PROCEEDINGS

WORKSHOP ON THE EFFECTS OF ANTHROPOGENIC NOISE IN THE MARINE ENVIRONMENT,

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Prepared by:
Robert C. Gisiner, Ph.D.
Marine Mammal Science Program
Office of Naval Research

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FOREWORD

Robert Gisiner, *Office of Naval Research, Arlington, VA*; (Workshop Organizer)
Ed Cudahy, *Navy Submarine Medical Laboratory, Groton, CT*; (Team Leader – Physiological Effects)
George V. Frisk, *Woods Hole Oceanographic Institution, Woods Hole, MA*; (Team Leader – Ocean Acoustics)
Roger Gentry, *National Marine Fisheries Service, Seattle, WA*; (Team Leader - Behavioral Effects)
Robert Hofman, *Marine Mammal Commission, Bethesda, MD*; (Inter-Agency Coordinating Group Leader)
Arthur N. Popper, *University of Maryland, College Park, MD*; (Team Leader - Hearing Effects)
W. John Richardson, *LGL Ltd. environmental research associates, King City, Ontario, Canada*; (Team Leader - Monitoring and Mitigation)

BACKGROUND

This volume is intended to provide a current summary of the state of knowledge about the effects of human-generated noise on marine organisms, along with suggestions about where additional scientific research is most needed, most ready for further development, or both. Marine mammals were emphasized, but fish, sea turtles and other marine animals were considered to some extent.

WORKSHOP FORMAT AND REPORT PREPARATION

Thirty-seven experts from five relevant subject areas were convened for a three-day workshop in February 1998. The subject areas were ocean (physical) acoustics, non-hearing physiological effects of sound, hearing, behavior, and monitoring and mitigation of noise effects. The subject areas were not mutually exclusive and the workshop format was also designed to allow all members to participate in the half-day discussions of subjects other than their own. All participants were provided with read-ahead materials so that they could participate in the one to two hour review of each team leader's proposed format for discussions and reports that were to follow.

After the workshop, team leaders for each of the five discussion groups prepared an initial draft report of the proceedings for their topic area, and then distributed it for review by the entire membership. Some team members were asked to prepare additional special material after the workshop. These special reports are labeled to indicate that they were not part of the workshop discussion, but were prepared later at the request of the membership. The five topic area chapters in this volume therefore represent a considerable amount of interdisciplinary scrutiny by top professionals across the range of subject matter.

ORGANIZATION AND SUPPORT

This workshop arose from a mutually recognized need among several federal agencies that the issue of anthropogenic noise is of considerable public interest and that their agencies have a potential role to play in addressing the issue and its impacts. Representatives of the Department of Defense, National Marine Fisheries Service, Geological Survey, Minerals Management Service, and Coast Guard met under the leadership of the Marine Mammal Commission to devise a process for providing their respective agencies with the information they would need to make informed decisions about acoustic effects on the underwater environment. This workshop was planned as a first step in a process intended to lead to a national policy and plan of action on this topic. This policy and plan should be integrated across agencies, should include a solid foundation of accurate scientific information, and should address public concerns about national security, economics, and environmental quality.

GOALS

The reader may view this report as a "blueprint". It should not be treated as an exhaustive in-depth look at the scientific data, but rather as a framework to provide context to subsequent more exhaustive efforts focused on critical technical areas. Likewise, it should not be treated as a fully-realized template for policy, guidelines or regulations, but again as a framework upon which project proponents, resource managers, biologists and acousticians, legal experts, economic experts, advocacy groups and the public can structure their discussions during the formulation of policies and plans of action with regard to anthropogenic underwater noise. Since many people view the environmental impact from anthropogenic noise as potentially serious and extensive, there is a sense of urgency to many discussions of the subject. We urge the users of this document not to allow their sense of urgency to shortcut the above process by treating this document either as an encyclopedic reference on all relevant information (which it is not) or as a set of recommendations as to what are "safe" levels of acoustic exposure for marine life (in fact, this question was deliberately avoided).

TEAM REPORT SUMMARIES

OCEAN ACOUSTICS

During the past fifty years, significant progress has been made in our understanding of sound generation, propagation, and signal processing in the ocean. This report summarizes those aspects of underwater acoustics which are relevant to the subject of anthropogenic noise in the marine environment. These topics are addressed in the context of the passive sonar equation and include source level, transmission loss, ambient noise, and processing gain. In addition, a discussion of sound measures and boundary conditions is presented. Finally, recommendations are made for future collaborative research efforts between the ocean and animal bioacoustic communities.

HEARING

The following summarizes the major issues targeted in this section of the report: 1) Sounds of high intensity and/or long duration are known to cause physiological effects on the auditory system of terrestrial mammals and birds and there is evidence that such sounds can

effect the ears of fishes. Effects may be temporary or permanent. Multiple exposures causing temporary hearing loss may ultimately result in permanent hearing loss, 2) Loss of hearing, whether it be temporary or permanent, can affect animals in a number of ways. As a minimal effect, a temporary loss could prevent an animal from detecting predator or prey, or result in the animal entering an area that would be dangerous for its survival. In addition to these effects, permanent loss of hearing could result in loss of an animal's ability to communicate with conspecifics, find mates, care for young, or find food. Over the long term, loss of hearing capabilities by large numbers of a species could lessen reproductive potential and survival of the species, 3) Permanent effects that are most readily seen clinically involve damage to the sensory hair cells (the mechanotransducers) in the inner ear. In mammals these cells are not replaced once they are damaged, and damage to these cells results in permanent loss of hearing. Replacement does occur in birds and fishes, but it is not clear that their hearing returns to normal even with the new hair cells, 4) the aquatic environment has numerous natural sound sources, including wind on the surface, rain, shoaling waves, and seismic events. There are also substantial biological sources such as from snapping shrimp, fishes, and marine mammals that are significant sound sources within their own right. Sounds are widely used by aquatic animals in their everyday survival including foraging, detecting predators, finding mates, and caring for young, etc. Any sounds present in the environment that interfere with natural communication or perception of relevant sounds potentially compromise the survival of an animal, 5) There is a wide range of human-generated (anthropogenic) sounds in the aquatic environment. These include sounds produced by ships, for exploration, hydroelectric plants, etc. There is substantial evidence that the overall level of sound in the aquatic environment has increased significantly in the past 50 years and this is cause for concern vis a vis effects on aquatic organisms. At the same time, because the major increase is attributable to shipping, most added noise is likely to be below 500 Hz, and so the major effects of anthropogenic sounds may only be on those species that readily detect sounds at lower frequencies, 6) The effects of intense sound on the hearing of aquatic animals is not well known and has only been minimally investigated to date. However, there is evidence that temporary and permanent hearing loss occurs in dolphins and some pinnipeds, as well as in at least one species of fish. There are no data on the effects of sound on hearing capabilities of mysticete whales, or semi-aquatic mammals such as otters, 7) There are also almost no data on the effects of intense sounds on hearing by aquatic birds, reptiles, or invertebrates. The concern for hearing loss in these animals needs to be as great as it is for marine mammals since many of these species are of economic importance to humans and/or keystones in the marine food chain. Damage to hearing, and thus to the ability of these animals to survive, may affect the survival of other animals that interact or depend upon these species; 8) The levels of sounds needed to cause permanent hearing loss in aquatic mammals are not known. These levels are very hard to assess using behavioral techniques since it would be necessary to damage hearing capabilities in order to assess these effects. Other techniques are under development, including ABR and morphological methods, which may enable us to predict the levels of sound that will damage hearing based upon extrapolation of the effects from lower levels of sound stimulation.

NON-HEARING PHYSIOLOGICAL EFFECTS OF SOUND

The major focus of this group was on physiological effects of sound in the marine environment apart from effects on hearing. The paucity of current information in this area was underscored in the read-ahead materials by Richardson, Popper, and Cudahy and Sims. In view

of the lack of information, it was decided to use some of the work done with human divers to investigate physiological effects of low-frequency sound as a starting point and relate diver target areas to marine research areas. The primary research areas reviewed included blast, extreme vibration, impulse noise, and stress along with low-frequency sound. Factors identified during the session that limited conclusions about the effects of underwater sound included the diversity of sound stimuli, the diversity of target animals (marine mammals, fish, reptiles, sea birds and invertebrates), and the diversity of marine environments. The information presented therefore was scattered rather than focused and there was considerable discussion regarding measurement technology, such as the least intrusive way to track and get real-time information on animals in the ocean, and what constitutes the most cost-effective research strategies, such as focusing on acute versus long-term effects.

BEHAVIOR

The team recognized the significance of assessing both the immediate and long-term direct effects of alteration of behavior by anthropogenic noise. The team also recognized the role of behavior assessment as a means of predicting and thus preventing more immediately serious physically injurious effects. Background discussions focused on issues of data collection methods and data interpretation that must be considered in the generation of useful behavioral data in this topic area. Biological significance was a recurring theme in discussions of acoustic behavior and alteration of acoustic behavior by introduced noise. Biological significance has very specific meaning in population biology and is the baseline scientific metric used to measure the impact of both natural and manmade environmental changes on the living world. The group recognized that many measurable behavioral responses to anthropogenic noise, such as brief temporary alterations in heart rate or breathing, may have little or no biological significance, and that possibly significant behaviors may currently go unassessed, particularly those behaviors that are associated with cumulative long-term effects. New developments in monitoring technology were discussed in light of their ability to better reveal and quantify biologically significant behavioral change. The team made recommendations on the use of behavior to assess noise impacts. In addition to emphasizing the selection of behaviors that have clear biological significance the team discussed the implications of cessation or alteration of vocal behavior in response to an introduced noise source, since these easily measured behaviors can indicate impacts ranging from profound immediate adverse effects to trivial and easily accommodated effects. Additional recommendations included the measurement of sound fields to more accurately determine the cumulative "dosage" of sound an individual animal might receive as it travels through an acoustically heterogenous three-dimensional world. The importance of control procedures in behavior assessment was also emphasized, since few areas of scientific endeavor are more sensitive to observer biases, or more influenced by uncontrolled variables.

MONITORING AND MITIGATION

The session focused on marine mammals. It began with a discussion of the reasons (regulatory and research) for monitoring, and some of the limitations. The participants reviewed the capabilities and limitations of several monitoring methods, including currently-used and potential methods. Topics included visual surveys from ship, shore or aircraft; photographic, electro-optic and remote methods; passive and active acoustics; dataloggers and telemetry; and determination of sound exposure. There was consensus that, in most situations, no single

monitoring method is sufficient. A combination of complementary methods is usually required. Participants also discussed the limitations of project-specific short-term monitoring, and considered approaches for monitoring long-term effects and the combined effects of more than one human activity. Regarding mitigation, the group devoted the limited time to a discussion of ramping-up, bubble screens, and active noise cancellation. The group recognized that other mitigation methods are often useful, including optimizing seasonal and hourly timing, routing, and positioning and equipment design, along with shutdown or other operational adjustments when monitoring shows that marine mammals are nearby.

CONCLUSION

This volume is, therefore, a broad, inclusive (but not exhaustive) summary of the current scientific knowledge relevant to assessing the effect of anthropogenic noise on marine life. It is intended to be a guide to the topics that should be included in policy, legal, regulatory and management plans for dealing with this issue. It includes a review of current scientific knowledge along with expert opinions about the science areas in which information is most needed and/or in which there is a high probability of near-term success in obtaining more information. However, no attempt was made to recommend a particular course of action with regard to using the information in policy and legal matters. In fact, such a course was deliberately avoided because it would necessarily involve issues other than science, and should therefore be addressed by a broader spectrum of participants. In spite of that caveat, we are gratified that scientific evidence is given such great importance by all sides of the debate on this issue, and are acutely aware of our societal responsibility to provide high quality information as quickly as practicable.

WELCOME - MARINE MAMMAL COMMISSION

Dr. Robert J. Hofman
Scientific Program Director
Marine Mammal Commission
Bethesda, MD

This workshop is one of a series of workshops intended to determine (1) what is known about the effects of anthropogenic sound on the marine environment; (2) what more we need to know to identify the risks of environmental impacts from human sound sources and to ensure that the risks do not outweigh the benefits of the sounds produced by those sources; and (3) how best to interpret and implement relevant legislation such as the Marine Mammal Protection Act. The workshops are products of consultations initiated early last year (1997) among representatives of the Navy, the National Marine Fisheries Service, the Marine Mammal Commission, the Minerals Management Service, the U.S. Geological Survey, the U.S. Coast Guard, and other federal government agencies with interests and responsibilities related to human sources of ocean noise.

This workshop was organized by Dr. Gisiner and was funded by the Office of Naval Research. Participants include invited experts in the relevant fields of science and engineering (see Appendix A).

The fact that this workshop is being held reflects growing interest in the possible effects of sound from human sources on the marine environment. That interest has scientific, political, and legal components, all of which need to be kept in mind. The scientific interests are well known, and need no introduction here. The political interests and related statutory matters may be less well known. They are the products of concerns raised by scientists, environmental groups, and others regarding the possible effects of anthropogenic sound on marine mammals, fish, and other components of the marine environment, and conflicting concerns regarding regulation of sound-producing activities raised by affected scientists, industries, and other producers and users of anthropogenic sounds.

Nationally, much of this concern has been precipitated by three things:

1. the Acoustic Thermometry of Ocean Climate (ATOC) Program funded in 1993 by the Defense Department's Advanced Research Projects Agency;

2. the National Defense Authorization Act's requirement that new designs for the hulls and other critical components of Navy ships and submarines undergo shock tests before service in the fleet; and

3. the Navy's planned operational deployment of a surveillance towed array sonar system (SURTASS) low-frequency active (LFA) sonar.

In Alaska and California, there has been much concern expressed regarding the possible effects of noise associated with offshore oil and gas exploration and development. Much of what we know about the effects of sound on marine mammals and other marine organisms is the result of research that either has been conducted or supported by the Navy and by the Minerals Management Service in response to these types of concerns.

When the Marine Mammal Protection Act was enacted in 1972, there was no apparent recognition that noise could or would be a marine mammal conservation problem. For example, there is no mention of noise or noise-producing activities in any of the Congressional Committee reports that explain the rationale for the various provisions in the Act.

The Act was unique in several respects. One was that it placed the burden on those wanting to take marine mammals for commercial or other purposes to show that the taking would not have adverse impacts, rather than on the regulatory agencies or the conservation community to show that it would, which had been the traditional approach to regulation until that time. That is, prior to passage of the Marine Mammal Protection Act, marine mammals, like fish and other wildlife, were generally viewed as common property resources that could be used without restriction until someone could show that the use was adversely affecting the resource.

As originally written and subsequently interpreted, the Act made it illegal, with certain specified exceptions, to hunt, capture, kill, or harass marine mammals in any area under U.S. jurisdiction without first obtaining a waiver of the Act's moratorium on such taking. The conditions for obtaining a waiver were procedurally burdensome and, as a consequence, few waivers were sought or granted.

The Act was amended in 1981 and again in 1986 to make it easier to obtain taking authorization when only small numbers of animals are expected to be taken and certain other conditions are met -- i.e., the taking is unintentional; the effects on population size and productivity will be negligible; and the responsible regulatory agency (either the National Marine Fisheries Service or the Fish and Wildlife Service) have prescribed regulations specifying the permissible methods of taking and setting forth requirements for monitoring and reporting to ensure that no more than the authorized number of animals are taken and that the effects are in fact negligible. In 1994, the Act was amended again to make it easier to get authorization for taking that is by unintentional harassment only.

Several points regarding these amendments merit special mention. One is that the House of Representative's Report that accompanied the 1981 amendments stated that the term "negligible" impact was intended to mean an impact that was so insignificant that it could be disregarded. In this regard, the report noted that Webster's Dictionary defines the term "negligible" to mean "so small or unimportant or of so little consequence as to warrant little or no attention." Although it has not been subject to interpretation in any court suits, it appears that this negligible impact standard is more restrictive than the "no significant impact" standard in the National Environmental Policy Act.

A second point meriting special mention is the provision in the 1994 MMPA amendments in which Congress differentiated two types of harassments. The first, titled "Level

A harassment" is defined as "any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild." The second, titled "Level B harassment" is defined as "any act of pursuit, torment, or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering."

The National Marine Fisheries Service and the Fish and Wildlife Service are responsible for interpreting and promulgating regulations to implement these and the other provisions of the Act, and for insuring compliance with the Act and its implementing regulations. It is important in this regard to keep in mind that any individual or organization can challenge the actions of the regulatory agencies in court suits if they believe that those actions do not reflect Congressional intent. Thus, the courts often are the final interpreter of Congressional intent.

Recognizing this, the National Marine Fisheries Service plans to hold a workshop later this year (1998) to seek expert advice as to how -- given the available information -- guidelines or regulations can be best formulated to reflect Congressional intent regarding authorization of the taking marine mammals incidental to sound-producing activities. It is hoped that this workshop will provide the foundation for the follow-up workshop. In particular, it is hoped that this workshop will --

- provide a thorough and objective summary of what is known about the sources, characteristics, transmissions, and effects of anthropogenic sound on marine mammals and other marine organisms;

- identify uncertainties that should be taken into account in developing appropriately precautionary management guidelines or regulations; and

- describe the research that will be required to resolve the uncertainties and, pending their resolution, the kinds of monitoring programs that would be required to verify that sounds from anthropogenic sources are not having unacceptable effects on marine mammals or other marine organisms.

Team

Reports

OCEAN ACOUSTICS

Team Members:

George V. Frisk, *Woods Hole Oceanographic Inst., Woods Hole, MA*; (Team Leader)
Darrell Jackson, *University of Washington, Seattle, WA*
Harry DeFerrari, *University of Miami, Miami, FL*
Jeff Simmen, *Office of Naval Research, Arlington, VA*
Robert C. Spindel, *University of Washington, Seattle, WA*
John R. Buck, *University of Massachusetts Dartmouth, North Dartmouth, MA*
Gerald D'Spain, *Scripps Institute of Oceanography, La Jolla, CA*
John A. Hildebrand, *Scripps Institute of Oceanography, La Jolla, CA*
Charles R. Greene, *Greeneridge Sciences, Inc., Goleta, CA*

INTRODUCTION

The ocean acoustics component of the effects of manmade sound on the marine environment can be analyzed in terms of the passive sonar equation, which describes the signal excess SE in decibels (dB) measured at a receiver in the ocean (Urick, 1975),

$$SE = SL - TL - AN + AG, \quad (1)$$

where SL is the source level, TL is the transmission loss, AN is the ambient noise, and AG is the processing gain associated with the receiving system. Since the decibel is inherently a relative quantity,

$$SE(dB) = 20\ \mathrm{Log10}\ [\text{Measured Pressure/Reference Pressure}], \quad (2)$$

it is essential to define a reference pressure level when we attempt to describe absolute signal levels in terms of dB. In ocean acoustics, the convention for quite some time has been to choose the reference pressure level as 1 microPascal. The source level is then defined as the pressure at a unit distance, typically 1 meter, from the source, while the transmission loss describes all of the attenuating effects of the medium associated with propagation, scattering, and absorption as the signal travels from a position 1 meter from the source to the location of the receiver. The ambient noise is a descriptor of the acoustic level that would be measured under conditions where the source of interest is absent and may arise from sources that are natural and manmade, near and far, and discrete and continuous. Finally, the processing gain indicates the enhancement of the received signal that can occur through the application of clever signal processing techniques and, perhaps, through the use of multiple sensors in the receiving system. Thus, Eq. (1) states that the excess signal level detectable at a sensor in the ocean due to a source with output level SL depends upon the degradation which the transmitted signal suffers as a result of the propagation process (TL) and the ambient noise context (AN) within which the

signal is observed. Once the signal is received at the sensor(s), some of these losses may be recovered through signal processing techniques (AG).

During the past fifty years, primarily because of Naval interest and support, significant progress has been made in our understanding of all of the components of the sonar equation. However, there is a unique set of problems which offer challenging research opportunities to both the ocean and animal bioacoustic communities working in collaboration. These include both basic and applied issues ranging from instrumentation development and database transfer to theoretical wave propagation and signal processing. In what follows, we will provide a brief summary of state-of-the-art knowledge in each one of the four areas associated with the sonar equation and offer recommendations for future research.

SOURCE LEVEL

In this section, we will consider sources of sound whose origins are well defined and for which the output levels can be measured in controlled experiments. Furthermore, we will focus on sources whose occurrence is sufficiently episodic that they are not typically considered a part of the long-term ambient noise environment. Thus, in this context, a continuous wave (CW) projector used in a shallow water acoustics experiment would be considered a source, while the sound produced by breaking waves would be treated as ambient noise. We point out that, in the context of Eqs. (1) and (2), a correct and unambiguous description of the output level of such a single-frequency source would be, for example, 150 dB re 1 microPascal @ 1 m. In the case of signals which are not pure tones, the source level may be described in terms of a peak pressure in the time domain or as a power spectral density (dB re 1 microPascal squared per Hz @ 1 m) in the frequency domain. The issue of appropriate and consistent units among the various sub-disciplines continues to be an active area of debate in the acoustics community (Carey, 1995; Medwin and Clay, 1998; Appendix).

SHIPPING

The sound radiated by the enormous number of ships plying the world's seas is the single largest contributor to the total acoustic budget of the ocean. The effects of these vessels are both local, where they act as discrete sources of sound, and global, where they comprise the dominant component of the overall ambient noise level at frequencies below 500 Hz. As examples, the source levels associated with low-frequency pure tones radiated by supertankers and container ships lie in the range 180-190 dB re 1 microPascal @ 1 m, while drillship and dredging operations generate broadband source levels of 185 db re 1 microPascal per Hz @ 1 m (Richardson et al., 1995). There is a considerable amount of information available in the literature on both ship traffic and source levels (Gray and Greeley, 1980; Institute of Shipping Economics and Logistics, 1989; Jennete, 1993; Lloyd's Register of Ships, 1989; Molinelli et al., 1990; Revello and Klingbeil, 1990; Ross, 1987; Scrimger et al., 1990; Scrimger and Heitmeyer, 1991).

OFFSHORE OIL EXPLORATION

The activities associated with the oil exploration industry have historically constituted a major source of acoustic activity in shallow water (<200 meters) and, in recent years, in deeper water (several hundred meters) as well. These activities range from oil and gas drilling and production operations to marine geophysical surveys and, in some geographic areas (e.g., the Gulf of Mexico), are of sufficient extent that they might be considered to be part of the background ambient noise level. Richardson et al. (1995) provides an extensive and comprehensive summary of the available data in this area and clearly shows that the strongest sources of sound are associated with seismic surveys. The extent to which our knowledge base is limited by the proprietary nature of oil exploration activities is unclear. Airguns and arrays of airguns are the most commonly used geophysical survey tools and are typically fired repeatedly every several seconds, providing broadband signals at tens of Hz with peak levels ranging from 216 to 259 dB re 1 microPascal @ 1 m. Other less commonly used sources in the exploration industry include sparkers, boomers, and water guns, all of which produce levels comparable to those generated by airguns. By far, the most powerful sources of underwater sound are explosive charges of TNT, with charge weights in the range 0.5-20 kg producing broadband, peak levels in the range 267-279 dB re 1 microPascal @ 1 m (Richardson et al., 1995). For a variety of reasons, the use of explosives as acoustic sources has diminished dramatically in both the oil industry and the ocean acoustics community since the 1960's.

SONARS AND OCEANOGRAPHIC RESEARCH

Sonar signals permeate the ocean environment from the most practical to the most esoteric levels in the sense that every ship on earth has at least an echo sounder to determine bottom depth and almost every oceanographic experiment has at least a pinger to determine instrument depth. In some cases, the transmission, reception, and positioning systems are far more elaborate and complex. Typically, pulsed high-frequency (kHz) signals are used over relatively short ranges (km) for echo sounding, bottom imaging (side scan and multibeam sonars), bottom and surface scattering studies, fish finding, navigation, communication, and Acoustic Harassment Devices (AHD's). Their output levels range from 180 to 230 dB re 1 microPascal @ 1 m (Richardson et al., 1995). It should be noted that high frequencies are rapidly attenuated in range, and therefore the sound emitted by even high source level devices diminishes quickly. For example, the absorption at 100 KHz is 0.01 dB/m, so that owing to absorption alone, a 200 dB emission @ 1 m is reduced to a 100 dB level at a range of 10 km. Geometrical (spherical) spreading loss reduces this an additional 80 dB at that range. In underwater acoustic and acoustical oceanographic research, low-frequency (tens to hundreds of Hz) CW (Constant Wavelegth) and coded signals are normally used to study the transmission characteristics of the ocean waveguide and to infer oceanographic properties of the surface, the water column, and the seabed. These experiments are typically conducted over short to moderate ranges (ones to hundreds of km), are of relatively short duration (2-4 weeks), and utilize sources such as the NRL J15-3, with an output level of 170 dB re 1 microPascal @ 1 m. In isolated instances (e.g., the ATOC Project), low-frequency sources with output levels of 195 dB re 1 microPascal @ 1 m have been used to study long-range (thousands of km) transmissions and their oceanographic implications.

RECOMMENDATIONS

One of the exciting possible areas of future research involves the use of animals as sources of sound for the study of ocean acoustics in conjunction with investigations of animal behavior. A significant challenge here lies in localizing and tracking the sources in an uncertain environment. But both the inverse source and inverse environment problems have been studied extensively in ocean acoustics using matched field processing and inversion, as well as other, techniques (Brekhovskikh and Lysanov, 1991; Frisk, 1994; Jensen et al., 1994). The use of marine mammals as sources therefore offers a unique opportunity for collaborative research between the ocean and animal bioacoustic communities.

Another interesting area is the electroacoustic/physiological mechanism by which animals generate sound. Although some research work exists in this area, a unified effort among physicists, engineers, and biologists would be very useful and productive.

TRANSMISSION LOSS

During the past twenty-five years, enormous progress has been made in our understanding of the physics of acoustic wave propagation through the ocean and our ability to model, both analytically and numerically, the interaction of sound with complex ocean environments (Brekhovskikh and Lysanov, 1991; Frisk, 1994; Jensen et al., 1994). These include oceanographic features, such as fronts, eddies, currents, internal waves, bubbles, and surface gravity waves, as well as multilayered, rough, heterogeneous, elastic seabeds. The classical approaches of ray theory, normal modes, and wavenumber integration have all been extended to include both range and depth-dependent properties of the ocean. The parabolic equation method, originally intended for paraxial (small angle), range-dependent propagation in the water column, has been extended to accommodate steep angles and elastic bottoms. In addressing the realities of the ocean environment, these computer codes are typically most effective and efficient in dealing with 2D (depth and range-dependent) problems, and must invoke some approximation (e.g., Nx2D slices) in order to deal efficiently with the full 3D problem. Thus, with these approaches, as well as the less commonly used finite-difference and finite-element methods, the computational complexity increases at least as rapidly as kR, where k is the characteristic wavenumber in the problem, and R is the distance (in each of the three spatial dimensions) over which we desire to compute the acoustic field. In practice, therefore, efficient and accurate high-frequency 3D calculations are limited to short ranges, while effective low-frequency calculations can be made for longer ranges. The computational challenge is further escalated in broadband calculations, where the typical, though time consuming, approach is Fourier synthesis of the time-dependent signal from its frequency components.

RECOMMENDATIONS

Despite the above-mentioned limitations, our modeling capabilities far exceed our ability to measure the ocean environment with the level of accuracy required for input data to the models (e.g., 3D sound velocity profiles in the water column and seabed on spatial scales of an acoustic wavelength or less). That is to say, inaccuracies in the transmission loss calculations are more likely due to inadequate input data than they are to deficiencies in the models. This is particularly true in shallow water environments, where our knowledge of lateral variability lags

far behind that in deep water. Since surface, bottom, and water column effects can easily introduce spatial and temporal fluctuations in the received acoustic signal that are 5-10 dB or more, acoustic characterization of the ocean environment continues to be an important area of research.

Another important area lies in the creation of a virtual ocean/animal bioacoustic model that integrates ocean acoustic environmental information as well as animal behavior data. Such a model would be very useful in experiment planning as well as monitoring and assessment studies and could be continually updated as new measurements are acquired. Such an effort would also involve the transfer of the appropriate oceanographic, bottom geoacoustic and ambient noise databases to the animal bioacoustic community.

Still another exciting area for collaborative research is the investigation of animal exploitation of the marine acoustic environment. For example, do animals in some sense anticipate acoustic shadow and convergence zones and use noise sources as navigational benchmarks? This is one of many areas in which human sonar system designers may benefit from investigations of animal sonar systems.

Finally, the variable nature of the ocean environment implies that the components of the sonar equation are, in general, statistical variables. The ramifications of the stochastic nature of the problem must be incorporated into the bioacoustic context.

AMBIENT NOISE

Considerable effort has been expended over the years in attempts to measure and model both natural and manmade ambient noise in the sea. The early work is summarized in the Wenz curves (Richardson et al., 1995; Wenz, 1962), which are still very useful, but more recent efforts have added significantly to our knowledge base in this area (e.g., Hamson and Wagstaff, 1983; Jensen et al., 1994; Kerman, 1988; Kuperman and Ingenito, 1980; Medwin and Clay, 1998; Renner, 1993; Richardson et al., 1995; Ross, 1987; Wagstaff, 1973; Zakarauskas, 1986). Generally, the ambient noise spectral level is about 140 dB re 1 microPascal squared per Hz at 1 Hz and decreases at the rate of 5 to 10 dB per octave to a level of approximately 20 dB re 1 microPascal squared per Hz at 100 kHz. The dominant sources of ambient noise and their frequency ranges are (Richardson et al., 1995): seismic activity, turbulent-pressure fluctuations, and second order pressure effects due to surface gravity waves (1-100 Hz); ship traffic and industrial activity (10 Hz-10 kHz); biologics (10 Hz to 100 kHz); sea ice activity (10 Hz-10 kHz); breaking waves, bubbles, and spray (100 Hz-20 kHz); precipitation (100 Hz-30 kHz); thermal (molecular agitation) effects (30-100 kHz). There are also airborne sources of noise from aircraft, helicopters, and industrial activity, and these are discussed extensively in Richardson et al. (1995). The relative prevalence and frequency of occurrence of these various noise sources are not well understood, particularly in shallow water. Furthermore, it is important to attempt to relate ambient noise levels to actual source levels by taking into account the propagation conditions associated with a particular ambient noise measurement. Thus, although the ambient noise level due to ship traffic may be nominally 75 dB re 1 microPascal squared per

Hz at 100 Hz, the source level associated with a large tanker is actually 186 dB re 1 microPascal per Hz @ 1 m.

RECOMMENDATIONS

The time is ripe for the translation of existing ambient noise databases and models into a useful and accessible set of curves for the animal bioacoustic community. These will need to be location and time specific. Ambient noise varies on small to large time scales, and can depend on time of day and season. Rather than plotting broad means as in the Wenz curves, spectrum percentiles as employed in LGL and Greeneridge (1995) might be more useful. In addition, the determination of the total sound budget of the ocean and its principal constituent parts is a pressing need. Another interesting question which ocean acoustics can help to answer is whether and how animals could use ambient noise, e.g., for navigation using (fixed) noise sources. Also, do they have means of ambient noise imaging? Could they use acoustic daylight (Buckingham, Potter, and Epifanio, 1996)?

