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# SACLANT ASW RESEARCH CENTRE

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## BOTTOM-INTERACTING OCEAN ACOUSTICS

Proceedings of a Conference held at SACLANTCEN on 9-13 June 1980

Organized by

WILLIAM A. KUPERMAN and FINN B. JENSEN

15 JUL 1980

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NORTH ATLANTIC TREATY ORGANIZATION

LA SPEZIA, ITALY



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# BOTTOM-INTERACTING OCEAN ACOUSTICS

Proceedings of a Conference held at SACLANTCEN
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# INTRODUCTION

In recent years the SACLANT ASW Research Centre has been conducting a research programme concerned with various aspects of bottom-interacting ocean acoustics. This conference represented an attempt to assemble as much state-of-the-art information as possible in order to further stimulate this research field, both at the Centre and elsewhere. To accomplish this, papers were called in the following areas:

1. Coastal-water acoustics,
2. Low-frequency deep-water acoustics involving bottom interaction.
3. Acoustic properties of marine sediments.
4. Ocean seismic studies as related to ocean acoustics.
5. Signal-processing techniques that include the effects of bottom interaction.

After receiving the abstracts presented on the following pages, the papers were re-categorized as follows:

I. Geoacoustic properties of marine sediments

II. Bottom loss: reflection and refraction

III. Bottom-interface and seismic-wave propagation

IV. Acoustic modelling

V. Sound propagation: techniques and experiment vs theory

VI. Fluctuations, coherence and signal processing.

These categories seem to represent the basic breakdown by field of present-day research in this area. Though each paper was classified into one of these categories for conference purposes, many papers overlapped two or three areas. Not only were scientific results communicated, but the latest techniques and the state-of-the-art tools of the trade (existing and in development) were also presented.

The proceedings of the conference will be published by the Plenum Publishing Co.* and we hope that this will provide a timely compilation of present-day research. More important, we hope that the person-to-person contact at the conference itself provided the ambience for a dialogue and cross-fertilization of ideas for future research.

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* The present document reproduces only the original abstracts of the papers and is published to maintain the continuity of the SACLANTCEN CP- series. Readers are referred to the forthcoming Plenum publication for the full texts.

# I

# *GEOACOUSTIC PROPERTIES* OF MARINE SEDIMENTS

# ATTENUATION OF SOUND IN MARINE SEDIMENTS

by

Jens M. Hovem
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Trondheim, Norway

## ABSTRACT

Attenuation of sound in water-saturated sediments may be caused by frictional losses in the grain-to-grain contacts or to viscous loss due to the movement of the fluid relative to the solid frame. Both losses can be included in the Biot theory for sound propagation in porous media. This theory gives an attenuation coefficient for the frictional loss that is proportional to the frequency (f) and a viscous attenuation increasing as $f^2$ at low frequencies and as $f^{\frac{1}{2}}$ in the high-frequency region. The Biot theory depends on a number of parameters that are difficult to estimate, particularly for high-porosity silt and clay. In these cases one may instead use a model for the sound velocity and attenuation based on multiple-scattering theory. This model gives the same frequency behaviour as the Biot model, but fails when the concentration exceeds a few percent. The reason for this is discussed, a modification to the suspension model is proposed, and the result compared with the Biot model. It is shown that, depending on the grain-size distribution, viscous attenuation may also increase linearly with frequency over a wide frequency band.

# DIRECTIVITY AND RADIATION IMPEDANCE OF A TRANSDUCER EMBEDDED IN A LOSSY MEDIUM

by

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und Geophysik
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ABSTRACT

For many reasons in underwater acoustics there is an urgency for in-situ measurement methods that describe the local acoustical properties of the sea bed. Knowledge of these properties enables one to derive the complex reflection factor under arbitrary angles of incidence, which is an important quantity in modelling sound propagation. Though preference has been given to all methods that operate remotely, no successful breakthrough has yet been achieved in providing a shipborne method that is reliable and easy to handle. In 1977 D.J. Shirley demonstrated that when an acoustical transducer is driven into the sediment, its radiation impedance depends on the specific acoustical properties of the surrounding environment. Though he gave only laboratory results and did not take into account the attenuation of the sediment, this proposal seems to offer a basis for the development of an appropriate shipborne in-situ measurement method. A prerequisite for such a development is the detailed knowledge of the relationship between the specific complex acoustic data of the sediment and the radiation impedance of the transducer. An analytical treatment of this problem is rather complicated, even under the assumption of compressional waves only. A mixed method of analysis and numerical evaluation is presented.

# ANISOTROPY RELATED TO DIAGENETIC STAGE IN DEEP-SEA CARBONATE SEQUENCES

by

Murli H. Manghnani and Seymour O. Schlanger
Hawaii Institute of Geophysics
University of Hawaii
Honolulu, Hawaii

## ABSTRACT

Acoustic anisotropy, expressed as $\Delta V_p\%$, $\Delta V_s\%$ and $\Delta V_{sh}\%$, measured in relatively pure carbonate deep-sea sequences exemplified by DSDP Site 289, increases irregularly but steadily as a function of sediment age, depth and burial history. In such sequences the dominant constituents are discoasters, caccoliths, and planktonic foraminifers made up largely of 1 to 10 mm calcite crystals. At shallow depths (close to the sediment/water interface) these crystals are randomly oriented. As diagenesis proceeds calcite crystals become preferentially oriented with their c-axis tending to lie perpendicular to the bedding: compaction dominated in the upper 200 m where dissoluation and in-situ precipitation of calcite dominate in deeper diagenetic stages. Strontium-content/age/depth relations show that the amount of calcite cement and overgrowth are largely correlated with sediment age. Petrofabric analysis shows the progressive development of crystal orientation as diagenesis proceeds. Porosity studies show that modal pore diameter as well as bulk porosity decreases with age and depth of burial. Poisson's ratio decreases with increasing density (depth) through the diagenetic transformation of ooze to chalk to limestone. A geoacoustic model of DSDP Site 289 is presented and interpreted.

