

Report on the Office of Naval Research High-Frequency Acoustics Workshop

16-18 April 1996

by Eric I. Thorsos

Technical Report
APL-UW TR 9702
June 1997

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TABLE OF CONTENTS

ABSTRACT	v
EXECUTIVE SUMMARY	vi
INTRODUCTION	1
Structure of Workshop.	1
Background on Applications of High-Frequency Acoustics	3
1. SURFACE SCATTERING (including ambient noise and scattering from biologics) ...	6
1.1 Acoustical Issues and Applications	6
1.2 Fundamental Science Issues	9
1.2.1 Bubbles	10
1.2.2 Biologics	13
1.2.3 Microscale turbulence	13
1.3 Environmental Considerations	13
1.3.1 Environments: Coastal Waters and Open Ocean	14
1.3.2 Bubbles	15
1.3.3 Biological Organisms	16
1.4 Overview of Experimental Program Goals	17
2. BOTTOM SCATTERING	19
2.1 Acoustical Issues and Applications	19
2.2 Fundamental Science Issues	21
2.2.1 Background	21
2.2.2 Issues	22
2.3 Environmental Issues	25
2.4 Experiments	26
2.4.1 Tank Experiments	26
2.4.2 Experiments at Sea	27
2.4.3 Additional Remarks	29

3. PROPAGATION	29
3.1 Volume Propagation in a Deterministic Environment	30
3.1.1 Ray Theory Methods	30
3.1.2 Wave Propagation Modeling at High Frequency	33
3.1.3 Broadband Propagation	34
3.1.4 Imaging	35
3.2 Volume Propagation in a Fluctuating Environment	35
3.2.1 Issues Related to Near-Term Applications	36
3.2.2 Basic Science Issues	38
3.2.3 Oceanographic Description Issues	42
3.3 Propagation with Boundary Interaction	43
3.3.1 Technical Issues	43
3.3.2 Ray Theory	44
3.3.3 Wave-Propagation Methods	46
3.4 Goals for High-Frequency Propagation Experiments	50
3.4.1 Volume Propagation in a Fluctuating Environment	51
3.4.2 Propagation with Boundary Intereaction.	52
References	53
Points of Contact	54
APPENDIX A. ONR High-Frequency Acoustics Workshop Attendees	A1–A5
APPENDIX B. ONR High-Frequency Acoustics Workshop Agenda	B1–B2
APPENDIX C. ONR High-Frequency Acoustics Workshop Working Groups	C1

ABSTRACT

The results of the High-Frequency Acoustics Workshop, sponsored by the Office of Naval Research Code 321OA, are presented. The workshop was held on 16–18 April 1996 at the Ramada Inn in Golden, Colorado. The three principal objectives of the workshop were (1) to promote communication among the basic research investigators and between the 6.1 and 6.2 communities on high-frequency acoustics issues, (2) to identify the fundamental scientific issues and to clarify important goals for research in high-frequency acoustics, and (3) to suggest major field experiments that could address these goals. This report summarizes the scientific issues in high-frequency acoustics and suggests research goals for field experiments in the following three areas: acoustic interaction with the sea surface, acoustic interaction with the sea-floor, and acoustic propagation.

EXECUTIVE SUMMARY

On 16–18 April 1996, the Office of Naval Research Code 321OA sponsored the High-Frequency Acoustics Workshop at the Ramada Inn in Golden, Colorado. The three principal objectives of the workshop were (1) to promote communication among the basic research investigators and between the 6.1 and 6.2 communities on high-frequency acoustics issues, (2) to identify the fundamental scientific issues and to clarify important goals for research in high-frequency acoustics, and (3) to suggest major field experiments that could address these goals. The full frequency range of interest extends from a few kilohertz to 1 MHz, though the frequencies associated with the main areas of applications are usually more restricted: 10–50 kHz for torpedoes and mine detection and 100–400 kHz for mine classification.

After an initial day of presentations, three working groups were formed to focus on surface, bottom, and propagation issues, respectively. The surface group addressed surface scattering, bubbles, ambient noise, and scattering from biological organisms in the water column. The bottom group considered acoustic scattering from and into the seafloor and prospects for acoustic remote sensing of seafloor properties. The propagation group addressed propagation within the water column, propagation involving boundary interactions, and imaging.

The main body of the report surveys the scientific issues discussed at the workshop and includes additional topics and information in order to produce a balanced and coherent presentation of the issues. Within each topic area, this report starts from the issues of direct interest to the 6.2 community and progresses to the related basic research issues. In this way it should be evident how progress on the basic research issues would be of benefit to the broader high-frequency community.

A major objective of the workshop was for each working group to suggest field experiments that address the most important scientific issues in their respective areas. A summary is presented here of the major goals of the experimental program for each working group and of the key scientific issues to be addressed.

Surface Working Group

Although both surface roughness and wind-generated bubbles are relevant to high-frequency surface interaction, improving our understanding of the acoustical effects of bubble phenomena is at the core of the most important research issues, because surface roughness effects appear to be better understood. Present models for backscattering strength and for forward scattering loss treat the bubble field as a homogeneous nonrefracting surface layer. There are a number of indications, however, that such a simplified picture of the bubble field is not appropriate, especially if more comprehensive descriptions of the acoustic interaction with the sea surface are considered.

To improve our understanding of basic science issues related to high-frequency surface scattering and to move to a higher level in modeling this process, improved descriptions of the spatial and temporal nature of the bubble field are needed. The requirement is a stochastic, space-time description of the bubble field sufficiently complete to form the basis of acoustic model development. For this purpose it is also necessary to understand the important environmental descriptors, in addition to wind speed, that determine the properties of the bubble field. Recent advances in near-surface environmental characterization over the last few years make such an effort a reasonable extrapolation of present capabilities. The goal must be to develop a comprehensive hydrodynamical model of the near-surface circulation coupled with a model of bubble sources, modification, and dissolution.

The focus of an experimental acoustics program relating to the sea surface could be the dual goals of (1) developing the needed space-time bubble-field descriptions through environmental characterization efforts, and (2) using these descriptions to demonstrate improved understanding of high-frequency surface scattering and improved accuracy in modeling the experiments. It will be necessary to develop improved theoretical scattering techniques that utilize the more detailed bubble-field description, and, in the forward scattering case, it will be necessary to account for rough surface scattering in addition to the bubble field effects. The goal from the view of Navy applications would be to elevate the paradigm for modeling high-

frequency surface scattering from one using a simple model of homogeneity in the bubble field to one using models of the space-time structure of the bubble field. An important assumption here is that such improvements in the environmental description would lead to significant improvements in model accuracy. Verification of this assumption would be an important part of the program goals.

Bottom Working Group

1) Penetration of Sound into the Seafloor at Low Grazing Angles

Field experiments are needed to understand the anomalously high penetration of sound into the seafloor at incident grazing angles below the critical angle. Hypotheses for this penetration include generation of a Biot slow wave, scattering by roughness at the water-sediment interface, and scattering of the evanescent wave by volume inhomogeneities just below the interface. This experimental investigation will require the burial of receivers and, possibly, sources. Since, in some cases, compressional waves, shear waves, and (possibly) the Biot slow wave may exist, geometries and sensor placement that allow the identification and measurement of these waves are essential.

It is also essential that these experiments include the sedimentological and oceanographic measurement support necessary to allow understanding the physics of both propagation and scattering. Necessary for understanding acoustic behavior are the following: stereophotography of the seafloor for measuring roughness, high-frequency and broadband acoustic profilers for determining layering and variability over a wide range of spatial scales, and instruments for studying physical composition and behavior, such as porosity, density, permeability, gas content structure, and shear and compressional wave velocity and attenuation.

This program would have immediate relevance to the Navy in the area of buried mine detection and would also contribute to an understanding of reverberation due to scattering within the sediment. It may be relatively straightforward to also address issues on the acoustic response of buried scatterers within the same experimental program.

2) Reflection and Scattering from Sediments

A promising approach for improving the accuracy of bottom reverberation modeling would be to infer the relevant bottom parameters using acoustic remote sensing techniques. However, before inverse techniques could be reliably used to rapidly determine the seafloor environment, the forward problem needs to be investigated further. This need exists because the individual contributions to the scattering (e.g., surface roughness, volume inhomogeneities, and bubbles) have not been adequately isolated and related to measured properties of the environment. Thus, there is a need for an experimental program in high-frequency bottom acoustics with the goal of convincingly identifying the various scattering mechanisms and relating these contributions to measurements of the environment through theoretical and numerical analyses. The frequency coverage should be comprehensive (from a few kilohertz to a few hundred kilohertz) and the full bistatic geometry utilized. The key element of such a program should be a detailed environmental characterization effort at length scales down to one quarter of an acoustic wavelength. Many previous experimental investigations at high frequencies have lacked the rigorous environmental study appropriate to a 6.1 level effort. It is felt that only by making such an investment could the forward scattering problem be understood to the degree required for reliable remote sensing applications.

3) Remote Sensing of Seafloor Properties for Use in High-Frequency Acoustics

An experimental program focused on acoustic remote sensing of seafloor properties would be a logical follow-on to the effort outlined in item 2. With an improved understanding of the fundamental scattering mechanisms over a wide frequency band, the stage would be set for developing and optimizing remote sensing methods. The sediment characterization methods employed in the previous two experiment programs would provide ground truth presently lacking in tests of acoustic remote sensing. As part of this program it would be important to better understand the occurrences of spatial variability in seafloor properties and to determine the impact of spatial variability on remote sensing strategy. A potential Navy payoff here would be significantly improved predictions of high-frequency reverberation

based on a real-time assessment of the seafloor scattering properties. In addition, remote sensing of sediment geotechnical properties, such as shear strength, could have diverse applications.

Propagation Working Group

A number of important propagation issues can be addressed without experiments. Issues related to propagation in a deterministic environment (Section 3.1) are largely in this category, since very accurate numerical solutions are available. In addition, the ocean will inevitably contain volume fluctuations, making it less suitable as a high-accuracy test bed for deterministic propagation. Similarly, progress on a number of issues related to volume propagation in a fluctuating environment (Section 3.2) can be made utilizing simulations. Predictions of various field moments based on the theory of wave propagation in random media can be verified with simulations using a range of environmental descriptions, and many of the unanswered questions on the basic science issues list in Section 3.2.2 can be addressed with the help of simulation techniques. For propagation with boundary interaction (Section 3.3) high-accuracy “benchmark” simulations based on wave propagation methods are needed to test the faster, but less accurate, ray-based methods.

Propagation experiments, however, are needed for several reasons. The most basic reason is that only through experiments can we be certain that all the important environmental and acoustical processes are understood and can be simulated or modeled. Reaching this goal will require the cooperative efforts of the oceanographic and acoustic communities.

Volume Propagation in a Fluctuating Environment

Among the many topics discussed in Section 3.2, experimental investigations in the following areas would be of special interest:

- 1) A space-time picture of the acoustic field has been developed for deep water at lower frequencies (< 20 kHz) which indicates that, because of the presence of internal waves,

regions of high acoustic intensity form into undulating ribbon-like structures, which may have important implications for Navy sonar operations. Experimental investigations of the space-time structure of the acoustic field occurring at higher frequencies and in more complicated shallow-water environments would clarify the degree to which related phenomena exist in these regimes. These observations should include sampling over the vertical, cross-range, and down-range spatial scales of these structures and should track the temporal evolution as well. A concomitant part of this program should be an effort to improve oceanographic descriptions of the small-scale structure in shallow-water environments. We need to understand the spatial and temporal resolution necessary to allow accurate simulation of such experimental data. Associated signal processing research should proceed in parallel with this program.

2) To utilize our understanding of fluctuating oceanographic environments in high-frequency acoustics, it will probably be necessary to develop acoustic inversion methods for obtaining oceanographic statistics. Otherwise, needed environmental information would generally not be available in a timely fashion for use in operational scenarios. An experimental program designed to further develop and test these inversion techniques could open up significant applications of stochastic acoustics in scenarios involving volume propagation.

Propagation with Boundary Interaction

In general, since full three-dimensional simulations involving boundary interactions will probably remain a challenge for some time to come, experiments will be essential for verifying the accuracy of simulation methods for geometries involving boundary scattering and, in particular, for testing the accuracy of approximate boundary scattering descriptions to the extent feasible. Here, in analogy with the volume scattering case, the issue becomes the following: How well do we have to know the boundary description? Among the topics discussed in Section 3.3, the following deserve special mention in regard to experimental programs:

1) High-intensity spikes in the propagated field can arise in several ways: from deterministic caustics, internal-wave focusing, boundary scattering, or combinations of these.