PROCESSING GAIN

It is important to recognize that the signal level measured at a sensor can be enhanced by subsequent signal processing by the total receiving system, whether it is designed by humans or marine mammals. These processing gains can be achieved through a variety of techniques including matched filtering, correlation processing, and array processing (Burdic, 1984; Johnson and Dudgeon, 1993; Medwin and Clay, 1998; Urick, 1975; Van Trees, 1968). The method used to process the signal received at a sensor depends critically upon whether it is perceived to be a real signal of interest or largely undesirable background noise.

RECOMMENDATIONS

The determination of the signal versus noise context in which marine mammals place the large variety of sounds in the ocean described above is an important area of research. In addition, the investigation of the signal processing systems employed by animals in both the transmission and reception modes is of considerable interest both to ocean and animal bioacousticians. In the area of technology and instrumentation, a high-frequency active sonar system for tracking animals should be investigated. We should also be pursuing more advanced, compact, and robust sensors and tags for these animals.

APPENDIX: SOUND MEASURES AND BOUNDARY CONDITIONS

SOUND MEASURES

Sound is manifested by two physical influences: sound pressure and particle velocity. Sound pressure is force per unit area and has amplitude. Particle velocity is length traveled per unit time and has a direction associated with it as well as an amplitude. The "particles" moving in sound are not the molecules of the medium, but millions of molecules whose motion can be viewed as that of a unit of the medium. Sound sensors detect either sound pressure or particle velocity, or some quantity related to particle velocity like displacement or acceleration. In the

MKS system of units in physics, sound pressure is measured in micropascals and particle velocity is measured in meters per second.

Sound intensity is the product of sound pressure and particle velocity. Sound intensity has the same direction as the particle velocity. One usually computes sound intensity as some average of the product of pressure and particle velocity over some period of time. The MKS unit of intensity is watts per square meter, which represents the power flow through an area in a direction normal to the area.

There can still be sound in a medium even if the intensity is zero. That is, the intensity is zero if either the pressure or the particle velocity is zero, but it is not necessary for both to be zero. This is important in considering sound in standing waves (in which the average power flow is zero, so the time-averaged intensity is zero) and sound at boundaries between media.

Acousticians accustomed to working in only one medium (usually air or water) use the fact that for plane waves the pressure and particle velocity are related by the characteristic impedance of the medium, given by the product of the density and the sound velocity. That is, sound pressure equals the particle velocity times the characteristic impedance. Then, they can relate intensity to either the pressure or to the velocity by substituting appropriately. In fact, the intensity is then proportional to the pressure squared or to the particle velocity squared, where the constant of proportionality is the characteristic impedance or its inverse. All this is true for plane waves, or for spherical waves, but not for waves in general.

Sound pressure is much easier to measure than particle velocity, and it serves us well. A consequence is that acousticians speak of sound intensity in terms of sound pressure, even to the point of referring a sound intensity level in decibels to a unit of pressure (the micropascal). This is naturally confusing to non-acousticians who wonder how intensity, which they have been told is power per unit area, can simply be a pressure, or force per unit area. The answer lies in the assumptions of one medium and plane waves/spherical waves, and therefore a simple characteristic impedance relating intensity to pressure squared.

In general, source level can be a function of angle; it is the power level per unit area at unit distance (or per steradian) at the angle of emission. Total power is the surface integral over the unit sphere of the angle-dependent source intensities. For an omnidirectional source, the source power level is about 11 dB greater than the source level.

BOUNDARY CONDITIONS

Boundaries between media are special places to sound waves. The ocean has two major boundaries: the surface, above which is very "soft" air, so different in characteristics from water as to be little different from a vacuum, in which there can be no sound; and the bottom, below which is sand or muck or rock. The greatest contrast between the water and bottom media is when the bottom is very hard rock.

The surface is important to marine mammals, they all have to breathe, and therefore they use the surface regularly. What happens to sound from underwater sources when it encounters the surface? The pressure and the horizontal components of particle velocity effectively go to

zero (the air is too "soft" to support pressure or horizontal particle motion at the boundary). However, the vertical particle velocity is actually enhanced by a factor of two compared to what it would have been had the boundary not been there and the sound wave had continued unimpeded. Here is an important case of there being sound but no intensity.

The reverse happens at a hard boundary, such as a rock bottom. The sound pressure and horizontal particle velocity are doubled compared to what they would have been without the boundary being present, However, the vertical particle velocity goes to zero, the boundary below being too "hard" to move. This boundary condition is important in airborne acoustics when sound waves hit the hard ground and the sound pressure is doubled compared to what it would have been in "free space".

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EFFECTS OF ANTHROPOGENIC SOUNDS ON THE HEARING OF MARINE ANIMALS

Team Members:

Arthur N. Popper, *University of Maryland, College Park, MD*; (Team Leader)
Darlene Ketten, *Woods Hole Oceanographic Institution, Woods Hole, MA*
Robert Dooling, *University of Maryland, College Park, MD*
J. Richard Price, *Army Research Lab, Aberdeen Proving Ground, MD*
Randy Brill, *SPAWARSYSCEN San Diego, San Diego, CA*
Christine Erbe, *Institute of Ocean Sciences, Sidney, BC. Canada*
Ronald Schusterman, *University of California, Santa Cruz, CA*
Sam Ridgway, *SPAWARSYSCEN San Diego, San Diego, CA*

INTRODUCTION and BACKGROUND

Noise and other loud sounds can have a detrimental effect on animals by causing stress, increasing risk of mortality by changing the delicate balance in predator/prey detection and avoidance, and by interfering with their use of sounds in communication especially in relation to reproduction and in navigation. Very significantly, acoustic overexposure can lead to temporary or permanent loss of hearing (e.g., Kryter, 1994; Richardson et al., 1995; see chapter 14 in Yost, 1994). While temporary hearing loss (often called temporary threshold shift - TTS) is reversible over time, more prolonged and/or intense exposure (as from cumulative TTS) can result in non-reversible permanent hearing loss (or permanent threshold shift - PTS) in mammals. The situation can be more complicated in fish and birds, where regeneration of damaged hair cells is also possible. Over the long term, large-scale loss of hearing can potentially affect the viability of a population or species if there is a significant reproductive consequence of hearing loss in a sufficiently large segment of the population. More specifically, loss of hearing can affect behavior since it alters the ability of an animal to process acoustic signals providing information about reproductive behavior, parental care, feeding, predator avoidance, navigation, and migration (e.g., Green et al., 1994).

The anatomical and physiological effects of acoustic overexposure on the auditory systems of some experimental animals such as guinea pigs, chinchilla, and several avian species, have been well documented (e.g., Miller, 1974; Bohne et al., 1985; Nielsen et al., 1986; Salvi et al., 1986; Awbrey, 1993). While less is known about the effects of acoustic overexposure on the hearing of wild mammals or on fish (including elasmobranchs), amphibians and reptiles (reviewed in Myrberg, 1990a,b; Richardson et al., 1995), we can hypothesize that similar parametric effects are likely to exist for these animals since there are significant inter-specific similarities in the ear and receptor cells in most vertebrates. Thus, since acoustic overexposure has deleterious effects on hearing and on the ear in humans and various experimental mammals, it is likely that it also has similar effects on many other species including marine mammals,

fishes, and sharks. Supporting this argument are recent data showing that hearing loss in older dolphins is accompanied by hair cell and neural degeneration patterns similar to those found in older humans with hearing loss (Ketten et al., 1997). Because there are also significant differences in how sound get to the ears, and in the structure and the middle and external ears, of marine and terrestrial mammals, caution should be exercised in directly extrapolating data from terrestrial to marine species.

Over the past few decades a great deal of interest has arisen concerning the effects of anthropogenic (human-generated) sounds on animals in the wild, and particularly on marine mammals (e.g., Richardson et al., 1995). Interest by the public has been heightened with the Heard Island study and the ATOC program, as well as by ship-shock tests. However, the sounds associated with this work represents only a very small portion of all of the anthropogenic sound in marine and freshwater environments today (e.g., Myrberg, 1990a, b; Green et al., 1994; Richardson et al., 1995). As described elsewhere in this document, there is very substantial anthropogenic underwater sound produced by sonars, shipping, oceanographic oil and mineral exploration methods, offshore construction, ocean drilling, etc. In the frequency range of hearing for marine mammals, the prevailing background noise in the vast majority of ocean areas is composed of ship-generated and sea-surface noise. As for the shipping noise component, it has been observed (Ross, 1987) that the increase in ship traffic led to an increase in ambient noise (in the low-frequency bands) of as much as 10 dB over the period from 1950 to 1975. Ross predicted a continuing increase, by as much as an additional 5 dB by the year 2000. Thus, Ross estimates a 15 dB increase in noise levels in the past 50 years, with ship noise as a major factor in the environment. Of course, it is also the case that ambient noise levels vary in different parts of the ocean, depending upon human and non-human activity in different areas.

Freshwater environments also contain anthropogenic sounds. In addition to boating and shipping sounds, there are also significant levels of noise associated with hydroelectric dams and power plants. These sources not only put a great deal of acoustic energy into the water by the nature of how they operate, a number of power plants also use underwater sound in attempts to keep fish from water intakes and turbines (reviewed in Popper and Carlson, 1998).

Responses by animals to anthropogenic sounds and noise overexposure can take several forms. At lower sound levels, animals might detect the sound before damage could occur and simply leave the area of maximum ensonification. This decreases the duration of sound exposure and may protect the animal from noise damage if the sound is very loud. Alternatively, the animal might be involved in feeding, breeding, or caring for its young, and therefore remain in the area of ensonification for a longer period. In these instances, the animal may suffer TTS or PTS or some other physiology and/or behavioral effects such as increases in stress level, cardiovascular effects, etc. The same would be true for animals not mobile enough to move from the site of ensonification. Intense acoustic overexposure, on the other hand, might damage an animal's hearing even before it has a chance to move.

IMPORTANCE OF SOUND TO AQUATIC ORGANISMS

Sound is an important communication channel for a large number of terrestrial and aquatic vertebrates and invertebrates (e.g., Atema et al., 1988; Hauser, 1996; Fay and Popper, 1998; Zelick et al., 1998). The advantages to sound over other channels (e.g., light, chemical) are that it is relatively fast (typically at least 4.5 times greater in salt water than in air), highly directional, independent of light levels or water clarity, and not subject to disruption by currents as are chemical signals (although density differences in current speeds can alter sound propagation).

We are just beginning to become aware of how important environmental sound has been for the evolution of hearing. Indeed, it has been suggested that one of the major factors affecting the evolution of vertebrate (and perhaps all) hearing was to provide animals with an acoustic image of their environment (e.g., Popper and Fay, 1997; and see Bregman, 1990). The marine environment is naturally noisy, with sounds being produced by animals (fish, invertebrates, marine mammals) (e.g., Tavolga, 1960, 1964; Tavolga et al., 1981; Myrberg, 1990a, b), as well as by wind and rain, water hitting the shoreline, seismic events, etc. (Richardson et al., 1995). This information can potentially provide an acoustic image that encompasses a broad expanse of the ocean, enabling an organism to know about portions of its environment far beyond visual range. It is not hard to imagine that such information might enhance the ability of an animal to survive.

One of the consequences of increased anthropogenic sound is the considerable increase in ambient aquatic noise. Thus, we need to be concerned not only that anthropogenic sounds alter the ability of aquatic organisms to communicate and use sound in normal behavioral situations, but also that such sounds alter the ability of these organisms to glean an overall acoustic image of their environment that might be very necessary for survival. Such sounds might mask the ability of aquatic organisms to hear their environment, with potential serious consequences for the organism.

AQUATIC NOISE LEVELS

One of the major issues with underwater sound is determining what noise levels can impact animals. Another issue is identifying the sources of sounds that are most likely to affect animals. A number of sound sources are likely to be the major cause of damage or annoyance. Shipping noises are generally considered to be the single biggest factor, contributing energy in the region of 20 Hz to 500 Hz. At higher frequencies (1 - 100 kHz), noise is dominated by sea surface and wind action. The primary significance of ship-generated sounds would be for those animals that detect and use sounds in the lower frequency ranges. This clearly would at least include baleen whales, some pinnipeds, and fishes (Fay, 1988; Kastak and Schusterman, 1998). The significance of such sounds to odontocetes is less clear since there are few data on low frequency hearing in these species (see Green et al., 1994; Richardson et al., 1995; Au et al., 1997). Of the approximately nine species of small odontocetes that have had hearing thresholds measured, all appear to have relatively poor hearing at frequencies below about 500 Hz, where shipping noise dominates. In fact, thresholds for these species over 120 dB (re 1 µPa) for tones are not unusual and would preclude detection of ship noise in most areas.

The number of ships in various sea lanes has increased substantially over the past decade. Among commercial ships, radiated noise increases with ship speed and with ship displacement (usually correlated with length). The supertanker, large tanker, fast container ship, and other large merchants are all important contributors, with radiated noise levels being nearly10 dB of the average level. The broadband radiation is dominated by noise from propeller cavitation and resembles a dipole source because of surface-image interference. For a typical deep ocean case, a large tanker might have a source spectrum level of 180 dB (re 1 $\mu Pa/Hz^{1/2}$ at 1 m) at 50 Hz. The contribution to the ambient noise at 10 miles might be about 85 dB and at 100 miles 75 dB and 1000 miles 65 dB. For a typical, North Atlantic noise spectrum level of 85 dB at 50 Hz, the level may be dominated by noise from one nearby ship or ten ships at 100 miles or 100 ships at 1000 miles. It is usually a dynamic combination of many ships at many ranges. Nonetheless, in medium to high noise areas, the long-term average levels tend to be stable and predictable.

Ship radiated noise tends to fall off at a rate 6 dB per octave (Ross, 1987) above 50 Hz, and the shipping-generated ambient noise at about 8 dB per octave. In even the heaviest shipping areas and calm seas, the ship-generated component becomes secondary to the sea-surface noise above 1000 Hz. It is rare to detect the effects of shipping noise above 500 Hz. Spectrum levels must be compared to the auditory filter bandwidths of the animal in question. In beluga whales, for example, hearing sensitivity increases by -10dB/octave up to 20kHz. All other things being equal, this will result in increasingly higher perceived sound levels. Because noise levels are integrated within the animal's so-called critical band filters, that widen with increasing frequency, this effect counteracts any density spectrum drop-off (Erbe, 1997).

There are any number of potentially harmful anthropogenic underwater noise sources in operation today, and these are discussed at length in other parts of this workshop report. While shipping may be the most significant source of sounds, oil drilling, removal of oil rigs by blasting and other construction-related explosions, etc. may all be significant sources of impulse and short-duration noise-related impacts.

SPECIES OF CONCERN

Sound is used for communication by a wide range of aquatic and semi-aquatic animals including invertebrates, fishes, aquatic birds, aquatic reptiles (e.g., turtles), and various mammals that are obligate or semi-obligate water dwellers. Thus, the presence of anthropogenic sounds in the environment of these animals potentially affects their behavior and their physiology (Green et al., 1994). When considering anthropogenic sounds, we must not only consider the most 'visible' aquatic animals, the marine mammals, but also be concerned about other taxa. In particular, it must be remembered that not only are all of these species important members of the aquatic ecosystem, but many non-mammalian species make up important components of the marine mammal food chair, or are of economic importance to humans. Thus any physiological damage to aquatic animals lower on the food chair could have profound effects on organisms higher on the chain. It must also be remembered that if anthropogenic sounds effect the physiology or behavior of rare and endangered species, this could profoundly alter the survival of those species.

An important issue to raise is whether data from one species or group of species dealing with the physiological effects of anthropogenic sounds can be accurately extrapolated to other species. One of the major issues here, as discussed below, is whether it is possible to extrapolate from levels of sounds that effect the ear and hearing of terrestrial vertebrates to the levels of sounds that would have similar effects on aquatic vertebrates. One difficulty in such an extrapolation is interpreting absolute levels of sounds in two very different environments. Another difficulty arises because of significant differences in the structure of the peripheral auditory system of aquatic and terrestrial animals and the possibly different pathways for sound to get to the ear. But, until new data are available, the general pattern of damage to the ear in terrestrial mammals from acoustic overexposure provides the best estimate as to the effect on marine animals (e.g., damage to hair cells of the inner ear). Extrapolation from terrestrial mammals to fishes and invertebrates may be even more difficult since the structure of the auditory system is so different between these groups.

It is also important to note, as pointed out by Schusterman (1981), that it may be difficult to extrapolate data on physiological effects of sound among mammalian species that are different anatomically, physiologically, and phylogenetically (also see Moore and Schusterman, 1987; Renouf, 1991). Moreover, there are also likely to be differences between species that only need to hear in water and other species, such as pinnipeds, otters, walruses, etc. that have to be able to hear in air as well as in water (e.g., Schusterman, 1981; Fobes and Smock, 1981). Thus, interspecific differences in aspects of hearing such as the role of the middle ear in sound conduction, and whether detection is via bone or soft tissue conduction, the hearing bandwidth of a species and whether it can detect sounds in the range of the human-made sounds in its environment, could all influence whether a particular sound can damage hearing (see discussion by Ketten below). As a consequence, what we ultimately can say about the general effects of anthropogenic sounds on marine mammal hearing may be most germane to only some species, or perhaps related species, rather than to larger phyletic groupings.

AIR VS. WATER ISSUES FOR HEARING

This section considers the essential differences in the medium; i.e., how do the physics of air vs. water relate to parameters of hearing. While this discussion primarily considers issues related to marine mammals, it must be remembered that the physical principles involved in air vs. underwater sound may also be important for understanding differences in hearing mechanisms between fishes and terrestrial vertebrates.

All marine mammals, including whales, evolved from land-based animals with air-adapted ears (Barnes et al., 1985). Over the next 50 million years, their ears evolved in tandem to effectively process underwater sound. Water, with a density nearly 800-times that of air (ρ=1.03 g/cc vs. 0.0013 g/cc), has a sonic velocity that is over 4 times faster than the speed of sound in air (c=1530m/sec vs. c=340m/sec). To examine the sensory implications of these values, consider a hypothetical mammal, that hears equally well in water and in air. An animal with an intensity based ear would require the same acoustic power/unit area in water as in air to have an equal sound percept, or ($I_{air} = I_{water}$):

$$I_{air} = p_{air}^2/(0.442\ g\text{-}m/sec\text{-}cc) = p_{water}^2/(1575.g\text{-}m/sec\text{-}cc) = I_{water} \quad (1)$$

which implies the sound pressure in water must be 59.7 times that required in air to produce the same intensity and therefore the same sensation. The units of intensity are watts/m^2, but to put this into the context of conventional hearing measures, recall that intensity is related to the mean square pressure of the sound wave over time. Consequently, most studies report hearing thresholds as effective sound pressure level (SPL), expressed in decibels (dB), which in turn are complicated by arbitrary reference pressures. For air-borne sound measures, the reference is generally dB SPL or dB re 20 µPa rms; for underwater sound measures, the reference pressure is dB re 1 µPa. Thus, accounting both for the function of 59.7 dB and the difference in reference levels, underwater sound pressure levels numerically are about 61.5 dB greater than sound pressure levels in air for an equal intensity. Whether viewed in terms of pressure or intensity responses, there are substantial differences implied in the measures and physics for an equal percept at the mammalian ear in water. (Note, the pressure level of a sound under water is 35.5 dB greater than that of an airborne sound of equivalent intensity. Because the standard reference level under water (1 µPa) is lower than that used in air (20 µPa), 26 dB must be added to this difference, but only if comparisons are made with respect to the two different reference levels [i.e., a sound level of 90 dB re 20 µPa in air has the same intensity as a sound level of 151.5 dB re 1 µPa under water - thus, 90 + 35.5 + 26]). Therefore, one of the most interesting aspects of hearing in marine mammals is the fact that anatomically they follow much of the basic land mammal pattern, but they have also solved the fundamental problems of how to hear in water including the attendant complications for acoustic cues; e.g., increased pressures and shortened interaural arrival times. This successful coupling of a mammal ear to water-borne sound also has some intriguing implications for the potential for marine mammal ears to sustain acoustic impacts. On one hand, having inner ears that are similar to those of land mammals implies they may be susceptible to conventional mechanical loss mechanisms. If this is so, what is worrisome is that even moderate increases in the naturally noisy oceanic environments could accelerate loss from simple acoustic impacts. On the other hand, perhaps these ears have adaptations that could prevent ear damage from barotrauma, pressure changes, and concussive forces. That is why careful research is required to answer these questions.

EFFECTS OF SOUND ON THE AUDITORY SYSTEM

This section considers the effects of sound on the auditory system. At the same time, sound or vibration can have other effects than on organs of hearing, and these effects are discussed in the section on "Non-hearing Effects of Anthropogenic Noise."

Noise trauma is a well-investigated phenomenon for air-adapted ears (see Lehnhardt, 1986; Lipscomb, 1978; and Richardson et al., 1995 for reviews). Noise trauma has been divided into lethal and sub-lethal impacts, although only sub-lethal impacts are likely to be relevant except in extraordinary or blast-related events.

LETHAL IMPACTS

Lethal impacts are those that result in the immediate death or serious debilitation of the majority of animals in or near an intense source; e.g., profound injuries related to shock wave or blast effects which are not, technically, simple acoustic trauma. Sub-lethal impacts are those in which a hearing loss is caused by exposures to sounds that exceed the ear's tolerance to some acoustic parameter. In general, the ear component which is the most fragile or liable to acoustic impact is the inner ear, and specifically, the hair cell and its support structure in the organ of Corti, although intense sounds can also damage the middle ear and outer ear.

SUB-LETHAL IMPACTS: TEMPORARY AND PERMANENT THRESHOLD SHIFT

To determine whether any one animal or species is subject to a sub-lethal noise impact from a particular sound requires understanding how its hearing abilities interact with that sound. Basically, any noise at some level has the ability to damage hearing by causing decreased sensitivity. The loss of sensitivity is called a threshold shift. Hearing losses of this type may be temporary (TTS - temporary threshold shift) or permanent (PTS). Whether a sound causes TTS or PTS is highly correlated with the extent of inner ear damage. Moreover, all frequencies do not produce equivalent damage at the same exposure level, nor will the same frequency-exposure combination cause equivalent damage in all species. The extent and duration of a threshold shift depends upon several acoustic features, including the sensitivity of the subject, and the level, frequency, and duration of the sound.

Most recent research efforts have been directed at understanding the basics of how frequency, intensity, and duration of exposures interact to produce damage: that is, what sounds, at what levels, for how long, or how often will commonly produce temporary (TTS) vs. permanently (PTS) hearing loss. Three fundamental effects are well documented at this time.

1. There can be considerable variation within and between species.
2. For tones and narrow-band noises, the loss centers around the exposure frequency or slightly above.
3. For all types of exposures, there is some combination of noise level and exposure time for which the loss is irreversible.

Temporary threshold shifts might extend over a wide range of frequencies or be restricted to a narrow frequency range, according to source characteristics. The majority of studies have been conducted with cats and rodents (especially chinchilla) using relatively long duration stimuli (> 1 hr.) and mid to low frequencies (1-4 kHz) (see Lehnhardt, 1986, for summary). Virtually all studies show that losses are centered around the peak spectra of the source and are highly dependent upon the sensitivity of the subject. There is always some spread to other frequency regions of the ear, but this is generally greater in the high frequency direction. For narrow band high frequency signals, maximum losses typically occur in or near the signal band or slightly above, but intensity and duration can act synergistically to broaden the loss.

It has also been established that repeated exposures to TTS level stimuli without adequate recovery periods can induce permanent, acute threshold shifts (e.g., Saunders et al., 1991). Liberman (1987) showed that losses were directly correlated with graded damage to the outer and inner hair cells, and that the majority of cells recover. Generally, for sounds that are less

than 80-90 dB SPL, with exposures of a few hours or less, and are relatively narrow band, the loss is limited and temporary, with recovery periods taking from hours to days. The amount of TTS is correlated with both the length of time and the intensity of exposure. The actual effect is related to sound pressure level, signal spectrum, and signal duration. To give a general idea of the kinds of signals that result in hearing damage, note that the current allowable limits for human workplace exposures for broad spectrum signals over an 8 hour period is 80-90 dB re 20 µPa (Lehnhardt, 1986; NIOSH, IO 1999).

PERMANENT THRESHOLD SHIFT (PTS)

The majority of PTS effects are also complex. In the case of impulse signals, rise-time and duration of peak pressure are significant factors. If the exposure is short, hearing thresholds are often recoverable (depending on signal level); if long, or the sound has a sudden, intense onset and is broadband, hearing, particularly in the higher frequencies, is more often permanently lost. Experimentally, PTS can be induced by high intensity multi-hour exposures to narrow- or broad-band noise or by tones. It can also be induced by impulse signals. In humans, PTS occurs most commonly from protracted, repeat intense exposures (e.g., occupational auditory hazards from background noise) or sudden onset of intense sounds (e.g., rapid, repeat gunfire). In humans, hearing loss with aging (presbycusis) is essentially the accumulation over time of PTS and TTS insults to the ear at multiple frequency regions. In presbycusis, sensitivity to high frequencies is lost first with the permanent loss gradually spreading to lower frequencies with age.

Although the inner ear changes related to TTS are fairly well documented, to date, only the PTS level effects of impulse noise have been reliably mathematically modeled (Price and Kalb, 1996). While the correlation between sound level and damage to the inner ear is high and well established, far less is known about the fate of neural centers in the brain stem and cortex to intense acoustic stimulation. Recent data show evidence for "toughening" or "sound conditioning" of neurons in the auditory brain stem to sound exposure once these neurons have been previously stimulated with moderate to loud sound levels (Canlon et al., 1988). That is, following previous sound exposure some brain stem neurons appear less affected by high sound levels. The functional consequences of such neural toughening have not been elucidated.

UNDERWATER HEARING LOSS IN HUMANS

TTS has been produced in humans for frequencies between 0.7 and 5.6 kHz (our most sensitive range) from underwater sound sources when received levels were 150-180 dB re 1 µPa (Smith and Wojtowicz, 1985; Smith et al., 1988). Taking into account differences in measurements of sound pressure in air vs. water (see above), these underwater levels are consistent with the 80-90 dB re 20 µPa exposure levels that induce TTS in humans at similar frequencies in air, assuming an appropriate media-dependent shift in the human minimum sensitivity. It should be noted, however, that, sharp rise-time, impulsive signals produce broad spectrum PTS at lower intensities than slow onset signals both in air and in water, as has often been demonstrated both experimentally in animals and accidentally in humans through occupational or recreational noise exposures (Lipscomb, 1978; Lehnhardt, 1986; Price et al., 1989).

NOISE EFFECTS ON MARINE MAMMALS AND ACOUSTIC TRAUMA

There are simply too many structural and functional differences between marine mammal and land mammal ears to assume that acoustic trauma effects are isomorphic between the two groups.

Vocalization data in marine mammals are frequently cited as indicating high tolerance for intense sounds. Some whales and dolphins have been documented to produce sounds with source levels as high as 180 to 220 dB re 1 µPa at 1 m (Au, 1993; Richardson et al., 1995). Vocalizations are accepted indicators for perceptible frequencies because peak spectra of vocalizations are near best frequency of hearing in most species, but it is important to recall that the two are not precisely coincident and recorded intensity may have little to do with sensitivity. Animals, including humans, commonly produce sounds which would produce discomfort if they were received at the ear at levels equal to the emitted level. Mammal ears are protected generally from self-generated sounds by both intervening tissues (head shadow and impedance mismatches) as well as active mechanisms (eardrum and ossicular tensors).

Arguments that marine mammals can tolerate higher intensities simply because of their size and tissue densities are also not persuasive. The large head size of a whale is not acoustically exceptional when the differences in pressure and sound speed in water vs. air are taken into account. Exactly how head size in water affects attenuation of incident sound at the inner ear has not been investigated and remains an important open question.

Data from several pilot studies provide some useful insights into both facets of the paradox that also need further investigation. In one study, inner ears from a long-term captive male dolphin with a documented hearing loss were compared with the ears of two young adult dolphins (Ketten et al., 1995). Micrographs from young adult dolphin ears show several important cochlear duct cellular adaptations that are markedly different from those of conventional land mammals and seals. Transmission electron micrographic studies revealed dolphins have active fibrocytes in the spiral ligament and five times as many cell layers in the stria vascularis as any other mammal. The stria is considered to be the principal dictator of mammalian cochlear metabolism and the health and resiliency of the spiral ligament is a key factor in basilar membrane response. If these results are confirmed in other odontocete ears, these structural differences could mean dolphins in general have faster hair cell recovery times than air-adapted ears and/or some resistance to degenerative processes within the cochlea and may therefore be less subject to temporary threshold shifts. It is also quite possible that these are simply adaptations in response to increased acoustic pressures, etc. inherent in an aquatic environment and do not infer any special protection, but in any case they do suggest that dolphins may be more resilient than the typical land animals or pinnipeds, which are subject to similar ambients and have cochleae without any apparent hypertrophy.

CT, MRI, and histologic studies of the older dolphin ears showed cell loss and laminar demineralization like that found in humans with presbycusis. The location and degree of neural degeneration in these ears implied a substantial, progressive, hearing loss beginning in the high frequency regions. This too is consistent with the pattern commonly observed in humans. Recently, a behavioral audiogram from a second older dolphin showed a parallel loss (Brill et al., 1997; Ketten et al., 1997). Similar significant differences in the hearing thresholds of two

Zalophus have also been reported by Kastak and Schusterman (1995) that are consistent with age-related hearing differences between animals. The reasonable conclusion from these data is that despite any resistance to acoustic trauma that any marine mammal may be shown to have to threshold shifts in the short term, they are not immune to long term degenerative effects of noise exposure.

Unfortunately, the present data are far from definitive, and in some ways, only beg the basic question of what are the most sensitive species and what noises cause significant impacts. The problem of hearing loss has not been systematically explored until very recently (Ridgway and Carder, 1993, 1997). The most studied group to date, the odontocetes, are also the least likely to sustain a substantial impact from common anthropogenic sources because odontocetes have relatively poor low frequency sensitivity. Still, there are some high- frequency sources within the most sensitive range of many odontocetes. Further, the sensitivity of the odontocete ear to intense low-frequency sounds has not been investigated. In some cases, a captive animal's age or history has not been considered in analyzing its auditory responses, and, in the absence of overt data (e.g., antibiotic therapy), we assume any test animal has a normal ear with representative responses for that species. It is not clear that this is both reasonable and realistic. Particularly when data are obtained from one animal, it is important to question whether that hearing curve is representative of the normal ear for that species. The pilot studies noted above suggest age and/or exposure to noise can significantly alter hearing in marine mammals. In some cases, it is clear that some individual differences observed in "normal" captives may be the result of permanent hearing loss. The fact that some studies show losses in marine mammals consistent with age-related hearing changes considerably complicates the diagnosis and assessment of hearing loss from anthropogenic sources based on small samplings of exposed populations.

Cetaceans ears are purely aquatic and are structurally more derived than land mammal ears and are probably incapable of hearing in air in any normal functional sense. Whale and dolphin middle and outer ears are adapted exclusively to hearing underwater with specialized fatty tissue elements that have acoustic impedances comparable to water that are unique soft tissue analogues to the external canals of other mammals (Brill et al., 1988, 1998; Ketten, 1994, 1997). Given the acuity of odontocetes, this group should be among the most liable to acoustic impacts from sources within their hearing ranges, but it is possible that inner ear hypertrophy in odontocetes provides protective mechanisms from high intensity noise. If the middle ear is dysfunctional in cetaceans, that could also substantially affect the potential for acoustic impacts by eliminating the filter and reflex attenuation functions common in land mammal ears. Pinnipeds, however, present more complex pictures and may be the most fragile marine mammal ears because of their similarity to land-based ears (Kastak and Schusterman, 1998; Wartzok and Ketten, 1998). (See section by Schusterman, below.)

