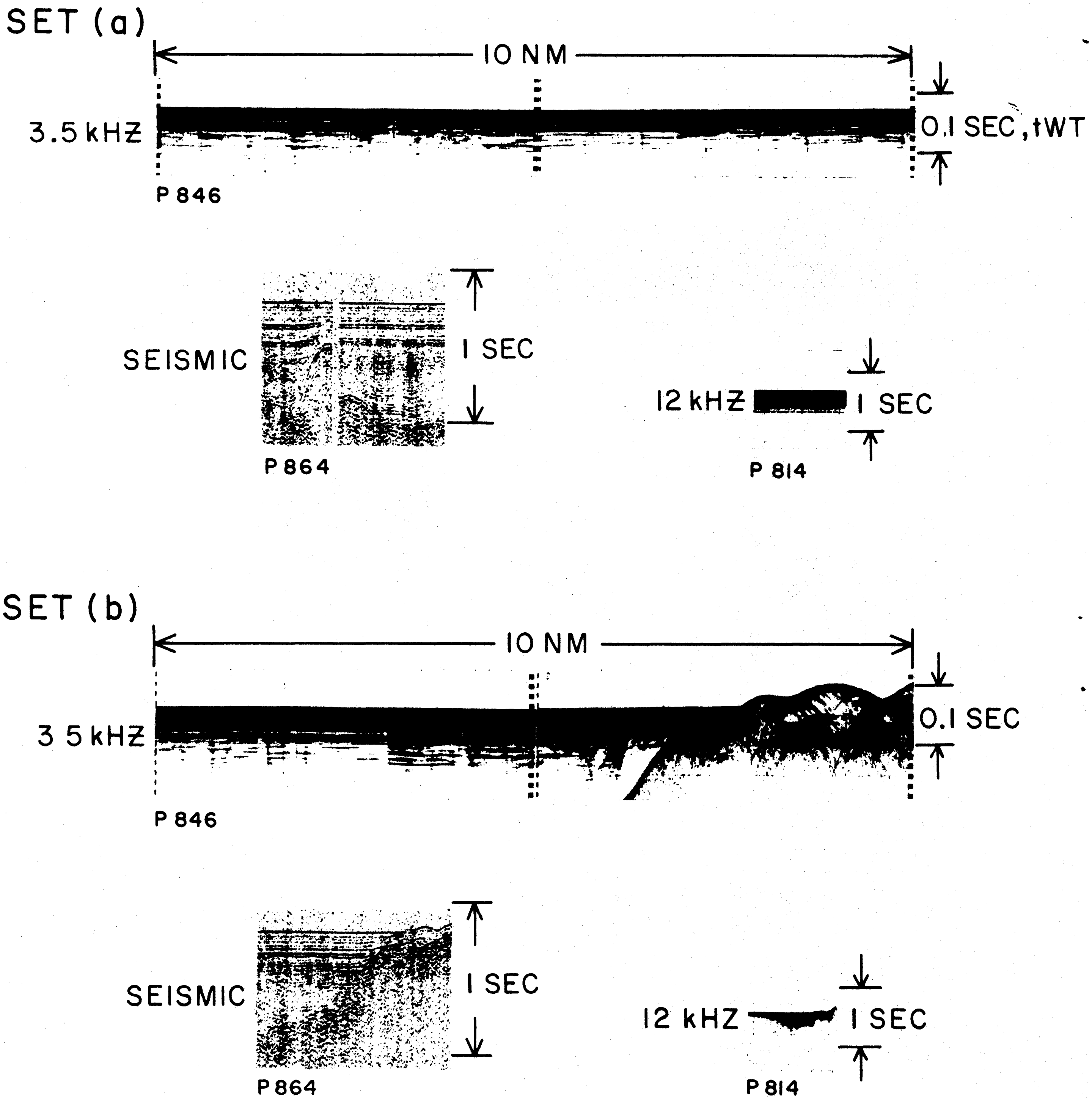
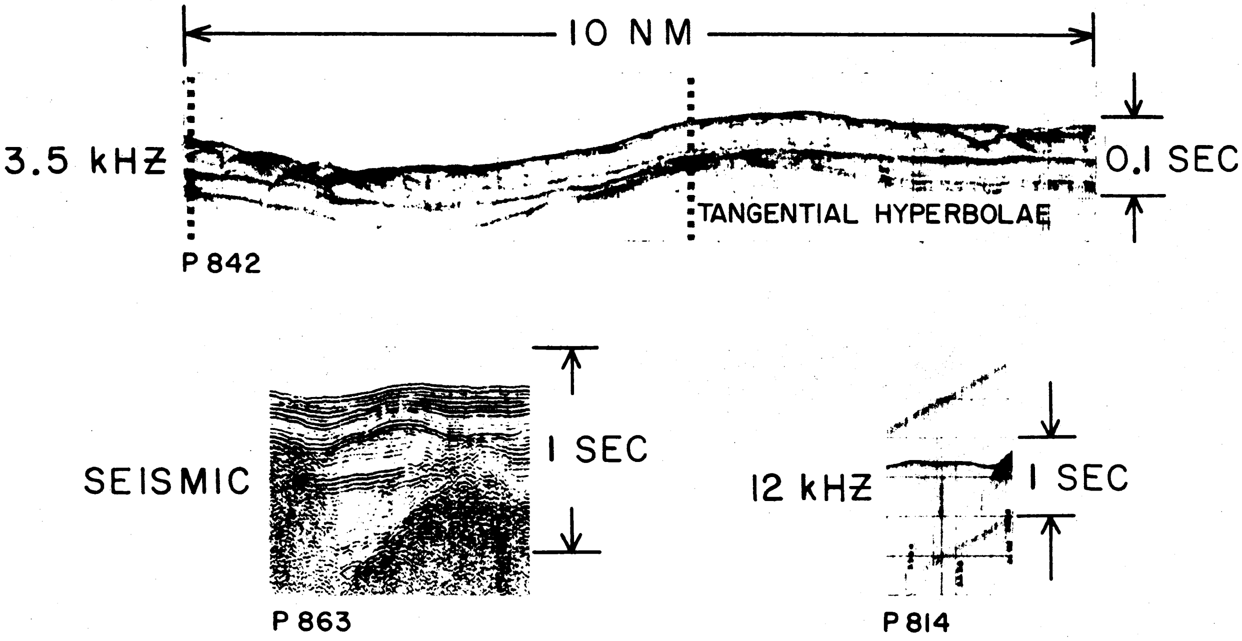


Figure 10. Bottom and sub-bottom profiles selected from the Kane 9, 1968 cruise. Profiles within each set were taken from the same rough area. Note that bottom roughness is apparent from the 12 kHz profiles in sets (a) and (b), but not in sets (c) and (d), in following page. Probable σ values for (a) $0.05 < \sigma < 2$m; (b) $0.1 < \sigma < 2$ m; (c) $2 < \sigma \leq 10$ m, and (d) $0.7 < \sigma < 2$ m. twT, two-way travel time.