# APPLICATION OF GEOPHYSICAL METHODS AND EQUIPMENT TO EXPLORE THE SEA BOTTOM

by

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## ABSTRACT

In marine seismic surveys the acoustic signal is starting and spreading in the water, reflected or refracted at discontinuities of the bottom and subbottom, and then returning into the water to the detecting sensors. The exploration for hydrocarbons usually requires deep penetration by application of low frequencies (between 5 and 150 Hz) and does not need detailed information about the sea bottom. Increased frequencies lead to higher resolution of structures but to decreased penetration. In that direction the advanced seismic methods and equipment can be developed to determine the interesting acoustic parameters of the sea bottom by continuous profiling. This paper will give a summary of the seismic technique and references for practicable developments in respect to research of the sea bottom.

# THE ACOUSTIC RESPONSE OF SOME GAS-CHARGED SEDIMENTS IN THE NORTHERN ADRIATIC SEA

by

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## ABSTRACT

High-resolution profiles obtained in the northern Adriatic Sea with a Uniboom (EG & G) sub-bottom profiling system have revealed peculiar acoustic features down to a depth of about 70 m below the sediment surface. Several different structures due to high gas content are described and explained for the first time in the northern Adriatic. Some acoustic voids are discussed in relation to the local stratigraphy, and a tentative explanation is given. The abrupt disappearance in some areas of acoustically significant horizons is discussed and evidence is given of the occurrence of the "bright spot" effect, instead of the bleaching-out phenomenon due to a highly diffused gas content. Possible migration of gases and trapping effects are also discussed. The importance of high-quality, high-resolution recording is stressed in order to detect the anomalies - due to gases - in the geotechnical properties of the sea-floor sediments and to evaluate their potential as geological hazards for off-shore installations.

# SIMULTANEOUS APPLICATION OF REFLECTION-STRENGTH RECORDER, SIDESCAN SONAR, AND SUB-BOTTOM PROFILER IN SEAFLOOR SEDIMENT MAPPING

by

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## ABSTRACT

The results of mapping the seafloor sediment distribution by simultaneous application of different acoustical methods, such as measuring reflection intensities from the echosounder returns, sidescan sonar, and sub-bottom profiling supplemented by cores and surface samples, are compared. The reflection intensities are integrated from the echoes of the top 75 cm of sediment and from 75 cm to about 8 m. The instrument is very sensitive to slight changes in the compositions of muds and clearly define the boundaries between muddy sediments and sands. In sands, however, since the lateral variation is intensive in the test area, only the average reflection intensities from an area (28.5 $m^2$ at 25 m water depth) are obtained. The sidescan sonar records, with their higher resolution in sandy/rocky terrain, provide data on the composition, smaller morphological features, and areal distribution; clay and mud generally show no returns. Interpreted together with the reflection intensities, the sediment distribution in the area as well as the physical parameters of the sediments such as grain size, porosity and density can be determined. The subbottom profiler (Uniboom) has better resolution in harder sediments than the echo sounder and furnishes the spatial distribution of the lithological units, permitting further interpretation of provenance, tectonics and the geological causes for this distribution.

# RESULTS AND METHODS USED TO DETERMINE THE ACOUSTIC PROPERTIES OF THE SOUTHEAST ASIAN MARGINS

by

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ABSTRACT

More than 700 sonobuoy sound velocity solutions have been analyzed statistically to develop 15 regional velocity functions from the Southeast Asian shelves and marginal basins. The velocity functions are least-squares regressions of the form $v = v_o + Kt$, where $t$ is one-way vertical travel-time to layer mid-points. The value of K shows surprisingly little variability on the shelves and ajoining basins from the Bay of Bengal to the Japan Sea. The average value is $1.67 \pm 0.35$ km/s$^2$. Very large values of 3.2 km/s$^2$ from Western Australia (not included in the average) are unique, and seem to result from the special combination of very low sedimentation rates on quite old crust. Paired comparisons of interval velocities and refraction velocities from the same sonobuoys show that the two measurements are interchangeable if they are compared at equal depths at layer mid-points. This is not a new result, but earlier demonstrations of equality were susceptible to sampling errors, which have been eliminated by use of paired comparisons. High-resolution velocity inversions from the Southeast Asian shelf data reveal that seafloor velocity gradients predicted from statistically derived functions are not in satisfactory agreement with the observed values.

# CIRCULAR STRUCTURES OBSERVED IN THE DEEP SEA BY THE SWATHMAP LONG-RANGE SIDESCAN SONAR

by

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## ABSTRACT

Swathmap observations of the deep sea are long-range sidescan sonar profiles with lateral ranges of up to 20 n.mi. A track from Guam to the Philippines has revealed four circular structures on and near the Palua-Kyushu Ridge. Three of these structures appear to be collapse calderas on the summits of medium and large sea mounts. Diameters of the central depression range from about 0.5 to 4 n.mi. A much larger structure was also observed on the ridge, with a diameter of approximately 12 n.mi and a roughly oval outline. In this structure there is a depression inside the rim which outlines a large central plateau. The large size and absence of great relief on the sides of the feature, suggest that it may not be a collapse caldera, but that it may be a ring dike or cone-sheet structure. Observations of this type suggest that current thinking on deep sea volcanism may need to be revised.

# II

# BOTTOM LOSS:

# REFLECTION AND REFRACTION

# A PERSPECTIVE ON BOTTOM REFLECTIVITY AND BACKSCATTERING

by

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ABSTRACT

A review of available data and description of observed effects permit an assessment of progress made since the 1970 SACLANTCEN Conference on this same topic. Physical models have been developed and refined which can both explain the observations and serve as a basis for predictions. Examples will be presented which contrast values determined from the physical models with measured data in order to identify problem areas and to recommend directions for future efforts.