NOISE-DAMAGE IN NON-MAMMALIAN SPECIES

There is evidence that high intensity sounds can temporarily alter hearing sensitivity in goldfish (Popper and Clarke, 1976) and cause permanent loss of sensory cells of the ear in several species (Enger, 1981; Hastings et al., 1996). While TTS in fish was followed by complete recovery of hearing over several hours, noise damage resulted in hair cell death.

Although these data support the idea that fish could be affected by anthropogenic sounds, only a few studies give any insight into this problem. Moreover, there is very substantial interspecific variation in the structure of the ears of fishes, and how sound gets to the ear. For example, the ear of the goldfish and the oscar are very different from one another (e.g., Popper and Platt, 1993), and there are also differences between these species in how sound gets to the ear (e.g., Fay and Popper, 1974, 1975). Thus, it may be almost impossible to extrapolate results between fish species that have very different ear structures. Moreover, whereas many fish species could be expected to move rapidly from areas of high ensonification, there are other species that move very little in times of stress, and their potential exposure to damaging anthropogenic sounds could be much higher than in species that move rapidly and readily.

The effects of anthropogenic sounds on other aquatic species, such as reptiles, aquatic birds, invertebrates, etc. is totally unknown. We might be able to extrapolate to aquatic birds from TTS and PTS data on terrestrial birds (see below); however, the exposure to anthropogenic underwater sounds by aquatic birds, other than diving species such as penguins, is likely to be limited due to their short time under water. Of course, if the sound levels are sufficiently intense, even a short exposure could be problematic.

For land birds, there are considerable data available on the effect of acoustic overexposure (see, for example, Saunders et al., 1996; Ryals and Dooling, 1996; Saunders and Dooling, 1974; Saunders et al., 1991). As with terrestrial mammals, the amount of TTS, and whether it leads in PTS, depends on factors such as the spectral characteristics of the acoustic stimulus as well as its duration and level and the amount of exposure (Saunders and Tilney, 1982; Roberto et al., 1996). In general, birds are less susceptible to both TTS and PTS than are mammals (Saunders and Dooling, 1974). Moreover, relatively severe acoustic overexposures that would lead to irreparable damage and large permanent threshold shifts in mammals are moderated somewhat in birds by subsequent hair cell regeneration. Interestingly, recent work has also shown that birds may have other mechanisms for reducing the damaging effects of continuous acoustic overexposure altering the transmission characteristics of the tympanum (Larsen et al., 1997).

RECOVERY OF SENSORY HAIR CELLS

While there is no evidence to suggest that damaged hair cells are replaced or recover after cell death in mammals, there is ample evidence showing that such recovery occurs in both fish and birds. Lombarte and colleagues (1993) showed hair cell recovery in the cichlid fish, the oscar, after treatment with ototoxic drugs (gentamicin). In addition, a large and growing body of literature shows that a number of avian species can regenerate sensory hair cells after noise or drug damage (e.g., Corwin and Cotanche, 1988; Ryals and Rubel, 1988; Ryals and Westbrook, 1990). Still, such recovery does not mean that the replacement hair cells are sending the same kinds of information to the brain as were sent by the original hair cells, or that there is full recovery of function in either birds or fishes. However, if such recovery occurs, this could mean that effects of noise damage are only temporary. At the same time, there would likely be some significant TTS during the recovery, and this could significantly compromise the survival of these species.

If acoustic overexposure is so great that other structures in the cochlea are damaged, in addition to hair cells, then the prospects for long term recovery of hearing are reduced. If only hair cells are lost or damaged, studies in several species of birds have now shown that hair cell regeneration results in the return to near normal auditory sensitivity with a lingering PTS of only about 10-15 dB (Ryals and Dooling, 1996; Niemiec et al., 1994).

RESEARCH REPORTS

In the following sections, several investigators report on the results of studies that are germane to the issues of the effects of noise on hearing. These include investigations that directly assess TTS in both odontocetes (Ridgway and Carder, 1997a) and pinnipeds (Schusterman). The impact of sounds on the ear itself are considered by Ketten, while Erbe discusses the potential effects of ship noise on cetaceans. Dooling provides an overview of the effects of sounds on birds that could readily be applicable to aquatic birds, and also demonstrates that results from avian studies are applicable to a general understanding of the effects of sound on marine organisms. Finally, Price provides theoretical methods to evaluate the effects of sound on marine animals.

DETERMINATION OF HEARING CAPABILITIES IN MARINE MAMMALS (prepared by Randy Brill and Sam Ridgway after the workshop at the request of the team leader)

The Navy's marine mammal program and its associated activities have provided most of the available data on the auditory capabilities of small cetaceans. There is an awareness that certain antibiotic regimes, especially high-dose aminoglycosides, can cause hearing damage. The application of behavioral and clinical techniques with animals of known health histories and hearing capabilities throughout its history has provided an important database that continues to grow.

Audiograms have been measured for several species of small odontocetes including the Atlantic bottlenose dolphin, *Tursiops truncatus* (Johnson, 1967; Brill et al., 1997) and its Pacific relative, *Tursiops truncatus gilli* spp. (Ljungblad et al., 1982), the harbor porpoise, *Phocoena phocoena* (Andersen, 1970), the beluga whale, *Delphinapterus leucas* (White et al., 1978), the killer whale, *Orcinus orca* (Hall and Johnson, 1972), and the false killer whale, *Pseudorca crassidens* (Thomas et al., 1988). These audiograms reveal typically mammalian, U-shaped, broadband curves that are all, by comparison to humans and other terrestrial mammals, shifted to higher frequencies with greater sensitivity. Johnson (1968) and Au and Moore (1990) reported measurements of critical ratios and bandwidths that likewise suggest adaptation for high frequencies. There are few, if any, data regarding low-frequency hearing for cetaceans.

The biosonar capabilities of the Atlantic bottlenose dolphin have received a good deal of attention (cf. Au, 1993). Ancillary investigations have provided useful measurements of several characteristics of hearing in these marine mammals; not the least being their ability to localize on a sound source. Renaud and Popper (1975) reported a minimal audible angle (MAA) of less than

1E of arc. Au and Moore (1984) described receiving beam patterns. Moore et al. (1995) reported interaural thresholds for time, 7 μsec, and intensity differences of less than 1 dB.

As discussed above, TTS is an important indicator of sound beginning to exceed the ear's ability to respond. With the intent to determine whether TTS occurs in marine mammals, efforts are currently underway to investigate the effects of loud sounds on the hearing thresholds of five bottlenosed dolphins (*Tursiops truncatus*), and two white whales (*Delphinapterus leucas*). Following measurement of baseline hearing thresholds, animals were exposed to 1-second tones at 3, 10, 20, and 75 kHz at gradually increasing levels up to 202 dB re: 1μPa. Masking noise was used to create a floor effect, thereby eliminating between-session threshold variability due to an ever-changing ambient noise floor in San Diego Bay. Both dolphins and whales began to exhibit alterations in their behavior at levels around 180 dB. TTS was determined to have occurred when there was at least a 6 dB increase in hearing thresholds from baseline testing. TTS was considered to have occurred when tone levels increased to 194-201 dB at 3 kHz, 192-196 dB at 10 kHz, 193-196 dB at 20 kHz, and 192-194 dB at 75 kHz. In all cases, hearing thresholds were back to pre-exposure levels by day's end. Future plans for this study include extending the range of test frequencies and the inclusion of California sea lions, *Zalophus californianus*, to examine taxonomic differences. Evidence of behavioral alteration and TTS in marine mammals will be used to establish criteria for safe noise levels around marine mammals both in open ocean, and in zoos and aquaria.

There are no audiometric data regarding the hearing sensitivity of baleen whales, although there are models based upon anatomical data. Two different groups have developed portable equipment (Carder and Ridgway, 1990, 1994; Dolphin, 1997) to do an audiogram as a function of the auditory brainstem responses. ABR may be used to gather data from stranded, beached, or entrapped whales, and if the animals die, an examination of the health of the ear and other organs that might be impacted by intense sound would assist our understanding of natural incidence of hearing loss.

Biomedical and husbandry studies conducted by the Navy's marine mammal program have provided reason to consider that medical ultrasound techniques can be used to study bubble formation in tissue or blood and CNS effects. The issue of bubble formation is especially important because it appears to be a mechanism that could produce acute death under certain circumstances. Bubble formation and possible embolism are mechanisms that could explain sudden deaths of whales in the presence of intense acoustic events such as have recently been described (Frantzis, 1998). Human divers are susceptible to bends or decompression sickness, a disabling and sometimes fatal condition in which gas bubbles form in blood, joints and other tissues. In human divers whose tissue is saturated due to breathing pressurized gas at depth, low frequency sound might induce bends episodes that would not otherwise occur. Crum and Mao, (1996) suggested that intense low-frequency sound (160 to 220 dB) may induce bubble growth in tissues (also see Lettvin et al., 1982) and therefore divers radiated with low-frequency pulsed sound when they are near decompression limits could be severely injured (Crum and Mao, 1996).

Although cetaceans do not carry a tank of pressurized breathing gas as divers do, they do make repetitive dives to great depth which may produce overpressure of nitrogen in muscle after

repetitive dives (Ridgway and Howard 1979, 1982). Dolphins do not bend even at nitrogen overpressures that would produce the disease in humans; however, in light of the suggestions of (Lettvin et al., 1982) and (Crum and Mao, 1996), we must consider whether intense sound might be a bends threat to diving cetaceans.

TEMPORARY THRESHOLD SHIFT IN PINNIPEDS (prepared by Ronald Schusterman after the workshop at the request of the team leader)

During aerial threshold testing at 100 Hz, a male harbor seal (*Phoca vitulina*) was fortuitously exposed to loud, broadband construction noise, which occurred intermittently for about a week. Kastak and Schusterman (1996) took advantage of this situation, and measured several reliable shifts in the animal's threshold at 100 Hz immediately following cessation of the noise, on each of several occasions. Unfortunately, not only did this experiment not control the intensity of the noise or the period that the seal was exposed to the noise, but the measurements were all made in air, and it was important to determine whether similar results would be obtained under more controlled conditions and also under water. Because of the uncontrolled aspects of the initial aerial TTS experiment, and following completion of basic underwater audiometric work with this 8-year-old harbor seal, (Kastak and Schusterman, 1996) then tested for TTS in a much more controlled fashion in water. The purpose of this work was not to get into issues involving PTS, but merely to demonstrate small but statistically reliable noise induced TTS in pinnipeds.

Octave band noise (OBN) levels of about 60 dB above the subject's threshold at center frequency and exposure durations of 20 minutes were used. Thresholds were obtained using an up-down psychophysical procedure prior to noise exposure, immediately following noise exposure (1-2 minutes between cessation of noise and first trial of threshold testing), and following a variable recovery period. Frequencies of 1 kHz and below were tested with the harbor seal, and 2 kHz and below for the two California sea lions. The subjects were trained to submerge and station in a chin cup near the bottom of a 2.5-meter deep pool. While stationed, filtered white noise was projected from two underwater speakers built into the stationing platform. Noise levels were calibrated before and after daily sessions were completed. Threshold testing was conducted at a separate apparatus.

Results for the harbor seal showed a reliable TTS of approximately 5 dB, followed by recovery within at least 24 hours. In this animal, there was also an effect separate from threshold shift, but clearly related to the signal detection task. The effect manifested itself as a change in response criterion on the majority of post-exposure sessions. The change in criterion was reflected in an average 15% increase in false alarm responses from baseline sessions. When a signal detection analysis was applied, the average adjustment to threshold shift (to account for response bias) was 3.7 dB (producing a corrected average TTS of about 8 dB). False alarm rates during recovery fell back to approximately baseline levels. These results are suggestive of noise-induced tinnitus, changes in motivational state subsequent to exposure, or simply the lack of ability to discriminate previously supra-threshold tones from background noise. Regardless of the physiological mechanism, such dramatic changes in response criterion are likely to have effects as severe as temporary threshold shift in free-ranging circumstances (i.e., inappropriate responding to irrelevant or non-biological acoustic signals).

Results with the two California sea lions showed that a 22-year-old animal showed statistically reliable TTS (in the range of about 5 dB) at the time of the experiments. However, a 12-year-old animal showed only a marginal and statistically insignificant TTS of only about 1 dB, even when she was exposed to OBN levels up to 69 dB above her threshold at center frequency. Unlike the harbor seal, in the sea lion that did show reliable TTS, there appeared to be no change in the animal's response criterion.

It is important to emphasize that these studies were designed to induce small, temporary threshold shifts with exposure noises of moderate intensity. It was not desirable to produce permanent hearing loss in these subjects due to repeated TTS's. Two reasons for avoiding levels sufficient to induce PTS are 1) ethical concerns about inducing deafness in the subjects; and 2) future experiments involving the same subjects will require that there be no loss of hearing sensitivity or acuity (in terms of frequency discrimination and temporal resolution). It is very clear from these early experiments that TTS can be readily induced both in air and under water in pinnipeds, and that future experiments should take advantage of both harbor seals and sea lions being at least as sensitive to airborne noise as they are to underwater noise. The advantage here refers to the fact that duration and intensity of noise exposure is much more readily controlled in aerial testing than in underwater testing. TTS data will assist in predicting the potential for auditory damage resulting from short exposures to more intense sounds and prolonged exposure to less intense sounds (i.e., aid in the development of noise exposure risk criteria).

MARINE MAMMAL EARS AND MODELS (prepared by Darlene Ketten after the workshop at the request of the team leader)

A fundamental assumption in hearing models is that hearing capacities are the output of the integrated components of the whole ear. All mammalian ears, including those of marine mammals, have three basic divisions: 1) an outer ear, 2) an air-filled middle ear with bony levers and membranes, and 3) a fluid-filled inner ear with mechanical resonators and sensory cells. In terms of the common models used to analyze mammalian hearing, the outer ear acts as a sound collector; the middle ear transforms acoustic components into mechanical ones detectable by the inner ear, and the inner ear acts as a band-pass filter and mechano-chemical transducer of sound into neural impulses.

Hearing models are generally anatomically derived but use electrophysiologic and behavioral data as controls. Modeling of land mammal ears has a long and well-established pedigree (Fay, 1992). One strength of models is that they emphasize species-specific structural differences and, given that there are sufficient anatomical data, models can provide an extraordinarily accurate estimate of the hearing characteristics for virtually any species (Fay, 1992). Clearly an important issue is model accuracy, and this is where the interface of behavioral or electrophysiologic data plays an important role, particularly for marine mammals.

As marine mammal ear anatomy data becomes more comprehensive, and as we gain more information on the comparative aspects of marine vs. land species, anatomically derived models become more sophisticated and more reliable. While some aspects of land based inner ear models are valid for marine mammals, it has been shown that there is a different frequency to

ear morphometric relationship in marine mammals compared to land mammals which must be taken into consideration (Ketten, 1992). That is, while conventional land mammals models provide a starting point, they must be modified to incorporate the underwater bauplan. Because there are sufficient control data (e.g., Brill et al., 1997), primarily in the form of behavioral audiograms correlated with ear lesion data (discussed below), a basic *Tursiops* frequency model has been properly tested. The high level of correlation between the model and the *Tursiops* audiogram means that we can now be reasonably confident that current frequency-membrane mapping models for delphinids and phocoenids are good predictors of hearing ranges for species in those groups (Ketten, 1994; Ketten et al., 1997). Hearing range models have also been generated for some mysticetes (e.g., right whales, humpbacks, and bowheads) using these techniques, but as indicated earlier, while these models have good agreement with vocalization data, no audiometric data are available to definitively test baleen models. No model data are yet available for pinniped inner ears.

Major issues in marine mammal hearing that are unresolved, but for which anatomy is providing some useful indicators are: (1) what are the paths to the ear; (2) what is the function of the middle ear; (3) how is localization accomplished underwater; and (4) what structural mechanisms account for the exceptional frequency ranges of cetacean ears?

Mammalian outer ears are subdivided into a pinna or ear flap that assists in localization, a funnel-shaped concha, and the ear canal or auditory tube. In most mammals, the pinnal flaps are distinct flanges that may be mobile and aid in localization (Heffner and Heffner, 1992). Of course, these structures are reduced or absent in most marine mammals.

Whales have no external ear and the canal is blocked by debris and wax. Currently, the lower jaw is considered the primary reception path for ultrasonic signals in odontocetes. Norris (1968, 1969) speculated that fat filling the lower jaw as a preferential low impedance path to the middle ear and the pan bone as an acoustic window to the middle ear region. Brill et al. (1988) confirmed this role, but some studies also found best thresholds for low to sonic frequencies near the external meatus (Popov and Supin, 1990). Recent CT and MRI data, suggest there are two discrete, orthogonal fat channels, one inside the jaw and a larger one underlying the meatus that may conduct sound to the inner ear (Ketten, 1994, 1997). The presence of two channels may first explain reported discrepancies among sensitivity measures, but equally important it suggests relatively complex dual channel processing that may be unique among mammals.

Pinniped ears are less derived. External pinnae are reduced or absent and ear canal shapes vary. The exact role of the canal underwater has not clearly been determined. Otariids have terrestrial-like, broad bore external canals; phocids, particularly *M. angustirostris*, have narrow ear canals that are nearly occluded (Ketten and Schusterman, unpublished). Whether the external canal remains patent and air-filled, collapses, or becomes flooded during dives continues to be debated. There are strong theoretical arguments for each position. Flooding the canal would provide a low impedance channel to the tympanic membrane, if the middle ear is fluid-filled, the oval and round windows can receive simultaneous stimulation that would compromise normal basilar membrane response. If the canal remains air-filled, the canal should be less efficient for sound conduction to the middle and inner ear than surrounding soft tissues when the animal is submerged. Mohl and Ronald (1975) found that underwater, the most sensitive region

was not the canal but a region parallel to it. CT and MRI data from live harbor seals suggest there are distinctive fats near the meatus (Ketten et al., 1998). Therefore, fatty tissues may also play a role in underwater hearing for some seals, but no discrete soft channels have yet been clearly identified and tested in any pinniped.

Land mammal middle ears are commonly described as impedance-matching devices or amplification transformers that counteract the expected 36 dB loss between air and a fluid-filled inner ear. The gain is achieved by the mechanical advantages provided by area differences of the middle ear membranes (large tympanic vs. small oval window) and by the lever ratio of the bony chain of ear ossicles which create a pressure gain and a reduction in particle velocity at the inner ear.

Improving the efficiency of power transfer to the inner ear may not, however, be the only middle ear function. Recent studies suggest a "tuning" (see Yost, 1994 for overview). Each species has a characteristic middle ear resonance based on the combined chain of impedances. The sum of impedances is lowest; *i.e.*, middle ear admittance is greatest and energy transmission most efficient, at a species-specific middle ear resonant frequency, which depends upon middle ear mechanical characteristics. This frequency is generally at or near the frequency of best sensitivity for that species (Fay, 1992). Ultrasonic species like microchiropteran bats and dolphins have high frequency middle ears with ossicular chains stiffened with bony struts and fused articulations; low frequency species, like heteromyid desert rodents, mole rats, elephants, and mysticetes, have large, flaccid tympanic membranes and massive middle ears components (Fleischer, 1978; Ketten, 1992).

Middle ear function in cetaceans and pinnipeds is still debated. Mass and stiffness of the ossicles and the size and shape of the eardrum vary widely among marine mammals. None are overtly degenerate or vestigial. Both cetaceans and pinnipeds have specialized middle ear mucosa that lines and may fill the middle ear when submerged but has not been definitively shown to do so. Logically, whales would seem to have little need for the classic amplification role of the middle ear, given that they have fluid (ambient) to fluid (inner ear) coupling. CT shows the middle ear of dolphins is air-filled *in vivo*, but some authors hypothesize it does not remain so when submerged. It has been suggested that seal middle ears are capable of operating entirely liquid-filled and that this may enhance high-frequency sensitivity in water (Renouf, 1992). Neither suggestion has been proven. At this point, neither a tuning role nor a particle velocity related role can be ruled for any marine mammal middle ear.

The inner ear consists of the cochlea (hearing) and the vestibular system (orientation and balance). Marine mammal inner ears have the same general format as land mammal ears, but again, there are unusual extremes, particularly in basilar membrane construction. Key components of mammalian cochleae are the basilar membrane, which is a tonotopically ordered resonator, and the organ of Corti that rests atop the membrane. When the basilar membrane moves, cilia on the hair cells of the organ of Corti are deflected eliciting chemical changes that release neurotransmitters. Damage to the hair cells is the primary mechanism underlying most hearing loss.

Differences in hearing ranges are dictated largely by differences in basilar membrane thickness and width along the cochlear spiral. From the base of the spiral to its apex, the basilar membrane becomes progressively thinner and broader. Consequently, the highest frequency an animal hears depends upon the membrane's resonant frequency at the base where the membrane is generally stiffest (narrow and thick). Moving towards the apex, the lowest frequency region of the spiral, the membrane becomes broader and more pliant.

Like land mammals, pinniped and cetacean basilar membranes scale with animal size, and most marine mammals have basilar membranes longer than the human average. If marine mammals had the same stiffness characteristics vs. length as land mammals, most would have relatively poor high frequency hearing. For example, the conventional land mammal length-based hearing model (Greenwood, 1961) predicts an upper limit of hearing of ~16 kHz for bottlenosed dolphins rather than the actual functional high frequency hearing limit of 160 kHz for this species (Au, 1993). This is because marine mammals, and particularly odontocetes, do not have the same thickness gradients, or basilar membrane ratio of width to thickness over length as land mammals. In addition, some odontocetes also have extensive stiffening support elements in the basal regions of the inner ear. By incorporating all these factors, the marine specific model that has been developed not only accurately predicts odontocete hearing ranges but also led to the development of generic multi-feature hearing models that are better predictors of hearing characteristics for all mammals than traditional, single-dimension models (Ketten, 1994; Roitblat et al., 1996).

Anatomically and acoustically, cetacean inner ears divide into three formats. Type I ears, found in the highest frequency animals (functional upper bound >160 kHz), have basal membrane ratios (t/w) >0.8. Type II ears (functional upper bound <160 kHz), have less acute basal membranes (ratio ~0.6) and slightly wider apices, which is consistent with their broader hearing range. Type M ears, common to baleen whales, have unremarkable basal ratios but exceptionally broad apical membranes (up to 2200 μ) and apical ratios near 0.002, consistent with infrasonic resonances and suggestive of a functional hearing limit as low as 10 Hz. Odontocetes have extensive hypertrophy of virtually all cellular elements of the cochlear duct. Mysticetes have no obvious cochlear duct specializations, but both odontocetes and mysticetes have auditory nerve to hair cell innervation ratios three-times those of land mammals, which suggests that both infrasonic mysticetes and ultrasonic odontocetes are capable of equivalent complexity in acoustic processing (Ketten, 1997).

Seal inner ears have not been extensively studied. The consensus of available data suggest that pinnipeds include both high and low frequency adapted species as well as aerial vs. aquatic specialists (Renouf, 1992), but there is no evidence for extreme functional hearing ranges as was found in cetaceans. Most pinnipeds have inner ears that resemble terrestrial high frequency ears, and there are no exceptional developments in either the cochlear duct or auditory nerve. Preliminary data on larger species suggest they may have some low frequency adaptations consistent with their size. Pinnipeds share one feature with cetaceans, a large cochlear aqueduct. Mohl (1968) suggested that this would facilitate bone conduction, but this theoretical function is not consistent with equally large aqueducts in odontocetes.

Data on marine mammal head sizes, ear placement and abilities to localize sound underscore the completeness of adaptations to water-borne sound in these animals. In land mammals, two cues important for localizing sound are interaural arrival time and intensity differences. Interaural time distances (IATDs) depend upon the sound conduction path in the animal and sound speed in the media through which the signal travels. For land mammals, the key entry point is the external auditory meatus and the normal path is through air, around the head, pinna to pinna. The IATD is therefore the intermeatal (IM) distance around the head divided by the speed of sound in air. In aquatic animals, sound could travel around or through the head, depending upon the tissue impedances in comparison to sea water. Moore et al. (1995) demonstrated that bottlenosed dolphins have an IATD of ~7 μsec, well below that of most land mammals, including humans (10 μsec). The values obtained by Moore et al. are effectively equal to rat or bat IM based IADs, and, taking into account sound speeds, rat interaural distances are in fact equivalent to straight line intercochlear and interjaw distances of dolphins. If IM distances are used for land mammals and otariids in air and IC distances are used for cetaceans and underwater phocid data, marine mammal and land mammal data for IATD vs. high frequency limits follow the same regression as land mammal data (Heffner and Heffner, 1992; Ketten, 1997). These data for odontocetes are consistent with the jaw fat hypothesis of (Norris, 1969) and the results of (Brill et al., 1988). Similar efforts to measure IATD in a variety of pinnipeds would be extremely helpful for solving the question of air vs. water sound conduction mechanism for seals and sea lions.

EFFECTS OF NOISE ON ACOUSTIC COMMUNICATION IN BIRDS - A HEURISTIC EXAMPLE (prepared by Robert J. Dooling after the workshop at the request of the team leader)

The potential for noise to adversely affect acoustic communication by masking is probably the most ubiquitous but least well understood effect of noise on animals. Moreover, the complexities of studying acoustic communication in the sea greatly exacerbate this situation. For this reason, examples of similar problems in land vertebrates, such as birds, can serve to highlight the important issues, identify the critical variables for consideration, and suggest approaches to solving the problem of noise interference on acoustic communication. Clearly, when noise masks the biologically important signals of animals in the wild, and interferes with their ability to communicate effectively, it almost surely has a detrimental effect on their normal behavior and breeding biology. However, the situation is really quite complex and different species of birds (as well as other vertebrates) each have their own unique ecology and have evolved various strategies for communicating in noise. The proper approach to the problem of whether anthropogenic noise interferes with acoustic communication, then, is a combined approach involving rigorous hearing and masking studies on the animals in question combined with ethological and ecological data. For example, two of the well known strategies used by humans and other animals include binaural release from masking (e.g., the ability to improve signal-to-noise ratio by turning the head when the signal and noise come from different locations) and either voluntary or involuntary control over the level of vocal output (e.g., the ability to increase the level of vocal output to enhance communication in noise).

It is rare that such considerations enter into discussions on the effect of anthropogenic noise acoustic communication. As a result, attempts to assess the effects of noise on acoustic communication are often simple-minded, unrealistic, and incorrect. As one recent example

illustrates, recent concerns that traffic noise might interfere with acoustic communication in several endangered species of birds in California (the California Gnat-catcher and the Least-Bell's Vireo) have led to the impractical adoption of single noise level (60 dB(A) SPL) as the environmentally acceptable limit of noise produced by freeways.

Taking this problem as an example, a better approach for birds might include the following elements. Most of what we know about hearing sensitivity of birds comes from laboratory tests with simple stimuli such as pure tones. Also, there is a wealth of data from laboratory studies measuring the masking of pure tones by noise (Dooling, 1982, 1991). Pure tone thresholds in the quiet and in noise can be combined with the scattered information available on other more ethological and ecological factors that we know influence the distance over which biologically meaningful signals can be used under natural conditions (Dooling, 1982). These other factors include such things as the location and source intensity of a singing bird, the sound-attenuating and masking characteristics of the environment, and the location and hearing sensitivity of the bird receiving the signal. By combining such laboratory and field data, we can at least roughly estimate possible communication distance between birds for *detecting* simple sounds such as pure tones in noise.

This is a first step. One should not assume that the ability to *detect* a sound in noise is the only relevant variable. To understand how environmental noise might affect acoustic communication, laboratory tests must be conducted on how noises of different types effect not only the *detection*, but also the *discrimination*, and *identification* of species-specific vocalizations. Such laboratory data are critical for understanding the full effect of noise on acoustic communication and for developing reasonable guidelines for noise abatement. At present, predictions made for detection of vocalizations in the environment only address the simplest case, the ability of a bird to tell whether a sound occurred (i.e. detection). It is clear that such a measure does not reflect a bird's ability to communicate effectively in a particular acoustic environment, and may, in fact, have little bearing on it. One need only consider the case of human speech communication. It is one thing to hear a voice, and it is quite another to understand what is said. That is the problem that must be addressed, so that from the perspective of the receiver, acoustic communication abilities can be divided into three broad categories. The ability to detect a signal involves only being able to tell whether a sound occurred or not (Wiley and Richards, 1978, 1982; Klump, 1996). The ability to discriminate or distinguish whether a sound is different from another sound requires yet a higher signal-to-noise ratio than simple detection (Miller, 1974). And identification, or the ability to recognize a specific, biologically relevant signal, may require even higher signal-to-noise ratios. We are now acquiring equivalent data for birds and we need such data on marine animals in order to fully understand communication in noise. It is the ability to discriminate or identify relevant sounds - not just detect the presence of a sound - that are the critical pieces of information.

It is known from recent laboratory tests that, in cases where the signal (a tone) and a masker (a noise) come from different locations, small birds (as well as humans and other animals) can gain a tremendous advantage (up to 10-15 dB) by simply turning their heads (Dent and Dooling, 1997). Moreover, at least some birds can voluntarily control the level of their vocal output and can learn to increase or decrease the level of their vocal output by as much as 15 dB (Manabe et al., 1998). In humans, the increase in vocal level in the presence of noise is

called the Lombard effect. If vertebrates as different as humans and birds show the combined effect, it would not be too surprising to find a similar capability in marine animals.

Another robust phenomena in human speech communication is that of binaural unmasking or, as it is sometimes called, "the cocktail party effect." Under free-field conditions, both speech detection and speech intelligibility in humans are considerably improved as the signal is spatially separated from a masker such as noise (Santon, 1986, 1987; Saberi et al., 1991). Using pure tones, it has been shown that this is true for birds as well using broadband noise as the masker (Dent et al., 1997). Such spatial "release" from masking is a relatively well-known characteristic of the binaural auditory system. A separation in space of signal and noise sources will certainly improve a bird's ability to hear biologically-relevant signals. The degree to which separation in space between noise and signal sources improves the ability of birds to detect the presence or absence of a communication signal must be a part of any effort to understand the effect of noise on communication since this strategy may enable a bird to communicate effectively even in noisy environments.

Finally, there is the type of ecological environment in which an animal lives that can be a critical parameter in estimating interference by noise. Calculating the maximum distance for song detection has to be considered in relation to the animals ecology. Song sparrows have relatively small territories (a diameter of 20 -30 m) and reside in relatively open habitats (Wingfield, 1994). Thus, in contrast to many other songbird species, signal attenuation and masking is therefore expected to be minimal for this species. Songbirds occupy a wide array of habitat types and have a broad range of territory sizes, with some songbirds having territory diameters in excess of 200 - 300 m (Catchpole and Slater, 1995). Therefore, predictions for distances over which a tone may be detected in the environment will vary widely depending on the species in question.