SET (c)



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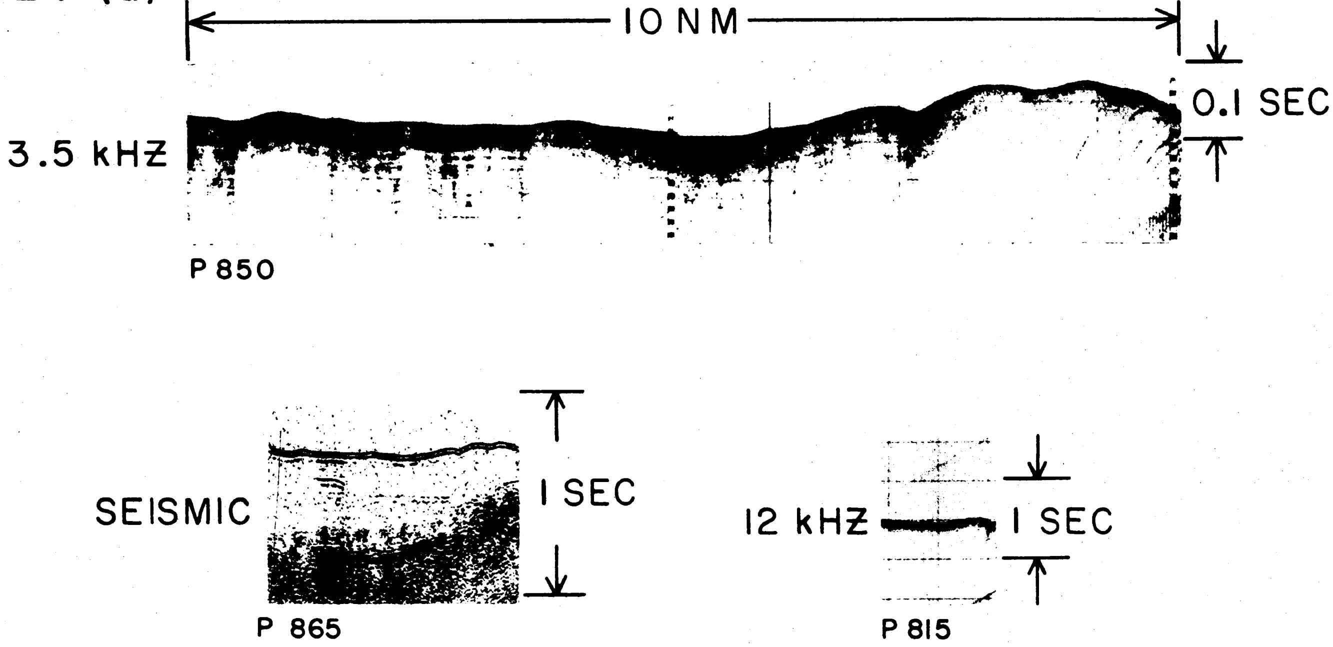

Figure 10 (continued)

data were taken at 4 km depth and with a standard depth sounder having about 30° beamwidth. From bottom photographs(24) and deep-towed side-scanning sonar records,(3) we know that many different sizes of features may be in the same area and superimposed on each other. Thus, we made a crude spectral analysis by estimating the roughness in several wave length regions of the sea floor features.

From preliminary examination of the echo sounding records, statistically homogeneous physiographic areas were identified as having the same spectrum of roughness and bottom type. Within each of these areas, large scale features were identified on the echosounding records, and the roughness within each wave length region was estimated. The roughness of unresolved features was estimated by comparing the character of the reflection at the water-bottom interface for 12,000, 3,500, and 25 Hz sound signals. Based upon scattering theory, an acoustically smooth bottom, $k\sigma < 1$, had a well-defined reflection and, except for subbottom reflections, was like the transmitted ping.(25) Over an acoustically rough bottom, $k\sigma > 1$, the scattering of sound caused the signal to have a "tail", and the echosounding trace to be fuzzy. These effects are sketched on Figure 9. Data from the Kane 9, 1968 cruise are shown on Figure 10. On the first example, a bottom was locally rough for 12 kHz signals and very smooth for seismic signals. On the second example, the bottom had about 30 m of relief over 10 nm, but was locally smooth for 12 kHz signals.

We chose to study the sea floor west of Spain.(5) Laughton furnished a copy of his bathymetric chart of the area. Leong changed the original chart to show depths in meters, and the revision is shown on Figure 11.

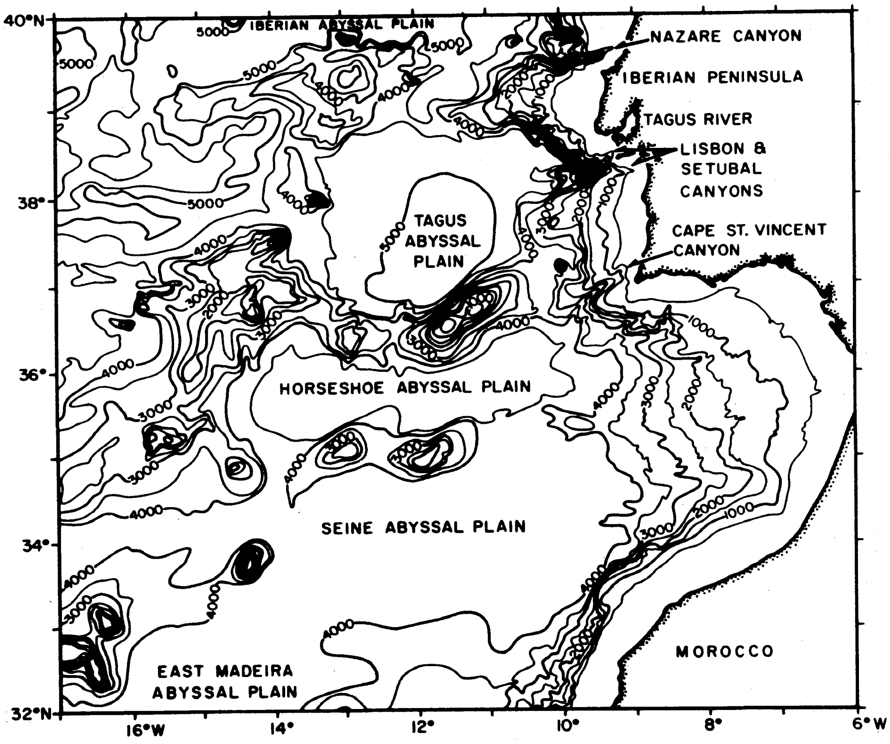

Figure 11. Bathymetric map. The contours have been redrawn in meters from unpublished bathymetric maps furnished by the British National Institute of Oceanography (courtesy of Dr. A. Laughton). The track density of the original charts is much greater than that of Figure 12.

We needed the original seismic profiles and echo soundings. Most of the data were obtained from the Marine Geophysical Surveys and were furnished by the Naval Oceanographic Office. These data were supplemented by data obtained by Lamont-Doherty Geological Observatory. The area and ship tracks are shown on Figure 12.

The echo sounding records were analyzed by first measuring the relief of large scale features (12 - 60 km), and these results are shown on Figure 13. Smaller scale features may be superimposed on the large scale features. The distribution of features having wave lengths less than 12 km is shown on Figure 14. The relief of features in the 2 - 12 km wave length range is shown on Figure 15.