Experiments will be needed to better understand the occurrence of these effects and to help develop modeling techniques that can accurately “propagate” these statistics in the presence of boundary interactions.

2) Prediction of shallow-water propagation and reverberation will be typically hindered by a lack of relevant environmental detail. The general problem is to make these predictions with limited information and, at the same time, establish a range of predictions with some associated probability statement. Experimental measurements will be essential in verifying this methodology.

INTRODUCTION

On 16–18 April 1996, the Office of Naval Research Code 321OA sponsored the High-Frequency Acoustics Workshop at the Ramada Inn in Golden, Colorado. The group assembled for the workshop consisted of 55 investigators and program managers spanning a wide range of disciplines related to high-frequency (HF) underwater acoustics. (A list of attendees is given in Appendix A.) Investigator specialties included propagation, scattering, ambient noise, oceanography, geoacoustics, biological acoustics, and imaging. While the “center-of-mass” of this group was in the basic research (6.1) community, the exploratory development (6.2) community was also represented by a sizeable contingent. There were three principal objectives of the workshop: (1) to promote communication among the basic research investigators and between the 6.1 and 6.2 communities on high-frequency acoustics issues, (2) to identify the fundamental scientific issues and to clarify important goals for research in high-frequency acoustics, and (3) to suggest major field experiments that could address these goals. The full frequency range of interest extends from a few kilohertz to 1 MHz, though the frequencies associated with the main areas of applications are usually more restricted: 10–50 kHz for torpedoes and mine detection and 100–400 kHz for mine classification.

Overview

Structure of Workshop

The first day of the workshop was devoted to a series of 36 short presentations (Appendix B). Following an introduction by Jeffrey Simmen (ONR), the next eight presentations gave an overview of 6.2 acoustics programs and issues. Because the goals identified for basic research in high-frequency acoustics should also address the needs of the applied acoustics community where appropriate, this overview provided useful background for the workshop participants. The remaining presentations summarized a wide range of topics related to high-frequency basic research issues.

Agenda

On the second day the group divided into three working groups which focused on surface, bottom, and propagation issues, respectively. Each working

Working
groups

group had two discussion leaders, one representing acoustics issues and the other representing environmental issues. This structure emphasized the interconnections between acoustics and the environment. The surface group, led by Suzanne McDaniel (acoustics) and David Farmer (environment), addressed surface scattering, bubbles, ambient noise, and scattering from biological organisms in the water column. The bottom group, led by Ralph Goodman (acoustics) and Mike Richardson (environment), considered a wide range of topics related to acoustic scattering from and into the seafloor, including the appropriate geoacoustic descriptions of the sediment, and prospects for acoustic remote sensing of seafloor properties. The propagation group, headed by Henrik Schmidt (acoustics) and Terry Ewart (environment), addressed propagation entirely within the water column, propagation involving boundary interactions, and imaging. Membership of the three working groups is given in Appendix C.

Goals

The goals of each working group were twofold:

- 1) Identify the important scientific issues and research goals associated with each subject area.
- 2) Develop suggestions for major field experimental programs that could address these research goals.

On the third day the entire group reassembled and each working group gave a report, followed in each case by lively and informative discussions. At the conclusion of the workshop, it was quite evident that considerable progress had been made toward the goal of promoting communication among the members of the high-frequency community. The workshop atmosphere was informative, constructive, collegial, and, occasionally, chaotic. Although three days was too short a time for consensus to be reached among this diverse group of investigators, the workshop provided an important forum for exchange of ideas.

Workshop: Just a beginning

The body of this report summarizes progress on the second and third principal objectives of the workshop, which are also listed above as the goals for each working group. In developing this report, I chose to use the workshop dis-

cussions as the initial stage of a lengthier process of exploring high-frequency acoustics issues. My goal was to create a coherent and, I hope, useful overview of high-frequency acoustics rather than simply reporting on the ideas expressed at the workshop. Working with discussion leaders and others, I added to and modified significantly the contributions from each working group. If any workshop participants feel this report diverges too far from the collective views expressed, I accept primary responsibility.

In the sections that follow, references to results of particular investigators and to published work have been kept to a minimum, and therefore those included are certainly not comprehensive. The references included are of two types: those with names and dates refer to published papers or reports, and the full citations are given in the References section; those with names and affiliations are points of contact who can supply further information. Details on reaching the points of contact are given after the References section. (Names alone simply note prominent investigators in the field under consideration.)

References
and points of
contact

Background on Applications of High-Frequency Acoustics

The performance of high-frequency acoustic systems for detection, localization, imaging, tracking, and communications is limited by reverberation, attenuation, and distortion of the acoustic signals by the environment. Because of the high cost of in-water system testing, it is necessary to rely more on modeling and less on in-water testing in the design, evaluation, and performance optimization of these systems with respect to environmental degradation. Therefore the Navy R&D community needs accurate high-frequency acoustic modeling and simulation capability and accurate models of the relevant environmental processes. While considerable progress has been made toward these goals in phenomenologically oriented 6.2 and 6.3 programs, a more fundamental understanding of high-frequency acoustics and associated environmental processes is required to develop the full potential of modeling/simulation techniques. Indeed, reliance on purely empirical models for the impact of the

More reliance
on modeling

environment on high-frequency acoustics has important drawbacks: model extrapolation away from the conditions encountered is often unreliable and misleading, and adequate coverage of the full range of environmental variation would be costly and probably not even feasible.

Need for
fundamental
understanding

A more fundamental understanding of the acoustic and environmental processes will provide several benefits. Acoustic interaction with the sea surface, for example, is often characterized in terms of only wind speed, and improved model accuracy can be expected if the additional environmental processes most important to high-frequency interaction with the sea surface can be identified. In Naval applications where these primary environmental descriptors would be difficult to measure, a fundamental understanding of the environmental processes could allow substitution of more easily measurable descriptors. If the measurement of all environmental descriptors important to an acoustic observable were not practical, then assessment of the resulting model inaccuracy could be made. However, the potential applications of basic research in high-frequency acoustics extend well beyond physics-based simulation tools. In some cases, results of theoretical analyses may have direct application as a supplement to modeling/simulation studies. Perhaps even more important, innovative approaches for addressing problem areas in underwater acoustics can and do evolve out of an understanding of the acoustics/environment in terms of basic science.

Ship-wake
acoustics

While the primary focus of high-frequency basic research involves a better understanding of acoustics in the natural environment, discussions at the workshop also brought out the importance of a better understanding of high-frequency propagation in the vicinity of ship wakes. The advances in experimental measurement techniques and progress in acoustic modeling that would occur in a focused research effort on the fundamental science questions involving the natural environment should have important applications to ship wake acoustics as well.

Modeling of propagation and reverberation has been one of the main areas of interest in 6.2 and 6.3 high-frequency acoustics programs. Modeling of reverberation at high frequencies generally employs ray tracing for determining propagation, and requires models for volume backscattering, boundary backscattering (including bistatic backscattering), and boundary forward loss. In this approach, near-specular forward scatter is treated as if it were specular reflection with a loss. The spatial, temporal, and frequency coherence of a propagated signal and of the reverberation/noise background are also of high interest for signal processing. The spatial coherence, for example, will be useful for estimating the performance of beamforming algorithms. Statistics relevant to optimizing signal-processing algorithms, especially adaptive methods, are not limited to these, however, and statistics related to space-time coherence and to spatial and temporal variability are also needed. Since the various coherence statistics cannot be readily modeled or simulated using the present generation of propagation/reverberation models, they are typically addressed with theoretical analyses for simplified environments or via experiments. Wave-based propagation codes, such as those that use the parabolic wave equation (PE), can be used to model coherences, but the high computational requirement has limited the use of this approach in the high-frequency community. Modeling broadband propagation and reverberation is also of interest at high frequency, and this is especially challenging when coherence across the full frequency band is an important issue. In the latter case, traditional ray methods are generally inadequate, whereas methods that take proper account of the phase have considerable potential.

Propagation
and
reverberation
modeling

In addition to models of field intensity and other second moments of the acoustic field (e.g., various coherences), other statistical quantities are relevant to the design, evaluation, and optimization of high-frequency acoustic systems, especially those using adaptive techniques. These quantities include higher moments and the statistical distributions of the propagated signal and of the reverberation. It would appear that this aspect of high-frequency acoustics has

Need for
other field
statistics

not been extensively exploited and is an area where significant advances may evolve out of furthering our understanding of the basic science.

To establish the connection between current basic research issues and possible advances in areas of applications, more specific discussion will be given in each of the three sections that follow: Surface Scattering, Bottom Scattering, and Propagation.

1. SURFACE SCATTERING (including ambient noise and scattering from biologics)

In this section, acoustical issues as they relate most directly to applications are reviewed first, followed by a further elaboration of acoustical and environmental issues from a more fundamental perspective. An overview of goals for an experimental program is then given.

1.1. Acoustical Issues and Applications

Rough
surface vs.
bubbles

To view the acoustical issues in perspective, it is important to review our present understanding and modeling of high-frequency surface-related acoustical phenomena, including the relative role played by surface roughness and wind-generated bubbles in scattering processes. Near-forward scatter, which encompasses a narrow angular cone about the specular direction, is believed to be dominated by scattering from the sea surface at low to moderate wind speeds. As the wind speed and bubble density increase, the bubbles below the surface attenuate the acoustic field, so that at very high wind speeds the acoustic field incident on the sea surface can be highly attenuated. Away from the forward direction, surface scattering is attributed to scattering from subsurface bubbles at all but the lowest wind speeds, often well below the onset of visible wave breaking. The high-frequency ambient noise field is also related to the wave breaking and bubble formation process.

Backscatter
modeling

While there are ongoing efforts to develop improved theories to predict ambient noise and the scatter from rough surfaces and bubble clouds, we con-

sider here only the acoustic models employed in applications. Although no bistatic surface scattering model is in general use, models for monostatic backscattering strength and forward scattering losses are available. The predictions of these models depend only on the depth-integrated bubble density within the surface layer. Spatial variation of the bubble population, multiple scattering, and the effects of refraction are not treated. The bubble populations in the surface layer, which both scatter and attenuate the acoustic field, are empirically derived. The backscatter model is capable of duplicating the wind speed dependence of measurements, with the backscattering strength increasing with wind speed, overshooting a predicted saturation level by approximately 3 dB, and finally decaying to this saturation level as attenuation within the bubble layer increases. This model thus appears to predict many of the observed features of the data, provided bubble populations are known as a function of wind speed. (See for example *McDaniel*, 1993, and *Dahl*, 1997.)

The surface forward-scattering model assumes no losses due to rough surface scatter for an omnidirectional source and receiver. This assumption is in accord with measurements at low wind speeds and also with the predictions of the Kirchhoff-Fresnel approximation. The zero-loss model for rough surface scatter may be less accurate when multiple surface interactions occur, since treatment of all scattered energy as propagating in the specular direction will become less accurate as multiple surface interactions increase the angular spread of the scattered energy. The surface forward-scattering loss now accounts only for the attenuation occurring during propagation through the horizontally homogeneous bubble layer. While the bubble-layer model predicts many features of the observed backscattering strength, it is less successful for forward scattering loss. The model predicts increasing forward loss with wind speed, in agreement with measurements, but predicted scalings with wind speed and grazing angle are not in accord with measurements (*Dahl*, APL-UW). The model predicts very high losses (in some cases complete extinction) at high wind speeds, whereas observed losses tend to be substantially less. Horizontal

Forward-loss
modeling

inhomogeneities within the bubble layer, neglected in the model, may need to be included to model the forward loss accurately.

Single
parameter:
Wind speed

The surface scattering and ambient noise models used by the high-frequency acoustics community are based on a single environmental parameter—wind speed. However, even the earliest measurements of backscattering strength published some 40 years ago reported higher reverberation levels at a coastal site than at an open ocean site for the same wind speed. More recent measurements also show considerable variation (up to 10 dB) in scattering levels for measurements at different sites, but also for those at the same site; somewhat higher levels on average have been reported from sites near shore, but with considerable variability. The results show that wind speed alone does not determine the backscattering level. Not surprisingly, ambient noise levels in coastal waters also tend to exceed those in the open ocean in this frequency range. In addition, the greater abundance of biological organisms in coastal waters, whose individual and collective acoustical properties are not well characterized at high frequencies, may contribute to both surface and volume scattering and to ambient noise. Only acoustical scattering and ambient noise experiments, carefully coordinated with measurements of relevant oceanographic parameters, subsurface bubble distributions, and marine organisms, can clarify which environmental factors need be included to more accurately model surface scattering and ambient noise.