With appropriate laboratory studies on hearing and knowledge of the sound attenuating characteristics of the environment, excellent estimates can be obtained for the maximum distance over which a song produced by one bird can be heard and understood by another. But this information is only valuable in the context of the animal's ecology as the song sparrow example shows. Because this species has a relatively small territory, a given level of noise will be much less disruptive on intraspecies acoustic communication in this species than on another species which may have a much larger territory size.

ZONES OF MASKING IN THE WILD (prepared by Christine Erbe after the workshop at the request of the team leader)

As part of an environmental assessment of icebreaker noise in the Canadian Arctic, the masking of beluga whale vocalizations was studied. The work presented included acoustic experiments with a beluga whale at the Vancouver Aquarium, various software methods to model such experiments, and the application of ocean sound propagation models to calculations of zones of masking in the wild (Erbe, 1997).

Similar to a shortage of data for birds pointed out by Dooling, masking in marine mammals has so far only been studied in experiments where the signal was a pure tone and the

masker either a pure tone or a random, white noise. As hearing is highly nonlinear and depends on both frequency and temporal structure of signal and noise, results from pure tone experiments cannot be superposed to predict the masking of complex communication signals by structured noise. A different approach is necessary.

At the Vancouver Aquarium, masked hearing thresholds were measured behaviorally with a trained beluga whale (Erbe and Farmer, 1998). The signal was a typical beluga vocalization; the maskers were two types of icebreaker noise (bubbler system noise and propeller cavitation noise) and naturally occurring, thermal ice cracking noise for comparison. Results showed that bubbler system noise was strongly masked with a detection threshold at a signal-to-noise ratio of -15 dB, followed by propeller cavitation noise (-18 dB), then natural ice cracking noise (-29 dB). The reason for the different thresholds lies in a complex interplay between the individual time and frequency characteristics of call and noise. In general, pulsed noise as compared to temporally continuous noise exhibited a smaller potential of masking, because the animal could identify the call from very short pieces that emerged through quieter gaps in the noise field.

For the same reason, temporally continuous calls such as whistles are more robust to masking than are pulsed calls. Furthermore, masking depends on the amount of energy call and noise share in so-called critical bands which are characteristic of the animal's auditory frequency filter.

As pointed out by Dooling, there is a need to develop a set of algorithms for predicting noise interference. Animal experiments are very time and cost consuming and often impractical, but necessary. Reliable software models could produce data very efficiently. The detectors tested for their ability to simulate the masking of beluga vocalizations included human listeners, matched filtering, adaptive noise cancellation, spectrogram cross-correlation, critical band cross-correlation, visual spectrogram discrimination and artificial neural networks. The only software algorithm which produced masked hearing thresholds similar to those of the whale was a back propagation neural network (Erbe et al., 1999). The neural net was then used to predict the masking of artificially created, Gaussian white noise. Afterwards, data were collected from the whale. The net's prediction was accurate to within 5 %. This raises confidence in the network's ability to replace animal experiments. At this stage, further ground-truthing with different calls and noises as well as comparison to data from other beluga whales of different age and sex would be advisable. Ultimately, the applicability of the neural net technique to other marine mammal species should be tested.

Masked hearing thresholds (measured or predicted) are of little use unless they can be related to noise types and levels in the wild. An ocean sound propagation model was applied to a conversion of critical signal-to-noise ratios to distances between a noise source, a calling whale and a listening whale. Results were that propeller cavitation noise masked furthest with a maximum radius of masking of 22 km. Bubbler system noise masked over 15 km. A naturally occurring ice cracking event only masked if the listening whale was within 8 m of the event.

This study produced the first data on the masking of animal vocalizations by real underwater noise. Assumptions made previously in hypothetical analyses of masking turned out

to be inadequate. For example, results showed that the zone of masking around a noise source will in general be smaller than the zone of audibility. In addition, ambient noise will often not add to the masking effect of man-made noise.

This project identified the following primary research needs: (1) The utilization of tools from computer science to develop robust models for masking and other effects of noise on marine life is invaluable. (2) Because masking cannot be isolated from other effects described in this report; an integration of data from behavioral, physiological and other studies is needed. For example, arctic beluga populations show disturbance reactions to large vessels long before masking occurs; whereas for the St. Lawrence population, the disturbance distance is shorter than the masking distance. Are habituation or hearing impairment due to PCB contamination an explanation? (3) Do animals have means of avoiding masking? Evidence exists that animals can increase the source level of transmitted signals in the presence of noise. Also, active frequency-shifting has been reported in the case of echolocation (Au, 1993), but in the case of communication, can a call with different spectral characteristics convey the same information? It seems "reasonable" that if vocal communication involves variable signals such as mating or warning signals, then masking will be "biologically significant." However, we basically don't have any data on the importance of communication for survival and on long-term effects on an individual and an entire population.

MODELS OF AUDITORY PROCESSING (prepared by J. Richard Price after the workshop at the request of the team leader)

The list of incomplete knowledge in the area of noise effects on marine mammals is staggering; however there are a few welcome instances where lines of inference can be drawn and previous work in related areas can shed some light on avenues of likely approach. There is an interesting similarity between the natural environment and the military environment. In both, hunter and prey seek to survive, one at the expense of the other. The US Army has dealt with problems of auditory detectability through measuring the source, then modeling the propagation path, the noise background, and the properties of the detector (ear). This program (Garinther et al., 1985) has served as the basis for the Army's non-detectability standard (DOD, 1996) and its structure fits the structure of the marine mammal problem, if not the medium. With the assistance of these algorithms it was possible to calculate the effects of noise on detectability and identifiability of complex sounds or to predict the effects of any particular change in hearing on a soldier's ability to perform various tasks (Price et al., 1989).

If one simply trusts in the great similarity of the basic structure of mammalian ears (as we are usually asked to do when animal models are used to predict human responses), or in the similarity of detection of speech signals (complex transient sounds) and those complex transient sounds used by other animals to communicate, then the applicability of this work to the problem of predicting the effects of man-made sounds on marine mammals is obvious. As always there is the caveat that unique qualities may exist in the model or the system modeled and that these differences may be not only interesting but crucially significant; but development of this parallel has promise. In fact, work is underway under a collaborative effort by Ketten and Price to determine minimal anatomical measures to make these transitions.

A similar parallel also exists where intense sound exposure is concerned. Both the battlefield and the underwater environments have exceedingly intense sound sources and the mammals in both have similar cochleas (the primary site for structural changes which fundamental to hearing loss). It is apparent that an important dividing line exists in the mammalian ear's response to intense sound as pressures rise higher and higher. At lower pressures, the ear can be thought of as "tiring out." Thresholds are elevated for a short while, but they recover to normal and the cycle can be repeated almost indefinitely. However, at higher pressures the damage mechanism may shift into effectively irreversible mechanical stress (the ear is "torn up") (Price, 1981; Liberman, 1987). In this case, the loss is immediate and shows only limited recovery. The damaged cells are replaced by scar tissue and the hearing loss is permanent. The important parameter here is the *intensity* of the sound rather than what source produced it. In this case also, the Army has developed a mathematical model of the mammalian ear to predict hearing loss from such intense sounds (Price and Kalb, 1991; Price, 1998). The model is an electroacoustic analog of the ear and predicts hearing loss based on displacements within the cochlea. The path to applicability of this technology in the case of marine mammals is to develop methods to predict stapes displacements (which drive the inner ear) from pressures in water. Given the great parallelism of mammalian cochleas, it seems likely that the loss algorithms that work within the cochlea should also be useful for predicting the responses of the marine mammals. If so, then it should be possible to make some useful statements with respect to the hazard from really intense sounds in the marine world as well.

[end of requested special reports]

MAJOR QUESTIONS

In general, the effects of anthropogenic sounds on aquatic organisms are likely to be essentially the same as the effects of air-borne sounds on terrestrial organisms. While we have much less knowledge of the effects on aquatic organisms and on the sources of the sounds underwater, the same kinds of questions asked regarding problems in air are applicable underwater.

During discussions, we identified several areas that are particularly important if we are to understand the effects of anthropogenic sound on marine organisms. These areas are briefly discussed in this section.

What are the effects of anthropogenic sounds on the ability to communicate, navigate, find food, avoid predators, etc.?

It was agreed that this issue is somewhat different than masking *per se* since the amount of noise needed to interfere with detection may be quite different from the amount of noise that would interfere with the understanding of a biologically relevant communication signal. In the speech perception literature, it is well known that intelligibility of speech in a noise background continues to improve from no intelligibility when speech is completely masked by noise to complete intelligibility as the speech-to-noise ratio improves over a 20-30 dB range (Hirsh, 1952). At the same time, if it is not possible to measure the effects of sounds on understanding of communication sounds, a second best approach would be to understand masking effects.

Specifically with regard to marine mammals, (Erbe, 1997) found that when measuring the hearing threshold for a complex vocalization consisting of a fundamental frequency and four harmonics, the animal stopped reacting to the call as soon as the lowest frequency either dropped below the audiogram in the absence of noise or was masked in the presence of noise. The higher frequency components, however, were still audible at much lower signal levels. The difference between the call detection and call recognition (identification) level was about 15 dB.

What level stimulus is needed to produce temporary vs. permanent damage to the underwater auditory system?

A critical question is whether anthropogenic sounds have the potential to damage the function of the auditory receptors in different animals. Our knowledge on this subject is minimal. With the exception of a few studies on fishes (Enger, 1981; Hastings et al., 1996), no investigators have ever demonstrated that acoustic overexposure can damage the auditory receptors of aquatic organisms. In the most quantitative of these studies, Hastings et al. (1996) found damage only after the most intense sound stimulation, and then only after the animals were allowed to survive for four days following one hour of stimulation. Whether such results are meaningful for organisms that may avoid or flee from the region of intense sounds is highly questionable (e.g., Popper and Carlson, 1998). Indeed, this question is germane not only to fish, but also to marine mammals. The effects of intense sounds may be much greater on slow moving or sessile organisms, particularly if they are located near stationary sound sources.

Two aspects of the question of direct damage to auditory receptors were discussed. The first was whether sounds can result in a temporary loss of hearing ability that has short-term consequences for an animal. The second was whether sounds can permanently damage the auditory system and lead to long-term consequences. Within the consideration of permanent damage, it is important to keep in mind that damage could be to the hair cells or to any other component or set of structures in the outer, middle, or inner ear. Unlike the inner ear, which is at least fundamentally the same in marine and land mammals, the outer and middle ear anatomies of many marine mammals are rather different and very diverse (see above). For instance, it is still a matter of debate how or if the eardrum and middle ear ossicles function in cetaceans. Even among pinnipeds which have ears that are more similar to land animal ears than to whales, the external ear canals vary considerably from those of land mammals. It is likely that many of the differences found in marine mammals are in part related to their diving requirements, but these adaptations surely imply an acoustic price as well. By example, in land mammals, damage due to high intensity impulse sounds can, presumably, cause a tear in the tympanic or round window membranes, and thus alter the contributions of the eardrum and middle ear to hearing. At the same time, the tympanic membrane, unlike the hair cells of the mammalian inner ear, generally will repair spontaneously and rapidly (within 24 to 48 hours) if less than one-third of the eardrum is compromised. In marine mammals, the tympanic membrane is extraordinarily varied in size, shape, and thickness. In some animals, it is like that of a dog or cat; in others, it is both far larger and tougher, which may well mean it is resistant to high acoustic pressure based tears.

The only information we have on permanent hearing loss in marine mammals comes from several recent studies showing that different individuals of a single species can have different hearing sensitivities (see sections above by Brill and Ridgway, and by Schusterman),

and that some have inner ear damage consistent with their hearing loss (Ketten et al., 1997). For example, age related hearing loss has been found in a female California sea lion, especially at high frequencies (Kastak et al., 1995). This sea lion's aerial hearing had originally been measured when she was two years-old. Sixteen years later, audiometric reassessment using extrapolated comparisons ranging in frequency from 800 to 6,400 Hz showed that the animal had an aerial hearing loss averaging about 22 dB. Comparing the underwater hearing of this older female California sea lion (18 years-old) and that of a younger counterpart (8 years-old), the older animal's hearing loss at low frequencies is almost negligible (a few dB at 100 and 200 Hz), but her losses at the higher frequencies (400 to 6400 Hz) are nearly 17dB. In light of the earlier finding of TTS in this older California sea lion but not in the younger one (see earlier section on TTS in pinnipeds), age related hearing loss may be especially important to consider in older individual pinnipeds. This single study in California sea lions is consistent with the synergistic effects of aging and noise in humans (Kryter, 1994).

Ridgway and Carder (1993, 1997) initially reported evidence of hearing deficits in Atlantic bottlenose dolphins as a function of age. Three older males (23, 26, and 34 years of age), observed in the conduct of an acoustic response time study, exhibited abrupt or progressive hearing losses between 70 kHz and 120 kHz at 111-135 dB *re*:1 µPa while an older female (33 years of age) exhibited a loss of sensitivity only to frequencies above 100 kHz. In contrast, dolphins in the same study (three females of age 11, 32, and 35, and a 7-year-old male) exhibited no evidence of hearing loss to the same stimuli. All of the subject animals were considered to be of normal health without any history of auditory irregularities.

Much more telling are data from the same animal taken several years apart showing a decrease in hearing sensitivity over time [Ridgway and Carder (1993, 1997b) reported a dolphin that had good high frequency hearing at age 13 but had lost hearing at 70 kHz and above at age 26]. Brill et al. (1997) uncovered a significant loss of hearing sensitivity in a 33-year-old male dolphin while measuring a baseline hearing thresholds in preparation for another study. Thresholds at 4-10 kHz measured with the same animal at age 26 indicated a 2-3 dB difference between the ears, which was not considered significant at the time. Seven years later, the same male exhibited a threshold difference 16-33 dB between the two ears over the range of 10-40 kHz and a sharp cutoff in sensitivity above 55 kHz in both ears. Compared to the audiogram for the species originally reported by (Johnson, 1967), Brill et al.'s dolphin exhibits a substantial loss in the normally most sensitive frequencies (65 - 70 kHz). Ketten et al. (1997) compared radiologic data and audiograms from the male dolphin tested by Brill et al. to postmortem histologic analyses of ears harvested from older dolphins with similar hearing losses. In the x-rays they found structural damage in the ears of the live animals that were similar to that seen in the sectioned temporal bones from the other male with hearing loss. In other words, both older males had the same gross changes that are consistent with age-related sensorineural loss.

These gross effects are very similar to those found in humans and other terrestrial mammals and in the histological data were correlated with a loss of sensory hair cells (see discussion by Ketten). Moreover, unpublished data from recent morphological studies in pinnipeds suggests that similar aging-related structural losses can occur in those species. These results are consistent with the work reported by Schusterman (see above). Of course, it must be kept in mind that all of these data for marine mammals are based upon a far smaller sample size

than available from studies of terrestrial animals, and so the results of marine mammal studies should be taken with some caution, at least with regard to absolute values for threshold shift with age.

It is also important to question whether anthropogenic sounds can cause permanent hearing loss in marine mammals, particularly in view of the robustness of whale ears. At this point, however, virtually no data exist to specifically address this question. One reason that this is such a pressing issue is that PTS onset cannot be extrapolated from TTS data. Models that currently exist for PTS are appropriate only for impulse sources and were designed for the human ear alone. This is a question that may not be readily dealt with directly in the United States as a consequence of laws protecting marine mammals; therefore, the only way to ask questions related to the kinds of sounds (duration, intensity, frequency, etc.) that could permanently alter hearing capabilities is through indirect methods and, in some rare cases, through examination of animals that stranded after a known exposure to intense anthropogenic sounds. Of course, any such analysis is problematic since almost nothing would be known in these cases about the precise nature of the noise exposure to the individual ear or the history of the animal's exposure.

It was generally agreed that while a direct test of signals generating permanent threshold shift (PTS) would be of great value and would unequivocally answer questions that can only be dealt with circuitously today, it was also agreed that in our cultural and political and ethical climate direct PTS experiments are highly unlikely. It was noted, however, that because of the urgency of this issue and the potential gain at the level of marine mammal populations from such data, it may be worth considering that at least some level of testing (e.g., ABR measures with on-site intense exposures) be attempted with stranded animals that must, for medical reasons, be euthanized. Data from such studies, even if they were done very rarely, would be of enormous value by providing direct and unequivocal answers of when or how PTS occurs that could rapidly benefit many more individuals and species.

What are the hearing capabilities of animals in which direct audiometry cannot be done?

There are many species for which it is not likely that behavioral studies of hearing can be done. This includes most of the large whales. Still, it is critically important to understand hearing capabilities in these species, as well as to be able to predict the kinds of sounds that can cause temporary and permanent loss of hearing. One approach to this problem is to combine a detailed knowledge of the structure of the auditory system in these species with data extrapolated from physiological and behavioral studies of species for which we have data. This approach has been used to fairly accurately predict hearing capabilities in some marine mammals (Ketten, 1994). In addition, the idea of using electrophysiological measures (ABR) on beached or distressed animals (Green, 1994), even though done opportunistically and rarely, and this still remains a viable approach to gaining insight into hearing of the larger whales (see Brill and Ridgway, above).

What is the role of the middle ear in marine mammals and how does damage to the middle ear affect hearing capabilities?

The role of the middle ear in marine mammals remains controversial. There are significant structural differences from land mammal middle ears, but that there are, at the same

time, differences that are equally great among marine mammals as well that makes inter-marine and marine-terrestrial comparisons equally difficult. Because the middle ear can be a very important element in attenuating or preventing noise impacts; e.g., through stapedial reflexes, this is a fundamental issue that needs to be addressed through additional research. Some of the approaches should address the species diversity in middle ear function as well as the commonalities among species for underwater hearing and evolution to function in a noisy environment.

Indeed, it is also imperative to look at sound transmission at the next level: i.e., the outer ear or, in the case of cetaceans, the analogue of the outer ear. For example, there may be means for attenuating sound to the middle and inner ear of small odontocetes that is remarkably different in its function from land mammal pinnae and canals. The initial hypothesis that the lower jaw of the dolphin and associated structures provides acoustic pathways for the reception of returning biosonar signals (Norris, 1964, 1968, 1969) stimulated major debate and significant research. It was a dramatic departure from the typical mammalian auditory system. Argument about this hypothesis culminated in behavioral data that obstructing the signal at the lower jaw significantly hindered a dolphin's performance on an echolocation task (Brill et al., 1988). Brill et al. further recognized that their experiment had not eliminated the possibility of sound reception at the external ear. Ketten (1992, 1994), provided a comprehensive review of adaptations in the cetacean ear and that there may be two parallel systems for reception of higher and lower frequency signals (e.g., echolocation vs communication). Further investigation into possible sound reception sites in the dolphin's peripheral hearing system are currently underway (Brill, pers. comm.).

What are the effects of anthropogenic sounds on fishes and other aquatic organisms?

The questions regarding non-mammalian species are two-fold. First, will sounds damage the auditory receptors or other cells? Second, will non-damaging sounds have consequences for the ability of fishes to communicate and to "understand" biologically meaningful signals? These questions are pertinent to fishes, since many species make up a major component of the marine mammal food chain, and many of these and other species are of economic importance for humans. They are also germane to marine reptiles, and particularly to marine turtles and other obligate marine organisms.

Data on effects of sound on fishes, invertebrates, zooplankton, larvae, and eggs is almost unknown. There are some data showing that sound for one hour can cause some damage to sensory cells of the ears of fishes, but not of the lateral line or cristae of the semicircular canals (vestibular receptor) (Hastings et al., 1996). There are also very limited data suggesting that exposure to sounds will not damage eggs of several fish species (Bennett et al., 1994). However, as with the Hastings et al. study, these data are extremely limited and the sounds used (intensity, duration, frequency) may not reflect the types of sound most commonly assailing these organisms in their natural environments.

There are slightly more data on the second question. Behavioral studies have demonstrated that background signals can mask the ability of fish to detect test signals (e.g., Tavolga, 1967; Buerkle, 1969; Fay, 1974; Fay et al., 1978; Popper and Clarke, 1979; reviewed in Fay, 1988). These results suggest that anthropogenic sounds could affect the ability of fishes to

communicate using sound, and also detect, discriminate and recognize biologically meaningful environmental sounds. At the same time, data are available for only three or four of the more than 25,000 extant species of bony fish. What is more, the data on other marine organisms, such as elasmobranchs (sharks and rays) and agnathans (lamprey and hagfish), is non-existent.

Nothing is known about the effects of anthropogenic sounds on other aquatic or semi-aquatic species including turtles, aquatic birds, otters, beavers, etc. In order to properly assess the effects of anthropogenic sounds it will not only be necessary to expand efforts on marine mammals, but it is of *equal* importance to investigate the same basic questions in these other animals. Even if anthropogenic sounds do not affect marine mammals, this does not enable us to make the blanket statement that such sounds are inconsequential since they may affect non-mammalian species.

Finally, it needs to be kept in mind that with much of the anthropogenic sounds from the Navy, commercial shipping, transportation, oil and gas operations, etc., occur primarily near shore waters and these are the very regions of the marine environment in which these organisms are most abundant. Thus, concerns about non-mammalian species must be considered as equally valid and worthy of investigating.

Can We Expect a Single Number for TTS and PTS?

As discussed earlier, there is very good evidence that signals 80 dB above threshold are generally capable of causing TTS, at least in humans and experimental animals, when there is exposure for an extended period of time. The question then arises as to whether this value can be taken 'as is' and also whether this value can be extrapolated to animals in the aquatic environment.

With regard to the first question, it must be pointed out that there are numerous caveats when suggesting an 80 dB level for TTS. The presence, and extent, of TTS depends upon a number of factors including sound spectrum, duration, signal duty cycle, rise-time, etc. Thus, without a better description of the stimulus, the basis for using 80 dB (or any other single number) becomes questionable, and so its applicability to a broad range of situations is likely to not be useful.

Equally important, the applicability of this (or any terrestrially derived) value to the aquatic environment also has problems. Differences in the way sound gets to the ear and in basic ear structure in marine mammals, as well as in fishes and other non-mammalian aquatic animals complicates and undermines valid extrapolation. Thus, while the general mechanism of acoustic over-exposure may be similar in aquatic and terrestrial vertebrates, at what level the damage occurs, and the specific nature of a signal needed to produce damage, may differ markedly in water vs. air. Moreover, the effects of such sounds on invertebrates, eggs and larvae, and plankton, is not only unknown, but completely unpredictable.

Damage risk criteria (DRC) for sound levels that might place a human at risk have been largely based on TTS measures due to the unpredictability of obtaining controlled PTS data. Thus, several theories (see Melnick, 1991) and models (see Price and Kolb, 1991 and Price, above) exist as to the appropriate method of applying TTS measures to estimate the degree to

which someone might develop PTS. Damage risk criteria have been established for sound levels and durations of exposure that have a high probability of causing PTS for repeated exposures to workplace sounds. While DRC has been a useful tool for decreasing hearing loss in the workplace, and they are based on a set of relationships between level, duration exposure, and repeated exposure, not on a single number.

The acceptance of DRC's suggest that similar models based on TTS data and on known anatomical and physiological data from aquatic animals might prove useful in estimating the level/duration interactions that have a high probability of causing PTS. Any attempt to develop such relationships would be subject to the same limitations that apply to the application of DRC's to humans. The primary limits are that DRC's are based on TTS data compiled from both experimental animal data and from on-site studies with workers, as well as retrospective studies of individual with acute hearing losses. Much of the data relate best to simple stimuli that are continuously presented; DRC's are not as successful in predicting the possibility of PTS when the stimulus is complex and the duration of exposure is intermittent.

SUMMARY and CONCLUSIONS

The following summarizes the major issues targeted in this section of our report.

Sounds of high intensity and/or long duration are known to cause physiological effects on the auditory system of terrestrial mammals and birds and there is evidence that such sounds can effect the ears of fishes. Effects may be temporary or permanent. Multiple exposures causing temporary hearing loss may ultimately result in permanent hearing loss.

Loss of hearing, whether it be temporary or permanent, can affect animals in a number of ways. As a minimal effect, a temporary loss could prevent an animal from detecting predator or prey, or result in the animal entering an area that would be dangerous for its survival. In addition to these effects, permanent loss of hearing could result in loss of an animal's ability to communicate with conspecifics, find mates, care for young, or find food. Over the long term, loss of hearing capabilities by large numbers of a species could lessen reproductive potential and survival of the species.

Permanent effects that are most readily seen clinically involve damage to the sensory hair cells (the mechanotransducers) in the inner ear. In mammals these cells are not replaced once they are damaged, and damage to these cells results in permanent loss of hearing. Replacement does occur in birds and fishes, but it is not clear that there hearing returns to normal even with the new hair cells.

In contrast to the title of the first film by Jacques Cousteau, *The Silent World*, the aquatic environment has numerous natural sound sources, including wind on the surface, rain, shoaling waves, and seismic events. There are also substantial biological sources such as from snapping shrimp, fishes, and marine mammals that are significant sound sources within their own right. Sounds are widely used by aquatic animals in their everyday survival including foraging, detecting predators, finding mates, and caring for young, etc.. Any sounds present in the

environment that interfere with natural communication or perception of relevant sounds potentially compromise the survival of an animal.

There is a wide range of human-generated (anthropogenic) sounds in the aquatic environment. These include sounds produced by ships, for exploration, hydroelectric plants, etc. There is substantial evidence that the overall level of sound in the aquatic environment has increased significantly in the past 50 years and this is cause for concern vis a vis effects on aquatic organisms. At the same time, because major increase is attributable to shipping, most added noise is likely to be below 500 Hz, and so the major effects of anthropogenic sounds may only be on those species that readily detect sounds at lower frequencies.

The effects of intense sound on the hearing of aquatic animals is not well known and has only been minimally investigated to date. However, there is evidence that temporary and permanent hearing loss occurs in dolphins and some pinnipeds, as well as in at least one species of fish. There are no data on the effects of sound on hearing capabilities of mysticete whales, or semi-aquatic mammals such as otters

There are also almost no data on the effects of intense sounds on hearing by aquatic birds, reptiles, or invertebrates. The concern for hearing loss in these animals needs to be as great as it is for marine mammals since many of these species are of economic importance to humans and/or keystones in the marine food chain. Damage to hearing, and thus to the ability of these animals to survive, can dramatically affect the survival of other animals that interact or depend upon these species.

The levels of sounds needed to cause permanent hearing loss in aquatic mammals is not known. This is very hard to assess using behavioral techniques since it would be necessary to damage hearing capabilities in order to assess these effects. Other techniques are under development, including ABR and morphological methods, that may enable us to predict the levels of sound that will damage hearing based upon extrapolation of the effects from lower levels of sound stimulation.

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NON-HEARING PHYSIOLOGICAL EFFECTS OF SOUND IN THE MARINE ENVIRONMENT

Team Members:

Edward Cudahy, Ph.D., *Naval Submarine Medical Research Laboratory, Groton, CT*; (Team Leader)

Robert Kull, *Geo-Marine Inc., Newport News, VA*

Teri Rowles, Ph.D., *NOAA/NMFS, F/PR, Silver Spring, MD*

LT John Sims, MC, UMO, USNR, *Naval Submarine Medical Research Laboratory, Groton, CT*

INTRODUCTION

The major focus of this section was on physiological effects of sound in the marine environment. In view of the paucity of information regarding the physiological effects of sound on marine life, it was decided to use some of the work done with human divers to investigate physiological effects of low-frequency sound as a starting point and relate diver target areas to marine research areas. There is extensive literature on the effects of in-air blast demonstrating that the noise can cause non-hearing physiological effects, mostly the result of blast, extreme vibration, or stress, with stress being the most studied variable. In almost all cases for stress, noise does not appear to be the primary cause of the physiological effects. For instance, people were under stress due to communication interference or the noise prevented someone in the workplace from "hearing" important signals (e.g., from a drill press). The goals for this section were to identify relevant science issues regarding non-hearing physiological effects of noise on marine life and to prioritize these issues with respect to their importance. If there was information regarding the highest priority issues, this was used to identify research gaps as well as potential approaches to rectify these gaps.

The lack of knowledge about the physiological effects of sound in the marine environment was underscored in read ahead materials provided by Richardson, Popper, and Cudahy and Sims. Factors identified during the session included: the diversity of sound stimuli, the diversity of target animals (marine mammals, fish, turtles, reptiles, sea birds and invertebrates), and the diversity of marine environments.

In the overview, it was noted that there were two levels of physiological effects. The first was a functional disturbance in the performance of the physiological system. An example of this would be a change in heart rate. The second level would be a damage risk threshold. This would be the threshold for actual physical damage to the physiological system.

BACKGROUND

SURTASS LFA SUMMARY

There were two presentations. The first by Cudahy reviewed what is being done in the human diver study on the Surveillance Towed Array Sonar System - Low Freqency Active (SURTASS LFA) system. The idea was to indicate what areas were identified as key areas for the human diver and the current status of these areas. It was hoped that these research areas could serve as a bridge to discussion of physiological effects of sound in the marine environment. In addition, as noted by the National Resource Council (NRC) report (NRC, 1994) on the effects of low frequency sound on marine mammals, the ocean is a noisy place and most of the natural ocean sounds are concentrated below 1000 Hz. It is also the case that many of the anthropogenic environmental sounds such as supertankers, power plants and the like have their energy concentrated in the frequency region below 1000 Hz. The major target areas for the LFA research program are shown in Table 1.

Table 1
Target Areas for Human Divers
• Concussive Effects
• Lung Vibration
• Active Tissue
• Neural Transmission
• Vestibular Effects
• Reproductive Systems
• Sensory Systems

The presentation by Cudahy very briefly described (see below) the current effort for determining an interim guidance for recreational divers. The identity and task for each performer in the Navy laboratory and university consortium was also described. A report on a separate effort looking at the transmission of energy into the central nervous system through the skull was also provided. It was noted that some issues easily translated to marine mammals or fish, but others did not. For example, the central and peripheral nervous systems are key issues for human divers but do not translate well to marine life, whereas lung response may provide directly relevant information.

This research was driven by the US Navy's doctrine of moving into the littoral zone and the Navy's decision elected to produce an environmental impact statement (EIS) regarding use of the system. This expanded the impact of the LFA system from military divers and deep water to recreational divers and shallow water. It was noted by Popper that this significantly increased fish exposure to low frequency sound because fish are more numerous in the littoral region than in the blue water areas used for traditional operations.

The approach used by the Navy to address the EIS was to have two conjoint efforts: a living marine resources research program and a human diver research program. The human diver program uses a consortium approach among Navy and university laboratories to implement a multi-pronged research effort directed at providing damage risk thresholds using animal models and investigating vestibular, lung and psychological effects using human divers. These areas of effort were selected based on results of a previous research effort used to set interim guidance for military divers (NAVSUBMEDRSCHLAB, 1995). Lung effects are to be assessed

using both divers and animal models (rat, mice, and guinea pig). The human divers are military, recreationally trained (not US Navy trained) divers. The demographic (age, gender, health and experience) factors for the test population will be matched as closely as possible to the characteristics for the recreational diving population using the Diver Alert Network database. A questionnaire study reviewing current health status of the Diver Alert Network population will be done to assess the degree of match. All testing is done underwater.