# SOME BOTTOM-REFLECTION LOSS ANOMALIES NEAR GRAZING AND THEIR EFFECT ON PROPAGATION IN SHALLOW WATER

by

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ABSTRACT

The bottom-reflection loss from a hard bottom near grazing can in certain cases be fairly high and as such can result in a propagation in shallow water with higher losses than usually expected. Two frequently observed cases have been studied, one where the bottom can propagate shear waves and another where the bottom is covered by a layer of soft unconsolidated sediments. The first case causes a low-frequency attenuation whereby an optimum frequency is created for the propagation, whereas the second case creates selected frequencies for which the propagation is poor.

# DETERMINATION OF SEDIMENT SOUND-SPEED PROFILES USING CAUSTIC RANGE INFORMATION

by

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## ABSTRACT

Positive sound-speed gradients in ocean-bottom sediments may cause the formation of caustics in the acoustic field due to a point source located in the water. The caustics may extend into the water column and manifest themselves as high-intensity regions in the field measured near the bottom. The horizontal range to the caustic depends upon the source/receiver heights above the bottom and the parameters of both the water and bottom sound-speed profiles. For certain profiles, the analytic relationship among these quantities can be determined. Then if ranges to the caustic at different source/receiver heights can be identified in the data, the parameters of the bottom sound-speed profile can be calculated. The method is illustrated for the case of an isovelocity ocean overlying a sediment half-space with a linear sound-speed gradient, using data at 220 Hz.

INFERENCE OF GEO-ACOUSTIC PARAMETERS
FROM BOTTOM-LOSS DATA

by

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ABSTRACT

In areas of thick sediments the received level of shallow-angle long-frequency bottom interacting signals tends to be dominated by a bottom-refracted rather than bottom-reflected path. The loss along this path, assuming a constant gradient, g, and attenuation, $\alpha$, varies linearly with frequency, the shallow angle loss appears to increase linearly with both grazing angle and frequency. Hence bottom-loss data appear to be incapable of separating $\alpha$ and g, providing only estimates of their ratio. This paper describes a technique for estimating both $\alpha$ and g from classical bottom-loss versus grazing-angle data. In such data acquired in thick-sediment areas the lowest frequencies exhibit an abrupt increase in loss at an apparent grazing angle, $\theta_c$, corresponding to the development of a minimum-range caustic in the bottom-refracted paths. The gradient may be estimated from $\theta_c$ and the measurement geometry. The attenuation, $\alpha$, is then estimated from the linearity of loss versus angle and frequency. Examples using actual bottom-loss data and seismic time-domain data are shown. The implications for depth-dependent gradients and attenuations are also discussed

## ATTENUATION ESTIMATES FROM HIGH-RESOLUTION SUBBOTTOM PROFILER ECHOES

by

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### ABSTRACT

A sonogram expresses signal power as a function of both time and frequency. Sonograms of sea-floor echoes obtained with a high-resolution (0.2 ms duration) broadband (1 to 10 kHz) sound source (Huntec DTS) show effects of surface scattering at the sea floor, frequency selectivity of some sub-bottom reflectors, and the frequency dependence of sound attenuation in the sediment. By assuming attenuation to be proportional to frequency, sonograms of some subbottom reflectors (targets) yield an estimate of the attenuation in the overlying sediment. The quality of these estimates depends on the frequency range over which a good signal-to-noise ratio exists, the interference of scattered energy with the target reflection, knowledge of the transmitted pulse spectrum, and the frequency characteristics of the target. The estimates of attenuation obtained to date are lower than some obtained by other workers using samples and in-situ probes, but this may be due to the depth of burial.

LOW-FREQUENCY BOTTOM-LOSS MEASUREMENTS

IN THE TUFTS ABYSSAL PLAIN

by

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ABSTRACT

Ocean-bottom reflection loss has been measured at two sites over the Tufts Abyssal Plain in the northeast Pacific Ocean. The measurements were made with explosive charges along tracks of about 100 km. The bottom loss was obtained from the signals from the first, second and third bottom-bounce paths over a range of grazing angles from 5° to 75°, and for a number of 1/3 octave frequency bands from 50 Hz to 600 Hz. At these low frequencies the bottom loss versus grazing angle indicates a critical angle behaviour, and the loss extrapolated to a value of 5 dB at normal incidence. The theoretical bottom loss was computed using a simple two-layer model of the ocean bottom in which the sediment is modelled by a layer with a pseudo-linear sound-speed gradient and constant attenuation, and the underlying mantle crust is modelled by a half space with constant sound speed and attenuation. A good fit with the acoustic measurements was achieved using values of the model parameters obtained from seismic experiments carried out in the same region.

# RESONANCES IN ACOUSTIC BOTTOM REFLECTION AND THEIR RELATION TO THE OCEAN BOTTOM PROPERTIES

by

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## ABSTRACT

We have initiated a program to study the resonances in the acoustic reflection coefficient of a layered ocean bottom, patterned after the resonance theory of sound reflection from fluid or elastic layers <R. Fiorito and H. Uberall, JASA 65, 9 (1979); R. Fiorito, W. Madigosky, and H. Uberall, JASA 66, 1857 (1979)>. Computer programs have been written for obtaining the reflection coefficient from multilayered fluid or elastic media, with constant or linearly depth-dependent sound velocities in each layer. Resonances are evident in the reflection coefficient both as functions of frequency and of grazing angle of incidence, and are shown to depend on the properties of the layered ocean bottom. Results will be presented in the form of three-dimensional graphs.

# COMPARISON OF SYNTHETIC AND EXPERIMENTAL BOTTOM LOSS WAVEFORMS

by

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## ABSTRACT

The Naval Underwater Systems Center (NUSC) conducted a low-frequency (90 to 790 Hz) bottom loss experiment in June 1973 in the North Atlantic Hatteras Abyssal Plain. Acoustic signals from SUS charges were recorded by two unmanned submersibles (AUTOBUOYS). SUS and AUTOBUOY depths were selected to insure time-isolated direct and bottom-interaction arrivals. The distance between source and receivers was varied so that approximately 400 sediment-interacted signals were measured over a wide grazing angle range (5° to 66°). Supporting oceanographic and boomerang corer data were also obtained. Concurrently, the Lamont Doherty Geological Observatory (LDGO) conducted wide-angle seismic reflectivity measurements, using an air gun, line array, and sonobuoys and derived sediment-layer thicknesses and sound-speed profiles. Analysis of the NUSC and LDGO data has resulted in a detailed geophysical description of the subbottom for the experimental site. This inferred description was then used as input to the time-domain Fast Field Program (FFP), resulting in the synthetic impulse response of the medium. In this paper a comparison is made between the predicted and experimental sediment-interacted impulse responses.