Other field
statistics

In addition to backscattering strength and forward loss, various second moments of the surface scattered field involving space, time, and frequency are needed. Approximate theoretical results for many of these quantities are available for the rough surface alone, ignoring bubble effects, and further improvement can be expected with the incorporation of recent advances in rough surface scattering theory. Such results are mainly relevant to forward scattering, since in that case the dominant effect of bubbles is simply attenuation of the scattered field. Important questions remain about the effect of spatial and temporal struc-

ture of the bubble field on these coherences for forward scatter, but even more so for general bistatic scatter and backscatter, where scattering from bubbles dominates. Similar remarks apply to higher moments and the scattered intensity probability density function (pdf). A trend toward higher-resolution systems with correspondingly smaller scattering patches on the surface will likely increase the importance of understanding these quantities, and, again, understanding the scales of bubble cloud structure will be essential.

Finally, models for volume backscattering from marine organisms are needed for high-frequency reverberation modeling. Marine organisms, especially the ones bearing gas (fish and siphonophores) or a hard elastic shell, are potential sources of false alarms in certain Navy systems. In order to develop a predictive capability that will account for observed spatial and temporal variability in the absence of direct sampling on a very fine grid, it will be necessary to relate biological activity and its associated scattering strength to ocean mesoscale dynamics, diurnal migration, and seasonal variability, as well as to understand the trade-off between sampling requirements and accurate prediction (Stanton, WHOI).

Scattering
from biologics

The development and validation of acoustic models for use in high-frequency system simulations and other applications have traditionally been funded at the 6.2 level. The last major advances in modeling surface scatter occurred about ten years ago with the introduction of bubble effects into surface forward and backscatter models. Increased effort needs to be devoted at the 6.1 level to the surface-related issues discussed if further progress is to be made in this area.

Need for 6.1
research

1.2. Fundamental Science Issues

In this section, some fundamental acoustical issues related to the near-surface environment are summarized. In the process many of the issues touched on in Section 1.1 are revisited, but here the fundamental science aspects are emphasized. It should be evident that progress on these fundamental issues could form

the basis for modeling improvements in many areas of interest to the high-frequency community.

1.2.1. Bubbles

Bubbles and hydrodynamics

The upper ocean boundary layer is a distinct acoustical environment in which the active hydrodynamics of the wave zone combines with the surface bubble layer to scatter, refract, and otherwise modify high-frequency acoustic propagation. Our ability to generate useful predictions of high-frequency system performance near this environment is ultimately limited by our modest knowledge of the concentration and size distribution of bubbles near the ocean surface. Since the bubble field varies continuously in space and time, we can never hope to have a deterministic prediction, but we should be searching for systematic relationships between the stochastic properties that are important to acoustical predictions and the variables, such as wind speed, directional wave field, and air-sea buoyancy flux, that combine to determine these stochastic properties. The task is to some extent one of small-scale oceanography, since the pattern of bubble generation, diffusion, advection, and dissolution is a direct consequence of the hydrodynamics of the wind-driven ocean surface layer. The oceanography and acoustics are inextricably connected.

Bubble distributions

Bubbles are the strongest acoustical scatterers near the surface and can be measured remotely by acoustical means, so oceanographers concerned with measuring bubble distributions have turned to high-frequency acoustics. At present, the only reliable measurements of bubble size distributions are those made using in situ acoustic techniques. Lidar technology is an attractive alternative for obtaining the spatial distribution of bubbles, although not the size distributions; however, lidar has yet to be exploited for spatial distributions. Photography and related optical measurements can be used to determine size distributions in very dense bubble clouds close to the surface, which may be inaccessible to acoustical methods. Wave breaking is the primary source of noise in the ocean, so detection of ambient noise is an obvious route to measurement of breaking waves and bubble production. Bubble sizes and concentra-

tions are measured from the acoustical variables of sound speed anomaly, attenuation, and backscatter. These are just the parameters acousticians need for modeling acoustical scattering; backscatter, attenuation, and propagation speed can all be modeled from knowledge of the bubble size distribution. Most important, the relationship between the pattern of advection and turbulence associated with subsurface circulation, and the frequency and pattern of wave breaking itself, are the topics that need to be understood if we are to develop a firm foundation for acoustical prediction.

In the absence of bubble clouds, high-frequency acoustical waves are scattered by the ocean surface. At higher wavenumbers the surface wave field consists of capillary-gravity and capillary waves, the behavior of which differs markedly from that of lower wavenumber features. For example, there is strong modulation of high-wavenumber structure by the longer waves, and nonlinear capillary waves tend to peak downwards rather than upwards. High-frequency acoustic surface scattering in the absence of bubbles has not been well studied, but improved understanding and results obtained with radar investigations should have some application in this regime.

The rough sea surface

As waves break, ambient noise is produced as entrapped air relaxes to form spherical bubbles. The sound is generated intermittently in space and time in a way that cannot yet be reliably related to the details of the breaking process. Suggestions of using natural hydrodynamic and biological sound sources to image objects [Buckingham, SIO] can be fully exploited only if these processes are understood.

Imaging with ambient noise

Bubbles are extremely effective scatterers owing to their high quality factor (Q) at resonance. At low frequencies the collective properties of the bubbles are important; at high frequencies and moderate bubble densities, their individual resonant characteristics dominate. The transition between these two regimes is not well understood.

Single bubbles vs clouds

Bubble clouds can have distinctive geometrical characteristics that affect scattering. For example, average bubble density decays approximately exponentially with respect to depth with an e-folding depth determined by wind speed, typically one to a few meters. The bubble sizes that are most important acoustically have resonances ranging between 20 and 60 kHz, but there are important changes in bubble size distri-

Bubble cloud structure

bution with depth. At about the dominant resonance frequency the sound speed anomaly is zero, but the attenuation is maximum. Since the predominant bubble size is greater near the surface, the frequency of zero sound speed anomaly tends to increase with depth, leading to frequency-dependent refractive properties. Bubble clouds typically have a highly anisotropic structure, being generally aligned with wind direction. Corresponding anisotropy can be expected in the scattering and propagation characteristics.

Bubble cloud variability

Quite apart from the general characteristics identified above, observations of bubble cloud properties indicate very great spatial and temporal variability. Such variability can be expected to lead to corresponding variability in the spatial and temporal characteristics of the acoustic field interacting with bubble structures. Observations of ambient noise and imaging based on ambient noise may provide avenues for assessing such variability. In addition to the larger-scale and more systematic organizations caused, for example, by Langmuir circulation, local bubble cloud injections must occur as a result of breaking waves or near-surface shear flow instabilities. Doppler shifts in backscattered sound can be expected both from these background flows and from the wave orbital motions.

Single vs. multiple scattering

Multiple interactions of the acoustic field in dense concentrations of bubbles play an important role in scattering and attenuation processes. High air fractions will always be encountered in the immediate vicinity of whitecapping, but these persist for only very short periods, of order 1 s. Smaller air fractions persist for longer periods. The single scatter approximation is valid only for short propagation paths at low bubble density. For most cases the effects of multiple scattering can be treated using the Foldy approximation (an approximation used to describe collective scattering effects in terms of a complex index of refraction). The net result for most practical applications is that bubble scattering can be considered single scattering plus attenuation by the background bubble field. At extremely high bubble densities even the Foldy approximation may break down.

1.2.2. Biologics

Biological scatter may also be an important feature of ocean surface scattering, especially when dense thick layers of animals are present. One important issue is related to the modeling of acoustical scattering by the various anatomical classes of the animals (e.g., fluid-like, gas-bearing, hard elastic shelled). Another issue is the problem of separating scatter by plankton from scatter by bubbles (possibly through differences in their Doppler signatures). An especially important issue is understanding the resonance properties of the gas-bearing animals and the effects of tissue damping on the resonance.

Biological
scatter

1.2.3. Microscale turbulence

Finally, at high frequencies backscattering from microscale turbulence can sometimes be stronger than that from biological organisms. The important acoustical effects will occur primarily in regions of strong salinity and temperature gradients. Turbulence in these high-gradient regions will produce small-scale fluctuations in the index of refraction and density, which can be a source for backscatter. Regions of turbulence near the surface and bottom boundaries (e.g., bottom boundary layer turbulence) will often be well mixed, and in such cases the potential for scatter is reduced. It will be important to develop a capability to predict acoustically important microscale turbulence from knowledge of the environmental drivers of turbulence.

Scatter from
turbulence

1.3. Environmental Considerations

The previous section mentions a number of high-frequency acoustics issues related to the near-surface environment. This section describes several environmental topics in more detail that ideally should be studied in conjunction with acoustical measurements but could be examined independently. In either case, improved understanding of these topics will contribute to further progress on the acoustical issues. Physical Oceanography is the primary supporting discipline at ONR.

1.3.1. Environments: Coastal Waters and Open Ocean

In order to understand high-frequency acoustic variability in different environments for the same wind speed, it is necessary to better understand the variability of environments and, in particular, the variability in surface waves and near-surface bubble properties in different locations for the same wind speed. The environments could be broadly classified as open ocean, coastal waters, and surf zone.

Variability in coastal waters

The surf zone environment was not considered in any detail at the High-Frequency Acoustics Workshop and will be excluded from discussion here. Among the remaining two, the coastal waters environment likely presents the most variability and is also of higher interest; if the most important environmental processes for acoustical interactions in coastal waters could be understood, the open-ocean case would likely be in hand as well. A number of factors may significantly affect the near-surface environment in coastal waters. Possibilities include

- current/wave interaction
- short fetch
- wind channeled by topography
- suspended sediments
- salinity and temperature variations
- shallow-water effect on Langmuir circulation
- enhanced biological activity
- increased level of contaminants on bubbles.

While important issues remain concerning which environmental processes have the most effect on acoustic scattering, a better understanding of how the factors above affect wave breaking and, in particular, bubble distributions near the surface would make an important contribution to understanding the acoustic scattering variability problem.

1.3.2. Bubbles

When waves break, air can be entrained and bubbles form. Bubble radii can span several orders of magnitude; the largest bubbles rise quickly to the surface while smaller ones, typically $< 400 \mu\text{m}$, linger within the upper 1–2 m and may become entrained in Langmuir convergence zones where they sink to 10–20 m before going into solution. Direct injection by breaking waves or by fluid instability of the surface shear zone can also occur. As the bubbles sink they are subject to increasing hydrostatic pressure; the resulting increase in curvature enhances the pressure through surface tension. In addition gases pass into solution at a rate determined by the difference between the partial pressure in the bubble interior and what it would be in the surrounding water in the absence of the bubble. Although ocean observations support the notion that most bubbles sinking in convergence zones do dissolve, it is also possible that organic detritus or surface films may stabilize the bubbles and prevent them from going into solution. In addition, as Langmuir circulation brings water with dissolved gases back to the region near the surface, the lower pressure may cause the water to be supersaturated, with the result that bubbles near the surface may grow rather than dissolve and new bubbles may be generated. The distinctive acoustic properties of bubbles are related to their small damping coefficient (high Q), which makes them particularly efficient scatterers at high frequencies. However, this same high Q also implies that prediction of acoustical properties requires knowledge of the bubble size distribution. This distribution is as yet a poorly understood function of surface forcing and water properties, including dissolved gas partial pressures. The effect of organic detritus or surface films on the bubble damping coefficient remains an unresolved issue.

Bubbles and
Langmuir
circulation

Bubble clouds are anisotropically distributed in the ocean. Not only are they injected by the seemingly random and intermittent process of wave breaking, but they are also organized by subsurface motions that tend to align them with the wind direction (Langmuir circulation). Thus bubble clouds, which may persist for tens of minutes or more, appear to be fed intermittently by breaking

Spatial
structure of
bubble clouds

surface waves. In a well-developed sea, a more uniform distribution of bubbles lies close to the surface; there appears to be a much-enhanced tendency to form deeply penetrating bubble clouds when there is a strong upwards buoyancy flux. The link between bubble clouds, wind forcing, and buoyancy flux is only beginning to be explored by oceanographers.