The concussive (memory and learning), active tissue (cardiac muscle tissue), and lung effects are being studied by university laboratories using animal models. In addition, university performers are doing modelling of lung behavior and cardiovascular effects. The Navy labs are testing vestibular function and psychological effects in humans as well as the impact on microprocessor based dive computers. The Naval Submarine Medical Research Laboratory is studying the effects of low frequency sound on the skull and underlying neural tissue in a separately funded project. A university performer is measuring lung resonance in both animal and human subjects. One early outcome of this work is the development of the first enclosed low frequency plane wave underwater test enclosure for animals. Three will be built as part of the project and two will be retained by NSMRL for use in further research.

The need for studies of concussive, skull flexure, central and peripheral nervous system effects is driven by observations of those divers who have been adversely affected by low frequency sound. Many of the symptoms reported could be related to central nervous system effects. Examples include sleepiness, difficulty concentrating, and dizziness (probably a vestibular effect). The skull studies are attempting to determine the direct physical impact of the low frequency sound. The concussive studies in animal models are focused on functional memory or learning deficits elicited by low frequency sound. At the same time, psychological responses such as loudness and annoyance are being measured.

The goal of the psychological studies is to address issues associated with an inappropriate response by a diver to an unexpected low frequency sound. These responses are stress and anxiety reactions. The hazard for a diver is associated with an abrupt decision to ascend to the surface. For a variety of reasons, most importantly the potential for arterial gas embolism and/or decompression sickness, a hasty ascent could have painful or even fatal consequences. In addition, stress reactions such as an elevated heart rate or breathing rate will be monitored. Dizziness and/or feelings of tingling that have been reported in other studies will also be reported. The tingling suggested that low frequency sound was activating or overdriving skin sensors, in particular Pacinian corpuscles, but work in a previous study reported that very high levels would be needed to damage these skin sensors (Verrillo et al., 1996). Presumably similar types of studies could be done in animals.

Two of the three phases planned for the psychological study have been completed, with the final phase to be done in May. The first two phases measured threshold and aversion for low frequency sound and set up the baseline for the third phase which will measure the anxiety response of the diver. Some of the preliminary results suggest that divers' aversion depends on an interaction between vibration and loudness. This interaction effect occasioned some discussion about the complexity of measuring critical factors for behavioral effects. Most of the time, behavior is a reflection of a multitude of factors and as in human psychological studies, it

can be difficult to tease out the particular role that noise plays in the reaction of the animal. Field studies are particularly difficult in this regard, but field studies are necessary in many cases with these large animals so the issue becomes how to balance laboratory and field studies.

LITERATURE REVIEW OF PHYSIOLOGICAL EFFECTS OF UNDERWATER SOUND

The second presentation by Sims summarized some of what little is known about the physiological effects of sound underwater. Human and terrestrial animal data as well as marine animal data was included. It is important to remember that there are many variables that influence the effect of sound on biological organisms and it is difficult to extrapolate from one sound source and one organism to another. With this concept in mind it becomes crucial to identify some of the major variables that have a critical impact. Key variables of the sound source include: frequency, sound pressure level, impulse, peak pressure, and number and time of exposures. Key variables of the biologics include: size, anatomical variation and location in the water column.

Gas-filled spaces. Gas voids within organisms (swimbladders, bowel, sinuses, lungs, etc.) are structures that are particularly susceptible to the effects of underwater sound. The most dramatic effect occurs during exposure to blast and high-energy impulse noise. This susceptibility derives from the interface change of sound traveling from a fluid medium to a gas medium, which results in a pressure release phenomenon. This dramatic pressure drop from a high pressure in the fluid structures (adipose tissue and muscle) to a low pressure within the gas filled structure may cause rupture of hollow organs. The lack of gas voids in invertebrates and flatfish confer a resistance to injury from high sound pressure levels up to 217 dB SPL_{Peak} (Turnpenny et al., 1994) [Note: dB SPL will always be referenced to 1 µPa unless indicated otherwise.]

Bowel. Peak pressures of 129 kPa (222 dB SPL_{Peak}) will result in perforation and hemorrhage of the air filled bowel (Bauman et al., 1997). Although the entire digestive tract can be affected from the esophagus to the anus, the most likely targets are the small and large bowel or areas of trapped gas. Sublethal exposures of 83 kPa (218 dB SPL_{Peak}) result in minor petechial submucosal lesion of the bowel (Bauman et al., 1997). Although these lesions are not immediately life-threatening they have been associated with reduction of food intake in rats. Much of the data that has been generated for safe distances from blasts for humans was performed at the Lovelace Foundation for Medical Education and Research and was extrapolated from the sheep model (Richmond et al., 1973). Safe range graphs for humans derived from this data use shock wave pulses of 2 psi-msec and peak pressures of 100 psi (237 dB SPL_{Peak}) (Christian and Gaspin, 1974; Gaspin, 1983). These numbers represent extremely conservative estimates given no damage was evident for pulses of 6 psi-msec at peak pressures of 100 psi (237 dB SPL_{Peak}). Furthermore, minimal risk of damage is estimated for 10 psi-msec at peak pressures of 100 psi (237 dB SPL_{Peak}). British human test volunteers have been subjected to pulses of 35-45 psi-msec and peak pressures of 120-150 psi (238 - 240 dB SPL_{Peak}) without overt damage or significant discomfort (reported in Christian and Gaspin, 1974). These data are for open water conditions only. The intensity of pulse energy and peak pressure regarded as safe can vary significantly for such variables as location of blast and individual in relation to each other, the bottom and the surface. Blast effects for enclosed spaces and the effects of pulse rate or multiple exposures are not known. There is also minimal information on sub-lethal effects.

Other than direct damage to the bowel there remains the theoretical possibility of creating resonance of the bowel by low frequencies. The theoretical ramifications of resonating bowel would result in transient nausea, vomiting and decreased food intake or damage to the bowel wall. There are no studies that have systematically studied this effect although suggestive reports of digestive troubles at 16 Hz in air have been reported without details of sound pressure levels (Gavreau, 1965).

Lungs. Lethal peak pressures over 100 psi (237 dB SPL_{Peak}) result in pulmonary contusion, hemorrhage, barotrauma and arterial gas embolism in sheep (Fletcher et al., 1976). Arterial gas embolism has been demonstrated in multiple animal species including humans and correlates with the extent of lung damage. Arterial gas embolism usually results in immediate death (Yelverton et al., 1976). A significant linear correlation has been demonstrated between lung injury and lung weight-to-body ratio in air (Dodd et al., 1997). Arterial PO_2 appears to be the most sensitive indicator of sublethal pulmonary damage, which also occurs at the pressures reported above. Other signs of damage are laryngeal petechiae, decreased VO_{2max} and reduced exercise performance (Dodd et al., 1990; Januszkiewicz et al., 1997; Bauman et al., 1997). There is some suggestion that short duration mid-frequency sound may also cause damage at high sound pressure levels. Percy and Duykers (1978) demonstrated slight but consistent alveolar damage in submerged swine exposed to 3-7 kHz at 191-214 dB re 1 μPa for 30-90 sec, although no control animals were used.

Frequencies that result in resonance of the bronchopulmonary tree may also have a significant impact on the health of humans or marine animals. Resonance can stimulate stretch receptors in the bronchopulmonary tree impairing gas exchange as a result of coughing, gagging, or choking. These symptoms were reported by (Mohr et al., 1965) when subjects in air were exposed to frequencies between 1-100 Hz at 150 dB re. 20 μPa (176 dB SPL). Others have shown resonance in humans submerged in water at frequencies of 30-40 Hz, 70 Hz and between 100-200 Hz (Duykers and Percy, 1978; Rogers et al., 1996). Resonant frequencies for submerged terrestrial animals such as goat and swine also have been shown to occur at 40-50 Hz (Richmond et al., 1973; Duykers and Percy, 1978).

There are at least two extant models of the interaction of frequency effects and depth on lung resonance (Jackson et al., 1995; Rogers et al., 1994). These models are for human lung physiology, but Jackson's model is being modified for rat lung. An interesting aspect of these models is that they have opposite predictions regarding the change in resonant frequency with increasing depth, with one (Rogers et al., 1996) predicting an increase in resonant frequency and the other (Jackson and Lutchen, 1991; Suki et al., 1993) predicting a decrease in resonant frequency. This issue has clear implications for the physiological impact of sound on the lung and any guidance that would be issued across the frequency spectrum. Clearly, if the lung resonance changes as a function of depth then as depth changes, the frequency function for damage risk threshold will need to be adjusted. The experiments described earlier are designed to resolve this issue.

Lung effects for marine animals are more complex. For example, marine mammals have no apparent decompression obligation (also discussed later in the decompression section) and

part of the reason appears to be that the lungs collapse below about 60 meters (per Gentry, ref?). This suggests that any major effects on the lung would have to occur above that depth since there would be little air in the lungs below that depth. Fish, on the other hand, don't generally change depths to the same degree and have more stable gas-filled spaces such as swimmbladders.

Swimbladder. Studies in the United Kingdom have focused on the effects of high impulse noise or airguns on swimbladders (Turnpenny et al., 1994). In general, the dose causing 50% mortality (LD_{50}) for *Salmo trutta*, brown trout, occurred at frequencies between 95-500 Hz and at 170 dB SPL. The LD_{50} for bass, *Dicentrarchus labrax*, and whiting, *Merlangius merlangus*, occurred at 95 Hz at 176 dB SPL. There appeared to be no protective benefit between physostomous species, trout with vented swimbladder, and physoclistous, bass and whiting with unvented swimbladders. The failure of a vented swimbladder to protect fish between five species of ducted swimbladders and three species of nonducted swimbladders was also confirmed by (Yelverton et al., 1975). He also demonstrated a linear correlation of LD_{50} for impulse and body weight of the fish, which ranged from 1.7 psi-msec for 0.02-g fish to 49.5 psi-msec for 744-g fish. No studies have looked at the long-term or repetition effects of sublethal blasts on these fish or the possibility of resonance for continuous signals interfering with sound production of the swimbladder for reproduction rituals or warning of predators.

Other gas-filled structures. There are little to no data about other gas filled structures, which include sinuses and the middle ear. There exists some data on the effect of blast on the sinuses and middle ear but in general the bowel and lung effects predominate. Also, all of the blast data was done on terrestrial animals that have ears for air-to-air impedance matching compared to marine animals and should be interpreted with caution when applying to marine mammals or fish. Estimation of a 50% tympanic rupture in submerged canine heads occurs in the ear facing the blast at an impulse of 22.6 psi (223 dB SPL_{Peak}) (Richmond et al., 1973). For submerged Mallard ducks (used as a surrogate for diving birds), there was no eardrum rupture at the 1% lethal dose impulse of 35.2 psi-msec even though there was extensive lung hemorrhage and a 50% prevalence of liver and kidney damage (Yelverton et al., 1973).

Another organ that is dramatically affected by high intensity impulse sound is the fish eye. Blindness and hemorrhage commonly occur at sound pressure levels of 220 dB SPL_{Peak}. The hypothesis for the susceptibility of this organ may relate to the high levels of gas saturation resulting in cavitation damage (see Decompression below).

Cardiac. Lethal blasts as above result in superficial epicardial hemorrhage or scattered endocardial petechiae and rarely rupture (Yelverton et al., 1976). Sublethal blasts can result in decreased stroke volume and cardiac output resulting in decreased exercise tolerance in rats (Januszkiewicz et al., 1997). Resonance of the heart can theoretically induce pacing or arrhythmia. Arrhythmias have been induced in humans exposed to impulse ultrasound during lithotripsy for kidney stones (Matsuura et al., 1990). Dalecki et al. (1991) have demonstrated the ability to induce premature ventricular contraction in the frog heart. The most sensitive phase of the cardiac cycle for inducing premature ventricular contraction appears to occur during the T-P segment of the electrocardiogram. Depending on the phase of the cardiac cycle, pulsed ultrasound can also cause a reduction in the strength of the contraction of the heart muscle or enhanced relaxation of the heart muscle. These effects increased as the pulse length increased

from 100 Hz to 500 Hz (Dalecki et al., 1993). An acoustical reflector that prevents heat transfer and cavitation but allows the radiation force prevents premature ventricular contractions (Dalecki et al., 1997).

Reproduction. There are very few studies of the effect of sound on reproduction and most studies are case studies in humans that focus on vibration. Vibration refers to the motion of a mechanical system. Physiological examples of mechanical systems are the skull, organs such as the lung and heart and the skin. The limited animal studies also include vibration as a significant variable. The combination of noise and vibration appears to have a greater effect on rat reproductive function compared to noise alone (Shenaeva, 1990). Men with a high occupational exposure to vibration demonstrated a decrease in semen volume and motile spermatozoa and an increase in oligospermia, azospermia, and sperm malformation (Penkov et al., 1996). Other reviews have suggested that women in high noise or vibration environments have an increase in menstrual irregularities, abortions and stillbirths (Seidel and Heide, 1986; Seidel, 1993). Some studies have looked at fish eggs and larvae exposed to the high impulse noise of airguns (Turnpenny et al., 1994). Laboratory studies report that low frequency sound can affect egg viability and that growth rates of fish and invertebrates are affected by high intensity impulse sounds (Banner and Hyatt, 1973; Kostyuchenko, 1973; Lagardere, 1982; referenced in NRC, 1994). In general, a damage prevalence of 7.8-16.9% in reduced viability occurs in ranges of 223-236 dB SPL_{Peak}. There appear to be no studies evaluating higher frequencies or longer exposures, which theoretically may have a greater impact on egg viability than low frequency, high intensity impulse noise.

During discussions on how noise affects reproduction, the issue was raised of how to approach this issue. Bowles pointed out that the effects of noise on reproduction leading to changes in population size may be relatively small, on the order of 10 to 15 percent (see Injury Criterion section later for more discussion on setting effects criterion) and that it may be hard to tease this out of the variability introduced into population by other environmental factors. This was echoed by Rowles. Furthermore, Boness noted that choice of a dependent variable is important here. If sperm count is affected by noise, how does that translate into population effects? At the same time, impacting reproductive capability is extremely important in terms of survival.

Decompression. Deep diving mammals appear to have no decompression obligation after exposures to high pressures. It is unclear what the protective mechanisms for these mammals are. The possibility of sound increasing bubble burden for humans is of significant concern given the decompression obligation of humans. Ter Haar et al. (1981) using 750 kHz demonstrated the potential for sound to generate bubbles from micronuclei (in vivo cavitation). Consideration of low frequency rectified diffusion was investigated given that bubbles will continue to enlarge until they reach their resonant frequency, i.e., the lower the frequency the larger the resonant size. For example, a 250 Hz signal will result in a theoretical bubble growth up to 1 cm. The large size of these bubbles increases the potential for blocking medium sized arteries. Theoretical modeling by (Crum and Mao, 1993; 1996) demonstrated that bubble growth in the frequency range of 250-1000 Hz requires supersaturation and high sound pressure level to reach large diameters. Bubble growth theoretically reaches capillary-diameter size (10 μm) within a few minutes at sound pressure levels above 190 dB SPL.

POTENTIAL RESEARCH ISSUES

Discussion following the presentations initially reviewed potential research areas for physiological effects of sound in the marine environment. Those areas are shown in Table 2. Key issues highlighted in the discussion were extrapolation of human data in air to marine life, applicability of data collected for human divers, applicability of data collected on terrestrial mammals underwater ("diving"), stimulus issues, what are the key research issues, can we use a matrix approach to talk about the research issues, and priority areas for future research. In view of the interrelated nature of all these areas, there was also considerable discussion about how to relate the areas to each other.

Table 2
Marine Research Target Areas
• Internal Injuries
• Peripheral and Central Nervous System
• Sensory Systems
• Reproductive Systems
• Avoidance
• Stress

EXTRAPOLATION OF HUMAN DATA IN AIR TO MARINE LIFE

It was felt that there were areas, such as modelling physiology, especially in sensory areas, where human data could be extrapolated to marine life. However, significant limitations were noted due to the applicability primarily to marine mammals. Fish and other marine life were noted to have significantly different physiology.

APPLICABILITY OF DATA COLLECTED FOR HUMAN DIVERS

It was noted that the correlation with human diver data in some areas, such as lung behavior underwater, was considerably better than for in-air human data. On the other hand it was pointed out by Ketten that the human ear did not function the same in water as in air and thus extrapolations may not work well in this case. The sense of the group seemed to be that it was important to understand and match up mechanisms in order for this extrapolation to work.

APPLICABILITY OF DATA COLLECTED ON TERRESTRIAL MAMMALS UNDERWATER ("DIVING")

These data were felt to be extremely important for marine mammals, but of less importance for other marine life. The data has been primarily useful for work with human divers in that it is easier to extrapolate from in-air mammalian diving effects to human diving than from marine mammals. The possible exceptions were lung vibration and hearing.

STIMULUS ISSUES

A point made by several participants was the need to avoid the "one number fits all" solution. An example of this is the 120 dB criterion discussed in the NRC report (NRC, 1994). As noted by the NRC, the in-air community does not have a single worldwide number for permissible exposure to sound. Obvious arguments against using a single number are species differences, differential effects of sound parameters, and surrounding environmental conditions such as the availability of prey in a particular area. It has been shown that animals will tolerate very high levels of sound in order to get food. Human military divers would tolerate high levels of sound in order to complete a mission. There are simply too many factors to permit use of a single number, even though it can be appealing because of its ease of incorporation into guidances or as a fallback due to lack of knowledge. The discussion focused on four areas: ambient noise, continuous, impulse, and blast noise.

Ambient noise. Ambient noise was a concern regarding what signals were relevant or potential sources of damage. Definition of ambient noise varied depending on the application or the signal of interest. For example, ship noise could be considered ambient noise due to its regular frequent presence in the environment. However, in some cases it would be appropriate to focus on ship noise as a signal. There was also disagreement as to the level of hazard due to ship noise. The issue here would be the marine equivalent of sociocusis.

Continuous noise. Continuous noise has been studied the most in humans, fish, and marine mammals. Montague and Strickland (1961) noted that divers reported rotational movement of the visual field starting at about 165 dB re 20 μPa (191 dB SPL) for a 1500 Hz pure tone for one second. The effect coincided with the onset and termination of the tone and did not persist. The speculation was that this was from overstimulation of the vestibular system. The low frequency active sonar research on human divers conducted by Naval Submarine Medical Research Laboratory developed an interim guidance for military divers which was very restricted in terms of frequency and signal parameters (NAVSUBMEDRSCHLAB, 1995). It gave the maximum level as 160 dB SPL for a 100 second signal between 160-320 Hz for a total of 15 minutes with a maximum 50% duty cycle. This guidance illustrates the difficulty in specifying acceptable limits. Minimum parameters to be specified must include SPL, duration, frequency content and duty cycle. Other parameters are type and rate of modulation as well as total time span for exposure. Trade-offs between SPL and time of exposure can also be included. NAVSEAINST 3150.2 takes this approach for sonar exposures between 3 and 6 Khz. The interim low frequency guidance specified that the exposure was for a 24 hour period with no more than 9 exposures over a two week period. Trade-offs between SPL and time of exposure were not specified. The Navy Environmental Health Center (NEHC, 1997) specified that 130 dB SPL at dive sites was the maximum level allowed in the current sea research program. This number was based on the minimum threshold for vibrotactile sensing of an underwater sound between 100 and 500 Hz.

Discussion noted that duration and frequency for continuous noise is an extremely important variable. Effects noted for human divers have been dependent on duration and frequency and there is no reason to believe this would not be true in the marine environment. Duration is at the core of regulation for in-air exposures (a frequency weighting function [A-weighting] that is not available for the underwater environment due to lack of knowledge about

such effects is used to account for frequency effects) and the situation should be no different for in-water exposures. NAVSEAINST 3150.2 incorporates duration and frequency, but this is not done for in-ocean regulations. So duration is a parameter which must be studied.

A discussion arose as to how 160 dB SPL became the interim criterion for low frequency sound exposure intensity for US Navy divers. Cudahy and Sims responded that some divers exposed to that level in certain situations had shown symptoms suggestive of central nervous system and/or vestibular disorders when exposed to continuous noise at this intensity for durations up to 15 minutes. Although these effects were inconsistent, namely only a few divers reported adverse effects, the lack of knowledge regarding the mechanism or dose/response function for the symptoms precluded testing at higher levels. This lack of knowledge was the basis for the psychological experiments and other physiological assessments that are being made in the current research program as well as a long-term research program focusing on mechanisms. Without this knowledge, well-supported safety criteria as well as potential treatment methodologies cannot be established.

Impulse noise. Impulse noise has been studied primarily in the context of seismic airguns and seismic disturbances such as volcanic eruptions. Unfortunately, the data are just now being collected in an organized manner (reference was made to how US Navy ocean bottom arrays have been used to keep track of volcanic eruptions) and used for analysis. Significant issues remain with regard to how to apply it to the general area of physiological damage due to noise. It was agreed that one positive outcome of this meeting was the increased awareness of potential databases of noise that could be used to look at those effects.

Blast noise. Blast noise effects were described during the second presentation and additional information was provided for this summary. The typical effects are related to large pressure fluctuations and it is more useful to talk about waveform parameters and their relation to structural characteristics of marine anatomy than it is to use SPL to quantify the stimulus. It was felt that this was an important area needing more research because blast noise continues to be an ongoing issue for the Navy and for commercial interests.

MEASUREMENT ISSUES

A final area concerned the lack of concrete numbers regarding the exact sound exposure received by marine life. The current sea research project for the SURTASS LFA system is attempting to address this issue, but clearly careful attention needs to be paid to appropriate sound measurement if we are going to get meaningful data, particularly in field studies. One potential solution is improved tags (devices attached to animals which monitor a variety of signals, including the sound pressure at the animal). For a more complete treatment of this issue, see the discussion in the Monitoring and Mitigation section of this conference.

WHAT ARE THE KEY RESEARCH ISSUES?

There was an ongoing discussion about general research issues that impacted across target areas. These issues included injury criteria, short-term versus long-term effects, multidisciplinary approach, which biological parameters provide meaningful measures of behavioral effects, and a matrix approach to organizing the target areas.

Injury criterion. The discussion of criteria included what levels of injury should be used. Typical levels for physiological damage range from 10% to 50%. These are also used to refer to lethality criteria, namely the intensity of sound at which 10% (or 50%) of the animals died. It was pointed out that using a 10% criterion is more difficult because of the inherent variability in estimating damage near the edge of the range. The same applies at the other end of the range. As Ketten and Cudahy noted, moving beyond 30 - 50% becomes a problem because the data sets do not support it, namely individual differences start to play a major role. Ellison noted that this is needed for both lethality and damage thresholds. This discussion also included how much TTS is appropriate to assess effects. People agreed that 5 dB was too small and that 10 - 15 dB seemed to be the most common criterion. Recent work at NSMRL has used 10 dB (Smith et al., 1988).

Short-term versus long-term effects. Concern was raised by several participants regarding how to mix research on short-term and long-term effects. Areas especially impacted by this discussion were reproduction and stress (see later section for description of stress effects). As mentioned earlier, there was a concern about how to relate short-term effects such as reduction in sperm count to long-term effects such as population status. Tyack commented that we may be able to answer the question of what the impact is in terms of communication, orientation, feeding behavior and the like. If we understand those functions, which we can measure, we may be able to then relate these to long-term effects on reproduction. Price later supported that comment with a similar statement that damage mechanisms are brief and catastrophic, but more effort will be needed to understand the effects of lower level stimuli in terms of their long-term effects.

This issue also applied to stress measurement. Here the concern was not only about relation between short-term and long-term measures, but about the appropriate metric and control of ancillary variables. This discussion of how to define the role noise plays in determining stress relative to other variables was used an example of the latter but is described later so it is not repeated here.

What to measure. The issue of what measure is best to use had two aspects. First, what are the limitations imposed by current technology? This led to the discussion of tags, referred to earlier. The second, what measures provide the best generality? For example, heart rate is fairly easy to measure and can be done with current technology. However, heart rate may not be the best predictor of long-term stress. It may also not be a measure that can lead to good understandings of how levels of sound impact stress. Cudahy did mention dose response functions as one measure which may have good generalization potential because it addresses the problem directly by measuring the relation between, for example, intensity and loudness. The key then becomes the dependent variable and the outcome being predicted.

Another issue which received very little discussion (see Hofman comment later) is that all of this work will ultimately boil down to risk assessment. Namely, it is the combination of injury data combined with a risk/benefit analysis that drives guidances. The measurement metric is an important part of that assessment. It is clear that the measurement metric issue is unsolved and does not appear to be getting the attention it deserves in these discussions.

Multidisciplinary and interactive approaches. A frequent comment during the discussion was the interrelatedness of the target areas, particularly in the context of long-term effects. It was also clear that all of this work is multidisciplinary by its very nature, but is not always approached that way. One recommendation of the group was to insure that the multidisciplinary nature of the work be reflected in the team and institutions involved and that this interaction be actively pursued. It was pointed out that conferences like this were an excellent way to interact, but that creative ways were needed to force interaction on an ongoing basis.

Use of a matrix approach to talk about the research issues. It was generally agreed that this was a useful way to organize the issues, but there was insufficient time to set up such matrices. The potential matrix organization with which the group agreed would be a 3D matrix, with research issues prioritized based on sound stimuli (continuous, impulse, and blast noise) for each target animal population (marine mammals, fish, turtles, reptiles, sea birds and invertebrates). There would potentially have to be some further partitioning based on species variations, but the matrix should be as minimal as possible while still covering the range of variations exhibited in each category.

PRIORITY AREAS FOR FUTURE RESEARCH

The last part of the discussion was focused on trying to identify priority research areas. No area was identified as the key area for future research due to some of the issues such as interaction among areas already described. Areas which need attention are sensory (especially auditory and vibrotactile), internal injury (lung and gas-filled spaces), reproductive, and stress. There was discussion about two specific areas and that will be described here, but some general observations will be provided first.

SOME GENERAL OBSERVATIONS

Brill noted that there is a population, the US Navy dolphins, for whom histories are available, that could be used in these research efforts. This might be especially useful for relating short-term and long-term effects because of the tracking information on individual animals.

As noted earlier, there was a consensus on focusing on measuring short-term effects now, while keeping in mind the long-term effects. There was a feeling that a broad range of different species needed to be studied because it was clear that the priority research areas would certainly depend on species and that what had been identified here were the broad areas of concern, not how they might be implemented in each species. It was emphasized that the work needed to incorporate a multidisciplinary approach.

TYMPANIC MEMBRANE RUPTURE

During discussion of current knowledge about potential internal injuries, there was a query about eardrum rupture. Ketten noted that odontecetes show classic symptoms of blast damage such as slit rupture even though the structure of the membrane, namely an everted cone,

is different from that for terrestrial animals. Cavanagh pointed out 50% risk of eardrum rupture is now being used as the criterion for injury (level A harrassment) to marine mammals for the SEAWOLF shock trial environmental impact statement (Dept. of the Navy, 1996).

Ketten showed a tympanic membrane model and pointed out that approximately 30% of marine mammal carcasses that are being collected from beaches show signs of various types of hearing damage, suggesting that many animals in this population may be suffering from hearing loss or that hearing loss may be playing a significant role in these beached animals. Price pointed out that the eardrum is not only resistant to damage (everything you care about happens at lower levels), but that eardrum rupture can be protective in that it cuts the transmission chain to the inner ear and can help protect the inner ear from permanent damage. Unfortunately, it can also serve as an opportunity for bacteria and other infectious agents to enter the middle ear.

LONG TERM EFFECTS/STRESS

This brought up the issue of short-term versus long-term issues and stress was added to the list of physiological issues. Hofman made two points regarding this issue. First, no matter what is learned about the effects of anthropogenic sound on the hearing, behavior, and physiology of marine mammals, the Navy and others with related regulatory responsibilities ultimately are likely to be faced with the question -- "is chronic exposure to anthropogenic sound from any source, or combination of sources, causing psychological or physiological stress that is reducing the average longevity or the average number of offspring produced by individual animals and thus causing a decrease in the productivity (biological fitness) or size of the affected stocks (e.g., by suppressing the immune systems of individual animals, making them more vulnerable to disease)?"

Second, The National Marine Fisheries Service is directed by the Dolphin Conservation Program Act (Public Law 105-42) enacted in September of 1997 to undertake a series of studies in the next three years to determine whether continuing to allow the chase and capture of dolphins in the yellowfin tuna purse seine fishery in the eastern tropical Pacific Ocean causes stress which will prevent the recovery of depleted dolphin stocks, even if the level of mortality associated with the fishery is biologically insignificant. The study is to include:

(A) a review of relevant stress-related research and collection and analysis of samples from dolphins killed in the fishery in the next three years to look for possible indicators of stress (e.g., lesions in heart and skeletal muscle);
(B) a review of relevant historical demographic and biological data related to dolphins and dolphin stocks in the eastern tropical Pacific; and
(C) an experiment involving the repeated chase, capture, and collection and analysis of blood and other samples from live dolphins to look for possible indicators of stress.

Two comments regarding the measurement and use of stress as a physiological issue indicated that stress was difficult to measure and use. The first (Kull) pointed out that it is hard to weed out the fundamental cause of stress due to the presence of a variety of stressors in the

environment. Yost noted that in much of the work with humans, sound has often been shown to be the secondary cause of stress-induced non-hearing physiological changes. For instance, high noise levels in some cases produce physiological signs of stress because the noise interferes with sound communication. It is the loss of communication that caused the stress, not the noise level per se. There is also uncertainty about the cumulative effects of noise and how to measure them.

(Dr. Hofman provided some additional comments in a letter dated 17 February 1998, during review of the workshop proceedings. These points are included below.)

The first point was related to the issues of "acute" or immediate and obvious effects from anthropogenic noise, versus "chronic" or longer-term, accumulative effects that might not always be apparent during individual events of sound exposure. "First, while [acute effects are] important, no matter what is learned about the effects of anthropogenic sound on the hearing, behavior, and physiology of marine mammals, we ultimately are likely to be faced with the question -- Is chronic exposure to anthropogenic sound from any source, or combination of sources, causing psychological or physiological stress that is reducing the average longevity or the average number of offspring produced by individual animals and thus causing a decrease in the size or productivity (biological fitness) of the affected stocks (e.g., by suppressing the immune systems of individual animals, making them more vulnerable to disease)?"

The second, related, point was that "(a) The National Marine Fisheries Service has been directed to undertake a series of studies to determine whether continuing to allow the chase and capture of dolphins in the yellowfin tuna purse seine fishery in the eastern tropical Pacific Ocean will prevent recovery of depleted dolphin stocks, even if levels of mortality associated with the fishery is biologically insignificant, and (b) the results of those studies may provide some insight concerning the possible effects of noise-related stress on the health of the individual animal." More detail on the law mandating this study, and additional details of the specified actions Congress has directed NMFS to undertake, can be found in the International Dolphin Conservation Program Act (Public Law 105-42 [H.R. 408]; August 15, 1997.

SUMMARY

The goal of this section was to examine the current information regarding non-hearing physiological effects of anthropogenic sound on the marine environment and come up with a list of prioritized research topics. This proved to be a difficult enterprise for at least two reasons. First, there is a paucity of information. As described above, limitations in current technology and limited research efforts to date have hampered collection of sufficient data to get closure. This does not mean that there is no information, but rather that it is scattered and not focused, with the exception of the hearing work.