# REFLECTION AND REFRACTION OF PARAMETRICALLY GENERATED SOUND AT A WATER/SEDIMENT INTERFACE

by

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The University of Texas at Austin
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## ABSTRACT

The results of an experimental study of the penetration of highly directional acoustic beams into bottom sediments were recently reported by Muir, Horton, and Thompson <J. Sound Vib. 64, 539-551 (1979)>. Of special interest was the behaviour of a narrow beam generated by a parametric source. We have considered this problem theoretically. Simplified equations for the reflected and refracted beams at the water/sediment interface are derived and solved analytically subject to the non-dissipative boundary conditions. The range of validity is discussed. Results are presented that seem to explain the experimental observations.

*On leave from the Department of Mathematics, University of Bergen, Bergen, Norway.

# TRANSMISSION OF A NARROW BEAM OF SOUND ACROSS THE BOUNDARY BETWEEN TWO FLUIDS

by

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## ABSTRACT

In studying shallow penetration of acoustic waves into saturated marine sediments, narrow beams of sound (at kHz frequencies) have been used under controlled conditions, <Muir, Horton, and Thompson. J. Sound & Vibration, 64, June 1979>. In order to contribute to the understanding of the physical basis of the penetration of sound across the boundary, a model experiment was devised at a frequency of about 1 Mhz, using two non-mixing liquids. This paper presents the experimental results obtained and compares these results with a theoretical development. The theory developed also provides a means of understanding some of the effects observed by Muir and co-workers when a parametric source was used for penetration into a saturated sediment.

# EXPERIMENTAL DETERMINATION OF PROPERTIES OF THE SCHOLTE WAVE IN THE BOTTOM OF THE NORTH SEA

by

Florian Schirmer
University of Hamburg, Germany

## ABSTRACT

An experiment was carried out in the North Sea with the objective of exciting the Scholte wave and investigating its propagation. Shots of 1 and 10 kg TNT at the sea bottom provided the seismic source. 3-component seismometers were set up at distances between 0.9 and 2.5 km from the source. The seismic signal was transmitted by radio to the recording ship. An elastic wave with a propagation velocity of 111 m/s was detected. The hodograph shows a vertical, polarized, retrograde ellipse. The observed frequencies are in the range 4.5 ± 1 Hz. The vertical component accounts for around 64% of the elastic energy as measured at the sediment/water interface. After subtraction of the geometric attenuation ($E_r$ prop. 1/R1), it was possible to determine the order of magnitude of the Scholte wave ($7.10^{-3}$ dB/m).

# III

# BOTTOM INTERFACE
# AND
# SEISMIC-WAVE PROPAGATION

# MODEL COMPUTATIONS FOR LOW-VELOCITY SURFACE WAVES ON MARINE SEDIMENTS

by

Heinz H. Essen
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ABSTRACT

In seismology Rayleigh waves, which propagate along the free surface, are of great importance for determining the elastic parameters of the upper mantle. With regard to shear-wave velocities in the upper layers of ocean sediments the same may apply to Scholte waves, which propagate along the interface between ocean and sea floor. In the case of homogeneous half spaces both Rayleigh and Scholte waves are non-dispersive; however, the dependence of propagation velocities on the elastic parameters are different. But in the presence of layers both the Rayleigh and the Scholte wave split into a finite number of dispersive modes. This effect seems to be as important for Scholte waves as for Rayleigh. Measurements of Dr Schirmer et al from the shore belt of the North Sea show two different dispersive modes. This paper presents simple theoretical models in order to investigate the dispersion of "Rayleigh" and "Scholte" modes on ocean sea floors. Compared with the earth mantle the sea floor propagates Rayleigh (and Scholte) waves of much smaller wavelength, and, moreover, the ratio of shear to compressional wave velocity is lower by a factor of about 10.

# EXPERIMENTAL AND THEORETICAL STUDIES OF SEISMIC INTERFACE WAVES IN COASTAL WATERS

by

Dieter Rauch
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La Spezia, Italy

ABSTRACT

A digital three-component ocean-bottom seismometer has been developed at SACLANTCEN to study extremely-low-frequency sound propagation in coastal waters (e.g. below the cut-off of the shallow-water duct). It has been used successfully in conjunction with a variabledepth hydrophone during several sea trials off the Italian coast. By exploding small charges (45 to 900 g TNT) at various distances (up to 5 km) it has been demonstrated that the infrasonic energy is mainly transmitted via a seismic interface wave. In general this propagation mode may be termed a modified Scholte wave as it is guided by the acoustically most significant interface between water column (including liquid-type sediments) and solid basement. On a sedimentary sea floor very pronounced wavelets have been observed, at frequencies in the 1.5 to 6 Hz band, group-velocities in the 250 to 70 m/s range, and hodographs in the vertical radial plane. Together with this experimental program theoretical studies have been made using a seismic Fast-Field-Program, which has proved to be a very powerful tool to model infrasonic phenomena in shallow-water environments.

# AMBIENT AND SHIP-INDUCED NOISE IN SHALLOW WATER

by

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## ABSTRACT

This paper describes some features of low-frequency hydroacoustic and seismic noise (1 to 20 Hz) in coastal waters. The data have been collected by one or two three-component ocean-bottom seismometers equipped with an additional hydrophone. The following aspects are considered:

a. modification of the background power spectra by ship-noise.

b. splitting of the seismic energy with regard to the spatial coordinates.

c. direction finding based on the azimuthal power-distribution.