1.3.3. Biological Organisms

Acoustic signatures

Since it is well known that some zooplankton favor upward migration at dusk, it seems likely that under certain circumstances plankton can have an appreciable impact on near-surface high-frequency scattering and propagation. The acoustical properties of zooplankton are complicated (very much more so than bubbles!) and are only beginning to be investigated in detail. Models are being developed to account for acoustical interactions with different parts of the body for just one or two species. The acoustical signature of their motion is being categorized. Their collective behavior will be important in determining their overall significance to high-frequency scattering. Plankton are known to form elongated patches. If these patches are dense enough, they will become important high-frequency targets. Interesting questions arise with respect to their behavior in Langmuir circulation. Do they tend to congregate in downwelling or upwelling zones? How may they best be separated from bubble scatter in a wind driven surface layer?

Volume- scattering variability

Environmental conditions have a dramatic effect on the spatial and temporal variability of fish and zooplankton occurrence. Understanding these effects helps predict volume scattering by the animals as a function of time and location. For example, since certain zooplankton favor upward migration at dusk, volume scattering will have a strong component of daily variability. The animals also tend to aggregate (1) at depths where there is a strong vertical gradient in temperature, and (2) sometimes in the vicinity of mesoscale bathymetric features. Probabilities of occurrence of organisms with respect to the gradients and bathymetric features need to be estimated. Finally, their behavior in Langmuir circulation zones will affect volume-scattering variability.

1.4. Overview of Experimental Program Goals

A broadly based experimental program could address many of the issues discussed in the previous three sections. To provide a suitable focus, only an overview of a limited set of experimental goals will be discussed; these goals will have a straightforward connection to the needs of the high-frequency community. A further elaboration of fundamental issues that could be readily addressed in an experimental program will not be pursued here.

As previously discussed, both surface roughness and wind-generated bubbles are relevant to high-frequency surface interaction. Better understanding the acoustical effects of bubble phenomena forms the core of the most important research issues, since surface roughness effects appear to be better understood. As noted in Section 1.1, present models for backscattering strength and for forward scattering loss treat the bubble field as a homogeneous nonrefracting surface layer. Such a simplified treatment of the near-surface bubble field is motivated by (1) its apparent success at replicating many of the features of the average backscattered intensity, and (2) the present lack of available environmental models that accurately represent the spatial and temporal structure of the bubble field.

Bubbles:
Homogeneous
surface-layer
model

While work has been done on incorporating the refractive effects of the near-surface bubble layer, treatment of the bubble field as a surface layer without spatial or temporal structure is a significant limitation to further development of modeling and simulations involving surface interaction. Sea surface backscattering strength depends on integral measures (both vertically and horizontally) of the bubble field and is not highly sensitive to simplifications of present modeling methods for typical scattering patch sizes. Many other important properties of the acoustic interaction with the sea surface, such as loss in forward scatter due to attenuation by bubbles, are likely to be more sensitive to the bubble cloud structure. For example, when the average forward loss becomes high, it is reasonable to suspect that surface interactions involving

Need for
models of
bubble spatial
structure

propagation paths passing between the major cloud structures will become important in determining the average loss and fluctuations in loss. In addition, large space- and time-scale variability of the surface forward-scattered field should be strongly affected by the corresponding intermittency in bubble cloud structure. Accurate modeling of frequency shifts and spreads and various field coherences following surface scattering may also depend on suitable models for bubble cloud spatial and temporal structure; this is an area that requires detailed investigation. Understanding backscatter for small scattering patch sizes, important for high-resolution acoustic systems, will also require improved models for bubble cloud structure.

Bubble-field
models linked
to hydro-
dynamics

To improve our understanding of basic science issues related to high-frequency surface scattering and to move to a higher level in modeling this process, improved descriptions of the spatial and temporal nature of the bubble field are needed. The requirement is a stochastic, space-time description of the bubble field sufficiently complete to form the basis of acoustic model development. For this purpose it is also necessary to understand the important environmental descriptors, in addition to wind speed, that determine the properties of the bubble field. Recent advances in near-surface environmental characterization over the last few years make such an effort a reasonable extrapolation of present capabilities. The new generation of bubble sensing instruments is beginning to provide reliable and self-consistent bubble size measurements. These must be accompanied by two- and three-dimensional measurements of the velocity field and measurements of the surface wave field, including wave breaking, dissolved gas partial pressures, and related variables. The task is interdisciplinary, including both ocean acoustics and small-scale oceanography. More than in any other area of ocean science, there is a strong synergy of oceanographic and acoustic interests in the study of ocean surface processes. The goal must be to develop a comprehensive hydrodynamical model of the near-surface circulation coupled with a model of bubble sources, modification, and dissolution.

Experimental
and modeling
goals

The focus of an experimental acoustics program, then, could be the dual goals of (1) developing the needed space-time bubble field descriptions through environmental characterization efforts, and (2) using these descriptions to demonstrate improved understanding of high-frequency surface scattering and improved accuracy in modeling the experiments. As part of this work it will be necessary to (1) apply full three-dimensional wave propagation techniques to fully understand the effects of the space-time bubble field on acoustic processes, (2) assess the accuracy of more approximate modeling methods, and (3) develop improved theoretical scattering techniques that utilize the more detailed bubble-field description. In the forward scattering case it will be necessary to account for rough surface scattering in addition to the bubble-field effects. The goal from the view of Navy applications would be to elevate the paradigm for modeling high-frequency surface scattering from one using a simple model of homogeneity in the bubble field to one using models of the space-time structure of the bubble field. An important assumption here is that such improvements in the environmental description would lead to significant improvements in model accuracy. Verification of this assumption would be an important part of the program goals.

2. BOTTOM SCATTERING

As with Section 1 on surface scattering, acoustical issues as they relate most directly to applications are reviewed first. This is followed by a further elaboration of acoustical and environmental issues from a more fundamental perspective. Finally, an overview is given of goals for experimental programs.

2.1. *Acoustical Issues and Applications*

Reverberation from the seafloor is often the limiting factor for active sonars in shallow water, which enhances the importance of bottom reverberation prediction. In order to assess where progress in basic research topics could be of substantial benefit in high-frequency acoustics applications, it is important to

Present
modeling
capability

understand the present capability for reverberation prediction in the applied arena. The status of modeling high-frequency reverberation from the bottom has a number of similarities with the surface case. While bistatic bottom scattering models have been developed, they are not in general use. The required "submodels" for use with ray tracing predictions have traditionally been models for monostatic backscattering strength and bottom forward loss.

Limitations in environmental description

In the more detailed developments, monostatic backscatter is related to roughness at the water-bottom interface and to inhomogeneities within the upper few meters of the bottom. (At high frequencies absorption generally limits the acoustic field to the upper few meters.) In practice, more simplified scattering models are used than those that exist because detailed environmental descriptions are rarely available. For example, the Navy models reduce the bottom properties into a single parameter or descriptor. While a significant level of survey work has been undertaken to characterize the bottom, the survey data have not been sufficiently complete for use with more detailed scattering models. It is likely that the best approach for improving model accuracy will involve determining bottom parameters as they are needed, using either remote sensing techniques or in situ methods that are applied in tactical situations.

Bottom loss

Bottom forward loss models share the same limitation encountered in the surface case: they describe the near-specular forward scatter by specular reflection with loss. This is not due to the lack of bistatic scattering models for the bottom, but to the inability of ray tracing methods as presently implemented to account for bistatic scattering. While loss due to transmission into the seafloor can be modeled, the effective loss due to bottom roughness cannot be reliably estimated for use with ray tracing methods. This is an especially acute problem for the case of a rough rock bottom (Keenan, SAIC). Because the bottom can be rougher than the surface in some cases, the fundamental limitations of the forward loss concept become more evident for the bottom.

In addition to backscattering strength and forward loss, the ability to predict the spatial coherence and frequency coherence of the bottom scattered field is

important, and further progress is needed in this area. These coherence estimates are needed for the design of adaptive beamforming algorithms, for example.

The acoustic detection of buried mines is another area of Navy interest, and clearly such detection depends critically on the transmission of sound into the seafloor. Since detection at a distance is desired, a low grazing angle for the incident field is preferred. Accurate prediction of the intensity level and the spatial coherence of the acoustic field in sediments is therefore important in the low grazing angle region. This will require detailed knowledge of seafloor properties, which would likely be obtained through inverse techniques yet to be developed. It will be important to understand which geometries will allow for the detection of buried mines for given seafloor properties. Of major importance is the certainty that "no detection" implies "no mines," that is, there is no "incorrect dismissal."

Acoustic
detection of
buried mines

2.2. Fundamental Science Issues

2.2.1. Background

The role that the seafloor plays in the application of acoustics to the detection, location, and identification of objects in shallow water is well known and has been the object of investigation for about 50 years. Early studies identified reverberation characteristics as they related to sediment types (e.g., sand, silt, mud, rocks), but little was done beyond descriptive modeling. Early studies of in situ propagation developed empirical relationships of sound speed and attenuation to sediment characteristics (e.g., Hamilton, Richardson).

Background

Although much was learned empirically, little effort was made on the fundamental understanding of the physical properties of high-frequency acoustic propagation within the seafloor (limited to the upper few meters at high frequency) and scattering from the seafloor. This lack of effort on fundamental high-frequency bottom issues is due in part to the past emphasis on blue water

ASW. In addition, the enormous variation in the physical characteristics of the seafloor posed a formidable barrier to theoretical models. The work of Biot, however, stimulated interest in the basic understanding of propagation in poroelastic structures. This work was limited mostly to homogeneous structures.

More recently, with the revived interest in high-frequency shallow water studies, there have been advances in both acoustic theory and experimental measurements (Chotiros, Stoll, Jackson, Tang, Stanic, Zhang, Ivakin, and others). High-frequency acoustic measurements accompanied by adequate environmental support data (e.g., density, porosity, compressional wave velocity and attenuation, shear wave velocity, and roughness spectra of the seafloor) are still limited and have yielded many unexplained or inconclusive results. Thus there are still fundamental physics issues that need to be resolved. Some of these are given below.

2.2.2. *Issues*

Scattering mechanisms

1) Reverberation measurements have not generally been accompanied with 6.1 level environmental characterization. As a consequence it has not been possible to isolate the individual contributions to backscattering that are due to surface roughness, variation in impedance, volume inhomogeneities, bubbles, and other discrete scatterers. If the physics of reverberation is to be understood for a variety of sediment types, measurements to isolate and determine the importance of each process are needed.

Anomalous penetration

2) Some measurements have shown anomalously high penetration of sound into the seafloor for signals incident at grazing angles below the "critical angle." These results could have significant implications, both for the detection of buried objects and for the contribution of volume scattering to reverberation. Both the experimental verification and the concomitant theoretical explanation are important issues.

3) The wide variation in the physical characteristics of the seafloor (from very porous mud to highly consolidated sands and rock, with layering and random inhomogeneities of physical, biological, and biogeochemical origin) leads to a variety of models for the seafloor for use in propagation (and scattering) modeling. These include pure fluid, elastic, viscoelastic, poroelastic, and composite models. There are still important questions about which model is most appropriate for various phenomena being considered (e.g., sound speed, attenuation, frequency dependence of scattering, etc.). As one example, at most locations on the seafloor the upper meter is composed of sediment, and a fluid sediment model is commonly used in modeling high-frequency scattering. At the low end of our frequency range, where deeper acoustic penetration may occur, or for rocky bottoms at all frequencies, the effect of shear may be significant for scattering and for bottom loss modeling. It is important to clarify when a fluid sediment model is not adequate.

Seafloor
models

4) Experiments have shown considerable spatial variability (both vertical and horizontal) in bottom characteristics ranging from millimeter to kilometer scales and temporal variability ranging from seconds to years. In most cases, especially in operational environments, deterministic modeling of acoustic scattering based on spatial and temporal variations in sediment characteristics is unrealistic. It is therefore an important issue to determine the statistical characterization of seafloor properties and roughness that is required for physics-based modeling of acoustic scattering and propagation. Present theory and modeling techniques do not adequately allow for the heterogeneity that is observed in seafloors.

Seafloor
variability

5) The sound speed and density structure in the upper few meters of the sediment can significantly affect both backscatter and forward scatter but is usually ignored in high-frequency modeling. Fine-scale stratification, for example, can lead to frequency dependence in reflectivity and enhanced multiple scattering, and sound speed gradients can refract low grazing angle energy back into the

Stratification/
gradients

water column. The importance of these effects for modeling bottom interaction at high frequency needs to be better understood.

Bubbles in
sediments

6) Experiments have shown that bubbles in sediments can have significant effects on high-frequency bottom acoustics. The differences in the acoustical properties of bubbles in various sediment types versus bubbles in the water column need to be better understood.

Multiple
scattering

7) The importance of multiple scattering within the sediment needs to be clarified.