The character of the roughness of the sea floor has been used to define physiographic provinces. Similarly, we have used spectral estimates of the roughness of the bottom to define statistically homogeneous physiographic areas. Estimates of the roughness in the spectral regions (I) 0 to 0.2 km, (II) 0.2 to 2 km, (III) 2 to 12 km and (IV) 12 to 60 km are shown on Figure 16. The character of the roughness is indicated by the a, ''', g and corresponding echograms are shown on Figure 17.

Having estimated the roughness of the bottom, we consider how this information can be applied to the estimation of the reflection losses of bottom reflected signals. First, the densities and sound speeds of the layers of sediment on the bottom are needed to calculate a local reflection coefficient $\mathcal{R}$. The coherent reflection coefficient $< R >$ is nearly independent of the sonar system and the spatial correlation function of the sea floor.$^{(19)}$ It is

$$\left\langle \mathcal{R} \right\rangle \simeq \mathcal{R} \exp \left[-2 \left(-k\sigma \cos \theta \right)^2 \right]$$

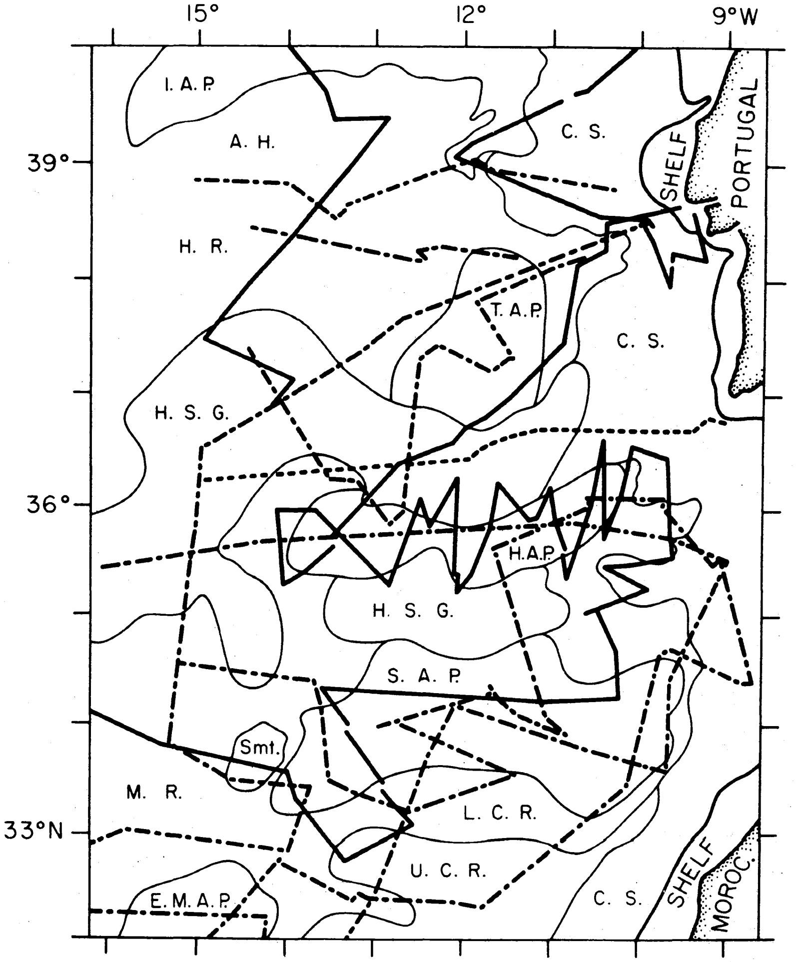

Figure 12. Location map showing ships' tracks and physiographic provinces. Solid lines are tracks from Vema 27 cruise, 1969 (L-DGO); long and short dashed lines are tracks from the Atlantic Seal and Arctic Seal, 1965-1966 (U.S. Naval Oceanographic Office); and short dashed line is a track from the Gibbs, 1966 (OP240, Brakl, 1968). Province boundaries were modified after Plate 4, SP95-5-5 (U.S. Naval Oceanographic Office, 1967a). Symbols used: A.H., abyssal hills; C.S., continental slope; E.M.A.P., East Madeira Abyssal Plain; H.A.P., Horseshoe Abyssal Plain; H.R., Horseshoe Rise; H.S.G., Horseshoe Seamount Group; I.A.P., Iberian Abyssal Plain; L.C.R., lower continental rise; M.R., Madeira Rise; S.A.P., Seine Abyssal Plain; Smt., seamounts; T.A.P., Tagus Abyssal Plain; and U.C.R., upper continental rise.

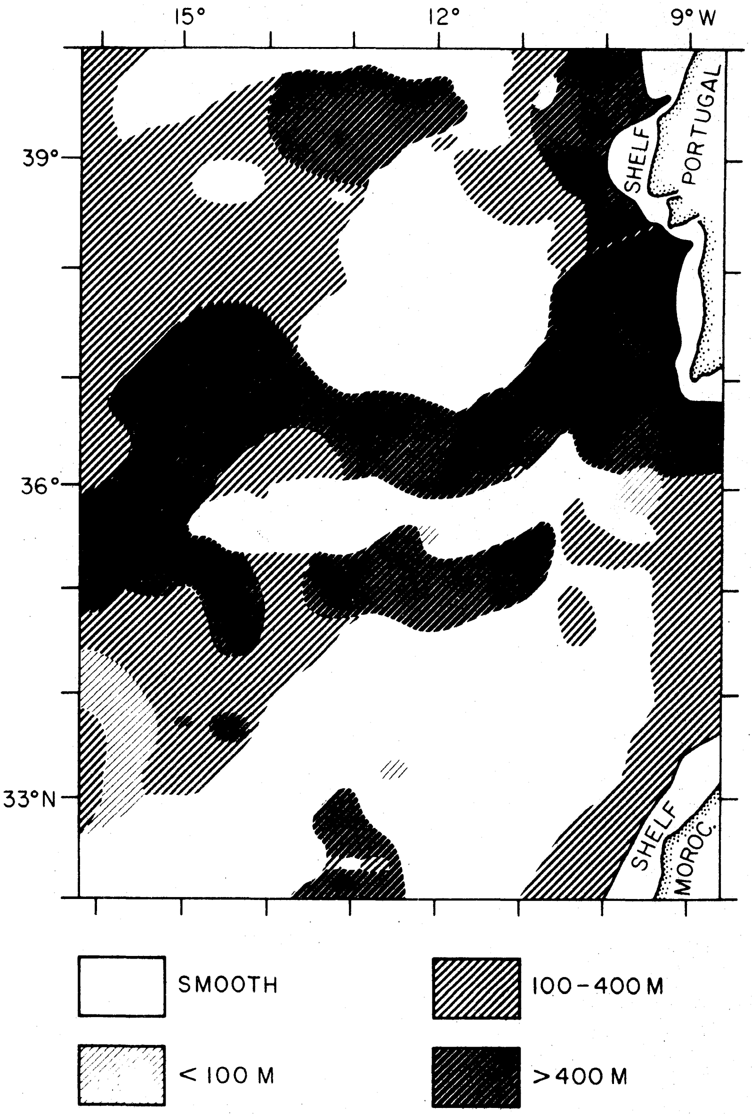

Figure 13. Large-scale relief. These features have wave lengths in the range of 12-60 km. The wave lengths were measured between peaks which stand higher than intervening peaks.