The hydroacoustic and seismic power spectra are very similar in general shape. However, for some significant lines the output of the horizontal geophones indicates a higher signal-to-noise ratio. The horizontally polarized energy may be used to determine the direction to the source once the propagation mechanism has been identified by means of all sensors. The efficiency of the method depends strongly on the geological composition of the ocean bottom.

# DISPERSION OF ONE-SECOND RAYLEIGH WAVES THROUGH OCEANIC SEDIMENTS FOLLOWING SHALLOW EARTHQUAKES IN THE SOUTH-CENTRAL PACIFIC OCEAN BASIN

by

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and

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## ABSTRACT

Shallow seismic events east of Gambier Islands (21°S, 127°W) routinely recorded at the seismic station RKT (Rikitea, Gambier Islands) at a distance of 7°, are characterized by a wavetrain lasting as long as 20 min, whose energy is concentrated around 1 Hz, between group velocities of 3.8 and 0.8 km/s. Two other paths in the area also show this dispersion pattern; all three are remarkably free of islands and seamounts, and offer a regular sedimentary layer. Modelling using normal-mode theory shows that this wave is a complex interference between modes principally concentrated in the water layer, but substantially coupled to the basement through the sedimentary layer; their excitation requires a very shallow source, not deeper than a few kilometres below the sediment/basement interface. This last point corroborates other seismic evidence related to these seismic events, such as observation of p(n)wP and T phases.

# VELOCITY SPECTRAL ESTIMATES FROM THE ARRAYS OF THE ROSE PROGRAM

by

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## ABSTRACT

The ROSE (Rivera Ocean Seismic Experiment was a large seismic/acoustic program conducted near the Clipperton Fracture Zone (12°N, 102°W) in Jan/Feb 1979 off the western coast of Mexico. One of its objectives was to analyze long-range, low-frequency acoustic propagation within the seabed. In this experiment an ocean bottom seismometer array, a moored 2 km vertical array, and a 2.5 km towed horizontal array were employed to record signals generated by explosive sources whose size ranged from 0.1 kg to 1000 kg. These array data have been reduced using high-resolution velocity spectra analysis for analyzing both the bottom-reflected acoustic and refracted seismic paths to obtain the phase velocity and path energy versus range and frequency. Several aspects of bottom interaction have been observed using these arrays. Experimental results to date of the ROSE multichannel indicate:

i) The bottom-reflected signals are strongly scattered due to roughness of the seafloor. The energy of the multiples is strongly spread in phase velocity and travel time.

ii) The refracted compressional signals has a phase velocity of approximately 6.5 km/s at a source/receiver range of 15 km and increases with range to 7.5 km/s.

iii) The refracted compressional signal has a "doublet" arriving 1 s after the primary, which suggests a low velocity zone.

iv) The refracted shear signal has a phase velocity of approximately 4 km/s and is 15 dB below the compressional. It also appears to have a doublet arriving 1½ s after its primary arrival.

# IV

# ACOUSTIC MODELLING

# BOTTOM INTERACTION REPRESENTED BY IMPEDANCE CONDITIONS IN NORMAL-MODE CALCULATIONS

by

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and

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## ABSTRACT

In the process of developing rigorous control models for use by the Acoustic Model Evaluation Committee, we have developed a normal-mode program that uses a bottom-loss table similar to that used by ray theory. To do this the reflection loss, r, must be entered as an impedance condition. Let such a normal-mode program be designated $NM_I$, and a similar program using a structured bottom sediment be $NM_s$. For $NM_S$, r can be computed at each mode eigenvalue, $k_n$, using the method of Bucker <J. Acoustical Society America 48,5>. This $r(k_n)$ is a complex number giving both reflection loss and phase shift at discrete grazing angles. The derivative dr/dk can also be computed at $k_n$. If identical water columns are used in the two programs and if exact $r(k_n)$ from $NM_S$ are used in $NM_I$, then the eigenvalues are equal. Several methods of normalizing the eigenfunctions of $NM_I$ were investigated. All methods require $dr/dk_n$. Thus not only the complex reflection coefficient but also its derivative must be known to obtain identical results between $NM_I$ and $NM_S$. Examples show that the $NM_I$ is inaccurate if terms involving this derivative are omitted but that a numerical evaluation of the derivative often gives reasonable accuracy.

# CYCLE DISTANCE IN GUIDED PROPAGATION

by

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ABSTRACT

The concept of cycle distance is reviewed, drawing initially on recent studies by C.T. Tindle, S.G. Payne, and the author. Note that in underwater acoustics the bottom loss and the cycle distance together control an important part of the attenuation, and this is the central theme of the work cited. For a given mode it is not easy to find a definition of cycle distance that is both precise and generally applicable; two new attempts are described. The most successful of these is in terms of group velocity; its implications, including those for bottom interaction, are still being examined.

# COMPUTATION OF AVERAGED SOUND-PROPAGATION LOSSES AND FREQUENCY/SPACE COHERENCE FUNCTIONS IN SHALLOW WATERS

by

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ABSTRACT

In the frequency range covered by active sonars (above 1 kHz) sound propagation in shallow waters is characterized by fast fluctuations of the propagation-loss term as a function of range, source depth, receiver depth, and frequency. These fluctuations may be interpreted as the result of interferences between a very large number of modes. A method is presented that allows the propagation losses to be decomposed into two parts:

1. An averaged propagation-loss term, which takes the form of a slowly-varying function of range, depth and frequency.
2. A fluctuation term, which will be assimilated to a random function and will be characterized by its coherence functions in the range, depth and frequency domains.

Assuming that the wavelength is much smaller and the horizontal range much larger than the water depth, some approximations may be introduced that allow the above functions to be expressed by continuous integrals; these integrals can be solved numerically through a rather simple computer program. The method is illustrated by some applications to a number of realistic cases in order to show the relative influence of the various parameters characterizing the bottom and the sound-speed profile.