Inversion for
seafloor
properties

8) The ability to use acoustical returns from the seafloor (i.e., reflectivity and monostatic or bistatic scattering) to deduce seafloor properties is clearly limited by the issues that are listed above. Since acoustic returns inherently depend on the physical properties of the seafloor, it is important to determine the degree to which acoustics can be of value as an "inversion" technique. Indeed, the practical difficulties of determining a comprehensive description of seafloor properties through direct sampling, such as with core samples, suggest that for Navy applications inversion methods will be essential if significantly improved modeling accuracy is to be obtained.

Response of
buried objects

9) The acoustic response of an elastic object, such as a mine, that is imbedded either partially or fully in a sediment depends significantly on the physical properties of the sediment as well as that of the object. Limited theoretical and experimental studies have been made to date. While some aspects of this problem fall within the applied acoustics domain, the acoustic response for simple shapes (e.g., spheres) is a basic research issue.

Poroelastic
model at HF

10) Bottom acoustics using the poroelastic model of a water-saturated sediment, based on pioneering work by Biot, is being actively pursued. [See, for example, *Stoll* (1986) and references therein.] In this approach, the sediment is modeled as a two-component medium: a lattice of solid grains, with the pore spaces between the grains filled with water. For high-frequency acoustics, this model is generally applied to unconsolidated sediments near the water-sedi-

ment interface, where the grains may not form a completely rigid lattice; that is, there may be relative motion between the grains. The proper treatment of non-rigid lattices in poroelastic models is an important issue. The depth dependence of the poroelastic properties may also be an important issue, owing in part to the effects of overburden pressure. Finally, the boundary conditions at an interface separating two different poroelastic media involve an "interface permeability," and the proper specification of this quantity is an issue.

11) At very high frequencies (100 kHz–1 MHz), the regime is reached where the acoustic wavelength approaches the size of the grains, and the continuum model of the sediment will break down. The "graininess" of the sediment could have important effects for acoustic propagation and scattering within the sediment, but the nature of these effects and the frequency at which they first become significant are not presently known.

Breakdown of
continuum
model

2.3. *Environmental Issues*

This section describes several environmental issues related to the seafloor. Improved understanding of these topics will contribute to further progress on the acoustical issues.

1) Statistical models are needed for describing sediment inhomogeneities, including wavelength-scale structure appropriate to backscatter. Present models have been formulated from quite limited measurements of the inhomogeneity structure. A systematic experimental investigation of sediment inhomogeneities would be of direct use in high-frequency bottom acoustics.

Sediment
inhomo-
geneities

2) A better understanding of the lateral variability of seafloor properties will help establish the spatial sampling requirements for seafloor characterization. If the processes that lead to lateral variability are better understood, better estimates of expected variability could be made prior to a characterization effort based on inverse techniques, for example.

Lateral
variability

3) A better understanding of fine-scale stratification and gradients in the upper few meters of the sediment would aid in bottom interaction modeling. A better understanding of where such features are likely to occur is also needed.

Stratification/
gradients

Bubbles in
sediments

4) The conditions that lead to bubbles in sediments need to be better understood. It would be a significant advance if the presence of bubbles could be inferred without direct measurement.

Temporal
variability

5) Several processes lead to temporal changes in bottom roughness and in sediment properties close to the water-sediment interface. These include biological reworking of sediments and sediment transport due to currents and surface waves. Further progress on understanding these topics would improve prediction of sediment properties.

Sediment
microstructure

6) Improved knowledge of marine sediment microstructure will aid in the application of poroelastic models to sediment acoustics.

2.4. Experiments

There are two types of experiments of importance for high-frequency bottom acoustics: laboratory tank experiments and experiments at sea.

2.4.1. Tank Experiments

Strengths

Tank experiments, if used properly, can be of considerable benefit, but tank experiments also have important limitations. While many acoustics investigations are better done on a computer, at least in the initial stages, not all aspects of the sound-sediment interaction can be reliably included. Tank experiments provide a useful intermediate ground between simulations and full at-sea experiments. The environment can be more controlled than for field experiments, and sediment properties can be varied over a wider range than found in the field to enhance physical effects.

Limitations

In general, tank experiments cannot accurately reproduce natural environments. Even when sand sediment is used, its preparation for the tank environment makes it unlike natural sediments. In addition, tank sediments will not have realistic surface roughness and volume inhomogeneities. Finally, results for the relatively high frequencies required in tanks cannot generally be scaled down to lower frequencies of interest.

Among the possible goals of tank investigations are the following:

- | | |
|---|----------------|
| <ol style="list-style-type: none"> 1) Testing methods for characterizing sediments. 2) Testing acoustic equipment and concepts prior to experiments at sea. 3) Examining isolated acoustic phenomena in controlled environments, e.g., propagation through known sediments, effects of gas bubbles in sediments, testing Biot model predictions, scattering from complex shapes, and effects of sand grains at very high frequencies. 4) Testing remote sensing concepts. 5) Testing scattering and imaging codes for the detection and classification of objects within the seafloor prior to at-sea experiments. | Possible goals |
|---|----------------|

2.4.2. *Experiments at Sea*

Three experimental programs that would address a number of the issues previously discussed are outlined here:

2.4.2.1. Penetration of sound into the seafloor at low grazing angles

Field experiments are needed to understand the anomalously high penetration of sound into the seafloor at incident grazing angles below the critical angle. Hypotheses for this penetration include generation of a Biot slow wave, scattering by roughness at the water-sediment interface, and scattering of the evanescent wave by volume inhomogeneities just below the interface. This experimental investigation will require the burial of receivers and, possibly, sources. Since, in some cases, compressional waves, shear waves, and (possibly) the Biot slow wave are expected to exist, geometries and sensor placements that allow the identification and measurement of these waves are essential.

Anomalous
penetration
into sediments

It is also essential that these experiments include the sedimentological and oceanographic measurement support necessary to allow understanding the physics of both propagation and scattering. Necessary for understanding

acoustic behavior are the following: stereophotography of the seafloor for measuring roughness, high-frequency and broadband acoustic profilers for determining layering and variability over a wide range of spatial scales, and instruments for studying physical composition and behavior, such as porosity, density, permeability, gas content structure, and shear and compressional wave velocity and attenuation.

Buried mine
detection

This program would have immediate relevance to the Navy in the area of buried mine detection and would also contribute to an understanding of reverberation due to scattering within the sediment. It may be relatively straightforward to also address issues on the acoustic response of buried scatterers within the same experimental program.

2.4.2.2. Reflection and Scattering from Sediments

Bottom
scattering:
The forward
problem

As mentioned in Section 2.1, a promising approach for improving the accuracy of bottom reverberation modeling would be to infer the relevant bottom parameters using acoustic remote sensing techniques. However, before inverse techniques could be reliably used to rapidly determine the seafloor environment, the forward problem needs to be investigated further. This need exists because the individual contributions to the scattering (e.g., surface roughness, volume inhomogeneities, bubbles) have not been adequately isolated and related to measured properties of the environment. Thus, there is a need for an experimental program in high-frequency bottom acoustics with the goal of convincingly identifying the various scattering mechanisms and relating these contributions to measurements of the environment through theoretical and numerical analyses. The frequency coverage should be comprehensive (from a few kilohertz to a few hundred kilohertz) and the full bistatic geometry utilized. The key element of such a program should be a detailed environmental characterization effort at length scales down to one quarter of an acoustic wavelength. Many previous experimental investigations at high frequencies have lacked the rigorous environmental study appropriate to a 6.1 level effort. It is felt that only

by making such an investment could the forward scattering problem be understood to the degree required for reliable remote sensing applications.

2.4.2.3. Remote Sensing of Seafloor Properties for Use in High-Frequency Acoustics

An experimental program focused on acoustic remote sensing of seafloor properties would be a logical follow-on to the effort outlined in the previous section. With an improved understanding of the fundamental scattering mechanisms over a wide frequency band, the stage would be set for developing and optimizing remote sensing methods. The sediment characterization methods employed in Sections 2.4.2.1 and 2.4.2.2 would provide ground truth presently lacking in tests of acoustic remote sensing. As part of this program it would be important to better understand the occurrences of spatial variability in seafloor properties and to determine the impact of spatial variability on remote sensing strategy. A potential Navy payoff here would be significantly improved predictions of high-frequency reverberation based on a real-time assessment of the seafloor scattering properties. In addition, remote sensing of sediment geotechnical properties, such as shear strength, could have diverse applications.

Bottom
scattering:
The inverse
problem

2.4.3. *Additional Remarks*

The focus in this section has been on discussing possible experimental programs for pursuing important basic research issues with clear Navy relevance. It is assumed that an accompanying theoretical/numerical effort would be an integral part of these programs, but further discussion of this component will not be given here.

3. PROPAGATION

This section addresses high-frequency propagation and imaging issues. Both propagation within the water column (volume propagation) and propagation involving boundary interactions are considered. It is convenient to organize the propagation topics into three categories: volume propagation in a determin-

istic environment (Section 3.1), volume propagation in a fluctuating environment (Section 3.2), and propagation with boundary interaction (Section 3.3). Propagation in a fluctuating environment is usually described stochastically; at high frequencies scattering due to boundary roughness will generally require that the third category also be described in terms of stochastic concepts. Imaging issues will be included as appropriate within these categories. Possible goals for experimental programs are summarized in Section 3.4.

Importance to the Navy

Deterministic volume propagation is important because of its relevance to modeling the mean acoustic environment in which Navy operational systems are utilized; topics include propagation in sound channels and range-dependent environments and the formation of caustics. The importance of stochastic volume propagation arises from the limits imposed on Navy operational systems by stochastic effects, e.g., the effects of ocean internal waves and turbulence on matched field processors and imaging. The randomizing effects of boundary interactions, when they occur, will usually far exceed those of volume propagation. At high frequencies the effects of boundary interactions on propagation are generally confined to shallow-water regions or to regions near the sea surface; however, when such interactions do occur the effects on the acoustic field are more pronounced than at lower frequencies.

3.1. Volume Propagation in a Deterministic Environment

The primary issues for propagation in deterministic environments are related to propagation modeling. [See, for example, *Jensen et al.* (1994) and *Etter* (1996).] Since ray theory is commonly used to model high-frequency propagation, this approach is considered first.

3.1.1. Ray Theory Methods

Generalized ray theory

Classical ray theory is obtained from the wave equation in the high-frequency limit. Though classical ray theory has been extensively used for high-frequency propagation modeling, it has well known difficulties, e.g., infinite intensity at caustics and vanishing intensity in shadow zones. Neither of these

predictions is accurate because diffraction is ignored. "Ray theory" has been developed further to approximately correct for these deficiencies in applications related to Navy R&D and to Navy operations. A prominent example is the work by Weinberg who has developed the multipath expansion model [included in the Generic Sonar Model (GSM), which assumes a range-independent environment] and more recently the Gaussian Ray Bundle model (GRAB), a range-dependent model. RAYMODE is another widely used range-independent model and is also based on the multipath expansion approach (*Etter, 1996*). Since these propagation models incorporate more of the propagation physics than included in classical ray theory, the terminology of "ray tracing" is itself somewhat misleading; the rays being traced are actually a form of generalized rays. Although such models have a long history of constructive use within the Navy community, they are seldom utilized in the research community. This is in part because the physics in these models is not easily accessible and thus is not well understood in the research community. Also, results of these models have been compared with wave propagation results in terms of propagation loss, but detailed comparisons of the complex field structure are generally not reported. In any case, research investigators have tended to use classical ray theory or, at the lower end of our frequency range, to invoke wave propagation methods such as PE, normal mode, or wavenumber integration [used, e.g., in SAFARI and its successor, OASES; see *Jensen et al. (1994)*].

An important general issue concerns the expected role of ray tracing in underwater acoustics in the near term: Will rapid improvements in the efficiency and computation speed of wave propagation models eliminate the need for ray tracing entirely and allow a general transition, even at high frequency, to more rigorous wave-propagation methods? It appears that, though the day of transition may be approaching, ray tracing has useful mileage left and could be further improved. The computation speedup for ray tracing versus full wave propagation is significant and could be used to advantage in analyzing more cases in real-time scenarios, for example, or more complicated geometries as computation times decrease. Ray theory will have a particular computational

Ray theory
remains useful

advantage for broadband propagation when the full time dependence of the arrival structure is of interest. Improved accuracy could be obtained using ray theory based on a more complete “semiclassical expansion” technique, including construction of the full complex wave field and the field near caustics (Henyey APL-UW; Brown, U. of Miami). Ray theory is also useful for visualizing the direction of energy flow and for physically interpreting the results of full wave methods. Finally, the inherent prediction uncertainty associated with an imperfect knowledge of the sound speed profile over the propagation path should not be ignored, since it may overshadow full wave/ray theory differences in many cases.