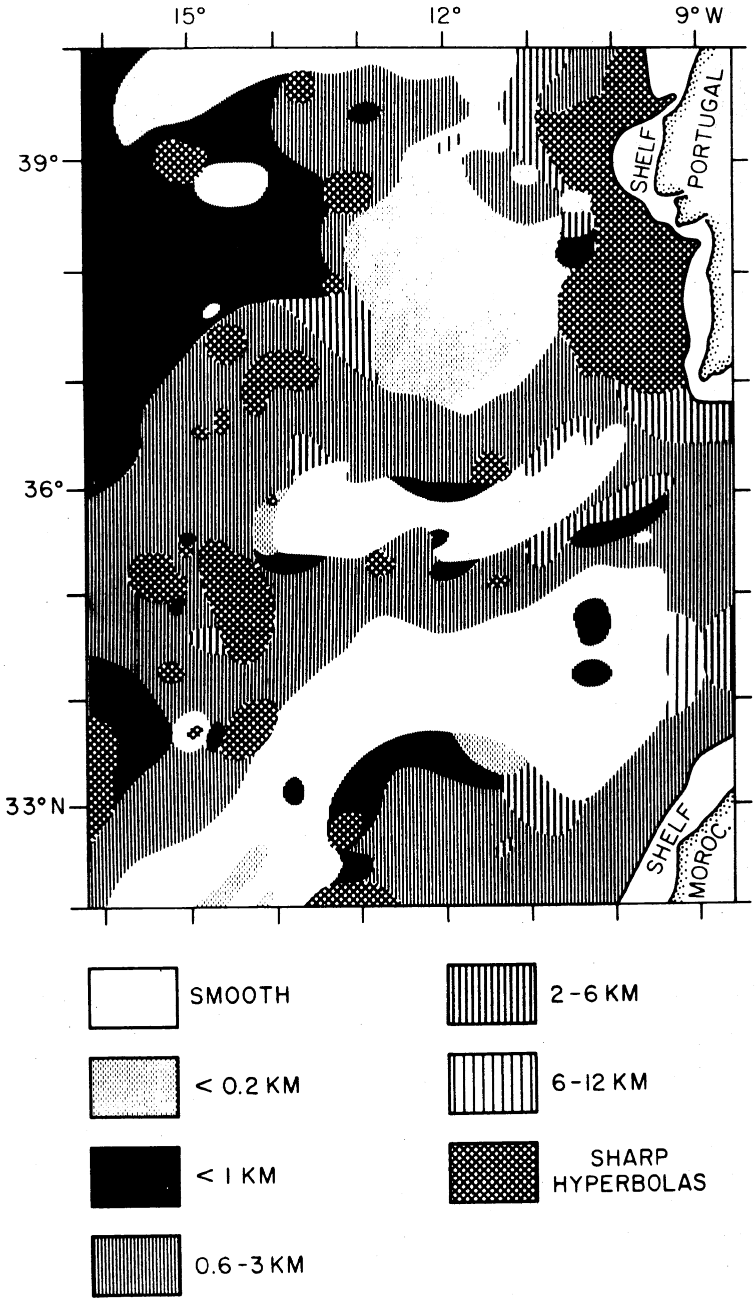

Figure 14. Topographic wave lengths for small-scale features.

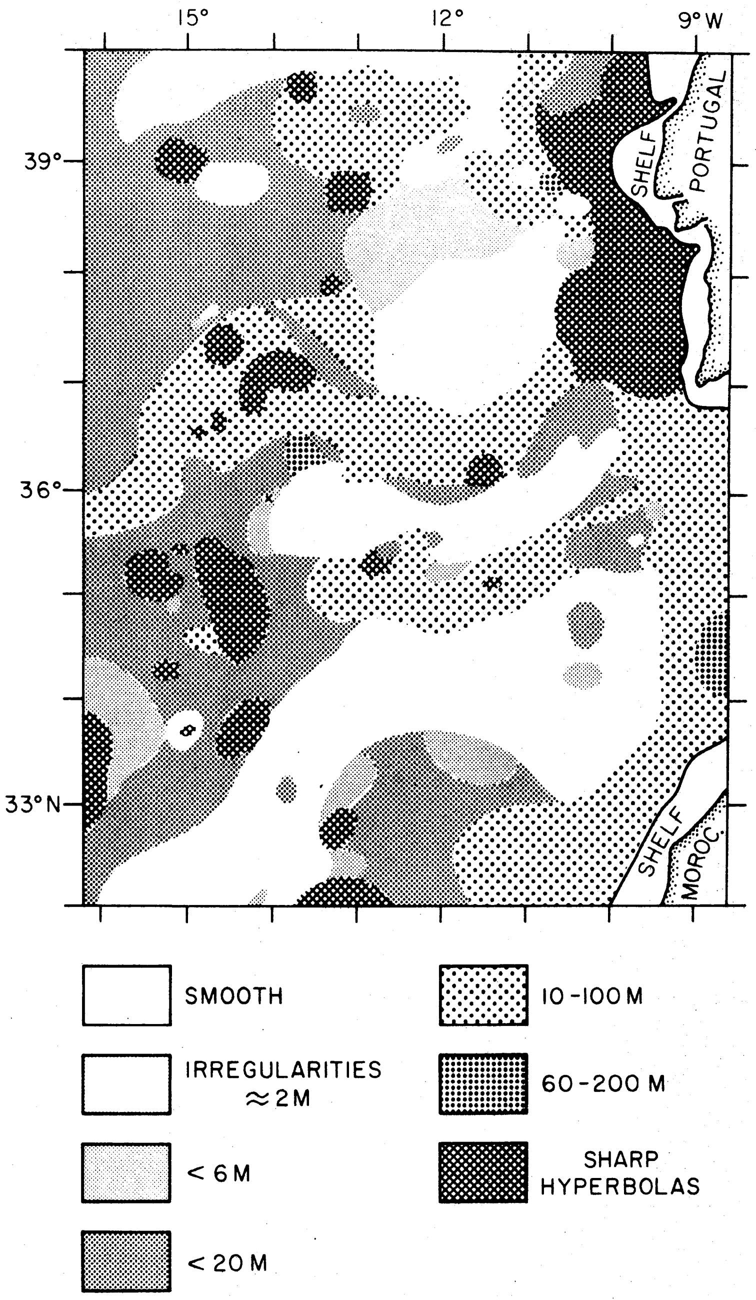

Figure 15. Relief for small-scale features. The features are in wave length range 2-12 km.