Second, there was considerable discussion about what criteria should be used to decide what is important. Points of view included: a) short-term, acute effects such as blast noise effects should be studied first and research on longer-term issues such as stress be done at a low level and focused on at a later date; b) select the most susceptible organ system for study; c) pick a minimum intensity level and study a broad range of physiological efffects at higher levels; and

d) use the matrix concept above and then select within each matrix. The issue of measures also arose. Potential measures were heart rate, aversion, blood chemistry, avoidance. The key here seemed to be ease of use should be balanced against relevance to physiological parameters.

No final conclusion was reached regarding the number one priority research area. However, key areas, namely internal injury, sensory systems, and stress were identified as important. Furthermore, it was agreed that discussions like this conference are critical to success in focusing research efforts and enabling the multidisciplinary action required to get appropriate results. It was strongly argued that this interaction be maintained.

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BEHAVIORAL EFFECTS OF ANTHROPOGENIC NOISE IN THE MARINE ENVIRONMENT

Team Members:

Roger Gentry, *National Marine Fisheries Service, Seattle, WA*; (Team Leader)
Daryl Boness, *Smithsonian Institution, Washington D.C.*
Ann E. Bowles, *Hubbs-Sea World Research Institute, San Diego, CA*
Stephen Insley, *Smithsonian Institution, Washington D.C.*
Roger Payne, *Whale Conservation Institute, London U.K.*
Ron Schusterman, *University of California, Santa Cruz, CA*
Peter Tyack, *Woods Hole Oceanographic Institution, Woods Hole, MA*
Jeanette Thomas, *Western Illinois University Regional Center, Moline, IL*
(Bob Gisiner assisted in portions of report preparation)

INTRODUCTION

Behavioral change is the metric used most often when humans try to judge the effect of noise on animals. There are probably two reasons for the emphasis on behavioral metrics over other measures of noise effects. One is that levels of noise which cause actual physical damage to the auditory systems or other physiological processes will obviously have deleterious effects at both the individual and population level. We therefore need a behavioral indicator of noise effects that will allow us to anticipate and avoid damaging physical effects. Considerable discussion in this workshop therefore centered on issues related to what types of behavioral responses might be predictive of adverse effects of noise, and how one would go about measuring such behaviors and then quantifying their impact on measures of fitness such as reproductive success, survivorship and fecundity. For example, there was considerable discussion as to whether such commonly used metrics as changes in heart and respiratory rates were indicative of biologically significant impacts on individual or population productivity, or whether such easily and commonly measured responses were indicative of simple attentional behaviors that would have little or no harmful effect.

The second reason for an emphasis on behavioral metrics is that the issues of physiological effects are relatively simpler and more fully explored (though by no means completely worked out). As readers of this volume will discover on reading the sections on Hearing and Non-hearing Physiological Effects we are seeing progress in quantifying such basic psychophysical parameters as hearing thresholds, filtering bandwidths, temporary and permanent threshold shifts, as well as models of noise impacts on lungs, vestibular system and other potentially reactive physiological systems. However, fewer data exist on the effects of noise on the behavior of marine mammals. The paucity of behavioral data is not for lack of effort, and the

methodological difficulties of collecting behavioral data themselves offer a good introduction to the nature and scope of the problem (See Background, below).

BACKGROUND

Two general classes of problems exist with behavior and its quantification; one class of problems is associated with limitations to the methods we have available for marine mammal behavioral study, the other class of problems includes factors that affect our ability to interpret behavioral data. These two "challenges" to the collection of meaningful behavioral data are discussed in greater detail in the background section (below). Additionally, there is discussion of long term cumulative effects that may be difficult to measure, or appear innocuous in the short term, but which may, over periods of years or decades result in biologically significant impact on individuals and populations.

METHODOLOGICAL ISSUES

Detecting and monitoring animals. Most behavioral data come from direct visual observations when animals are at the water's surface. But direct visual observations do not satisfy the need to see animals moving in three dimensions over great distances, and 24 hours per day. There was considerable discussion at this workshop of new methods for improving detection and monitoring of animals, such as passive acoustic monitoring, telemetry tagging, and alternative visual sensing (infrared, lidar, etc.), but the bulk of existing data are from visual observations of surface behavior. Observers are usually limited to viewing animals in the immediate vicinity of the observation platform at the surface; often observers are uncertain whether they see the same animal from breath to breath. Also, the animals' behavior can be affected by the ships or aircraft from which humans observe them. New instruments are available (Time-Depth recorders, video recorders, acoustic transponder tags, sound-recording tags, tags that record body temperature, blood lactate level, etc.) that permit behavior to be assessed at depth. But they bring with them other limitations. For example, per-unit cost and deployment logistics may limit the number of animals that can be telemetry tagged, passive acoustic methods will only monitor acoustically active animals, and some devices are archival, meaning that data cannot be accessed in real time.

Scale effects. At least in the case of marine mammals, humans often observe at a scale that is too limited to monitor the kinds of behavioral responses animals might make relative to an anthropogenic sound source loud enough to be of concern. Some animals travel over entire ocean basins and some sound sources may be audible over a range of tens or hundreds of miles under the certain propagation conditions (see section on Ocean Acoustics) so the potential areas needing coverage for impact assessment may be extensive. Yet shipboard visual observers are limited to a radius of about three to five nautical miles for the largest, most obvious animals or groups of animals due to the elevation of the observation platform, sea state or weather. Sightability may be even lower for less conspicuous animals: Richardson (reported in the Monitoring and Mitigation section of this workshop) showed that the sightability of ringed seals was near zero beyond a range of 500m from the ship. Observers can make only fleeting and limited observations from aircraft; identification of individuals is usually impossible from the air

(Roger Payne, at this workshop, noted that southern right whales may be an exception to that generalization).

Study methods. Most behavioral studies are either descriptive or comparative. Neither of these approaches is conducive to establishing cause and effect relationships. Controlled experiments offer the kind of data that are needed to establish reliable linkages between a given variable and its behavioral effect. To date experiments have not been widely used in investigating marine mammal behavior due to logistic constraints (animals too large to keep in captivity, difficulty of controlling dose level, controlling discreteness of stimulus, etc.). At present opportunities for field experiments such as the ATOC Marine Mammal Research Program, and the Low Frequency Active Sonar Scientific Research Program (LFA-SRP) are limited, and are relatively expensive and challenging to put together. Approaches need to be developed that minimize these difficulties.

ISSUES OF INTERPRETATION

Observers are often uncertain how to interpret a behavioral response. Part of this problem lies with the nature of behavior.

Context. The behavior an animal exhibits often depends, in part, on the context in which the sound is received. Context refers to a combination of the animal's external environment (such as when masking noise or acoustic shadows obscure a sound), ongoing distracting events (such as mating, feeding, or social contact), and the animal's internal state (hungry, sexually receptive, migrating, etc.). An animal may be sensitive or non-sensitive to a sound depending on the context (as defined above). Failure to exhibit an externally observable reaction to a sound does not necessarily imply that the animal has not detected the sound, or that the sound had no effect on the animal. Conversely, a strong behavioral response to a given stimulus may not be indicative of the typical responsiveness of that individual to similar sounds in other contexts or of other individuals in the population that are also receiving the sound at the same place and time. For these reasons, the group discussed at some length the concept of dose response measures of behavioral impacts to account for the natural variability in behavioral response between and within individuals. Dose response measures allow some confidence in the prediction of the relative probability that an individual will exhibit the predicted reaction, or that a given proportion of a sample group will produce the predicted reaction, but does not allow prediction of any one given individual's response in a given context.

Perception. The behavior depends on the animal's *perception* of a physical acoustic phenomenon (see Endnote 1 at the end of this paper), not on the physical parameters of the phenomenon itself. The animal's neurophysiological response, from the receptors that interface directly with the sound in the water to the most complex processing mechanisms in the brain, alter or condition the signal that eventually becomes available for behavioral response. It is therefore widely assumed that animals can therefore selectively "tune in" to special qualities of a sound, such as its temporal, spectral, or amplitude characteristics that can render it more perceptually "prominent" than some other equally loud sound with similar characteristics. This differential sensitivity may be limited, however, to the (masked) auditory threshold of the recipient at that frequency. Erbe (1997) failed to find any studies of animal audition to confirm the commonly-held belief that sounds critical to survival or reproduction may be perceived at

energy levels below the average energy level of masking noise in the same frequency band. In her own experimental study on masking of beluga whale sounds she found that the response threshold of beluga whales to replays of beluga whale sounds occurred at the detection threshold for pure tones. She interpreted this as confirmation of Fletcher's theorem on masking and equal energy in the critical band of signal and noise. Above that constraining lower limit, a sound that resembles the call of a predator could still elicit a stronger response than one that does not. Sounds that elicit strong responses will naturally vary by species, population, individual, and even by different levels of alertness or pre-existing emotional state of the individual. Treating a sound as a percept, rather than characterizing it by its physical characteristics alone, is central to realistic assessment of the behavioral effects of anthropogenic noise. Understanding received sounds as percepts, that may elicit a variety of behavioral responses, is also central to appreciating the importance of stochastic measures of effect such as dose response, that take into account variability in behavioral response under differing conditions.

Ontogeny I (experience, learning and memory effects). The behavior an animal displays can depend on its history of exposure to that sound (experience). Therefore, experience can affect the kind of response that is observed. If an animal shows increasingly strong responses to a sound over time this process is termed *sensitization.* If it shows decreasing responses to a sound over time this is termed *habituation* (see Endnote 2).

Ontogeny II (normal physiological processes of aging). There is limited evidence suggesting that loss of hearing with age (presbycusis) sometimes occurs in marine mammals, just as it does in other mammals (Ketten et al., 1997). Such changes are presumably referable to specific events that contribute to the overall decline, but the effects are so universal that it can be considered inevitable or normal that a given proportion of individuals within certain age classes will show predictable patterns of hearing loss. In the case of mammalian presbycusis, including the dolphins studied thus far, the loss of hearing occurs in the higher frequencies and more so in males than females. In such cases, behavioral responses can change over time as a result of the animal's declining ability to hear. Both the psychological changes that accompany an animal's history with a given sound and aging effects can produce vastly different behavioral responses in animals of different age, or in the same animal over time.

All predictions about behavioral response to a given sound must be probabilistic (e.g., animal X has a 40% chance of responding to this stimulus by fleeing). Dose-response models for noise have been developed (ring-billed gulls, Thiessen et al., 1957a,b; crested terns, Brown, 1990), but typically require very large sample sizes, which is a problem for studies of marine mammals.

Methods to reduce observer bias. The interpretation of observational behavioral data is perhaps more vulnerable to subjective biases than in other fields of scientific study. That is, the conclusions that are drawn from an observation are more easily influenced by assumptions the observer holds than in other disciplines where direct measures of physical states are involved, without requiring inferences about inaccessible complex internal processes. Methodological rigor is therefore of great importance in behavioral studies to guard against unintentional subconscious sources of bias in the recording of observational data. Methods to reduce the effects of bias include the use of multiple observers to assess inter-observer variance, blind or

double-blind control procedures to reveal or remove unconscious bias and cueing, and standardized instructions or score sheets to help reduce or at least quantify the contribution of subjective factors to observational behavior data.

LONG TERM EFFECTS

All of the above problems can coalesce when researchers use behavior to assess long-term, cumulative effects of sound. Individuals can be difficult to follow over time, and at the same spatial scale at which they may have been exposed to sound. The resultant behavior may have been affected by psychological processes associated with the animal's experience, innate defensive strategies, motivational state, the immediate environment, or age. Overcoming these difficulties defines the problem that researchers face in making long-term measurements.

Long-term, cumulative effects of anthropogenic sound could be the most important aspects of sound to marine mammal populations. They are also among the most difficult effects to measure. Where the effect of a single sound is so small that it will take a long time and/or a large sample size to measure responses, the question arises whether such a study is the best use of limited resources. Should research, for example, be focused instead on acute exposure to intense sound? As a general principle, sound is not usually considered to be an effective stressor of animals in the laboratory (Gray, 1991).

In marine mammals, acoustic harassment devices alone do not effectively deter all individuals, particularly when they have been exposed several times and when other motivating factors, such as food, are present (Reeves et al., 1996). In addition, the behavioral responses animals make to single, intense sounds, such as turning away or startle response, may be less biologically significant than responses that result from a lifetime of exposure. The emphasis of future research should be on responses that are biologically significant, and these responses may be biologically significant only upon cumulative repetition over relatively long periods of time. One of the great challenges to developing a behavioral metric of acoustic exposure will be to design short term, acute experiments that provide a basis for estimating what the long-term effects will be.

Sounds typically used in laboratory studies as "stressors" tend to be "meaningless"; that is, they are usually broadband white or pink noise without any particular significance to the recipient. However, anthropogenic sounds introduced into the marine environment may often convey very specific information about the sound source. To use an example from terrestrial noise studies, the sound of a human voice or a snowmobile in a national park can clear out sheep or deer within hearing range (Bowles, 1994). Therefore Dr. Bowles recommended an emphasis on identifying and preferentially studying the effects from anthropogenic underwater noises that tend to elicit the strongest behavioral responses, or which act as effective maskers of communications and environmental sensing. [This paragraph was added in the final draft, based on comments received from Dr. Bowles].

HOW DO ANIMALS USE SOUND AND HOW DO THEY REACT TO NATURAL SOUNDS?

At present, the questions of how animals use sound and how they react to sound cannot be answered definitively due to a lack of data. New approaches to the measurement of marine mammal behavior in the presence of sound are needed. Studies to date have emphasized the physiology, morphology, and behavior of hearing. Another promising approach is the physiology of stress. Most field assays use immediate and measurable responses to a noise, such as physical movements away from or toward the source, without regard to whether such movements impact biological fitness. Making the link to fitness allows the data to be related to relevant population biological constructs such as adaptation, reproductive success, age-specific fecundity and mortality, etc. Ontogenetic (development of responses within an animal's lifetime) and phylogenetic (comparison of responses among taxa that differ in genetic relatedness) approaches to studying noise impact are less common than desired. The ontogenetic approach has potential, given the likely importance of different forms of learning for many animals, such as habituation and sensitization. The phylogenetic approach also has potential in that groups of species, because of their evolutionary history, could be predisposed to react in a particular manner to sounds with particular physical characteristics. Another approach to linking behavioral effects with biological significance is through the use of energetic measurements. This subject is explored in greater detail below in the Section [Recommendations on General Guidelines: How to use, and not use Behavior in Measuring Response to Sound. (Changes in Vocal Behavior)].

COMMUNICATION

Interference with acoustic communication is often mentioned as a negative aspect of sound. To assess the potential for interference with communication, information is needed on what the animal is communicating about (how much and what part of a sound is the message?) and who the potential receivers are (conspecifics within a few hundred yards, or many kilometers away?). Data describing acoustic repertoires and behavioral contexts exist for *some* species and should be incorporated into impact studies. However, baseline data are still needed for most species.

Unambiguous advice beyond this primary level is difficult because of the complexity of the subject. For example, it is common to think of signals as containing a "package" of information that is decoded by the receiver to result in a signal's "meaning". Often, however, as in tonic signaling, the signal is repeated over and over. In these cases, the signal itself is meaningless. Instead, how it changes (e.g., repetition rate, temporal patterns, etc.) is the important factor. Another common misunderstanding is that signals, such as a vocalization, carry one meaning. On the contrary, signals may carry multiple meanings including identity (e.g., species, group dialect, individual), location, intention (e.g., aggression, submission, departure), and state (e.g., reproductive, nutritional). Most animal communication differs from human speech in the degree of referentiality, that is, an utterance referring to a particular object. Referentiality appears to be relatively uncommon in animals, although it has been shown for a few species. In humans, an individual sound often has a highly specific meaning, the understanding of which may be masked by small amounts of noise. Although animal communication appears to be more general in nature than for humans, it does not follow that communication in animals is less likely to be masked, and if masked is less likely to have a significant impact on an animal's fitness. The impact of blocking a signal will be a function of the importance of that particular communication. The biological significance of noise

interference must be evaluated in the context of its effect on functional communication or echolocation. More research should focus on the ways in which animals can vary the acoustical properties of their calls to circumvent the interfering effects of noise.

It is often useful to consider communication to be one part of the repertoire by which the animal regulates its behavior. The relationship between blocking a particular aspect of communication and an animal's homeostasis, and ultimately an animal's fitness, needs to be investigated.

Animals do not use sound to communicate in isolation from other sources of information. Sounds from a particular source could become associated with odors, visual signals, or tactile cues through association. This is referred to as cross-modal learning. A field of psychological investigation called equivalence theory investigates the ways animals group disparate stimuli into equivalence classes (Schusterman, 1998). Any stimulus in that class can be used as a reference to all stimuli. Therefore, if sound masks one of the stimuli in a class, other cues from that class (odor, vision, and tactile cues) can substitute. The result is that depriving an animal of a sound might not deprive it of responding as if the sound were there. However, in most marine mammals acoustic communication is the modality most likely to be used because of the physical properties of water (it conducts sound better than air, but conducts light and odor cues poorly).

Uses of sound for environmental sensing. One of the most noted features of marine mammal biology is the well-developed use of active acoustics (sonar) to "image" their environment. This ability of dolphins and many related species of odontocetes has been well documented by (Au, 1993). We will not discuss this in detail here, except to note that the relative importance of this sensory ability, while great, is often exaggerated in such popularized expressions as "a deaf whale is a dead whale". Anecdotal evidence of dolphins that rarely or never emitted echolocation signals is being joined with a growing body of scientific data, suggesting that older male dolphins can lose hearing in the upper frequency band (presbycusis), but still adjust echolocation signals and maintain nominal performance on basic echolocation tasks in a laboratory setting (Ketten et al., 1997).

Furthermore, active sonar abilities of any level have not yet been conclusively demonstrated for a number of marine mammal taxa, including pinnipeds and the baleen whales, despite considerable effort to find such abilities, at least in pinnipeds (Schusterman, 1981; Wartzok et al., 1984). Therefore, discussions of low frequency sound interfering with the "echolocation abilities" of large whales are premature, at best.

RESPONSES TO NATURAL SOUNDS

To assess the importance or significance of an animal's response to anthropogenic sound it is important to learn more about how they respond to natural sounds. For example, how do mammals respond to earthquakes, rain, thunder and lightning, glaciers calving or ice cracking, snapping shrimp or other species of marine mammals. These sounds have been present in the marine environment over geological time spans and animals are apparently adapted to cope with such natural noise sources. Wenz's (1962) graphic representation of loudness versus frequency for a variety of noise sources demonstrated that natural noise sources could be a significant source of the nondirectional acoustic background across the frequency range used by many

marine mammals. The study of animal behavior in the presence of such natural sound could indicate how they use or respond to anthropogenic sounds. For example, do animals use the sound of surf, snapping shrimp or croakers (Pisces: Sciaenidae) to guide their migratory pathway? It would be equally useful to study how animals deal with natural masking noise, such as rain or high wind and waves. It is likely that they evolved mechanisms to deal with such masking, and that these mechanisms also serve them when dealing with potentially masking anthropogenic sounds.

Data from terrestrial animals indicate that sound may be a particularly significant source of information about predators and similar dangers. Bowles et al. (1996) found that kit foxes listen preferentially for predator noise in the presence of masking sounds even when sounds associated with food were available. For most marine mammals, killer whales are the major, or only, predator other than humans. For that reason killer whale sounds have been employed in a number of playback studies synopsized in (Richardson et al., 1995). All of the uses of killer whale sounds presumably had the working hypothesis that the recipients would be most sensitive to acoustic features typically associated with killer whale sounds and sensitivities to manmade sounds could thus be measured against a sound that the recipient reacted to very strongly. While a variety of reactions have been obtained similar to what is seen in terrestrial animals; ranging from strong and rapid avoidance to cautious approach, a particular sensitivity to some feature or features of the sounds has not been clearly demonstrated. Anecdotal accounts have suggested that harbor porpoises and elephant seals may show special aversions to broadband clicks similar to killer whale echolocation signals, but these have not yet been followed by more systematic tests.

The role of passive acoustic sensing of prey swimming sounds, or vocal activity has received very little scrutiny. Wartzok et al. (1992) have shown that ice breeding seals can use sensing of ambient acoustics to find openings in the ice, and it is likely that cetaceans which inhabit ice-covered regions are also able to exploit passive, as well as active acoustic sensing (if present) to find breathing holes. Without a more complete understanding of the passive and active use of sound for environmental sensing, as well as communication, we are limited in our ability to assess the potential impact from anthropogenic noise which might reduce an animal's hearing abilities or mask information carrying signals from conspecifics or other sound sources in the environment.

USE OF SIGNAL PROCESSING THEORY TO HYPOTHESIZE ABOUT POTENTIAL SENSORY OR COMMUNICATIVE FUNCTIONS OF VOCALIZATIONS

The acoustic properties of sounds that animals use to communicate provide some clues as to how they are used. For example, sounds with significant bandwidth are less sensitive to multipath fluctuations than are narrowband sounds, and therefore are more likely to be heard by a nearby animal in the presence of strong multipath or noise. This may partly explain why most animals produce sounds having a significant bandwidth. (It should also be considered when deciding whether to use narrowband signals for measuring animal hearing responses, and whether broadband anthropogenic noise is more harmful than narrowband noise). An additional or alternative reason for the use of broadband signals is that the broader the band the better the time (and hence range) resolution. In addition, a broadband signal can communicate more information than a narrowband signal of equal duration. Broadband signals are relatively

insensitive to Doppler shifts, and hence may sometimes be preferred to Doppler-sensitive (narrowband) vocalizations for communications when relative motion is a possible cause of signal distortion. Similarly, clues to acoustic behavior may occur in other attributes of the animal's vocalizations, including its spectral, temporal, and spatial properties.

WHAT CAN BE LEARNED FROM RELATED STUDIES OF NOISE EFFECTS ON TERRESTRIAL ECOSYSTEMS?

THE U.S. AIR FORCE'S NSBIT (NOISE AND SONIC BOOM IMPACT TECHNOLOGY) PROGRAM

The U.S. Air Force's NSBIT (Noise and Sonic Boom Impact Technology) program developed dose-response models that relate aircraft overflight noise to animal responses. It also developed models that predict the long-term (energetic, reproductive) consequences of these responses. The program amalgamated the work of physiologists and behavioral researchers. First approximations of dose-response curves were developed for some groups of animals (domestic poultry and livestock, caribou). For ungulates, the team gathered data on distribution, physiology, and nutrition, and coupled these with real-world responses to sound, such as energy expenditure while on migration. Flight response was used as a variable for domestic animals that may accidentally strike barriers in small enclosures as a result of exposure. Flight responses could not be elicited from wild animals, making the task of creating dose-response models for short-term responses impossible, and long-term effects could not be detected. The program used a graded approach, consisting sequentially of 1) laboratory studies using artificial sound, 2) field environments using penned animals, 3) field experiments using very large pens (an entire mountain), 4) free-ranging animals.

The format of the NSBIT program could provide a valuable model for the study of wild marine mammals, and it has produced some general principles that may apply. First, the animal coping strategies were excellent, so it was difficult to elicit potentially hazardous responses using an intermittent source like aircraft noise. Second, the large number of variables that affect behavior (changes in weather, demands of reproduction, conflicts with conspecifics, etc.) made it difficult to measure population-level effects on free-ranging animals. Third, hundreds of animals must be carefully studied before and after exposure to reveal the subtle effects of even high levels of noise. Fourth, physiological responses were difficult to measure appropriately; those that were easiest to measure provided the least useful information about the long-term potential for significant biological impact. The conclusion of the NSBIT program was that future studies should concentrate on effects during the most vulnerable periods of animal life histories, e.g., during the nest establishment period for birds, or during mating and early pregnancy for mammals, nursing, molting, etc

WHAT RESEARCH FORMATS, INSTRUMENTS, AND METHODS ARE AVAILABLE FOR FUTURE RESEARCH?

ACOUSTIC DATALOGGERS

A new acoustic data logger has been built that records and measures sounds received by free-ranging mammals. Built by P. Tyack, B. Le Boeuf, D. Costa, and W. Burgess, this unit stores nearly 1 Gbyte of data on a hard drive. It records vocalizations, heart and breath sounds, as well as ambient, biological, and anthropogenic noise, and is not as affected by flow noise as was originally expected. The instrument's present weight prevents it from being used on animals smaller than elephant seals. However, modifications are under way that may overcome this drawback. The instrument has the potential of being used like a noise dosimeter for humans (daily measures of noise level against time are used to calculate a Leq value that is compared to OSHA standards). It can also evaluate many different behavioral responses and permits noise exposure to be coupled with response.

VIDEO SYSTEMS

At least three efforts, one by Greg Marshall of the National Geographic Society, one by Randall Davis at Texas A&M University at Galveston, and one by the NMFS National Marine Mammal Laboratory in Seattle, are being made to develop underwater video recorders for attachment to marine mammals. Such systems can add to our ability to interpret data from diving and velocity recorders, as well as visual observations from the surface. Like the acoustic data logger mentioned above, video recorders should be reduced in size for use on smaller species. At present such systems can only be used for limited periods of time due to weight and hydrodynamic drag effects on the animal and limitations to data storage, attachment, battery power and other hardware features.

USING BEHAVIOR TO ASSESS EFFECTS OF NOISE

What behavior should be used to measure responses to sound? What behavior should be considered "biologically significant"? Where should research be heading? To begin this discussion, some terms that appear later in the text will be defined.

IMPORTANT TERMS AND DEFINITIONS

Sensitization- at the behavioral level, sensitization refers to the process by which the presentation of one stimulus increases the likelihood of a response to subsequent presentations of the same stimulus. At the cellular level, sensitization is defined in terms of changes in neuron firing (see end note 2).

Habituation- a simple form of learning that results in reduced responses to repeated presentation of a stimulus. It differs from simple failures of nerves or muscles to respond (adaptation, accommodation or fatigue). Habituation allows the organism to ignore irrelevant input. (See end note 2).

Behavioral adaptation- adjustment to circumstances; accommodation; acquisition of behaviors that make an organism better suited to its current environment or way of life. (See end note 2).

Aversive stimulus- a stimulus that an animal will attempt to avoid or escape from. Aversion is the act of avoiding some painful or unpleasant experience or situation.

Avoidance- moving away from a sound source. Avoidance is often used as a metric of aversion, but the two terms are not equivalent: aversive stimuli may not elicit avoidance (for a variety of reasons), or elicit varying degrees of avoidance due to species, individual or circumstantial differences.

Biological fitness- relative reproductive success; the comparative abilities of individuals to transmit their genes to the next reproductively fertile generation. One result of using fitness as a metric is that mortality among post-reproductive age classes or juveniles might be weighted differently than mortality among adult females, for example.

Regulation (homeostasis)- behaviors that cause an animal to remain within, or to return to, a normal physiological state. Failure to regulate results in physiological and behavioral stress. Animals use various coping strategies to regulate themselves (Toates, 1995). (see note 3).

Cognition- the process by which animals compare various internal representations of the world (both actual and expected from experience) and use the comparison as a basis for predicting future events and taking action (example, freezing at sounds that resemble a predator call, etc.).

Biologically significant behavior- behavior that affects long-term survival and/or fitness, such as successful predator avoidance, nursing, foraging, or mating. An example of biologically significant behavior would be avoidance of critical habitat where foraging occurs. Most of the behavior used to infer a "take" in the sense of the Marine Mammal Protection Act, are transitory, short-term reactions that could be irrelevant to long-term fitness. An example of a short-term reaction that is probably irrelevant to fitness is making a minor deviation in migration path to avoid a sound source (e.g., Malme et al., 1983).

Startle- a reflex in which defensive behaviors (blinking, jumping backward, change in heart rate, release of catecholamines, etc.) occur shortly after danger. It occurs before an animal can evaluate the stimulus; that is, before any cognitive process is engaged. It differs from starting (an abrupt intention to run or fly) in that it occurs at a shorter interval from the stimulus.

BIOLOGICAL SIGNIFICANCE

A central question about animal reactions to anthropogenic noise is whether its negative impacts are biologically significant, as defined above. It is relatively easy to show that an animal reacts to a sound, but difficult to show that this reaction correlates with reduced fitness (fitness includes, but is not limited to, measures of survival because animals must survive to be able to reproduce). Unfortunately, most of the reactions to noise that are easily observable are immediate or less extreme responses, such as temporary avoidance behavior, that have little effect on predator avoidance, feeding, nursing, or reproduction (hence of little biological significance). Flight-or-fight responses are also transitory but can be biologically significant to the extent that the animal's survival is threatened in a given situation. It would be desirable to develop assays that are better indicators of fitness than are presently available, and apply these assays to animals over long periods of time--periods approaching the lifetime of animals. Without such indicators it will be virtually impossible to objectively quantify the impacts of noise. A potential problem exists in that the scientific view of biologically significant behavior focuses on sustainability of populations (e.g., numbers of animals surviving to a given age and

their age-specific reproductive success) whereas the public perception, and the prevailing legal interpretation of the MMPA, focus on the well-being of individuals.

Decisions about which sounds to measure should consider the threshold at which certain behaviors are likely to occur. All defensive behaviors have a threshold for expression, that is, it takes a certain intensity of stimulus to elicit each defensive behavior. In general, the greater the cost of the behavior (in terms of risk or energy required) the higher the threshold of response. Although great emphasis has been given to "startle response" as it relates to sound exposure, true startle response is actually only the first in a series of responses that occurs immediately after a sound stimulus. Startle can be followed by an orienting response, which is followed by defensive responses (fleeing etc.). After the initial set of responses, in what might be called the medium term, the animal typically undergoes one or more cycles of approach/avoidance, apparently investigating and then fleeing from the object, and eventually habituating to it. Aversion could develop after this period. In the long term, the animal learns about the stimulus through this iterative process. An animal's responses serve to help the animal maintain homeostasis. For that reason, avoidance responses to a sound stimulus should not necessarily be interpreted as "bad" or something that humans should automatically prevent: they may be part of a coping strategy. Rather, the investigation of a sound and the resulting learning should demonstrate the way that animals adapt to a potentially negative stimulus. The temporal sequence of behavioral responses for marine mammals exposed to unfamiliar objects or sounds has not been investigated often (but see Bowles et al., 1997; Anderson et al., 1998).

(This section was not discussed in the session but is included by agreement of the Behavioral Committee). The speed with which habituation (to transients) occurs depends on the level of the exposure. At low stimulus levels, the decline in responses is almost exponential. But as the stimulus level increases, the decline in responses is slower to develop and the animal does not return to the original baseline response. At very high sound levels (> 90 dB RMS re 20 μPa) almost no decline occurs, and in fact some sensitization may occur.

When measuring an animal's responses to a sound the effort should be to look for a distribution of possible responses, not merely a listing of specific types. Distributions tend to suggest which responses of many are the most significant. To interpret an animal's behavioral response to a sound it is most important to know the behavioral repertoire of the species by sex and age, including the repertoire of sounds used in communication. Standard research methods exist for compiling such repertoires (called ethograms, e.g., Eibl-Eisbsfeldt, 1970).

The negative responses animals make to sound have not been well documented. Therefore it is important to design research projects to reveal a broad range of possible responses. For example, responses might produce traumatic injuries from accidents during flight or aggressive interactions brought about by noise-induced irritability, abandonment or poor parenting of young, disturbance of thermoregulatory behavior, lack of adequate rest, avoidance of critical habitat, attention diverted from potential predators, movements that attract predators, or stress-induced inactivity.

WHAT ASPECTS OF BEHAVIOR ARE LEAST KNOWN?