INITIAL DATA FOR THE PARABOLIC EQUATION

by

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and

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ABSTRACT

When the Helmholtz equation is replaced by the related Parabolic equation, we obtain both a profit and a puzzle. The profit is the relative numerical ease of solving the Parabolic equation. This paper considers the puzzle of what to use for the required initial data for the Parabolic equation. We adopt the position that the solution of the Parabolic equation should correspond at long ranges to the solution of the Helmholtz equation, at least when the environment does not change with range. By considering the solution of the Parabolic equation that reduces to the modal decomposition of arbitrary data at the initial range, we recommend that $\Sigma\, \phi_n(z)\phi_n(z_s)$ be used for initial data. Here the $\phi_n$ are the mode functions, $z$ is the variable depth at the initial range, and $z_s$ is the source depth. The fewer terms in the above sum, the less variation in the solution of the Parabolic equation, and therefore the greater the profit from numerical ease. This would normally suggest including only those modes whose effects can be accurately computed. If, on the other hand, phase errors are to be corrected by a technique such as Polyanskii's <Sov. Phys. Acoust., 20 (1974), 90>, it does no harm to include all modes with the weights given in the above sum. Numerical examples are presented.

# THE SEAMOUNT AS A DIFFRACTING BODY

by

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## ABSTRACT

Diffraction over a seamount has been studied by construction of a three-dimensional physical model of Dickens seamount. When laboratory diffraction and scattering data for air are scaled to the ocean and added to ray refraction losses at sea there is excellent agreement with ocean experiments reported by Ebbeson et al <J. Acoust. Soc. Am. 64, S76 (1978)>.

# PROPAGATION OF SOUND FROM A FLUID WEDGE INTO A FAST FLUID BOTTOM

by

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Naval Postgraduate School, Monterey, Ca., U.S.A.

## ABSTRACT

When sound propagates up the continental shelf towards the shore, there is a loss of lower frequencies. The distances from the shore at which each frequency is lost correspond closely to the depth at which normal modes in the shallow-water channel would be cut off. After cut-off is reached for a specific frequency, the associated energy in that normal mode is dumped into the bottom forming a highly collimated beam with a shallow angle of depression. This problem is modelled by a wedge of fluid overlying a fast fluid bottom. The method of images is used to calculate the distribution of pressure and its phase at the interface; the interface is then treated as a distribution of sources and the radiated field in the bottom is calculated by the Green's function integral technique. Both calculations require a high-speed digital computer. The results of these programs compare well with laboratory experiments performed at the Naval Postgraduate School. The results of these programs are presently in the process of being analyzed to determine the parametric dependence of the beam on the angle subtended by the wedge and on the properties of the fluids in the wedge and bottom.

MODE-COUPLING EFFECTS IN RANGE-DEPENDENT SHALLOW-WATER PROPAGATION

by

F.B. Jensen and W.A. Kuperman
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La Spezia, Italy

ABSTRACT

A numerical simulation study has been performed using two different propagation models: 1) a parabolic equation model, which is a range-dependent model that includes mode-coupling effects, and 2) a normal-mode model that treats range dependence in the "adiabatic" approximation. The models have been applied to both up-slope and down-slope propagation demonstrating various mode cutoff and mode-coupling phenomena. Furthermore, a constant-water-depth example where only bottom properties change with range dramatically demonstrates the importance of energy coupling between modes in range-dependent propagation.

# V

# SOUND PROPAGATION:

# TECHNIQUES AND EXPERIMENT VERSUS THEORY

# A LOW-FREQUENCY PARAMETRIC RESEARCH TOOL FOR OCEAN ACOUSTICS

by

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Applied Research Laboratories
The University of Texas at Austin
Austin, Texas, U.S.A.

## ABSTRACT

The development and application of a parametric acoustic array system is described. Key features include a 720-element primary projector measuring 2.3 m in diameter with a fundamental resonance in the 11 to 16 kHz band. Eighty kilowatts of primary pulse power are applied to this array to develop difference-frequency radiations in the 500 Hz to 5 kHz band. Half-power beamwidths of the primary and the difference-frequency radiations are of the order of 2.5°. An array of 30 low-frequency elements is interspaced in the primary array for reception of the difference-frequency echoes as well as for transmission of linear signals in this band. The system has a capability for alternate parametric and linear transmission to enable near simultaneous acquisition of parametric and linear data. A capability for sequentially stepped center frequencies is also provided for near-simultaneous frequency response measurements. Shaped pulse (i.e. Gaussian, box-car, etc.) as well as variable bandwidth FM pulse operation is also provided. Mechanical features include mounting of an off-shore platform with continuously varying transducer tilt, train, and depth features, as well as VDS towing in a spherical fish with rope fairing. Application of the system to environmental acoustics research is also described.

# TRANSMISSION-LOSS VARIABILITY IN SHALLOW WATER

by

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ABSTRACT

Bathymetry, sediment type, and sediment thickness information are required to explain the variability of transmission loss in shallow water. Bathymetric and sediment charts may indicate uniform sediment type and relatively uniform bathymetry in shallow water. This uniformity leads to transmission-loss estimates with little, if any, spatial variability. Incorporating sediment thickness into model predictions explains much of the variability observed in experiments. Data and model comparisons are presented.

# INFLUENCE OF SEMICONSOLIDATED SEDIMENTS ON SOUND PROPAGATION IN A COASTAL REGION

by

S.T. McDaniel and J.H. Beebe
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## ABSTRACT

In 1976, acoustic measurements were performed in shallow water off the coast of Jacksonville, Florida. Seismic refraction and Stoneley wave experiments, performed as part of the measurement program, revealed that the seabed at the measurement site consisted of a semiconsolidated sediment overlaying by a thin layer of sand. Compressional and shear wave velocities determined for the semiconsolidated layer were 2400 m/s and 670 m/s, respectively. Using a normal-mode model that includes the effects of sediment rigidity, the attenuation of the first acoustic normal mode was computed and compared with experimental results for frequencies of 40 Hz to 800 Hz.