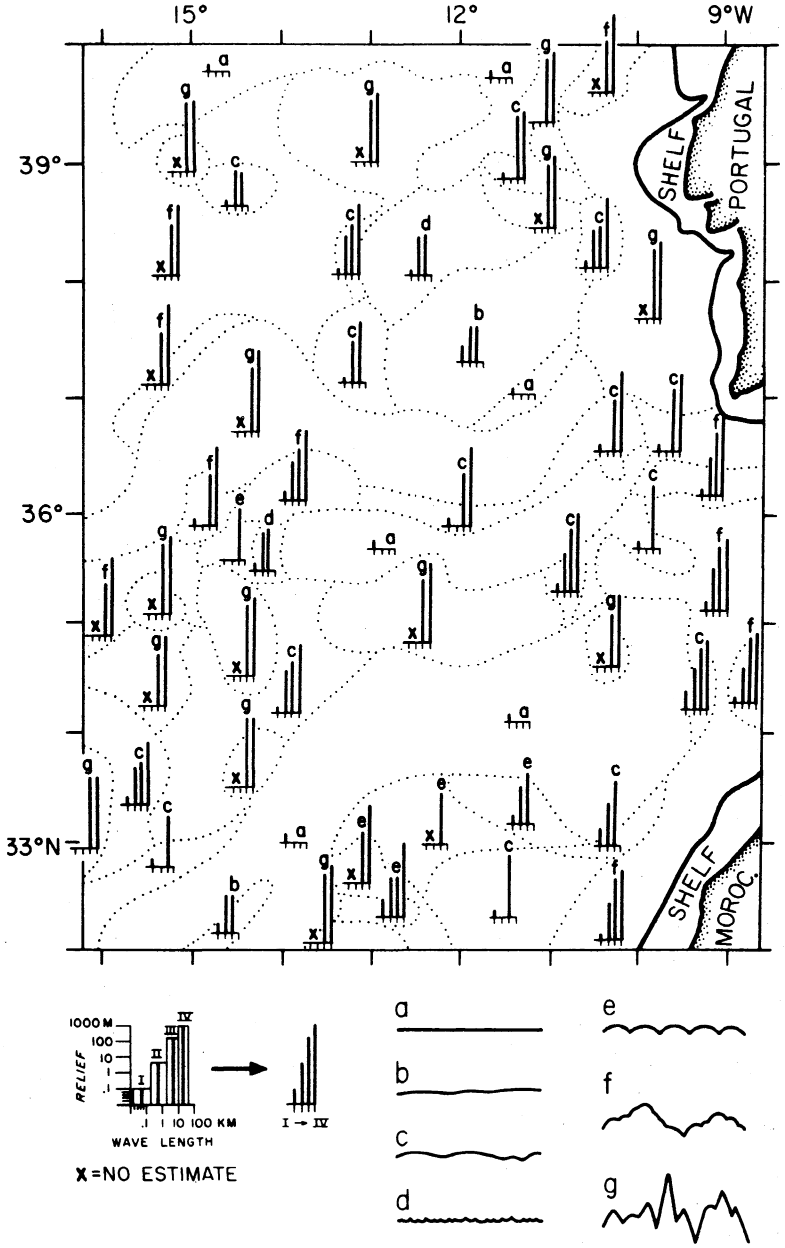

Figure 16. Roughness in different wave length regions. Each histogram shows the dominant or the roughest topography and microtopography within an area enclosed by dots. Typical examples of echo soundings for keys a-g are given in Figure 17.

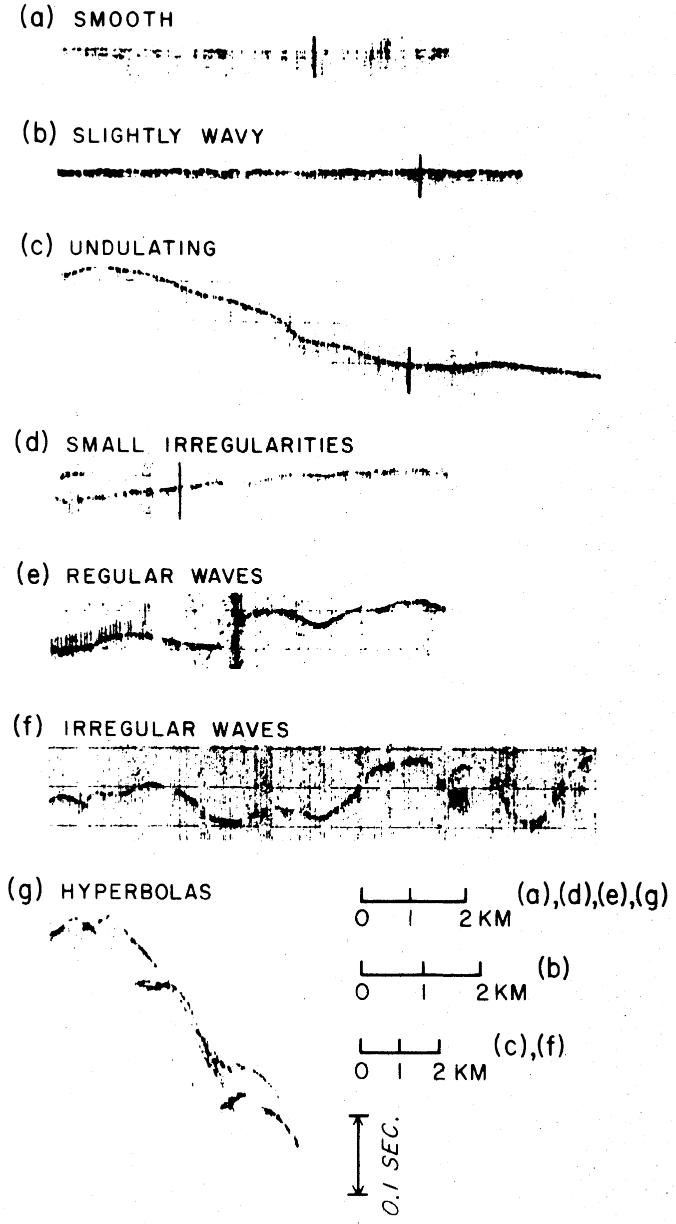

Figure 17. Echograms showing the small-scale topographic characters of the sea floor of Figure 16. (U.S. Naval Oceanographic Office records).

In deriving $\langle\langle \mathcal{R} \rangle\rangle$ the roughness is assumed to have a Gaussian probability density function.

If the received signal is processed by squaring and integrating over the arrival, then we have no knowledge of the coherent component and should regard the entire signal as being scattered. The second moment of the signal $\langle p^2 \rangle$ is

$$\langle p^2 \rangle = \frac{\langle p_o^2 \rangle R_o^2}{R_1^2} \quad \frac{A}{R_2^2} \quad S$$

Where $\langle p_o^2 \rangle$ is the mean square pressure signal at distance R_o from the source, R_1 and R_2 are the source and receiver distances to the scattering area A, and S is the scattering function. S is measured experimentally or calculated theoretically. S is a function of $k\sigma$, the spatial correlation function of the bottom, and the geometry of the measurement. We recall from Section III that S is dependent upon the beamwidth of the sonar system which is used to make the measurements.

In theoretical calculations of the magnitude of the scattered signal, the ratio of the spatial correlation distance of bottom features relative to the dimension of the first Fresnel zone is important. If the feature is larger than the Fresnel zone, then the signal can be reflected coherently by a facet even though the bottom is quite rough. For this case, the magnitude of the signal does not depend upon the beamwidth when the illuminated area is larger than the first Fresnel zone. Features smaller than the first Fresnel zone scatter incoherently, and the scattered signal $\langle p^2 \rangle$ is proportional to the area. This result has implications in the analysis of a sonar system's performance.