Researchers tend to be well informed about the physical properties of noise that affects humans and animals because these properties can be measured. These properties include sound level, duration, onset or rise/fall time, duty cycle (percent time on), repetition rate (sounds per unit time), or modulation rate (change in either frequency or amplitude). Other aspects of noise that are not as easily quantified, especially those that involve how sounds are internally processed or which sounds have important ecological or social consequences, are less well known. This section lists some key areas about which researchers presently know the least.

Perception, or the psychological interpretation of sound by the animal is a major factor in predicting long-term responses to sound (see note 3). Perception is considered to be the internal "context" in which an animal receives a sound. It is as important as the "external" context referred to in the introduction (feeding, mating, migrating or other behavioral states). Some poorly known psychological factors about sounds are:

Predictability--the extent to which a sound deviates from what the animal expects in its environment.
Control--whether the animal has an effective coping strategy available, such as avoiding or turning off the sound.
Interference--whether the sound interferes with a significant activity of the animal. For example, sounds that interfere with speech in humans are annoying to such an extent that interference with speech is used in OSHA guidelines for excessive noise. Sounds that interfere with echolocation, navigation or communication could be especially annoying or physiologically stressful to some animals.
Meaning--whether a sound causes the animal to recall an unpleasant experience, resembles the call of a predator or competitor, or triggers innate protective mechanisms.
Perceived proximity--nearby sounds can be perceived to present more danger because of their proximity than more distant sounds, irrespective of sound level.

If the behavioral effects of sound are observed in an ecologically valid setting with a large enough sample, and if the focus is on biologically significant responses as defined above, then these intervening variables may not matter much. They are defined here mainly because their importance is as yet unknown. Some of these factors, such as predictability, control and proximity, can be used as conditions for experimental playback. Others, like interference, can be measured directly in studies of behavioral disruption.

Classes of behavioral response. Some behaviors are more useful than others in measuring the potential for long-term impacts of sound. Interference with an important biological function, such as echolocation, is probably most important. Unpleasant associations, such as mentioned under "meaning" above are also important. Some sounds have physical properties (rapid onset or specific spectral/temporal characteristics) that are innately annoying or aversive due to perceptual processes in the listener. These properties probably differ among species and/or among individuals within a species, are largely unknown, and may differ in air and in water. Identifying these patterns for various marine mammal species should have high priority for future research. *Habituation* as a class of response should receive more attention.

Long-term, cumulative responses to sound. In wild terrestrial mammals only a few human-made stimuli are intense enough at the receiver to cause a meaningful change in the animal's health or well-being. The same is probably true under water, except for some explosions and some kinds of sonar pulses. Normally, damage from human-made noise results from cumulative exposure over significant portions of an animal's life, not one or a few isolated events.

Complex, higher order cognitive functions, including cross-modal learning, expectation, and goal-orientation. We know little about how animals "think" about noise in their environment, how they learn and remember the consequences of noise, or how they equate information gained from the auditory sense to information gained from the other senses.

Cascading ecosystem effects of sound (what are the effects of sound on the forage species on which marine mammals depend?). Few studies have been done on the effects of sound on fish eggs and larvae for example. Noise-related depletions of forage fish stocks could have a significant ripple effect on members of higher trophic levels (e.g., toothed whales, large sharks, tunas and billfishes). Conversely, noise that keeps predators out of an area may result in dramatic alterations in the abundance of certain prey species that would not otherwise dominate the ecosystem.

HOW DO DIFFERENT KINDS OF SOUNDS AFFECT ANIMALS?

Animals are exposed to a wide range of sounds in the sea, from pingers on fishing nets to acoustic harassment devices to shipping and other high-energy noise. Researchers tend to distinguish behavioral responses to two different types of noise; impulsive vs. continuous (see Richardson et al., 1995 for more detail).

How do they react? In recent experiments, seals and some land vertebrates (tortoises) were subjected to simulated sonic booms (Bowles, 1994). The response varied by species. Pinnipeds reacted in much the same way that terrestrial animals make an orienting response, by looking, holding their breath, and slowing their heartbeats. Also, the interval from the noise onset to the response was slower than in a typical reflex. One interpretation of these results is that they represent surprise (deviation from expectation) more than they do a startle reflex.

Cost-benefit considerations in the animal's response. The responses of animals to noise are generally elements of their normal repertoire, typically their defensive repertoire, as in terrestrial animals. It seems likely that the rules that govern risky defensive behavior are similar to those worked out for terrestrial animals. Animals must weigh the cost of exposure to noise against the benefit of remaining near it. For example, manatees in Florida congregate near power plants during cold weather to benefit from warm water discharge but at the cost of exposure to underwater noise from pumps and turbines. Apparently their requirement to remain warm has a higher priority than to remain in quieter, but colder water.

What does their reaction mean? Many studies of responses to human sounds, especially of cetacean behavior, have focused on the immediate response to sound. Measures typically include change in swimming direction, transitions from being at the surface to diving, and vocalization rates. While these changes are relatively easy to measure, our ability to interpret

what these responses mean, either in the short-or long-term, is very difficult. Attempting to investigate behaviors that are of clearer biological importance should be a priority. A good example is the recent study of the effects of sonic booms from the Concorde on the reproductive behavior of grey seals (Perry et al., 1998). The Concorde passes three times per day within 15 miles of Sable Island, a major grey seal breeding ground. Researchers quantified aspects of reproductive behavior immediately prior to a boom, immediately after a boom, and during a period before and after a random point in time to serve as a control. Although the researchers measured biologically significant behavior (see end note 5), no evidence was found of a substantial negative impact (no difference between control conditions and periods following the sonic booms for adult males, adult females and pups). While it appears that seals have adapted to 20 years of flights by the Concorde, the possibility that the population as a whole has suffered permanent hearing loss cannot be eliminated until appropriate hearing tests are conducted. However, judging from the lack of response by newborn and young pups, this possibility seems remote. If their hearing has been impaired, it has not affected reproduction: the grey seal breeding population at Sable Island has been growing at its theoretical maximum of about 13% per year for the past two decades.

RECOMMENDATIONS ON GENERAL GUIDELINES: HOW TO USE, AND NOT USE BEHAVIOR IN MEASURING RESPONSE TO SOUND.

ABSENCE OF VOCALIZATION (SILENCING IN RESPONSE TO SOUND)

Silence could signify that the animal is listening and choosing to remain quiet in response to the sound, as opposed to signifying that the animal has left the area, or lost the ability to maintain effective vocal communication. It is particularly important to measure the recovery time to a normal call rate from the onset of the silencing signal. While cessation of vocalization, even temporarily, is a readily obtained and potentially useful measure of response to sound, by itself it is merely indicative of an attentional response. Without knowledge of the biological significance of the vocalization, and additional measures of effects during and following cessation of vocalization, the absence of vocalization alone does not constitute a biologically significant event. While the animal could cease vocalizing to listen (attention), to reduce chances of being heard by a potential threat (predator, dominant conspecific, etc.), or to wait until interference with communication ceases, the biological significance of a cessation in vocal activity may be measurable in the percentage of calling individuals that cease calling following the onset of the noise stimulus, the persistence of the cessation following onset of the noise stimulus, and persistence of the cessation behavior with successive exposures to the noise source (habituation/sensitization issues).

CHANGE IN VOCAL BEHAVIOR

Animals may not cease vocalizing, but may change the frequency of calls, change the interval between calls, increase the loudness of their own calls or change other features of the call. The cost of making such changes may not be easy to assess. As discussed in the paragraph below, changing vocal behavior in the presence of natural noise is well known, though not sufficiently well studied to provide us with clear metrics for evaluating the likelihood of a change or the cost of such changes in all cases. In some cases physiological constraints will

make it impossible or energetically costly to change sound output. In other cases the animal may be physically capable of changing sound output, but can't convey the same information in a changed signal, e.g., vocal indicators of individual identity in social interactions.

The editors are grateful to Dr. Bowles for contributing the following review of energetic costs of acoustic output by animals. While this topic was not discussed in great depth during the workshop session itself, an energetic measure associated with the behavioral response is clearly useful to assessing the potential biological costs of interference from anthropogenic noise. Dr. Bowles has done an excellent job of laying out a framework of relationships between energetics and acoustic behavior, and provides an excellent set of references to demonstrate that such relationships can be and have been measured. She recommends Lambrechts (1996) and Bradbury & Vehrencamp (1998) as general background references.

[from Ann Bowles]: Unfortunately, there have been few efforts to determine the cost of altering vocalizations in the presence of masking noise. A wide range of animals modulate call amplitude to compensate for the presence of noise, particularly if it overlaps the band of species-typical vocalizations, e.g., white-lipped frogs (Lopez et al., 1988), zebra finches (Cynx et al., 1998), budgerigars (Manabe et al., 1998), quail (Potash, 1972), humans (the so-called 'Lombard effect'; Egan, 1972; Lane and Tranel, 1971), and macaques (Sinnott et al., 1975). However, the additional cost of compensation has not been measured in any of these species.

For large mammals, many have suggested that the energy required to produce sound is a small proportion of the animal's total energy budget, suggesting that noise masking will not cause significant energetic expenditures. However, this is a hypothesis rather than a proven conclusion (energy expenditure during calling has been difficult to measure in large mammals). Also, there are ways in which a moderate increase in call level could result in other costs. Drawing from studies of insects, anurans, and birds, the possible costs of modifying calls to compensate for additional human-made noise are as follows:

1. **Call production could become too energetically expensive.** In anurans, calling results in a large increase in oxygen consumption above resting rates (up to 20-fold; Bucher et al., 1982; Ryan, 1985; Prestwich et al., 1989; Taigen and Wells, 1985). In small birds, singing can result in a 5-fold increase in oxygen consumption rate (Eberhardt, 1994). Call production is an inefficient process, with power output/energetic cost ratios in the range from 0.5 to 4.0% (Brackenbury, 1979; MacNally and Young, 1981; Ryan, 1985; Prestwich et al., 1989). Evidence that this energy consumption can be limiting:

    - *Call output is limited by available food resources* - food provisioning at low ambient temperatures increases song output in small passerines (Garson and Hunter, 1979; Gottlander, 1987; Reid, 1987).

    - *Call output is limited by other demands on energy reserves.* Birds with high parasite loads have reduced song output (Miller, 1991). Birds with high resting metabolic rates have lower song rates than those with lower resting rates, independent of absolute size (Read and Weary, 1992).

- *Calling could be limited by muscular or neurophysiological fatigue, irrespective of overall bodily reserves.* Whether or not singing in birds is physically or neurophysiologically exhausting remains an unresolved problem. Humans that yell or sing for protracted periods experience exhaustion and vocal strain. Birds experience decrease in percentage of time spent performing song over long periods (days or weeks), suggesting that even efficient song production can eventually tire the singer. Some investigators believe the varied repertoire of birds is, in part, designed to minimize neurophysiological and muscular fatigue by allowing slightly different muscle movements to be used for each successive sound production (Lambrechts 1996, 1988; Lambrechts and Dhondt, 1988; Weary et al., 1991).

- *It is possible that specific substances are depleted at high rate during song, rather than overall energy stores, and it is the exhaustion of these limiting substances that causes individuals to cease calling.* For example, although glycogen represents only 25% of the energy reserves of calling *Hyla versicolor* males, vs. 75% from fat, glycogen was depleted relatively faster by long calls, which are emitted in a small proportion even though they are more attractive to females (Wells and Taigen, 1986).

2. **Increasing call level or altering call frequency may require a disproportionately large increase in effort.** The human larynx functions most efficiently at normal speaking levels and frequencies (Zemlin, 1988). Similar optimization is thought to occur in birds (Lambrecht, 1996). An increase in loudness or a deviation from the normal 'vocal register' (normal fundamental frequency) in humans greatly increases the effort required to produce sound because the physical structures of the vocal tract are operating outside their physically-optimized 'natural' range. It can also cause injury to the vocal folds.

3. **Noise masking can increase or alter conspicuousness.** It is well known that vocalizations can increase the probability of attack by predators or parasites (Ryan et al., 1982; Cade, 1979; Yasukawa, 1989). In the presence of a noise masker, the level of sound required for detection is relatively higher. However, once detection occurs, recruitment of loudness is much more rapid at high signal levels than it is at moderate signal levels. This means that a loudly calling animal could be proportionately more detectable. In addition, self-made noise could reduce the chances of detecting a predator.

4. **Females of many species prefer males that produce more intense sounds. In addition, a caller's active space may be reduced greatly by a small increase in noise.** Noise masking could therefore affect mating success.

[end special section by Bowles on costs of changing vocal output]

Measure vocalizations under a wide variety of natural conditions if the goal is to understand the importance of vocal changes in the presence of other sound. A change in vocalization in response to sound should not necessarily be interpreted as "bad" because such changes may relate to overcoming masking, or may be part of a coping strategy for both anthropogenic and natural masking. For example, false killer whales produce whistles with higher frequency and longer duration (Nester et al., 1998), and beluga whales change the peak

frequency and amplitude of echolocation clicks (Au et al., 1985) under conditions of higher ambient noise level from natural sources (e.g., snapping shrimp). Killer whales will change the frequency of their whistles depending on the presence or absence of leopard seals that use a particular part of the sound spectrum available to killer whales (Mossbridge and Thomas, 1998). Also, difference in calls in different parts of the species' range may not imply genetic differences as much as differences in the physical environment. For example, see Dahlheim et al. (1984) on the variation in gray whale calls related to changing ambient noise levels in breeding lagoons.

INCORPORATE APPROPRIATE CONTROL PROCEDURES INTO PROTOCOLS IN THE FIELD

Simply measuring a change in behavior following a sound is not sufficient. Behavioral states have a natural rate of change against which a response to a sound must be compared. Well-controlled data collection procedures are needed to separate noise induced effects from observed changes in behavior that merely coincide with a given acoustic event.

ATTEMPT TO MEASURE BEHAVIORS THAT HAVE CLEAR BIOLOGICAL SIGNIFICANCE

For example, behaviors associated with nursing, foraging, mating, migrating, are most likely to have an impact on survival and reproductive success. Behaviors that clearly signify fear or aversion are also more useful than behaviors with ambiguous significance (e.g., alert behaviors or minor changes in swim speed or direction). Whenever possible, link behavioral measures with physiological measures such as mass changes that indicate reduced foraging efficiency, or heart rate or other measures of physiological stress, such as hormone titres or immune system effects.

SOUND FIELD MEASUREMENT

When measuring a behavioral response it is important to have good estimates of the sound field properties at the animal's location. At least one reviewer of earlier drafts of this section considered this the "number one" measurement to make in any field behavioral study because of its importance in determining the actual noise exposure associated with observed responses. These data can be obtained by monitoring the sound with receivers on or near the animal. Alternatively, the source and propagation characteristics can be estimated using models and/or extrapolated measurements. For the latter case it is important to know the ocean environment and time-dependent locations of both source and animal. Such information permits tests of the hypothesis that animals selectively avoid noise by spending more time at depths and locations where sound is more highly attenuated. In coastal areas, the nature of underwater acoustic propagation may allow animals to reduce their noise exposure greatly by moving only minimally vertically or horizontally.

CONCLUSION

It is important in future research to move away from the kind of descriptive research that has characterized the past, and move toward controlled laboratory studies and naturalistic,

controlled field studies to the greatest extent possible (given that some species do not lend themselves to laboratory measurement). These new studies should examine behavior that has some biological relevance and is ecologically valid. They should be designed to produce large sample sizes, and should test specific hypotheses. Additionally, they should develop links between behavioral or physiological responses that are easily measured and effects that are biologically significant. Finally, there should be continued efforts to develop new technology in this field. The driving force for this development should be enhancing our understanding of biologically significant behavior (that is, reproductive, foraging, or mating behavior).

END NOTES

1. "Perception" as used here consists of perception *per se* (what features of the sound stimulus are received by the hearing apparatus and processed by the CNS), and *meaning*, which is determined by the associations and expectations that the animal has formed about the sound (meaning involves cognitive interpretation).

2. Sensitization and Habituation. (note by R.J. Schusterman contributed after the workshop). "These two processes [sensitization and habituation, ed.] are extremely complex and are considered non-associative learning processes because of the presumed (and to some extent empirically verified) role of central nervous system mechanisms (Davis, 1989; Groves and Thompson, 1970; Kandel, 1979). On the other hand, habituation is not always easy to distinguish from sensory adaptation, which also refers to a decrease in responses, to, for example, sound, light, tactile, pressure, and chemical stimuli. For example, light adaptation refers to bright white light that reduces sensitivity to light. The photochemical and neurological processes relating to light and dark adaptation are well understood in vision. Behaviorally, the animal's sensitivity recovers as it "dark adapts", i.e., receives no light stimulation for a period of time. During this period, threshold is gradually restored to "normal", and is no longer shifted. The same phenomenon occurs with sound, although the neural and chemical basis for hair cell restoration in the cochlea is less well understood. In the case of the auditory system, if an animal is exposed to loud noise, its subsequent responsiveness to an acoustic signal is decreased. If broadband noise is used (depending on the sensation level and the duration of the noise) then when the noise terminates, as in the temporary threshold shift in light sensitivity, there is a temporary threshold shift (TTS) to sound. When the animal is placed in a quiet situation, its "normal" sensitivity is presumably restored. Thus, habituation is a central learning process, while sensory adaptation (as described above) is strictly a sensory channel or peripheral process in which no learning is involved. In terms of noise impacts on behavior, habituation to sound and TTS are very difficult, if not impossible, to disambiguate."

3. Coping strategies. One of the properties of coping is that the animal will continue to cope until its limits are reached, and thereafter it will cope badly. The change from coping to not coping can be fairly abrupt, as can the change from one coping strategy to another.

4. Variables measured included: a) percentage of animals that leave the beaches where females are caring for their young and males are competing for mates; b) the frequency with which

nursing behavior is disrupted; c) the extent to which aggression between males, between females, and between males and females changes; and d) heart rates of individual animals to see if they might be indicative of increased underlying stress.

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MONITORING AND MITIGATION

Team Members:

W. John Richardson, *LGL Ltd., King City, Ont.* (Team Leader)
Raymond C. Cavanagh, *SAIC, McLean, VA*
Christopher W. Clark, *Cornell Univ., Ithaca, NY*
William T. Ellison, *Marine Acoustics Inc., Middletown, RI*
Christopher G. Fox, *NOAA PMEL, Newport, OR*
Robert J. Hofman, *Marine Mammal Commission, Bethesda, MD*
Sue E. Moore, *NMFS-NMML, Seattle, WA*

INTRODUCTION

Section 101(a)(5) of the U.S. Marine Mammal Protection Act (MMPA) directs the Secretaries of Commerce and the Interior to authorize the taking of small numbers of marine mammals incidental to activities other than commercial fishing in U.S. waters when the taking would have a negligible impact on the affected species or stock and certain other conditions are met. One of the conditions is that appropriate monitoring be done to confirm that animals are not taken in ways or numbers not authorized and that the impacts are in fact negligible. Such monitoring can be termed "compliance monitoring". There is also a need to document marine mammal numbers, movements, calls, and other behaviors during research projects on marine mammals in the field. Many of the same observation techniques are suitable both for compliance monitoring and for field research.

Mitigation measures designed to reduce potential impacts on marine mammals are frequently an integral part of monitoring and research projects on marine mammals. One purpose of monitoring is often to implement real-time mitigation procedures, e.g., to shut down a noise source when mammals are detected within some designated radius.

Mitigation often requires a multi-tiered approach to the development of acoustic exposure criteria for species of concern. One type of criterion is a safety radius, designed to protect animals from physical harm. Additional levels of mitigation, often applied at greater distances from the sound source, may be designed to provide additional protection from physical harm or to reduce or avoid unwanted behavioral responses. To meet the mitigation requirements for each of these levels, different monitoring procedures may be needed. Procedures and equipment needed for this monitoring are themselves often in only the first stages of development.

Implementing the mitigation requirements can take several forms depending on the nature of the sound source. This may include restrictions on the locations or times of year when the activity is authorized, source shutdown, reduction in source level, reduction in transmit schedule, change in transmission characteristics (frequency, duration, etc.), or movement of the source away from a specific area.

Limited abilities to monitor marine mammals can substantially affect the effectiveness of mitigation. To introduce some of the problems, W.J. Richardson summarized visual and acoustic monitoring methods used during a recent open-water seismic project in the Alaskan arctic. He emphasized the results pertaining to ringed seals (Harris et al., 1997), although bowhead whales were also a major focus of the work (Richardson [ed.], 1998). Disturbance of small numbers of marine mammals was authorized by Incidental Harassment Authorizations issued for whales and seals by NMFS (NMFS, 1996a,b, 1997) and by Letters of Authorization issued for walruses and polar bears by the U.S. Fish & Wildlife Service. The IHAs required extensive visual and acoustic monitoring programs and various types of mitigation.

During this seismic program, the designated safety (=shutdown) criterion for seals was a received level of 190 dB re 1 μPa_{rms}. Here "rms" refers to average pressure level over the effective pulse duration. The measured 190 dB_{rms} radius was up to 260 m, depending on the airgun configuration in use and other factors (Greene, 1997). The effective source level for horizontal propagation was about 222 dB re 1 μPa_{rms} and 230 dB_{peak}. The latter was well below the nominal peak source level for downward propagation (Greene, 1997).

The detectability of seals in relation to distance from the observers began to decline well inside the safety radius (Harris et al., 1997; Richardson [ed.], 1998). The normal requirement during recent seismic programs has been for one "biologically qualified" observer to be on watch at any given time. However, in this project the sighting rate was notably higher at times with two observers than with one, indicating that many seals were being missed when just one observer was on watch. Visual monitoring at night was largely ineffective even using an image intensifier, and effective acoustical monitoring for seals was not practical. Furthermore, seals did not show sufficiently strong avoidance reactions to keep them outside the designated safety radius around the airgun array. Despite the inability to detect all seals present within the designated safety radius, seals were detected often, requiring 135 shutdowns of the airgun array during one 57-day operating season. That constituted a significant operational disruption.

Subsequent detailed discussions during the Monitoring and Mitigation session addressed many of these issues. Notwithstanding the broader title of the workshop, this session addressed monitoring and mitigation only with respect to marine mammals.

MONITORING

This group's discussions encompassed monitoring techniques suitable for both compliance monitoring and for field research. However, it was recognized that somewhat different monitoring techniques (or combinations of techniques) may be optimal for different purposes. For example, in some studies, one objective is to implement mitigation measures (such as shutdown of potentially harmful human activity) when marine mammals are within a designated "safety radius". In this situation, it is important to use methods that detect a high proportion of the mammals present. However, if the objective is to compare numbers of mammals in one area vs. another (e.g., ensonified vs. control area), it may be sufficient to detect a consistent proportion of the mammals present in both areas even if that proportion is well below 100%.

The discussion of monitoring methods dealt with visual methods, electro-optic and photographic methods, passive acoustics, active sonar, dataloggers and telemetry, and estimation of sound exposure. Particular attention was given to the need for combinations of methods that complement one another.

As an example of this, the LFA SURTASS Scientific Research Program (LFA-SRP) has used a multi-faceted approach integrating several forms of visual observation (aircraft-, shore- and ship-based) along with various methods of acoustical tracking (bottom mounted autonomous systems, shore-based Navy systems, and ship-based towed arrays), as well as depth-logging tagging methods (Clark et al., 1998). This approach served several objectives: (1) The various techniques, singly and jointly, provided a methodology for meeting the various mitigation requirements of the research permit, (2) the resultant data will be used both for analysis of behavioral responses and to update existing databases, and (3) the methodologies themselves will be further tested and refined for use in future similar projects.

The group also discussed the need for long-term studies. In addition, the group felt that, to maximize both productivity and cost-effectiveness, it would sometimes be advantageous to combine the monitoring efforts for various related projects rather than to monitor them in isolation. For similar reasons, there was a widespread opinion that better access to data from previous survey and monitoring projects would help in monitoring long-term effects and in planning mitigation measures.

The following subsections summarize the discussion on each topic. It was not possible within the available time to discuss all topics in detail.

WHAT TO MONITOR, AND WHY?

Dr. R. Hofman summarized the U.S. legal requirements for monitoring. "Taking" of marine mammals is defined under the MMPA to include disturbance ("Level B harassment") as well as injuring, killing or capturing. Taking is prohibited by the MMPA unless a waiver or small take exemption is obtained. Waivers are very rare. Small take exemptions can be of two types: (1) Rulemaking under MMPA §101(a)(5)(A), which may authorize issuance of Letters of Authorization for harassment, injury or even mortality of small numbers of marine mammals by specified human activities over a 5-year period. (2) Incidental Harassment Authorizations under MMPA §101(a)(5)(D), which may authorize harassment but not serious injury or mortality by specified human activities during a 1-year period. The two small-take authorization processes have been used to authorize small takes of marine mammals by various noisy human activities including oil and seismic exploration activities, missile launches, explosive removal of obsolete oil platforms, and ship shock trials.

Under both small-take exemption processes, monitoring may be prescribed to confirm that animals are taken only in the ways and numbers authorized, that the impacts on the affected species or stocks are negligible, and that (in Alaska) there are no unmitigable adverse effects on the availability of the species or stock for taking by Alaskan Natives for subsistence purposes. Monitoring is also important to assess whether required mitigation measures are effective.

Dr. Hofman noted that, to date, monitoring has been project specific and locality specific. He noted that Swartz and Hofman (1991) had assessed the intent and possible means for meeting the monitoring requirements and suggested that it would be reasonable to ask whether this type of project- and locality specific monitoring is the most effective approach. To change this approach, there might be a need to change the MMPA and associated regulations to be able to require broader population-specific monitoring. This might be possible if there were good justification.

VISUAL SURVEYS FROM SHIP, SHORE OR AIRCRAFT

A memo circulated in advance of the meeting identified the following as being potentially worthy of discussion:

speed and altitude standards,

standard monitoring ranges for different species/sizes, correction factors for time spent at surface, visibility, etc.

standards for number of watch standers, rotation schedules,

standards for training of "qualified" observers,

The attendees did not attempt to discuss these topics in sequence, but touched on most of these points in one form or another.

It was noted at the outset that conventional visual monitoring is a two-dimensional technique that is largely limited to detecting mammals during the times when they are at the surface. (Aerial observers often can see large mammals when they are as much as a few meters below the surface.) Some species are at the surface for as little as 10% of the time. Recently, there has been a tendency to use combinations of methods, including visual, acoustic and tagging, to complement one another. The use of multiple techniques was discussed in more detail later in the workshop. One of the benefits of multiple techniques is cross-validation of methods. This provides the potential for improvement in both technique and quality of data. This applies not only to population surveys but also to behavioral response observations.

There is often concern that some visual observations, especially from small craft near the animals, may be confounded by the presence of the craft itself. This is also a concern for aircraft-based observations. The use of coordinated monitoring techniques, including shore-based observations, tagging, and acoustic methods, can help evaluate such concerns.

Visual as well as acoustic survey methods provide information about *relative* numbers of animals present. Absolute numbers can only be estimated if appropriate correction factors are available, although visual methods do provide direct information about the minimum numbers present. In general, correction factors are better developed for visual than for acoustic surveys, but improvements are needed for both types of surveys.

Despite their limitations, visual techniques are the standard methods for many types of surveys and behavioral observations. Visual procedures are relatively well developed as compared with some other methods. However, significant improvements still can and should be made in developing or improving correction factors for missed animals. The probability of sighting marine mammals depends on observer ability and alertness, survey procedures, visibility, sea state, and behavior of the animals, all of which vary. These factors are widely

discussed in the literature. However, for many combinations of species, survey type, and environmental condition, little information is available about the proportion of the animals detected by visual observers.

It is often possible to develop correction factors for missed animals based on data collected during surveys. Useful approaches during routine surveys include double-survey methods, analysis of sighting distances, and analysis of sighting rates vs. environmental conditions and individual observer. However, there are situations when special studies are needed, e.g., behavioral observations and/or tagging to document surfacing/dive cycles.

It was suggested that visual techniques tend to be more applicable in coastal areas, but are difficult and costly far offshore. However, there is a long history of visual surveys both for large whales and for dolphins in offshore areas. Methodologies for ship-based visual surveys in offshore waters are well developed. Attendees were advised that results from a combined visual-acoustic survey in offshore waters of the North Pacific will soon be available, and that this study showed that some species were often detected acoustically when they were not seen (see also "Combinations of Complementary Methods", below).

The merits of consistency in survey procedures vs. adaptability to particular circumstances was discussed briefly. Tradeoffs are inevitable. The stricter the requirement for consistent survey conditions, the lower the proportion of time when surveys can be done and thus the lower the sample size. At the least, there needs to be careful documentation of the conditions under which all surveys were done. This is necessary to allow appropriate data selection, post-stratification, and correction factors.

PHOTOGRAPHIC, ELECTRO-OPTIC, AND REMOTE METHODS

Photo-identification methods can be useful for long-term monitoring of survival, population size, and movements, especially of site-tenacious populations. This can be directly relevant in assessing long-term changes in population status. Long-term effects of human activities are, in general, of more concern than the easier-studied short-term behavioral effects, and photo-identification provides one method for assessing long-term effects. However, ascribing any changes in population status to a particular human activity is difficult.

Photographic re-identifications over the short term can also be useful in assessing whether marine mammals return after being displaced by human activities.

For some species, e.g., pinnipeds that haul out in large groups or cetaceans that congregate in large pods, photographic methods are also important in allowing precise counts. However, correction factors are needed to allow for the proportion of the animals that are on land or at the water's surface and available to be photographed.

Nighttime observations of marine mammals are difficult. There is often a need for nighttime observations, e.g., during censuses of animals migrating past fixed census locations, or when noisy activities are to be shut down when marine mammals are present within some distance. Image intensifiers work well at close range and under some lighting conditions, but have not proven very useful during some recent seismic monitoring/mitigation projects (Arnold,

1996; Harris et al., 1997). Long-wavelength passive infrared sensors can be effective in detecting whale blows (Perryman and Laake, 1995), and are to be used in an imminent seismic monitoring project (NMFS, 1998). Forward-looking infrared (FLIR) sensors may sometimes be useful in detecting seal lairs and polar bear dens under snowdrifts (Kingsley et al., 1990).

Some other types of sensors have been tested or suggested for use in a few situations. Sensors operating in the ultraviolet can also be useful in detecting polar bears and seal pups on white ice (Lavigne and Øritsland, 1974; Lavigne, 1976). Airborne synthetic aperture radar (SAR) can detect whale wakes under some conditions (Radford et al., 1994). SAR works through clouds and at night. An aerosol detector might be useful in detecting whale blows.

Non-conventional platforms for deployment of photographic, video and electro-optic sensors were not discussed. In addition to conventional shore, ship and aerial platforms, blimps, kites, aerostats, and remotely-piloted aircraft have been tried or suggested at various times.

PASSIVE ACOUSTICAL METHODS

Calling whales have been heard on passive sonars for many years, and sometimes (but not always) recognized as such. Detection and tracking by passive acoustical methods is a particularly suitable approach given the fact that many marine mammals are below the surface much of the time, call often, and can be heard over long distances. One result from the recent SOSUS studies of calling whales is that species like blue and fin whales are more vociferous than previously suspected. However, even the more vocal species can be silent at some times, and then they are impossible to detect or track by passive acoustical methods. Also, acoustical monitoring programs can have significant costs, as do visual programs involving ships and/or aerial surveys. Choices often must be made regarding the level of effort to be devoted to acoustical, visual, or other forms of monitoring.