# GEOACOUSTIC MODELS OF THE SEABED TO SUPPORT RANGE-DEPENDENT PROPAGATION STUDIES ON THE SCOTIAN SHELF

by

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The Applied Research Laboratory
Pennsylvania State University
State College, Pa., U.S.A.

ABSTRACT

Joint long-range propagation experiments were performed at two sites off the coast of Nova Scotia by the Applied Research Laboratory (ARL) of the Pennsylvania State University, and the Defense Research Establishment Atlantic (DREA) of Dartmouth, Nova Scotia. One result of this program was the development of geoacoustic models of the seabed along the propagation tracks between the shallow (ARL) and deep (DREA) receiving arrays. The seabed models are based on profiling performed with the Huntec Deep-Tow System, grab sample data supplied by the Bedford Institute of Oceanography of Dartmouth, Nova Scotia, and dispersion and seismic refraction analysis. Each track is divided into a number of regions, with each region characterized by a geoacoustic model of two to four layers. Compressional wave attenuation values are predicted for each layer, from Huntec and grab sample data, by the Biot-Stoll Sediment model and by historical data. Using the seabed models as inputs to an adiabatic, normal-mode propagation model, transmission loss is predicted and compared with experimental losses measured at the ARL array.

PROPAGATION-LOSS MODELLING ON THE SCOTIAN SHELF:

THE GEO-ACOUSTIC MODEL

by

D.M.F. Chapman and Dale D. Ellis
Defence Research Establishment Atlantic
Dartmouth, Nova Scotia, Canada

ABSTRACT

A model of the acoustic environment of the ocean bottom sediments has been prepared for a selected area on the Scotian Shelf where both summer and winter propagation-loss data have been collected. This geo-acoustic model is part of the input to a shallow-water propagation loss model described in the accompanying paper, "Propagation-Loss Modelling on the Scotian Shelf: Comparison of Model Predictions with Measurements". An attempt has been made to provide an independent bottom model, based on geophysical evidence, including continuous records from a high-resolution seismic profiling system, seismic refraction experiments, core samples, and consultation with ocean geologists familiar with the area. The final criterion for acceptance of the model parameters is the agreement between propagation-loss model predictions and experimental measurements for both summer and winter conditions.

PROPAGATION-LOSS MODELLING ON THE SCOTIAN SHELF:
COMPARISON OF MODEL PREDICTIONS WITH MEASUREMENTS

by

Dale D. Ellis and D.M.F. Chapman
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Dartmouth, Nova Scotia, Canada

## ABSTRACT

Propagation-loss data using explosive sources have been obtained over a 180 km track on the Scotian Shelf during both summer and winter conditions. The water depth varies between 55 and 75 m over a sandy bottom. A sub-bottom model is discussed in the accompanying paper, "Propagation Loss Modelling on the Scotian Shelf: The Geo-acoustic Model". In the present paper the bottom properties determined from the geo-acoustic model are used as part of the input to the DREA range-dependent normal-mode program. The predictions from the normal-mode calculations are compared with the summer and winter propagation-loss measurements for a number of ranges, depths and frequencies. The difference between the calculations and measurements can be used to refine the geo-acoustic model.

# SEA-FLOOR EFFECTS ON SHALLOW WATER ACOUSTIC PROPAGATION

by

T. Akal
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La Spezia, Italy

ABSTRACT

The acoustic propagation in the 25 Hz to 8 kHz band has been measured in a large number of coastal-water areas using explosive charges and digital techniques. When displaying the losses as a function of range and frequency a marked optimum frequency is observed in most of the cases. The acoustic characteristics of the sea floor over which the propagation measurements were made have been compared with the loss levels and the optimum frequencies and have shown, among other things, a relationship between the optimum frequency and sediment porosity.

# A SUMMARY OF BROADBAND MODEL/DATA COMPARISONS AT SACLANTCEN FOR ACOUSTIC PROPAGATION IN COASTAL WATERS

by

M.C. Ferla, G. Dreini, F.B. Jensen, and W.A. Kuperman
SACLANT ASW Research Centre
La Spezia, Italy

## ABSTRACT

Broadband propagation data collected by SACLANTCEN in various shallow-water areas in the Mediterranean Sea and in the North Atlantic have been modelled using a normal-mode propagation model. The data covers a frequency range of 50 to 3200 Hz, with experiments performed under a variety of different environmental conditions including seasonal changes in sound-speed structure, different sea states, variations of water depth (50 to 300 m) and bottom composition with range, propagation through oceanic fronts, etc. The conclusions of the model/data comparisons are presented with emphasis on difficulties encountered (e.g. lack of environmental information), on detected model limitations, and on inferred conclusions concerning the actual environments. The importance of bottom rigidity (shear) as a low-frequency loss mechanism is evident in many model/data comparisons, particularly through its effect on the optimum propagation frequency, which is found to increase with increasing shear speed.

# COMPUTER MODEL PREDICTIONS OF OCEAN BASIN REVERBERATION FOR LARGE UNDERWATER EXPLOSIONS

by

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ABSTRACT

Ocean basin reverberation results from interaction of the pressure wave from a large underwater explosion with the boundaries of the basin and of the seamounts and islands within it. Its net effect is to raise the ambient noise level at low frequencies for periods of from 30 min to 3 or 4 hours, depending on the acoustic source level and the size of the ocean basin. A computer model has been developed to predict the reverberant field. This model has adequately matched experimental data for varying conditions in the North Atlantic, for explosive yields of up to ten tons. As an important test of its validity, we have applied the model for three high explosive shots, 0.5 to 1 kiloton in yield, one in the Atlantic and two in the North Pacific, a basin with much greater area and myriad seamounts and islands. The remarkably good agreement between model results and data indicates that the assumptions made in developing the reverberation model are valid not only in the Atlantic, but can be applied equally well to making predictions of the character of the reverberant field for much larger sources in the much more complex Pacific Ocean environment.