In analyzing echo sounding records, we found the presence of reverberation to be useful in identifying acoustically rough bottoms. The dependence of the coherence of the reflected signal upon frequency enabled us to estimate the roughness. However, once the lateral dimensions of the features were unresolved by the ship's sonar, we had no way to estimate the lateral dimensions. We believe the next step in sonar studies at the sea floor should be the measurement of the spatial spectra or correlation functions of the sea floor in statistically homogeneous areas. These data are needed for studies involving the second moment of scattered signals.

These results and the theory are given in detail in the book Physics of Sound in Marine Sediments, pp 373-446. (1974), Plenum Publishing Corp., New York, N. Y.[26]

VI. Directional Systems.

Our skill in measuring the sea floor is limited by the resolution of the sonar systems and our ability to process and display data. Computational technology has improved orders of magnitude since echo sounders were first used for bathymetric data in complicated areas. Higher resolution measurements are required to measure the spatial correlation functions. A large array can be synthesized by towing. A source can be towed in a large sonobuoy field. All of the signals can be combined to give the equivalent of large source and receiving arrays.

Two parts of the problem are: efficient processing is needed because of the large number of channels of information, and the array is in an inhomogeneous medium. Professor Hinich and I have collaborated on a number of papers on optimal array processing techniques.

ACKNOWLEDGMENTS

I came to the University of Wisconsin, Department of Geology and Geophysics, in January, 1968. The Office of Naval Research supported me and my students while we built a hydroacoustic laboratory and learned to do the research which I have described. I am grateful to my student collaborators in the research, J. M. Berkson, W. L. Leong, T. K. Kan, and G. A. Sandness. Professors Hinich and Medwin have joined me in the research. I particularly wish to thank Dr. J. B. Hersey for the opportunity to work with him on marine geophysical problems. Hersey's problems directly influenced my research.

The University of Wisconsin's Geophysical and Polar Research Center supported our physical needs and helped us construct things like water tanks and sonar fish. Paul Dombrowski created the illustrations in our technical reports and papers. Kathryn Hanson and Ruth McCormick transferred our equations and prose into drafts and finally into papers and reports.

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APPENDIX

POLARITY COINCIDENCE ARRAYS

C. S. Clay

The purpose is to examine the performance of a multiple polarity signal-processing system for an array having a small number of channels. The system has a narrow directional response and small side lobes for CW signals. In the m-channel system, the instantaneous signals are sampled to determine the sign of the signals. If all m channels have the same sign, the output is 1 and otherwise the output is 0. The system performance is measured by the ratio of the mean output of system s_N to the standard deviation of the output σ_N. Gaussian noise is assumed to be in each channel and is uncorrelated between channels. At small input-signal to noise-power ratios, s_N/σ_N was proportional to the input-signal to noise-power ratio, $N^{\frac{1}{2}}$ and $f(m)$, where N is the number of independent observations and $f(m)$ is a system function. $f(m)$ has a maximum value at $m=6$. The response of a six-receiver array was simulated on a delay line. The signals were delayed the times 0, T, $2T$, $4T$, $7T$, and $13T$. For a CW signal, the output was 1 at the frequency T^{-1}, and the null-to-null width of the main lobe was $(15T)^{-1}$. The side lobes were less than 0.1.

J. Acoust. Soc. Amer., 47, (Part 1), p. 432-434, 1970.

CORRELATION OF ACOUSTIC SIGNALS SCATTERED AT A ROUGH SURFACE

C. S. Clay

The cross correlation and covariance of the acoustic signals reflected from a statistically-rough surface is given. The transition from small roughness to large roughness is given for a randomly corrugated surface. The transition is smooth; however, application of the low roughness equations to the transition region can lead to too small of estimates of the scattered signals. The effect of divergent sound beam was studied, and it is necessary to define sub-areas, over each of which the plane-wave Helmholtz-Kirchhoff treatment is valid. The criteria used was that the wave front was within $\gamma/8$ of the plane tangent to the wave front over the sub-area. The sound reflected and scattered at each sub-area were separated into coherent and incoherent components. It was necessary to add the coherent components from the sub-areas coherently. The incoherent components were added incoherently. Numerical examples are given to show the magnitude of the signals scattered from the sub-areas. The covariance of signals observed at a pair of receivers are given as a function of the separation. The conditions of applicability of the theory to a geophysical problem have shown that: 1) The upper limit on the size of sub-areas is given by the $\gamma/8$ criteria for the plane wave approximation. 2) The lower limit is given by the requirement that the dimensions of the sub-area be many correlation distances of the rough surface. 3) Far field conditions require that the source and receiver be many acoustic wave lengths from the surface.

University of Wisconsin, Department of Geology and Geophysics
Research Report No. 69-1, 1969.

USE OF A TWO-DIMENSIONAL ARRAY TO RECEIVE AN UNKNOWN SIGNAL IN A DISPERSIVE WAVEGUIDE

C. S. Clay and M. J. Hinich

A relatively simple method is discussed for estimating the phase velocity and direction of an unknown plane-wave signal, propagating across a two-dimensional array in a dispersive waveguide. The finite Fourier transform is applied to the output signal of each sensor, and the phases of the smoothed frequency components calculated. The phases of the components are linearly regressed on sensor positions to produce estimates of the wave slowness components. Neither the phase nor group velocity dispersion curves need to be known, except for upper and lower estimates of the range. By smoothing over frequency and transforming, estimates are obtained of the direction and phase velocity of the signal. The precision of estimates depends on the signal-to-noise ratio, the square root of the number of sensors, and the number of wavelengths that fall in the array. Each frequency is treated separately, so that the direction and phase velocity are obtained as a function of frequency. Since the individual frequency components of the signal are separated, the signals observed on a large array can be combined, even though the dispersion is appreciable over the array. For good signal-to-noise power ratios, the dispersion curves are a direct result from the analysis.

J. Acoust. Soc. Amer., 47, (Part 1), p. 435-440, 1970.

DEPENDENCE OF SPATIAL AND TEMPORAL CORRELATION OF FORWARD-SCATTERED UNDERWATER SOUND ON THE SURFACE STATISTICS.

I. THEORY

C. S. Clay and H. Medwin

The correlation of underwater sound forward scattered from a time-varying statistically rough surface has been studied for the low-roughness case. The surface was illuminated by a divergent sound beam. Directionality of the source and receivers was included in a surface-illumination function. As an alternative to solving the Fresnel integral, the illuminated area was divided into subareas, for which the plane-wave Helmholtz–Kirchhoff treatment was valid. We used the criterion that the wavefront should be within $\lambda/8$ of the plane tangent to the wavefront over the subarea. The sound signals reflected and scattered at each subarea were separated into coherent and incoherent components, and the coherent components from the subareas were added coherently. The covariance of signals observed at a pair of receivers was computed with the aid of the bivariate Gaussian distribution function. Computations of the sound scattered by a traveling roughness, such as a gravity wave, showed that the covariance of the signals scattered into the first receiver and later into a second receiver can be large at a time delay, which is related to the group velocity of the roughness. The temporal and spatial covariances were also computed for a surface roughness having a damped cosinusoidal dependence upon space and time. The main contributions to the modulations of the spatial or temporal covariances came from the sound that was scattered from the subareas in non-specular directions.