Ray chaos

As emphasized by Tappert, Brown, and colleagues, there is a serious potential problem for applications of ray theory in range-dependent environments: the onset of “ray chaos” for nearly horizontal long-range paths (i.e., nearby rays diverge exponentially with range, and the number of eigenrays diverges exponentially with range) which could seriously impact modeling efforts (e.g., *Tappert and Tang*, 1996; *Collins and Kuperman*, 1994). This work has focused on classical ray theory at megameter ranges with mesoscale range dependence and therefore applies most directly to low-frequency, long-range propagation. At high frequencies the length scale of the corresponding sound-speed structures most likely relevant to ray chaos (e.g., internal waves) would be much less, moving this topic into the stochastic volume propagation category. When fluctuation phenomena such as internal waves are ignored in propagation modeling, ray chaos is unlikely to be an issue at high frequency. In any case, it is not known how the effects of ray chaos in classical ray theory carry over into the various generalized ray theories. Thus, the practical significance of ray chaos in the high-frequency region remains a topic that requires further scientific investigation.

Ray theory issues

In summary, there are several topics related to ray theory where further progress would be of considerable benefit. (Recall that ray theory with boundary interactions will be addressed in Section 3.3.) Additional research is necessary to put generalized ray theory for range-dependent environments on a firm

and accessible theoretical foundation; the importance of ray chaos for these generalized ray theories also needs to be established. Satisfactory answers to the following questions have yet to be obtained: Under what conditions will use of generalized ray methods lead to significant inaccuracy relative to full wave propagation methods? Could significant improvements to ray tracing be obtained using approaches such as improved semiclassical expansion methods? Especially in shallow water, how will uncertainties arising from generally unknown sound velocity structures compare with other aspects of propagation modeling uncertainty? In other words, under what conditions are the differences between ray and full wave methods overwhelmed by environmental uncertainties?

3.1.2. *Wave Propagation Modeling at High Frequency*

There is no doubt a consensus among workshop attendees that a full wave equation solution, or close approximation to it, should be the long-term goal for propagation modeling, even at high frequency. For this workshop, high frequency is considered to be from a few kilohertz on up, though traditionally much of the interest in high-frequency acoustics has been in the 10–50 kHz range (frequencies related to torpedoes and detection of mines). Even higher frequencies are relevant for acoustic imaging, e.g., mine classification. The specific frequency is clearly very important in assessing the viability of wave-propagation modeling in the high-frequency range. Until relatively recently, most applications of wave propagation modeling were below a few kilohertz, but rapid advances in computation speed and available memory combined with improvements in code architecture are allowing higher frequencies to be used. For example, Tappert presented broadband propagation results at 30 kHz obtained using a PE method. Clearly, the advent of high-frequency full wave propagation modeling is upon us.

Trend to
higher
frequencies

The PE approach is very appealing for high-frequency propagation modeling since range dependence is readily taken into account. Tappert's "split-step"

PE methods

FFT method enjoys the advantage that for some cases (including deterministic volume propagation) rather large range steps can be utilized, promoting an efficient computation. The finite difference or finite element (FD/FE) PE approaches can be extended accurately to wider angles from the mean propagation direction (Collins, NRL), but with the cost of shorter range steps. For deterministic volume propagation (no boundary interactions), the split-step PE method appears to have the computational advantage and therefore is most readily extended into the high-frequency region.

Transition to wave propagation

The issue of the competitiveness of full wave propagation methods at high frequency is not simple. As research codes, where computation time is not of the essence, wave propagation methods are already applicable at the low end of our high-frequency range, and upward extension to higher frequencies is occurring steadily. We should expect an evolution of wave propagation methods to high-frequency, time-critical applications in due course, but the time scale here is uncertain and could span a decade or more. In the meantime, it is essential that the high accuracy of wave propagation methods be exploited to provide accurate solutions (benchmarks) for evaluating and further developing generalized ray theory propagation methods, since the Navy community will most likely rely on them for some time to come.

3.1.3. *Broadband Propagation*

Pulse propagation modeling

Most wave-propagation methods operate in the frequency domain, so Fourier synthesis is necessary to develop time domain solutions, further increasing the computational burden. As previously noted, this is one area where ray theory approaches have a particular advantage. However, fast methods for computing pulse travel time from cw solutions have been developed. These methods involve estimating the derivative of the phase with respect to frequency from just a few propagated frequencies. There are related important research issues when signal processing methods are to be evaluated following pulse propagation modeling: the need is to minimize the number of required cw solutions based on particular signal processing methods.

3.1.4. *Imaging*

Here imaging will refer to the depiction of object structure but will also include the more general case of target detection when the resolution, relative to object size, is much less. Many target imaging algorithms employ plane-wave synthetic aperture or beamformer techniques. Near-field imaging techniques that account for the wave-front curvature over the aperture that occurs at close range are also well established. The imaging problem becomes more challenging when acoustic information is available over only part of the aperture (an unfilled array). Currently, methods are being developed to optimize near-field imaging when the complex field is measured with only a relatively few spatially separated receivers, possibly using spatially diverse transmissions. These techniques are quite robust when significant bandwidth is available and the imaging is accomplished through the use of nonlinear optimizer or simulated annealing techniques. Though such techniques have been tested in simulations with encouraging results, this is still a fertile research area.

Imaging

3.2. *Volume Propagation in a Fluctuating Environment*

For volume propagation in a fluctuating environment, the effects of internal waves, small-scale turbulence, and other processes causing fluctuations are taken into account using statistical methods. The ocean environment is divided into a deterministic part and a random part described with a statistical model. This ocean structure leads to volume forward scattering, referred to simply as volume scattering. As a consequence, predictions for the acoustic fields affected by volume scattering are made in terms of stochastic quantities. For the purely deterministic case, recent activity has focused on the accuracy and speed of numerical propagation modeling. In the stochastic case, research has focused on various moments of the acoustic field that describe the effects of randomness added to a deterministic environment. For purposes of propagation prediction, these moments can be obtained by averaging the results of many numerical propagation simulations or by using the theory of wave propagation in random media, usually with simplified deterministic environments. In addition to

Stochastic approach

moments, the full probability density function (pdf) of the propagating field or, more generally, the joint pdfs for a set of distributed space-time points are often of interest.

Importance to the Navy

The importance of stochastic effects to the Navy arises from the impact these effects have on the performance of systems designed, for example, to locate and classify targets or to reject clutter. The following questions are important in this context: What limits does the randomness of the acoustic field place on system performance? What steps can be taken to minimize the effects of the randomness on system performance? What features of the randomness can be utilized to enhance system performance?

The acoustics topics related to volume scattering have been organized into two sections: those in the first section (3.2.1) are the more directly related to possible near-term applications, and those in the second section (3.2.2) are more identified with basic science issues. A brief summary of relevant oceanography issues is given in Section 3.2.3.

3.2.1. Issues Related to Near-Term Applications

3.2.1.1. Impact on Signal Processing Algorithms

Non-Gaussian statistics

One important consequence of field randomness will be a degradation of spatial coherence across an array. Knowledge of the coherence as a function of spatial separation may be insufficient, however, for purposes of optimizing signal processing algorithms. Studies have shown that the propagated field undergoes multiple volume scattering in many practical source/receiver geometries. (Slant paths that are always more than a few degrees from horizontal, i.e., with no turning points, are important exceptions.) As the range, and hence the number of volume scatterings, increases, the complex field might be expected to reach the limit of Gaussian statistics. However, at frequencies of interest here absorption will limit the range (at least in deep water), so the Gaussian limit will usually not be attained (*Ewart*, 1989). This implies that the real and imaginary parts of the complex propagated field should be represented

by non-Gaussian random variables, whereas the normal assumption in performance prediction is that the field statistics are Gaussian. (It is known that the appropriate form of non-Gaussian distributions is typically long tailed, but more work is needed to have confidence in what distributions should be used, especially in shallow water environments.) It remains to be determined how this observed non-Gaussian randomness affects beamformers and other signal processing algorithms. This issue would be better addressed with a closer interaction than exists at present between ONR basic research programs in ocean acoustics and signal processing.

3.2.1.2. Exploitation of Signal-Intensity Fluctuations

At the low end of our frequency range of interest (less than about 20 kHz), random ocean structure due to internal waves has been used to model the randomness of the acoustic field. As the frequency increases, it becomes more important to include the effects of smaller-scale turbulence as well. The space-time behavior of the acoustic field at these higher frequencies has not been as well studied, and it is likely that smaller-scale ocean structure will modify the statistical description developed for the lower frequencies. In the lower-frequency range the volume scattered sound is characterized by intensity statistics with very high-tailed probability distributions (occurrence of high intensity "events"). The physics behind this is that typical ocean scattering is dominated by the focusing of sound due to refraction from localized regions of higher index of refraction. These foci tend to wander in depth and range in "ribbons" that can be very long in the range direction; as a result, the sound field is broken up into undulating pancake-shaped regions of high intensity. This has been observed in both experiments and modeling (Uscinski, U. of Cambridge; Ewart, APL-UW). These ribbons give rise to the high scintillation indices (normalized intensity variance) typical of ocean sound propagation in this frequency range, and understanding the structure of these ribbons provides a means to exploit this focused energy in Navy sonar operations. It is important to note that the existence of such distributions depends very strongly on single-path or separable multipath conditions. Severely overlapping path structure will rapidly lead to

"Ribbons" of high-intensity sound

exponential intensity statistics (Gaussian field statistics), destroying the effect. Important scientific issues here are (1) the prediction of the space-time statistics of these ribbons, and (2) the determination of how high in frequency this picture remains valid. Improved understanding of this phenomenon provides a possible Navy transition related to the development of strategies to enhance probabilities of target detection and tracking. Also, the high scintillation index of the signals can enhance detection by improving the instantaneous signal-to-noise ratio, possibly allowing detections that would not be available without the randomness.

3.2.1.3. Target Imaging

Wander and
spread

The ability to detect targets in the presence of noise and medium randomness is an application of acoustics inseparable from the issues of volume scattering. Two components of the scattering that affect imaging in different ways are the wander and spread of the scattered field observed by the imaging apparatus. Under certain range/frequency conditions, one or the other mechanism may dominate. If the image wanders in space-time, the resolution of the sonar system is unchanged, and only the apparent location of the object changes; in many cases, this will cause no difficulties. On the other hand, if the image is spread in space-time, the effect is to blur the details of the image and make detection, classification, and false target separation more difficult. The details of the volume scattering must be known in a statistical sense before an assessment of image quality can be made for specific geometry/frequency/range configurations. In this assessment the effects of wander and spread can and should be separated, both in experiments and in theoretical analyses.

3.2.2. Basic Science Issues

3.2.2.1. Stochastic Description of the Acoustic Field

Intermittency

Predicted statistics for ocean volume scattering have become much better known in the past 20 years, and many of the space-time moments of the complex field (up to 4th) are predictable when the deterministic and stochastic

ocean features are known. The moments describe the statistical behavior of an isolated deterministic path as modified by an internal wave or turbulence field, modeled as a stationary, Gaussian random process. Much of the numerical and experimental work supporting these stochastic predictions has been done at frequencies below 20 kHz. The acoustic field is affected by ocean structure at ever higher wavenumbers as the frequency is increased. This takes the oceanographic regime above the internal-wave bands to the regimes of ocean mixing such as turbulence and temperature and salinity diffusion. Such processes are known to be highly intermittent, and thus a stationary Gaussian model is probably inadequate; this intermittency should be describable by a stationary non-Gaussian process for time scales that are short compared to tidal periods, diurnal variations, and time scales of storms. At high frequency these intermittent processes must be taken into account in predictions of stochastic effects in acoustic propagation.

Stationarity also can be reconsidered in a shallow water environment. The level of internal waves and turbulence in shallow water tends to be correlated with the phase of the tide, for example, allowing an improvement over stationary statistical descriptions. In this case the mean, variance, and other moments of the medium and the acoustic field may evolve slowly. From an applications point of view, it may be possible to tie periods of good or poor acoustic performance to the phase of the tide. Obtaining an accurate oceanographic description at the short length scales required to account for intermittent processes and to take advantage of nonstationary descriptions is a difficult ocean measurement problem.