# VI

# FLUCTUATIONS, COHERENCE, AND SIGNAL PROCESSING

FLUCTUATION STATISTICS OF SEA-BED ACOUSTIC BACKSCATTER

by

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ABSTRACT

A theoretical model is developed that applies to statistics of sea-bed backscatter, including non Rayleigh envelope distribution, finite reverberation envelope auto-correlation at > 1 pulse width lag, and pulse-pulse envelope correlation. The model is based on a two-phase patch surface assumption, generated by a Markov process, and defined through parameters $\rho$ = high scatter area fraction, $\gamma$ = high/low backscatter strength ratio, and $\lambda$ = effective resolution cell/patch size ratio. Experiments at 1.8, 4.1, and 8.1 kHz with beamwidth of 3.6° to 17° at five sites and three range bands to minimum grazing angle 2.5° in 70 to 160 m water depth are analyzed, indicating non-Rayleigh envelope distributions, power envelope auto-correlations of 0.1 to 0.4 at > 1 pulse lag, as expected. Close experiment-model fitting requires $\rho = 10^{-4}$ to $2.10^{-2}$, $\Gamma = 3.5$ to 80, and a patch dimension of 100 to 400 m. Factorial analysis on model-fitting parameters, within experimental sensitivity, indicated beamwidth dependence of statistics as predicted; site, grazing angle, and site-frequency dependences were all significant at < 1% level; simple frequency dependence is not significant.

# MEASUREMENTS OF SPATIAL COHERENCE OF BOTTOM-INTERACTING SOUND IN THE TAGUS ABYSSAL PLAIN

by

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and R.S. Anderson**
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## ABSTRACT

Coherence of bottom-interacting sound in the Tagus Abyssal Plain was determined as a function of bearing and frequency (20 to 2000 Hz) for low grazing angles between 11° and 13°. An acoustic experiment was performed in which SUS charges were dropped in a circular pattern of 28 km radius around a deep hydrophone. The bottom-interacting arrival was isolated and deconvolved to remove the decorrelating effects of varying bubble-pulse periods. A spatial-coherence function was calculated between shot pairs corresponding to 5, 9, and 13 km separation. For frequency bands of 20 to 600 Hz and 1200 to 2000 Hz, the spatial coherence of the bottom-interacting arrival is high. For the frequency band of 600 to 1200 Hz, the spatial coherence is lower and more variable. The high coherence values are consistent with the Eckart theory for scattering from an interface having rms roughness less than 0.1 m. The sharply tuned nature of the low coherence values in a discrete frequency region suggests a sediment multi-path cause rather than scattering from bottom roughness.

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* U.S. Naval Research Laboratory

** U.S. Naval Oceanographic Office

# VARIABILITY OF ACOUSTIC TRANSMISSIONS IN A SHALLOW-WATER AREA

by

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ABSTRACT

The paper describes a series of sound-propagation experiments in the shallow-water area south of Elba, Italy, in 1977-78. The purpose was to study how one-way transmitted signals vary with

- centre frequency of transmission (1 to 6 kHz)
- space (location, source and receiver depth)
- time/season (summer and winter)
- time/duration of an experiment (30 min)

The variability is caused by medium parameter variations in frequency and space and fluctuations in time (internal waves). Signal variability is observed as phase and amplitude variations and variations in time length of pulsed signals. Spreading functions and their width in frequency have been studied as a measure of phase fluctuations We also looked at transmission loss and transmission-loss time variations over the duration of individual experiments as a measure of fluctuations in amplitude and time length of the signals. The mean values of the processed data are given by the existing sound-propagation conditions in the water masses and the bottom composition in the upper few wavelengths of the sediment layers. We observed bottom interaction in the transmission-loss results and also in two distinctly different classes of spreading function results. The experimental results are compared with model calculations.

# ANALYSIS OF TIME-VARYING SPATIALLY-VARYING SOUND-PROPAGATION SYSTEMS

by

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## ABSTRACT

It has proven very useful in the analysis of signal processing for sonar systems to represent signals by cross-ambiguity functions and systems - such as a target or the medium - that modify the signal by spreading or scattering functions. These functions measure respectively how signals are spread and how systems spread signals in time and frequency. In such systems sound-propagation paths play a significant part. This paper presents an extension of the temporal theory to consider spatial variations: as before, signals are represented by cross-ambiguity functions and systems by spreading or scattering functions; however, in the extension spreads in space and wave number are considered in addition. A major cause of such spreads is often bottom interactions. Two versions of the spatial theory are presented: a free-space version for use when ray theory is applicable and a layered-media version for use when it is not. In the layered-media version a normal-mode model of propagation is assumed and spreads occur in mode number as well as wave number. If the transmitted signal is assumed to be a plane wave modulated by a narrow-band time signal, the ambiguity function for the transmitted signal is the product of the temporal ambiguity function of the time signal and the beam pattern for the receiving array.

PHASE COHERENCE IN A SHALLOW-WATER WAVEGUIDE

by

U.E. Rupe
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La Spezia, Italy

ABSTRACT

A fundamental property in determining the response of an array is the spatial coherence across the array. Modelling the shallow-water waveguide in terms of normal modes, the phase-coherence factor among modes is known to control the modal interference term. This factor is defined using a generalized van Cittert/Zernicke theorem. The resulting expression for the phase coherence is calculated from a spatially extended single-frequency source, each source element generating m modes. Since single-source elements are assumed to radiate incoherently, the complex degree of coherence from an extended source is calculated without the explicit use of an averaging process.

THE INFLUENCE OF UNKNOWN BOTTOM PARAMETERS ON
BEARING ESTIMATION IN SHALLOW WATER

by

R. Klemm
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La Spezia, Italy

ABSTRACT

The spatial dispersion of the sound energy in the shallow-water channel causes bearing estimates obtained by conventional beamformers or similar estimators to be biased towards broadside direction. The bias depends on such environmental parameters as the sound-speed profile and bottom parameters. Error-free bearing estimates can be obtained if the sound field is entirely known a priori. In practice, however, the bottom parameters are usually unknown. This paper discusses the problem of mismatch between the actual bottom parameters and assumptions on the processing side. Comparisons are made with an alternative method using a test source for estimating the actual channel response.

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