J. Acoust. Soc. Amer., 47, (Part 2), p. 1412-1418, 1970.

DEPENDENCE OF SPATIAL AND TEMPORAL CORRELATION OF FORWARD-SCATTERED UNDERWATER SOUND ON THE SURFACE STATISTICS.

II. EXPERIMENT

H. Medwin and C. S. Clay

A large laboratory "sea" has been used to measure the spatial and temporal correlation of forward-scattered underwater sound and to interpret this behavior from the knowledge of the corresponding correlative properties of the statistically stationary time-varying surface. It is shown that the laboratory sea is a scaled replica of a low wind speed low-fetch ocean surface (Kinsman) in the acoustically significant parameters of displacement probability density and temporal correlation. The spatial and temporal sound correlations are found to have a modulated decrease with increasing displacement from the scattering axis and/or increasing time lag. The modulation is predicted by (a) dividing the insonified surface into defined, intracorrelated subareas and (b) describing the wind-driven surface in terms of a three-dimensional (space and time) height-correlation function that propagates in the windward direction. The experimental observations support the validity of the theory developed by Clay and Medwin which is described in the preceding paper, "Pt. I—Theory,"

J. Acoust. Soc. Amer., 47, (Part 2), p. 1419-1429, 1970.

TRAVELING CORRELATION FUNCTION OF THE HEIGHTS OF WIND-BLOWN WATER WAVES

H. Medwin, C. S. Clay, J. M. Berkson, and D. L. Jaggard

A wind-blown water surface can be characterized in terms of a traveling correlation function in which the group and phase velocities are given by the values at the frequency of maximum spectral energy density. The two-dimensional (space and time) surface displacement correlation function has been measured for low-divergence wind-blown waves in a laboratory tank. The measured phase and group velocities of the correlation function agreed with theoretical values for the peak frequency water-wave component when the measurements were transformed to coordinates that had the velocity of the surface (drift) current. This description, which may be useful in the ocean as well, has recently been used to predict the temporal correlation of sound scattered from a model sea of known three-dimensional surface correlation function (Clay and Medwin, 1970).

J. Geophys. Res., 75, p. 4519-4524, 1970.

USE OF ACOUSTIC SCATTERING THEORY TO INTERPRET MARINE GEOPHYSICAL DATA.

W. K. Leong, T. K. Kan, and C. S. Clay

The character of echo sounding profiles can be used to estimate the presence and magnitude of microtopography or bottom roughness. These are sea floor features whose lateral dimensions are smaller than the illuminated area and cannot be resolved by conventional vertical-beam echo sounding techniques. Vertical roughness may be estimated by studying the character of the returned signal. To test this, a laboratory experiment was conducted. The dependence of the reflected signal on the roughness of the surface was measured. It was found that coherent reflection from a smooth surface has $k\sigma \leq 0.5$ and phase coherency ≥ 0.6 (k is the wave number and σ is the rms roughness). Incoherent scattering from a rough surface has $k\sigma > 0.5$ and phase coherency < 0.6; phase distortion is most pronounced for $k\sigma > 1$ and phase coherency < 0.1. For $k\sigma > 1$, the duration of the echo was increased. Bottom and sub-bottom profiles were used to estimate bottom roughness. From the lengthening of the echo in some areas, we believe the sea floor can change from smooth to rough within short distances. If a rough sea floor is indicated on the 12 kHz record but not on the 3.5 kHz, the magnitude of σ can be bracketed between 0.02 m and 0.05 m. If roughness indication is present on the 25 Hz record, σ is greater than 5 m.

University of Wisconsin, Department of Geology and Geophysics, Research Report No. 71-1, 1971.

EFFECT OF BEAMWIDTH ON ACOUSTIC SIGNALS SCATTERED AT A ROUGH SURFACE.

C. S. Clay and G. A. Sandness

This problem originated in our efforts to measure remotely the acoustic properties of the sea floor. Conventionally, one measures the transmission loss for a path from the source to the bottom and back to the receiver. Analysis of the data is varied; sometimes the interaction at the bottom is treated as a reflection, and sometimes as a scattering process. We believe that the choice is not arbitrary and that the procedure needs to be examined carefully.

Underwater acoustic experiments were made in a laboratory tank in which the signals were scattered at a wind-blown surface. The rms roughness σ and spatial correlation function of the surface were measured by wave height probes. The ratio of the mean rectified signal scattered at the rough surface and that reflected at the smooth surface was measured for vertical incidence. Even though the surface was rough, $k\sigma > 1$, the mean rectified signal was inversely proportional to the source distance + receiver distance.

At large roughness the reflection-scattering function (bottom loss) depends upon beam width α and tends to the usual plane interface reflection function at small values of $\sigma/L\alpha$. (L is a measure of the correlation distance of the rough surface.) For large $\sigma/L\alpha$ the reflection-scattering function behaves like a reflection but it is much smaller than it would be for a plane interface.

Paper XVII, AGARD Symposium, Colorado Springs, June, 1971.

USE OF SIDE-SCANNING SONAR FOR CONTOURING BOTTOM FEATURES

L. L. Greischar and C. S. Clay

A side-looking sonar was used to study bottom features in Lake Mendota, Wisconsin. Interferences between direct and surface-reflected signals gave a tiger-striped pattern in the data. This pattern could be approximately interpreted as being the tracings of isoangle contours, However, this simple analysis was precluded by the strong gradients of sound-velocity profile. Ray traces were used to construct a profile of the interference field. The profile was used to interpret the data. Features having lateral dimensions of 10 m and a few meters depth were contoured. The data was taken when the sonar was about 100 m from the features.

J. Acoust. Soc. Amer., 51, p. 1073-1075, 1971.

NOTES ON OCEAN ACOUSTICS

C. S. Clay

Part of the notes are tutorial and part are an advanced development of acoustic scattering theory. I used the Fresnel approximation to evaluate the scattering integral for an arbitrary spatial correlation function ψ and a large range of surface roughness σ relative to the wave length of sound signals λ. The results are expressed in error functions for complex argument. The same function can be used from small σ/λ to large σ/λ. The scattering and reflection functions are dependent upon the beam width of the sonar system in addition to σ, λ, ψ, and the geometry.

University of Wisconsin, Department of Geology and Geophysics, Research Report No. 71-2, 1971.

MICROPHYSIOGRAPHY AND POSSIBLE ICEBERG GROOVES ON THE FLOOR OF WESTERN LAKE SUPERIOR

J. M. Berkson and C. S. Clay

The floor of Lake Superior northwest of the Keweenaw Peninsula has three zones of small-scale relief based on echogram character. The zones are roughly depth dependent. Zone A, located between the shore to about a 54-m depth, is generally smooth on the echogram and consists mainly of sand and boulder gravel deposits. Zone B, between about 54 and 165 m, has microroughness features with a 2- to 5-m relief and a 90- to 300-m spacing; the bottom consists of glacial till and lacustrine clay. Zone C, below depths of about 165 m, has narrow troughs with depths to 12 m and separation of 60 to 600 m; the bottom consists of lacustrine clay. The microrelief of Zone B consists of an intersecting network of grooves having widths of 5 to 75 m and lengths of as much as 1,950 m. Regular parallel features 15 to 30 m apart are also found in scattered areas of Zone B and the deepest parts of Zone A. Sand and boulder gravel deposits of Zone A may be beach and dune material of lower glacial-lake stages, and the border with Zone B may mark the lowest shoreline during the sequence of glacial lakes in the Superior basin. The grooves of Zone B were probably formed by scouring by icebergs during an earlier lake stage. Relief in Zone C probably was formed by a lacustrine process.