Non-
stationary
descriptions

In the frequency region below 20 kHz, the intensity probability distributions due to volume scattering can be modeled heuristically over very large spans of volume scattering strengths and ranges. A key question is whether this same distribution holds at higher frequencies where turbulence and intermittency are important. Attempts at first principle theoretical formulations of the intensity pdf have had success at very short range, where the intensity is log normally distributed, and at far ranges where the intensity approaches the exponen-

Intensity pdf

tial distribution. As mentioned in Section 3.2.1, practical ranges almost always lie between these two extremes.

3.2.2.2. Propagation Modeling

Accurate solutions

PE simulations can provide highly accurate solutions for propagation modeling with specific realizations of small-scale ocean structure, and therefore various moments and pdfs for the acoustic field can be obtained as well. Thus, simulation provides a method of testing theoretical formulations for moments and pdfs. Ray theory may also be useful in this area, but further effort is necessary to verify the domain of applicability. In particular, the significance of ray chaos with spatially broadband sound-speed perturbations needs to be investigated.

Moment propagation

Techniques are also well developed (and verified through simulations) for modeling the propagation of field moments using the PE approximation, i.e., the theory of wave propagation in random media. This can take the form of (field) moment equations or be based on path integral techniques. An approximation to the equation for the second moment yields the radiation transport equation, useful for average intensity.

Two additional points: (1) With full 3-D simulations it would be possible to examine, with essentially no approximation, the degradation in horizontal spatial coherence due to the randomness for comparison with simpler and thus more practical methods (e.g., moment propagation). (2) In the near term, random ocean processes are likely to be omitted from propagation modeling that is oriented to applications. It is therefore important to understand the degree of bias in mean intensity level that results from random effects.

3.2.2.3. Inversion for Oceanographic Statistics

Inverse methods

Determining an appropriate oceanographic description of the randomness in the water column presents the same difficulty faced in characterizing the seafloor: the level of detail required would essentially never be available from direct measurements made during Naval operations. Again, this circumstance

increases the importance of utilizing inverse methods for obtaining the needed information, in this case, inversion for statistical quantities. Little work has been done as yet in this area. However, it has been demonstrated that measured acoustic phase statistics can be used to invert for internal wave statistical parameters. It is expected that, in regions where the log amplitude (like the phase) is predicted using the Rytov approximation, inversions based on log amplitude statistics are also possible. Inversions based on amplitude statistics are much preferred, since precisely known receiver positions, necessary for phase measurements, would no longer be needed. Cooperative investigations among acousticians and oceanographers could produce a better understanding of ocean index-of-refraction statistics and produce reliable acoustic inversion techniques for both internal waves and turbulence.

3.2.2.4. Caustic Variability

When the deterministic component of the sound velocity structure gives rise to caustics, the presence of randomness causes energy to propagate into the forbidden regions (an effect well appreciated in atmospheric acoustics). The acoustic penetration into shadow zones produced by this mechanism exceeds that produced by the diffractive effects for a typical deterministic sound speed profile, as shown in broadband PE simulations presented by Tappert. Although this phenomenon could be very important for detection algorithms and have implications for reverberation simulation as well, there has been very little work on this research issue.

Effect of
ocean
randomness
on caustics

3.2.2.5. Some Unanswered Basic Science Questions

- 1) How do we incorporate intermittency and slowly evolving stochastic ocean processes in propagation theories? (This question has received attention in the field of optics.)
- 2) Field statistics for propagation paths with upper turning points in regions with high sound velocity gradients cannot be currently predicted, because a commonly used approximation (the Markov approximation)

Unanswered
questions

does not apply (*Henye and Macaskill*, 1996). What new theories can be applied here?

- 3) Many shallow water (or higher frequency) and deep water (or lower frequency) paths have both lower and upper turning points. How would we couple multiple-turning-point theory to predict the stochastic field for the combined effects?
- 4) In shallow-water propagation at high frequencies, how do we separate internal-wave and turbulence effects?
- 5) How do we know the conditions under which existing inverse techniques (based on the Rytov approximation) are accurate for inferring stochastic quantities?

3.2.3. *Oceanographic Description Issues*

Oceanography issues

Improvements in our present understanding of small-scale oceanography would help substantially in using stochastic descriptions for high-frequency acoustics. First, better statistical models are needed for internal waves in shallow water. At high acoustic frequencies, the shortest of the internal waves are the most important, and the horizontal structure of these waves has not been well studied. Other aspects of internal waves that need attention are nonstationary models to account for tidal-scale temporal changes, and the description of high-frequency wave packets associated with internal tides. (What part is deterministic, and what part is random?) Second, at smaller spatial scales, improved models of turbulence are needed that include effects of intermittency and that couple the strength of turbulence to larger-scale motions. For turbulence, the region near the outer spatial scale, on the order of 1 m in deep water, is of greatest importance for high-frequency acoustics. Oceanographic work under the Coastal Mixing and Optics program (1996–1997), together with associated acoustics experiments, represents a beginning in addressing these issues.

3.3. *Propagation with Boundary Interaction*

When a propagating field undergoes surface or bottom interactions, the complexity of the acoustic field is substantially increased. A brief discussion of relevant technical issues is given in Section 3.3.1. Modeling of propagation with boundary interaction will be discussed in the context of ray theory methods in Section 3.3.2 and of wave propagation methods in Section 3.3.3.

3.3.1. *Technical Issues*

An accurate description of the acoustic interaction with the surface or bottom is obviously required. Many of the boundary scattering issues were discussed in Sections 1 and 2 and thus will not be emphasized here. When boundary interactions occur there are two main geometries of interest: (1) one-way propagation with boundary reflection and forward scatter, and (2) boundary reverberation with two-way propagation. In the case of one-way propagation at high frequencies, boundary interactions are more accurately described as forward scattering from rough surfaces rather than as reflections from flat surfaces. Even in the case of one-way propagation (and certainly for reverberation), a deterministic description is rarely feasible, except perhaps in very shallow water at the low end of our frequency range. Interest is primarily in statistical quantities describing the field, such as the average intensity, the temporal and spatial coherence, and the intensity pdf. The focus in this discussion is mainly on our ability to model these quantities accurately.

One-way and
two-way
propagation

For some geometries and sound-speed profiles, modeling of propagation and reverberation may present little difficulty. However, other cases can be much more challenging. Effects listed below can be important for both one-way propagation and the full reverberation problem and, depending on the situation, may need to be included for accurate propagation modeling:

- 1) The angular spreading (vertical and horizontal) induced by forward scattering.
- 2) Scattering out of a surface duct via sea surface scattering.

Boundary
interaction:
Technical
issues

- 3) For narrowband signals, the frequency spreading that results from interaction with the moving sea surface. Even if only a small fraction of the acoustic energy interacts with the sea surface, it can be important to model this fraction accurately, with its appropriate frequency shift and spread.
- 4) Effects of volume fluctuations in allowing penetration into shadow zones near boundaries. This can lead to reverberation when otherwise the sound would remain trapped in a sound channel.
- 5) Regions of localized high intensity due to caustics caused by the deterministic sound speed profile or to focusing effects of internal waves. The interaction of these high intensity regions with boundaries can lead to non-Gaussian reverberation with high intensity spikes.
- 6) Non-Gaussian statistics that arise for scattering from relatively small scattering patches on the surface or bottom. How these statistics evolve as the field point recedes from such boundaries is a propagation issue.

Incomplete
environmental
information

Another issue arises when we consider the extent of environmental information required to accurately model one-way propagation (with boundary interaction) and reverberation. In the more challenging modeling situations, more information would likely be needed than is readily available, especially in Navy applications. The issue, then, is to take the limited environmental information available, use our best understanding of ocean and boundary processes to formulate a range of possible environments constrained by the information available, and then produce a range of possible acoustic outcomes with an assessment of their relative probability.

3.3.2. *Ray Theory*

Ray theory is widely used for high-frequency reverberation modeling. At the present time sonar simulation codes based on ray theory predict intensity but are not generally capable of predicting temporal and spatial coherence in the presence of boundary interactions.

3.3.2.1. One-Way Propagation

In presently available ray-based propagation models, forward boundary interactions are modeled as reflections, and an energy loss associated with the reflection is taken into account. The loss represents both true energy loss at the boundary (e.g., absorption by bubbles near the surface or transmission into sediment at the bottom) and the "loss" associated with energy scattered well away from the specular direction. Energy scattered near the specular direction is treated as reflected, and the split between scattered energy that is "reflected" and scattered energy that is "lost" is somewhat arbitrary. Paradoxically, the reflection-loss treatment of boundary interaction makes more sense (especially for the sea surface) at low frequencies, where the interface roughness is smaller in comparison to the acoustic wavelength but where ray theory is less applicable. At higher frequencies, where ray theory is more appropriate for propagation, the concept of reflection loss as now used will be less accurate, especially in shallow water or in surface ducts where multiple boundary interactions may occur. Uncertainty in the appropriate bottom reflection loss for gravel and rough rock bottoms is presently a serious problem for shallow water reverberation simulation (Keenan, SAIC).

Reflection
loss: The issue

Since boundary reflection loss is widely used at this time in the Navy community, work is needed to better clarify the limitations of ray theory propagation using this approach. Wave propagation simulations specialized to account for propagation with rough boundaries, for example, can supply accurate field solutions for one-way propagation with surface and bottom interactions. To improve ray theory accuracy for propagation with rough boundaries, it may be necessary to account explicitly for the angular spread of scattered energy about the specular direction, increasing the complexity of the approach. Since ray theory is normally used to find the average intensity, a radiation transport approach may have utility.

Reflection
loss:
Assessment
and
improvements

3.3.2.2. Reverberation

In general, reverberation involves bistatic scattering processes at both the surface and the bottom, with forward and backward propagation at arbitrary angles relative to the horizontal, though propagation at low to moderate angles should dominate in many cases of practical interest. Ray theory can readily utilize bistatic backscattering models

Need for
benchmark
solutions

developed from scattering theory or from experimental measurements, though the use of reflection-loss models may present problems, as noted above. Two-way propagation does not lead to special difficulties, and the common use of random phase addition of the many contributing paths to the reverberant field is probably adequate at high frequencies. Range dependence can be taken into account in some models, but the full three-dimensional nature of the propagation and scattering is not now treated. Full physics benchmark simulations of reverberation are needed to assess the accuracy of present ray-theory models.

3.3.3. Wave-Propagation Methods

Exact
solutions

In principle, representative propagation and reverberation problems can be solved to any desired accuracy by a full solution to the wave equation subject to appropriate boundary conditions on realizations of rough surface and bottom interfaces. Approaches include the finite difference, finite element, and coupled mode methods (*Jensen et al.*, 1994). These methods can in principle treat the full complexity of the reverberation problem, accounting for bottom elasticity and two-way range-dependent propagation. For pulse propagation, the finite difference (time domain) method can be used to provide essentially exact field solutions for broadband propagation when rough boundaries are present. For the more idealized problems where the propagation characteristics are known, the boundary integral equation method can be used to obtain exact solutions for fields scattered from rough surfaces or isolated scatterers. However, the very high computational requirements for exact solutions have generally restricted all of these approaches to frequencies well below our frequency range or to problems with very limited spatial extent, even when, as is usually the case, two-dimensional geometries are used.

“Nearly
exact”
solutions

Methods that will be referred to here as “nearly exact” can be used to provide solutions of high accuracy at higher frequency and/or over larger spatial scales. One technique uses a hybrid approach in which propagation away from boundaries or scatterers is treated with more computationally efficient means, such as PE or wavenumber integration methods, and “exact” treatments are

restricted to limited spatial regions near boundaries or scatterers. In a second approach, a one-way wave equation is used in place of the full wave equation, leading to significant simplifications when using any of the methods mentioned previously as exact. Reverberation simulations can be made with appropriate coupling of the forward- and back-going one-way wave equation solutions. This second approach may qualify as nearly exact only when shear effects in the seafloor can be ignored, but this should be true for most sediment seafloors at high frequencies. Solutions based on wide-angle PE methods, for example, fall within the second approach.

Even nearly exact results, however, will not directly satisfy the main needs in propagation and reverberation modeling for several reasons. First, to obtain realistic fields for prediction or comparison with experiments, the full three-dimensional geometry (with two-dimensional rough interfaces) would typically be required, a difficult task for exact (or nearly exact) methods. Second, environmental processes that contribute to scattering are not limited to rough interfaces but include bubbles near the sea surface and inhomogeneities within the sediment; accurate environmental models of these processes for full wave methods are not presently available. Finally, limitations on computation time and memory make it evident that even nearly exact solutions are overly ambitious for most practical problems of interest at high frequency, and, in any case, such accuracy is higher than typically needed. It appears that the main issue is to understand the scope of allowable simplifying approximations that will accelerate computation and at the same time minimally affect accuracy. For example, reduction to an effective two-dimensional geometry would be very beneficial in terms of computation time. Similarly, if explicit boundary structure can be limited to only large-scale structure, with results from scattering theory used to account for small-scale structure, further efficiencies can be obtained. Exact or nearly exact methods can be used to examine the applicability of such approximations.