Geolog. Soc. Amer. Bull., 84, p. 1315-1328, 1973.

MAPPING THE UNDERSIDE OF ARCTIC SEA ICE BY BACKSCATTERED SOUND

J. M. Berkson, C. S. Clay, and T. K. Kan

A narrow-beam scanning sonar was used to measure the relative backscattering strengths at 48 kHz of the undersurface of arctic sea ice. The graphic records displaying the range and relative scattering levels were assembled into a sonar map that displays the location and shape of under-ice features. The data indicate that there are two distinct types of backscattering: (1) very high level backscattering from well-defined under-ice ridges and (2) very low level backscattering from between the ridges. The higher scattering at the ridges is probably due to the increase in roughness and the tilting of the average plane of the scattering surface. Comparison of the sonar map and the aerial photograph shows that most surface features have subsurface expressions and that their relationship can be complex.

J. Acoust. Soc. Amer., 53, p. 777-781, 1972.

SPECULARLY SCATTERED SOUND AND THE PROBABILITY DENSITY FUNCTION OF A ROUGH SURFACE

C. S. Clay, H. Medwin, and W. M. Wright

The coherent component of specularly scattered underwater sound is sensitive to the probability density function (PDF) of displacements of the rough surface. For the specular reflection of diverging waves, the coherent component and the PDF are shown to be related by the Fourier transformation. Laboratory measurements of sound scattered at a partially shadowed nearly Gaussian model sea surface show the coherent component is much larger than would be expected for a Gaussian PDF. Fourier transformations of the measured PDF, on inclusion of a shadowing correction, gave the coherent component. Fourier transformation of the coherent component yields a surface PDF similar to the measured PDF with shadowing correction.

J. Acoust. Soc. Amer., 53, p. 1677-1682, 1972.

POSSIBLE SYNERESIS ORIGIN OF VALLEYS ON THE FLOOR OF LAKE SUPERIOR

J. M. Berkson and C. S. Clay

RELIEF features occur on the floor of Lake Superior in distinct zones which are related to bottom type and water depth Zone A occurs in sand and gravel deposits to about 54 m depth. Deeper, the generalized sequence of sediments is bedrock, glacial till and sand deposits, red clay, red varved clay, and brown clay. In zone B, a network of intersecting linear grooves of width 5 to 75 m having relief of 2 to 5 m and lengths of greater than 2 km occur in a till and red clay bottom at about 54 to 165 m depth. The grooves were probably formed by scouring by icebergs during an earlier lake stage when the continental ice sheet formed a border of the lake. In zone C, below about 165 m, the bottom consists of lacustrine clays, and a series of narrow, V-shaped valleys occur extensively on echograms. In this study, the valleys were examined by side-scan sonar, high resolution sub-bottom profiling, echosounding, and bottom sampling.

Nature, 245, p. 89-91, 1973.

ERROR ANALYSIS OF VELOCITY AND DIRECTION MEASUREMENTS OF PLANE WAVES USING THICK LARGE-APERTURE ARRAYS

C. S. Clay, M. J. Hinich, and P. Shaman

The statistical properties of estimators for plane-wave parameters are discussed. A thick large-aperture array is assumed to be detecting a signal emanating from an unknown continuous wave source. The signal is assumed to be a plane wave embedded in a spatially incoherent Gaussian noise field. Maximum-likelihood estimators of velocities and directions are derived and their root-mean-square errors are obtained, for single and multiple arrivals for linear arrays and square arrays with a large number of sensors. The rms errors of the propagation parameter estimators are proportional to K^{-1} for a square-lattice array of K sensors and to $K^{-3/2}$ for a linear array of K sensors. The rms error of the waveform estimator, however, is proportional to $K^{-1/2}$ in each case. Thus, for the propagation parameters, the figure of merit for rms signal-to-noise gain of the array is K for a square array of K sensors and $K^{3/2}$ for a linear array of K sensors.

J. Acoust. Soc. Amer., 53, p. 1161-1166, 1972.

ACOUSTIC ESTIMATES OF THE TOPOGRAPHY AND ROUGHNESS SPECTRUM OF SEA FLOOR SOUTHWEST OF IBERIAN PENINSULA

C. S. Clay and W. K. Leong

Echo sounding records were used to identify roughness features in the wavelength ranges 6 km to 12 km, 2 km to 6 km, .6 km and 3 km, and less than 1 km. The latter features are not resolved at 3.5 km ocean depths. The character of the echo sounding trace was used to find the location of microtopography or small features. Within each of the spectrum regions, the rms roughness has been estimated. We found some long wavelength features having small roughness and others that were smooth. Acoustic implications will be discussed. The area studied in detail is 32°N to 40°N and 9°W to 16°W. Marine Geophysical Survey (1965-66), Naval Oceanographic Office, and Lamont-Doherty Geological Observatory data were used.

Hampton, ed., Physics of Sound in Marine Sediments, Vol. 1, p. 373-446 (Plenum, New York), 1974.

EXPERIMENT AND NUMERICAL EVALUATION OF ACOUSTIC SCATTERING AT A ROUGH SURFACE

G. A. Sandness

The Helmholtz integral is often used as the basis for theories on scattering of acoustic signals from rough surfaces, but several approximations must be made to obtain analytical solutions. Many of the mathematical difficulties in analytical computations can be avoided by numerically evaluating the Helmholtz integral. A numerical technique is described which utilizes measured values of the acoustic pressure of the incident beam, including the side lobes, thereby removing the uncertainty which normally results from approximating the form of the incident beam. A comparison of numerical, analytical, and experimental results is made for the case of a vertically incident beam and a moderately rough surface. The numerical computations are shown to yield values of the scattered pressure which agree well with experimental data for both rough and smooth surfaces.

These initial results indicate that the pressure reflected or scattered from a smooth, or slightly rough surface is sensitive to the phase of the side lobes of the incident beam. The rms pressure scattered from a very rough surface is apparently less sensitive to the form of the approximation used to specify the incident pressure.

The geometrical slope factor, $f(\theta_1,\theta_2)$, is often used in the literature to account for the effect of finite surface slopes. Its validity is verified numerically for moderate scattering angles and a sinusoidal surface, and the limitations on its validity are discussed. A further study of the effect of surface slopes, and a study of the general boundary value problem, including the effects of shadowing and the limitations of the Kirchhoff approximation, are suggested as useful extensions of this work.

University of Wisconsin, Department of Geology and Geophysics, Research Report No. 73-2, 1973.

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The final report is a summary of our study of the effect of roughness of the sea floor on marine geophysical measurements. We show comparisons of our scattering experiments and theory, scattering characteristics of the sea floor, sonographs of ice grooves on the bottom of Lake Superior, and the roughness of the sea floor in the basin west of Spain. Abstracts of the publications (11 papers, 2 contributions to symposium volumes, and 4 research reports) are in the appendix.

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