Need for
simplifying
approximations

3.3.3.1. One-Way Propagation

Need for
benchmark
solutions

There is presently a need to develop “benchmark” problems and “reference” solutions for high-frequency propagation involving interaction with reasonably realistic rough surface and bottom boundaries that can be used to test the accuracy of a variety of approximate methods. Ideally, solutions would be obtained with fully exact methods, but reliance on “nearly exact” approaches may be necessary in larger-scale problems, providing that accuracy has been confirmed through comparison with exact solutions on smaller-scale problems. At present such solutions would probably be limited to one-dimensional rough interfaces, but nevertheless they would provide a means of testing the accuracy of other approaches with benchmark quality solutions. Wide-angle PE simulations based on the finite difference or finite element method should yield highly accurate solutions for one-way propagation in shallow water when using explicit realizations of rough surface and bottom boundaries, though the problem with both rough boundaries may not have been treated yet. Nevertheless, comparisons with independent reference solutions for such problems with realistic roughness are needed. The PE propagation method based on the FFT split-step approach can also accurately treat rough sea surface scattering, but the effects of approximations used in relation to bottom interactions, including bottom scattering, need to be assessed through comparisons with reference solutions. Similarly, other wave-propagation methods that have been extended to include rough boundaries and are being suggested for use at high frequencies (e.g., SAFARI and OASES; Schmidt, MIT) need to be examined through comparisons with high-frequency reference solutions.

Approxima-
tions needed
at HF

In order to avoid dealing with very large rough surface realizations, it will be important to develop approximate, yet reasonably accurate, treatments of rough boundary interactions for use in wave propagation simulations (presumably statistical methods would be used for at least the small-scale boundary structure). Such approaches would be especially useful for one-way propagation in the presence of two-dimensional rough boundaries, i.e., the full three-

dimensional propagation problem. In the same spirit, approximate treatments of propagation through near-surface bubble clouds will be needed to avoid the requirement of using three-dimensional realizations of bubble cloud structure in practical high-frequency propagation simulations. This problem is compounded by the fact that we do not have accurate models of this bubble cloud structure at present (see Section 1). Both PE and wavenumber integration methods have recently been extended to accommodate poroelastic models for the seafloor. It will be important to understand if this extension is necessary for accurate modeling at high frequencies.

As noted in Section 3.3.1, several important propagation issues arise from the combined effects of scattering from volume inhomogeneities and boundaries. For example, volume randomness that results in field propagation to the sea surface (that otherwise would not occur) will be especially important for narrowband signals when the frequency spreading effects of the surface interaction are of interest. Propagation simulations are needed that can accurately treat frequency spreading during surface scattering combined with important volume propagation effects. Similarly, simulations are needed that can develop fields with non-Gaussian statistics during volume propagation and then properly follow the evolution of these statistics through boundary scattering processes. Similar comments apply for reverberation simulations discussed below.

Combined
volume and
boundary
effects

3.3.3.2. Reverberation

PE reverberation simulations have already been reported at frequencies as high as 30 kHz based on the FFT split-step method (Tappert, U. of Miami). As should be expected, several simplifying approximations are employed. It will be important to develop exact or nearly exact reverberation simulations, at least for some restricted geometries, to verify the accuracy of approximations utilized to improve computational efficiency for the FFT PE and other wave propagation methods. For seafloors with important shear effects, issues remain on the accuracy of the PE method. The FFT PE implementations do not handle coupling

Reverberation
simulation at
HF

into shear waves in detail (it is included only as a loss mechanism), and questions remain on the accuracy of the FD or FE PE methods in the case of two-way propagation (*Goh and Schmidt, 1996*). At the present time, reference solutions are not available for the reverberation problem at high frequencies, and comparisons with measurements cannot satisfy the need for highly accurate ground truth because of the inevitable environmental uncertainties.

Working with
a realistic
environmental
description

For one-way propagation, the length scales of the important scattering structures at and near the boundaries will be tens of wavelengths. For backscattering, and thus for reverberation, these spatial scales are about a wavelength (half a wavelength for low grazing angle backscatter). These smaller spatial scales increase the need for hybrid approaches that treat larger-scale structures explicitly in realizations but treat the smaller structure with more efficient means while still preserving reasonable accuracy in terms of level and statistics. In some cases, it may be necessary to work from direct measurements of boundary scattering and develop scattering models compatible with wave propagation and reverberation methods without a full environmental description. Points in the last paragraph in Section 3.3.1 can be reiterated here: methods are needed for dealing with a limited amount of environmental information and for understanding the sensitivity of the results to unknown aspects of the environment. Predictions are desired that are consistent with the information available and that place bounds on the range of outcomes consistent with our knowledge of propagation and scattering processes.

3.4. Goals for High-Frequency Propagation Experiments

Value of
simulation

A number of important propagation issues can be addressed without experiments. Issues related to propagation in a deterministic environment (Section 3.1) are largely in this category, since very accurate numerical solutions are available. In addition, the ocean will inevitably contain volume fluctuations, making it less suitable as a high-accuracy test bed for deterministic propagation. Similarly, progress on a number of issues related to volume propagation in a fluctuating environment (Section 3.2) can be made utilizing simulations. Pre-

dictions of various field moments based on the theory of wave propagation in random media can be verified with simulations using a range of environmental descriptions, and many of the unanswered questions on the basic science issues list in Section 3.2.2 can be addressed with the help of simulation techniques.

Propagation experiments, however, are needed for several reasons. The most basic reason is that only through experiments can we be certain that all the important environmental and acoustical processes are understood and can be simulated or modeled. Reaching this goal will require the cooperative efforts of the oceanographic and acoustic communities.

Need for
experiments

3.4.1. Volume Propagation in a Fluctuating Environment

Among the many topics discussed in Section 3.2, experimental investigations in the following areas would be of special interest:

1) A space-time picture of the acoustic field has been developed for deep water at lower frequencies (< 20 kHz) which indicates that, because of the presence of internal waves, regions of high acoustic intensity form into undulating ribbon-like structures, which may have important implications for Navy sonar operations. Experimental investigations of the space-time structure of the acoustic field occurring at higher frequencies and in more complicated shallow-water environments would clarify the degree to which related phenomena exist in these regimes. These observations should include sampling over the vertical, cross-range, and down-range spatial scales of these structures and should track the temporal evolution as well. A concomitant part of this program should be an effort to improve oceanographic descriptions of the small-scale structure in shallow-water environments. We need to understand the spatial and temporal resolution necessary to allow accurate simulation of such experimental data. Associated signal processing research should proceed in parallel with this program.

High-
intensity
ribbons at HF

Inversion for
oceanographic
statistics

2) To utilize our understanding of fluctuating oceanographic environments in high-frequency acoustics, it will probably be necessary to develop acoustic inversion methods for obtaining oceanographic statistics. Otherwise, needed environmental information would generally not be available in a timely fashion for use in operational scenarios. An experimental program designed to further develop and test these inversion techniques could open up significant applications of stochastic acoustics in scenarios involving volume propagation.

3.4.2. Propagation with Boundary Interaction

In general, since full three-dimensional simulations involving boundary interactions will probably remain a challenge for some time to come, experiments will be essential for verifying the accuracy of simulation methods for geometries involving boundary scattering and, in particular, for testing the accuracy of approximate boundary scattering descriptions to the extent feasible. Here, in analogy with the volume scattering case, the issue becomes the following: How well do we have to know the boundary description? Among the topics discussed in Section 3.3, the following deserve special mention in regard to experimental programs:

High-
intensity
spikes

1) High-intensity spikes in the propagated field can arise in several ways: from deterministic caustics, internal-wave focusing, boundary scattering, or combinations of these. Experiments will be needed to better understand the occurrence of these effects and to help develop modeling techniques that can accurately "propagate" these statistics in the presence of boundary interactions.

Environmental
uncertainty

2) Prediction of shallow-water propagation and reverberation will be typically hindered by a lack of relevant environmental detail. The general problem is to make these predictions with limited information and, at the same time, establish a range of predictions with some associated probability statement. Experimental measurements will be essential in verifying this methodology.

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Appendix A

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Appendix B

ONR High-Frequency Acoustics Workshop Agenda

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- | | |
|--|-------------------------|
| 1. Meeting Overview | Jeffrey Simmen |
| 2. 6.2-6.3 Overview | Edward D. Chaika |
| 3. High-Frequency Environmental Acoustics Research for Mine Countermeasures | Daniel J. Ramsdale |
| 4. Mine Countermeasures High-Frequency Acoustics Needs | Douglas Todoroff |
| 5. HF Environmental-Acoustic Needs for Shallow Water Torpedo Guidance and Control and for Surface Ship Torpedo Defense | Richard L. (Lee) Culver |
| 6. Rough Rock and Gravel Bottom Forward Loss Observed in Torpedo Reverberation Data | Ruth E. Keenan |
| 7. High-Frequency Underwater Acoustic Communications | Tsih C. (TC) Yang |
| 8. ORCAS | Kevin L. Williams |
| 9. NRL High-Frequency Research Option | Luise Couchman |
| 10. High-Frequency Bottom Scattering: Environmental Controls | Michael D. Richardson |
| 11. High-Frequency Acoustic Penetration into Seafloor Sediment at Sub-Critical Grazing Angles | Eric I. Thorsos |
| 12. Considerations on High-Frequency Bottom Scattering Issues | Dajun (DJ) Tang |
| 13. Search for a Unified Model for Ocean Sediment Acoustic Propagation | Nicholas P. Chotiros |
| 14. Establishing a Baseline Model for High-Frequency Geoacoustic Studies on the Seafloor | Robert D. Stoll |
| 15. Seafloor Reverberation Fluctuations | Suzanne T. McDaniel |
| 16. 3-D Reverberation from Anisotropically Rough Interfaces in a Stratified Elastic Seabed | Henrik Schmidt |
| 17. A New Approach for Locating Objects Buried in Ocean Sediments | Subramaniam Rajan |

- | | |
|---|-----------------------|
| 18. High-Resolution Focusing Analysis and Inversion for Small-Scatterer Detection | Norman Bleistein |
| 19. High-Frequency Acoustical Scattering Processes for Finite Cylinders and Broad Bandwidth Scattering Experiments | Phillip L. Marston |
| 20. High-Frequency Simulated and Scale-Model Scattering Experiments from Sediments for Their Characterization and for Imaging of Proud and Buried Mines | Steven A. Johnson |
| 21. Full-Wave Modeling of High-Frequency Propagation and Scattering | Frederick D. Tappert |
| 22. Poroelastic Forward and Inverse Modeling | Michael D. Collins |
| 23. The Nature of Small-Scale Ocean Variability That Can Affect High-Frequency Propagation | Louis Goodman |
| 24. Some Comments on Ocean WPRM | Terry E. Ewart |
| 25. Measurement of Scalar, Vector and Dispersive Effects on High-Frequency Propagation | David M. Farmer |
| 26. A New Technique for Imaging Thermal Microstructure | Jules S. Jaffe |
| 27. Frequency Dependence of Acoustic Behavior in Very Shallow Water | Mohsen Badiy |
| 28. High-Frequency Acoustic Surveys of a Shallow-Water Region and Associated Scattering Models from Naturally Occurring Complex Bodies | Timothy K. Stanton |
| 29. Multifrequency Acoustics: Applications and Tools | Charles F. Greenlaw |
| 30. High-Frequency Ambient Noise Inversions | Michael J. Buckingham |
| 31. Comments on Bubble and Surface Scattering | Frank S. Henyey |
| 32. Scattering Measurements from a Laboratory Tank | Kenneth E. Gilbert |
| 33. The Acoustics and Structure of the Wave-Zone Boundary Layer | W. Kendall Melville |
| 34. High-Frequency Surface Backscattering: The Mean, Variability, and Their Relation to Near-Surface Bubbles | Peter H. Dahl |
| 35. Acoustic Doppler Imaging of the Sea Surface and Near Shore | Robert Pinkel |
| 36. Strata Formation on Margins (STRATAFORM) | James P. Syvitski |

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Appendix C

ONR High-Frequency Acoustics Workshop Working Groups

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