Dr. C. Fox and Dr. C. Clark summarized the usefulness of the U.S. Navy's SOSUS system for acoustical monitoring in deep water. SOSUS is effective for species whose calls contain significant energy at low frequencies. SOSUS has provided good acoustical coverage of the North Atlantic (Nishimura and Conlon, 1993; Clark, 1995) and North Pacific (Moore et al., 1998a,b). However, coverage is now reduced because some arrays and shore facilities have been decommissioned. Advantages of SOSUS include its real-time and beamforming capabilities. With beamforming, the approximate direction of the calling animal from the sensor can be determined. However, SOSUS is costly to operate and maintain. Also, security issues when using the beamforming mode are a complication. However, single-element techniques can also provide excellent seasonal data on calling activity. By monitoring acoustic activity on a widely-spaced network of SOSUS arrays over an extended period, seasonal movement patterns and relative vocal activity in various deep-water areas has been (or can be) documented (e.g., Moore et al., 1998b). The same dataset can be examined at a finer temporal scale to examine individual calls and shorter-term variation in calling.

Dr. Fox also described the usefulness of autonomous underwater recorders to monitor low-frequency calls in deep-water areas over extended periods (up to 6-12 mo). These can be spaced widely for single-sensor operation, or deployed in grids (e.g., 15 km apart) to allow localization (Moore et al., 1998a). These devices can be deployed in areas where there is little or

no SOSUS coverage, or where SOSUS operations have ceased. However, they provide data from a much smaller geographic area as compared with SOSUS. In addition to being useful for economical long-term monitoring, they can be deployed to monitor marine mammal calling activity during a particular project. These recorders can be placed on the bottom or buoyed up to channel depth. In addition to their deep-water applications, they can also be used to monitor whales in shallow water (as demonstrated by Drs. C. Clark and C. Greene). Most workers have used acoustic releases to retrieve their recorders, but Greene retrieves them from shallow water by grappling for a tag line at coordinates determined by D-GPS.

Sonobuoys, either off-the-shelf or modified for particular applications, can also be used (Richardson et al., 1995:38*ff*). Sonobuoys dropped or otherwise deployed near marine mammals have often been used to measure the man-made (and ambient) sounds to which the animals were being exposed (e.g., Richardson et al., 1986, 1990; Bowles et al., 1994). Hand-deployed arrays of modified sonobuoys have been the basis for the acoustic component of the spring bowhead census at Point Barrow (Clark et al., 1986). An array of sonobuoys is planned for deployment as a monitoring tool during the Seawolf ship shock trial (U.S. Navy, 1996). Various procedures have been developed to use data from sparse arrays of sonobuoys and other acoustic sensors to locate and track vocalizing whales. Relatively inexpensive systems that can determine direction to a sound source are available, including DIFAR (Directional low-Frequency Analysis and Recording) sonobuoys. These have occasionally been used in marine mammal studies (e.g., Ljungblad, 1986).

Towed arrays of hydrophones can determine the bearing to a calling mammal (or other source). With a very long array, the location of a vocalizing animal can be determined using nearfield time-of-arrival techniques out to ranges of approximately four times the array aperture. For any type of towed array work, it is important to take account of site-specific sound velocity profile data in order to compensate for local acoustic propagation characteristics. Towed arrays have occasionally been used in marine mammal studies, often in combination with visual surveys (Thomas et al., 1986; Evans, 1994; Spikes and Clark, 1996; Clark and Fristrup, 1998; Clark et al., 1998). Line arrays are becoming less expensive, and the computing power needed to process the data is now widely available. However, it takes new users significant time to learn how to use the array effectively and to implement the software.

In tests to study responses of marine animals to noise, there is also reason to employ arrays with vertical, as well as horizontal, aperture. One reason is the hypothesis that some marine mammals use the vertical arrival structure of the noise to estimate distance to the noise source (D'Spain et al., 1995; Premus and Spiesberger, 1997). Another is the information on sound propagation and depth dependence derivable from vertical directionality.

Procedures for use of passive acoustic methods in marine mammal studies are still evolving. Many approaches are possible, e.g., real-time vs. non-real-time monitoring; with or without localization; fixed, towed or drifting sensors. There is a need to select appropriate approaches for the purpose at hand. General advantages of acoustical methods include the fact that they work during periods with poor visibility (night, high sea state, fog) and in some cases can operate without the need for continuous human monitoring. Passive acoustic methods also

can monitor the natural and man-made sounds to which marine mammals near the hydrophones are exposed.

Acoustic methods have obvious value, but even the species that call frequently can be quiet at certain times. Quieting sometimes occurs when whales are exposed to man-made noise (Watkins and Schevill, 1975; Watkins et al., 1985; Bowles et al., 1994). Also, when the frequencies of man-made noise overlap those of the mammal calls, calls with low received levels can be masked and undetectable. Thus, caution is needed in using call detection rate as an index of mammal numbers or calling activity in the presence and absence of man-made noise. A further complication is that, for most species, we know little about the functions of the calls or the circumstances in which they are made. A better understanding of calling behavior will be very helpful in interpreting the results of acoustical monitoring, and the proportion of the individual mammals that will be detectable acoustically in various situations.

Even without additional information about calling behavior, passive acoustic monitoring can provide data about relative calling activity under different conditions, and about the occurrence, locations and sometimes the movements of those individual animals that call. This can be very valuable in monitoring and mitigation projects as well as for research purposes. However, it cannot be assumed that passive acoustic techniques alone will detect all the mammals that are present.

Several participants emphasized the value of using acoustical methods in combination with other monitoring techniques. These combined approaches can include two acoustical methods (e.g., SOSUS plus autonomous recorders), or one acoustic method plus one or more non-acoustic methods such as ship surveys, aerial surveys, tagging, and photo-identification. Visual methods can provide calibration data including typical group sizes and minimum estimates of the number of animals in the area.

ACTIVE SONAR

Participants briefly discussed the potential use of active sonar systems to detect and monitor marine mammals underwater. In general, the detection of animals by active sonar is controlled by several interrelated factors: source level, frequency, transmitted waveform, target strength, ambient noise, receive array gain, and two-way transmission loss.

High frequency systems will generally yield a higher target strength because of the short wavelength of the sound and relatively higher surface impedance of the animals. It is also easier to generate a high source level with a high frequency system, and the ambient and array gain issues are also better handled. However, high frequency systems are somewhat limited in range because of increased absorption and scattering. Very high frequency systems (>100 kHz) may be the best solution at very close ranges where the issue is detection and mitigation for nearby animals. Low-frequency systems may have some utility at longer ranges (on the order of miles), but in general will not work well closer in.

The signal levels needed to get a high SNR echo with an active system may themselves require mitigation, with baleen whales being the main concern with low frequency systems and odontocetes and perhaps pinnipeds with higher-frequency systems.

The most promising application could be in detecting submerged animals at close range when they are not calling. There have been reports of submerged mammals being detected by high-frequency fish-finding and mine-hunting sonars (e.g., Mullins et al., 1988). Sonar target strengths of various cetaceans have been measured (e.g., Dunn, 1969; Love, 1973; Levenson, 1974). If effective in detecting marine mammals at short-range, active sonar could be important for collision avoidance and other mitigation purposes, given the inability of alternative methods (visual and passive acoustics) to detect silent submerged animals.

Sonar detection of objects floating at the surface is a particular challenge. If the sonar were effective in detecting floating containers and logs as well as marine mammals, this could greatly increase the market for the device, given the hazard that these floating objects pose to vessels. To be effective for detecting mammals and other objects floating at the surface, a very high frequency would be needed. In any case, further consideration would need to be given to the effects of the active sonar signals on nearby mammals.

DATALOGGERS AND TELEMETRY

The NRC Committee on Low-frequency Sound and Marine Mammals (1994) recommended that development of improved tagging techniques was a high priority in order to have better tools for studying acoustic effects. Since then, considerable advances have been made. Time Depth Recorders, VHF and satellite telemetry, and sound-recording tags are providing data that are important in understanding noise effects on marine mammals. The use of a sound-recording tag on northern elephant seals swimming near the ATOC sound transmitter is a particularly notable example; these results were summarized by Dr. P. Tyack in a previous session of the workshop (see also Fletcher et al., 1996; Burgess et al., 1998).

The tagging and telemetry devices themselves are rapidly becoming more and more capable of recording relevant data, but there are still some significant problems. (1) Methods of long-term attachment to animals remain problematic. However, there have been important recent advances in the design and use of tags for short-term attachment. (2) Disturbance associated with deploying tags is a concern, especially for highly endangered species like northern right whales. (2) The failure rate of tags is still undesirably high, as is the cost. To date, the market has not been large enough to support the engineering development required for improved reliability, or to reduce costs through mass production. (3) The very limited amount of information that can be relayed via the ARGOS satellite system is also a severe limitation. It is hoped that this can be overcome as new satellite systems designed for worldwide communication are deployed.

Some attendees indicated that it may be an appropriate time to devote significant funding toward development of improved tagging and telemetry technology. The costs of this may be beyond the capabilities of any one funding agency. If the sound-recording tag mentioned above were developed from the current prototype stage to be an "off-the-shelf" device, there would probably be considerable demand for it. It was pointed out that TDRs were initially prototypes and then specialized research tools, but are now widely used in many research and monitoring studies. The same sequence can be envisioned for sound-recording tags if attachment and self-noise issues can be resolved.

DETERMINING SOUND EXPOSURE

Determining the sound levels to which marine mammals are exposed is critical when evaluating reactions to man-made sounds. It is also important when implementing mitigation procedures that are intended to avoid exposure to sound levels exceeding a specified received level. Measuring received sound level by a sound-recording tag attached to the mammal may become more practical in the future (Fletcher et al., 1996; Burgess et al., 1998). However, more studies are needed to determine the shadowing (at high frequencies) and impedance (at low frequencies) effects of the animal itself on the recorded level. Also, there will be a continuing need to estimate received levels near animals not carrying such a sensor. Even when acoustic tags are used, there will be a need to predict sound exposure before or during experiments, before the data from the acoustic tag can be accessed.

Until recently, underwater sound levels received by marine mammals during most acoustic disturbance studies were estimated based on simple propagation models, with or without calibration of the model by point measurements of received sound levels. In some studies, hydrophones or sonobuoys have been used to measure received sound levels near some of the mammals under observation. However, this is often difficult. Most workers have recognized that, even for a fixed projector source in a stratified ocean, the sound field can exhibit significant fluctuations in time, and may show large changes as functions of receiver depth, range, and azimuth. For a moving source, a broadband source, or a range-varying environment, the dependencies can be compounded.

In testing or interpreting the responses of animals to sound, it is thus important to keep in mind that the field can vary dramatically over short distances at all frequencies. Most of the physical mechanisms are understood. The larger scale variations can usually be estimated with deterministic models to a degree of accuracy consistent with knowledge of the ocean environment and source/receiver geometries. Modern data analysis and modeling techniques can often explain and predict the effect of such mechanisms as focusing at caustics (e.g., convergence zones), topographic blockage, multipath interference (including surface image interference), fronts, and shoaling. However, few marine mammal studies have attempted to take this small-scale horizontal or vertical variation into account in relating disturbance reactions to received sound levels.

The local variations are especially dramatic at low frequencies when the animal is near the surface (Urick, 1983:131). Here the level can drop by as much as 30 dB depending on the frequency of concern and the depth of the animal (Jensen, 1981). In a less extreme case, seismic survey pulses received within 3 m of the surface were confirmed to be several decibels weaker than at 9 m and especially 18 m depth (Greene and Richardson, 1988). This phenomenon is commonly described as the pressure release surface effect or the Lloyd mirror effect.

Some recent impact assessments and disturbance studies have attempted to estimate received sound levels based on sophisticated propagation models such as the parabolic equation or PE model (e.g., ARPA, 1995; Au et al., 1997). Versions of these models have been in use for many years, and their capabilities have improved in recent years. However, much care is still needed in choice and implementation of these models. Accuracy can be further improved by

incorporating measurements of sound velocity profile taken along the propagation path at the time of interest. Standard physical oceanographic databases do not adequately characterize water-column and boundary properties for some areas and problems of interest. When site-specific measurements or extrapolations of key features of the acoustic environment are available, modern propagation models have good capabilities to predict the important properties of the sound field.

Dr. W. Ellison described a further elaboration of this approach, which he calls an *Acoustic Integration Model* (AIM), as applied during the LFA-SRP Phase I research in September-October 1997 involving blue and fin whales off southern California (Clark et al., 1998). This model combines an empirically-validated PE model of sound propagation with information (modeled or measured) about whale movements and diving behavior. The results include the time sequence of estimated received levels, the proportion of time exposed to various levels, and the cumulative acoustic exposure.

During the LFA-SRP Phase I experiments, PE calculations done in advance of the fieldwork provided estimates of anticipated received levels under various scenarios. By modeling the movements and dive profiles of whales relative to the acoustic source, received level as a function of time was predicted for hypothetical whales. This procedure helped to determine what source level should be used in order to expose a whale at a given location to a chosen received level. The dive profile of a blue whale exposed to the LFA sounds was determined using a short-term tagging system developed by D. Croll (Univ. Calif. Santa Cruz). After the experiment, the received level of LFA sounds as a function of time was calculated by the AIM model based on the validated PE model and the measured depth vs. time profile of this whale. From this, the AIM model also calculated the proportion of the time the whale was exposed to various received levels.

Dr. Ellison indicated that, at least during the LFA-SRP Phase I test, the dive profile data were a critical factor in estimating acoustic exposure. Received level sometimes varied drastically as a function of depth in the water column. He recommended that tagging, to document diving behavior, should be a high priority in future acoustic disturbance experiments. In more general terms, when received levels are strongly related to positions of the animal and source (horizontal and/or vertical), estimation of noise exposure will require detailed knowledge of these positions and of the ocean environment between them. Alternatively, direct measurements by an animal-borne acoustic sensor may be feasible in some situations (Fletcher et al., 1996; Burgess et al., 1998).

COMBINATIONS OF COMPLEMENTARY METHODS

All methods for detecting and observing marine mammals have significant limitations. However, different monitoring methods have varying limitations and strengths, and thus can often complement one another when used in combination. The merits of using visual, acoustic and tagging methods in various combinations have been mentioned above. In studies of acoustic effects, the received sound levels also need to be determined. This requires physical acoustic measurements and modeling along with whatever combination of observational methods is used to study the animals.

The combination of visual and acoustic techniques can offer a significant improvement in population assessment efforts. One of the most extensive efforts of this type has been the census of the Bering-Chukchi-Beaufort population of bowhead whales, which is conducted during their spring migration past Point Barrow, Alaska. These studies revealed that use of wholly visual methods (shore-based and aerial) dramatically underestimates the population size (e.g., Clark et al., 1986; Ko et al., 1986; Clark and Ellison, 1989; Raftery et al., 1990; Zeh et al., 1993). To a large degree this discrepancy was a result of severe environmental limitations (ice and frequent fog) for visual studies in the Arctic during spring. Combined acoustic and visual methods (seafloor recorders and aerial surveys) have recently been shown to complement one another in monitoring the autumn migration of bowheads with and without marine seismic exploration (Greene, 1997; Richardson [ed.], 1998).

Several "dual-mode surveys" of baleen whales have been conducted recently combining traditional visual survey methods with passive acoustic methods using towed arrays, sonobuoys, or bottom-mounted sensors (Clark and Fristrup, 1997; Moore et al., 1998a). Results indicate that the acoustic detection rates and ranges for blue and fin whales are greater than the visual detection rates and ranges for these species. The integration of dual-mode visual and acoustic survey data into statistically meaningful results remains a challenge but is expected to offer improvement in survey reliability and confidence limits (Fristrup and Clark, 1997).

The LFA-SRP Phase I experiment employed a particularly extensive set of complementary monitoring methods, as summarized by Dr. C. Clark (see also Clark et al., 1998). Both the source vessel *Cory Chouest* and the observation vessel *Dariabar* used towed arrays of hydrophones to detect calling mammals and determine the bearings to them in real time. The towed array behind *Dariabar* also measured the received level of the LFA sounds for comparison with the results of the PE model running in real time. Four autonomous seafloor recorders ("pop ups") were deployed for 10 days in the area where the whales were expected to concentrate their foraging. These recorders provided non-real-time data on calling rates as detected at four fixed locations in the presence and absence of LFA signals.

Visual observations were conducted from both the source vessel *Cory Chouest* and the observation vessel *Dariabar*, simultaneous with acoustic monitoring from both vessels. Visual observations from the source vessel were needed to implement the shutdown requirements when mammals were detected close to the source. Visual observations from *Dariabar* as she followed "focal" whales provided data on the behavior of whales in the presence and absence of LFA sounds. Short-term photoidentification was used to confirm that the same whales were being observed from one time to another. As mentioned previously, short-term TDR and radio tagging was done to document dive profiles of foraging whales; this was important in determining sound exposure. These dive profile data, in conjunction with an echosounder suitable for plankton surveys, showed that the whales were indeed diving to the depths where their prey was concentrated. Aerial surveys were also conducted to document the distribution and relative numbers of whales in a broad region around the test site.

In the LFA-SRP Phase I experiment, no one method was sufficient to answer questions about the effects of the LFA sounds on whales. Integration of the results from the several observation techniques that were used is expected to allow meaningful interpretation. Fieldwork

involving so many interrelated components was complex to perform, and required compromises among the requirements of the different techniques and investigators. However, the combined approach had much better capabilities to address the key questions than would any one observation method.

The attendees also discussed some opportunities for further coordination of fieldwork, e.g., between physical oceanographers, marine mammalogists conducting visual surveys, and acoustical surveys. The cost of ship time is high, and opportunities for joint use of ship time should be followed up. Some institutions (e.g., Scripps) have procedures for publicizing their future cruise schedules. It could be useful to develop a more systematic mechanism for coordination of ocean science research. Some group would need to be identified to take on this function.

LONG-TERM MONITORING

Long-term effects are generally more difficult to study than are shorter-term effects. However, long-term effects on reproduction and populations are widely acknowledged to be of greatest biological significance. One of the problems is that pre-impact baseline studies often are not done, or are not started early enough to provide adequate baseline data. For example, the autumn migration corridor of bowhead whales through the Alaskan Beaufort Sea has been monitored annually since 1979 (e.g., Moore and Reeves, 1993; Treacy, 1997). However, seismic exploration was already underway by the time the whale surveys began. Without pre-impact data, the long-term effects of industrial activity on the bowhead migration corridor remain controversial (e.g., MMS, 1997).

Time constraints prevented a broad discussion of approaches for monitoring of long-term and cumulative acoustic effects on marine mammals. Richardson et al. (1995:397*ff*) include some discussion of this topic.

One approach that was discussed in some detail was the increasing interest in combining data across projects. Several workshop participants mentioned that they are involved in ongoing efforts to access and combine previously collected marine mammal survey data. These data can be valuable in selecting sites and seasons where marine mammals are either scarce or abundant (depending on the objective). If systematic, these data may also be valuable as baseline data for comparison with post-impact data.

There are problems in using previously collected data. Some researchers may be reluctant to share their original data. However, such reticence seems to be infrequent when the prospective users of the data are well qualified to interpret them, and when procedures to avoid potential misuses of the data are implemented. A more common problem is that the original data are often difficult to access and not well documented. Also, methods used during different surveys are often inconsistent. A further complication in using data collected a decade or more in the past is that population sizes of many species may have changed appreciably. In some cases, there may also have been qualitative changes in distributions.

Even so, previously collected data can, when used carefully, be valuable in identifying "hot spots" where marine mammals have been found to congregate. However, one should not

assume that the absence of sightings means that an area is unimportant unless there is good information about the survey effort in the area.

Workshop participants also mentioned the desirability of incorporating the results of ongoing and future research and monitoring studies into a longer-term framework. Field procedures and data formats should be well documented, and the data should be archived so that they will be accessible to qualified future researchers. Standardization of field procedures and data formats should be encouraged where feasible.

BEYOND PROJECT-SPECIFIC MONITORING

Incidental take exemptions issued under the U.S. MMPA require project-specific monitoring. However, as more and more exemptions are issued and more monitoring projects are done, questions arise as to whether monitoring might be more effective (and less costly) if done in some way that was not so project specific. For example, in areas with many human activities, acoustical monitoring could provide information about marine mammals that are exposed to sounds from a variety of different human activities.

A monitoring approach designed to document overall effects of a variety of noisy human activities might be more successful than present project-specific approaches in evaluating potential long-term and cumulative effects. When mitigation measures are needed, measures appropriate to the individual project should be applied. However, the associated monitoring might be done as part of a broader monitoring effort designed to assess the effects of more than one human activity. This approach might provide a way to handle noise-generating projects that cannot afford to fund project-specific monitoring. At present, some of these projects may fail to go ahead because of concerns about the costs of marine mammal monitoring. Others may go ahead without regulatory review, incidental take exemptions, or monitoring. With a more practical monitoring approach, it might be possible to bring more projects that have the potential to affect marine mammals into the monitoring and mitigation process.

A non-project-specific monitoring approach would differ from the monitoring now required under incidental take exemptions. Changes in the MMPA or related regulations may be necessary to require non-project-specific monitoring. However, these changes might be possible if there were a good rationale.

It may be appropriate to recognize a distinction between

1. a minimum level of project-specific compliance monitoring needed to confirm that each project satisfies the incidental take requirements, and
2. research designed to evaluate impacts; this would probably be done over a longer time and would be less closely tied to specific noisy human activities at sea.

Both types of monitoring, but especially type (2), should be based on hypothesis testing. During type (1) work, it may be important to detect a high proportion of the mammals present near the noise source. During type (2) work, methods that show relative but not absolute numbers may be sufficient for many purposes.

Some of the concepts of Adaptive Resource Management (ARM) may be applicable in this field. ARM is a general approach for gaining knowledge about complex environmental problems through an iterative, hypothesis-testing approach to management, regulation and monitoring (Walters, 1986; Lancia et al., 1993, 1996).

MITIGATION

Mitigation measures designed to reduce acoustic or other human impacts on marine mammals are often required by research permits, incidental take exemptions, or the environmental protection policies of operators or regulators. When a planned or ongoing human activity has significant impacts on marine mammals, effective, practical mitigation measures should be incorporated. Several categories of mitigation measures are often used to minimize noise effects on marine mammals. These can include appropriate seasonal and hourly timing, routing and positioning, equipment design, shutdown when mammals are nearby, and other operational procedures (Richardson et al., 1995:417*ff*). Shutdown when mammals are nearby requires detection of the marine mammals. Various combinations of visual, electro-optic, and acoustical monitoring methods have been used to accomplish this.

Time limitations prevented an extensive discussion of all of these known or potential mitigation measures. Instead, attention focused on three approaches that were considered especially worthy of discussion: ramping up, bubble screens, and active noise cancellation.

RAMPING UP

Marine mammal research permits and incidental take exemptions involving use of strong sources of underwater sound frequently require the source level to be increased gradually whenever operations are commencing after a period of silence. The rationale is that, if the sounds are aversive to marine mammals, any mammal close to the source will have time to move away before the source level reaches its maximum. If they do so, "ramping up" can be an effective mitigation measure even for mammals whose presence is unknown.

The ramping up concept has been used at least since the early-mid 1980s, when it was applied in industrial noise playback experiments with gray and bowhead whales (Malme et al., 1984; Richardson et al., 1990). Ramping up is a standard practice in the ATOC experiment (ARPA, 1995), during the U.S. Navy's LFA sonar operations and scientific tests (Johnson and Spikes, 1997; Clark et al., 1998), and during seismic exploration projects done under incidental take exemptions (e.g., NMFS, 1997, 1998).

Questions have been raised as the efficacy of ramping up. There have been no specific studies to determine whether marine mammals really do move away during the ramp-up phase. It has been suggested that ramping up may do more harm than good if it allows mammals to gradually accommodate to sound levels that are in fact harmful. Some mammals might even be attracted by the initially-weak sounds to move into the zone where exposure to the full-power sounds could be harmful. The frequent attraction of minke whales to slow-moving ships

(references in Richardson et al., 1995:272) was mentioned as an indication that this type of effect is possible.

On the other hand, there is anecdotal evidence that bowhead whales sometimes move away during the ramp-up phase of industrial noise playbacks or when exposed to a single airgun (W.J. Richardson, pers. obs.). Also, gray and bowhead whales often show some avoidance when exposed to industrial sounds from small projectors operating at full power. These tests with small projectors have some similarities to ramp-up operations with more powerful sound sources. Thus, it is probable that, at times, ramping up will be effective in dispersing certain marine mammals.

Rather than ramping up a sound that has no intrinsic meaning to marine mammals, an alternative approach might be to project sounds known to be aversive. Playbacks of killer whale calls have sometimes (not always) been shown to cause strong reactions in some by other cetaceans (Cummings and Thompson, 1971; Fish and Vania, 1971; Malme et al., 1983). However, animals might habituate to repeated playbacks of killer whale calls, making them more vulnerable to actual killer whale predation.

The responses of marine mammals to ramping up and to potentially aversive sounds are amenable to empirical testing. Because of the short term nature of the desired responses, such tests should be comparatively easy to conduct. When sounds that seem effective in dispersing marine mammals are identified, it would be useful to conduct more refined tests to determine the optimum stimulus parameters, and whether repeated exposure results in accommodation. These tests should receive high priority. Ramping up or "aversive stimulus" approaches—if effective—could operate without the need to detect the presence of marine mammals near the sound source. However, it should be recognized that the effectiveness of ramping up or aversive stimuli is likely to vary with species and situation. A more detailed review of experience during past and ongoing projects could be a useful starting point in designing tests of ramping up or aversive stimuli.

BUBBLE SCREENS

Air bubbles in water can strongly attenuate underwater sound because they change the impedance (bulk modulus) of the propagation medium. Significant attenuation can be attained even without a high concentration of bubbles. Bubble screens can be effective not only at moderate and high frequencies, but also at reasonably low frequencies. For example, they can be used to minimize the effects of underwater blasting on nearby structures (*in* G. Greene et al., 1985). Dr. C. Greene described a recent test demonstrating that a bubble curtain around a pile-driving operation in Hong Kong Harbour resulted in significant attenuation of the pile-driving sounds, including low-frequency components. Dr. C. Erbe mentioned a study in Victoria, B.C., which used bubble screens to attenuate high-frequency (10-20 kHz) sounds by 30 dB. The self-noise of the bubble screen was 95 dB re 1 µPa at 1 m. Bubble screens can be very efficient at attenuating narrow-band noise and can in fact be tuned in frequency. Other participants mentioned tests of bubble screens to reduce horizontal propagation of noise from airguns and ship propellers. Bubble emission systems around propellers are effective and practical in reducing propeller cavitation noise (Urick, 1983:340). However, bubble screens are not effective in attenuating very low frequency sounds such as blade-rate tones from large propellers.

ACTIVE NOISE CANCELLATION

Physical acousticians participating in the workshop indicated that active noise cancellation through projection of out-of-phase sounds was unlikely to be very effective underwater. This approach does not work well in open environments. To be effective, the sound to be cancelled must be narrowband and consistent, and the geometry of the propagation environment must be highly regular and restricted. One situation where active noise cancellation might have some utility could be in reducing turbine noise emanating from powerplant outfalls.

MITIGATION CRITERIA

This group did not discuss specific criteria under which mitigation would be desirable in order to avoid deleterious effects on marine mammals. It was understood that a follow-up workshop on acoustic impact criteria was being planned by the National Marine Fisheries Service. [That workshop was held during September 1998.] However, the present group recognized that questions about acoustic impact criteria have important and ongoing practical implications. There are implications both for marine mammals that are now being exposed to strong man-made sounds, and for human activities that are now being regulated based on very limited data concerning acoustical impacts (Richardson, 1997). During this workshop, much of the discussion by the "Hearing Effects & Non-hearing Physiological Effects" group and the "Behavior" group was relevant to the question of acoustical impact criteria.

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Appendix A

Short Biographies Of Workshop Participants

WORKSHOP ON THE EFFECTS OF MANMADE NOISE IN THE MARINE ENVIRONMENT

OCEAN ACOUSTICS TEAM

Dr. George V. Frisk (Team Leader)
Applied Ocean Physics & Engineering Department
Mail Stop #11
Woods Hole Oceanographic Institution
Woods Hole, MA 02543-1049

phone: (508) 289-2383
fax: (508) 457-2194
e-mail: gfrisk@whoi.edu

George V. Frisk received the B.A. degree from the University of Rochester in 1967, the Sc.M. degree from Brown University in 1969, and the Ph.D. degree from the Catholic University of America in 1975, all in physics. From 1968 to 1977, he was a physicist at the Naval Research Laboratory in Washington, DC, where he held an Edison Memorial Graduate Fellowship from 1970 to 1974. Since 1977, he has been employed by the Woods Hole Oceanographic Institution, Woods Hole, MA, where he is currently a Senior Scientist. From 1983 to 1989, he was Head of the Ocean Acoustics Laboratory, and from 1986 to 1989, held a J. Seward Johnson Chair in Oceanography, in which capacity he served as Educational Coordinator for the MIT/WHOI Joint Graduate Program in Applied Ocean Science and Engineering. From August 1992 to January 1997, he was Chair of the Applied Ocean Physics and Engineering Department. His research interests include acoustic propagation, reflection, and scattering in the ocean and seabed, acoustic surface waves, scattering theory of waves, computational physics, inverse methods, seismo-acoustic ambient noise, and Arctic acoustics. Dr. Frisk is a Fellow of the Acoustical Society of America and a member of the Institute of Electrical & Electronics Engineers and Sigma Xi.

Dr. John R. Buck
Center for Marine Science and Technology
University of Massachusetts Dartmouth
706 South Rodney French Blvd
New Bedford, MA 02744-1221

phone: (508) 999-9237
fax: (508) 999-8197
e-mail: jbuck@umassd.edu

John R. Buck received S.B. degrees in Electrical Engineering and English Literature from the Massachusetts Institute of Technology (MIT) in 1989, and subsequently received S.M., E.E., and Ph.D. degrees from the MIT and Woods Hole Oceanographic Institution (WHOI) Joint Program in Ocean and Electrical Engineering in 1991, 1992, and 1996, respectively. In 1996, he joined the faculty of the University of Massachusetts Dartmouth where he is currently an assistant professor in the Department of Electrical and Computer Engineering, and an associate research fellow at the Center for Marine Science and Technology (CMAST). Since 1996, he has been a Guest Investigator in the Marine Mammal Bioacoustics Group in the Biology Department at WHOI. His research interests include marine mammal bioacoustics, signal processing, and underwater acoustics.

Dr. Buck is a member of the IEEE and the Acoustical Society of America. He received the Goodwin Medal, MIT's highest honor for graduate student teaching, in 1994. His recent publications include the textbooks "Discrete-Time Signal Processing, Second Edition" by Oppenheim and Schafer with Buck (Prentice-Hall, 1999) and "Computer Explorations in Signals and Systems Using Matlab (TM)", by Buck, Daniel and Singer (Prentice-Hall, 1997). Dr. Buck was the recipient of an NSF CAREER award for research into applications of acoustics and signal processing to marine mammal behavior. He has also published papers on underwater acoustics, signal processing, and marine mammals signals. Dr. Buck is a member of Sigma Xi and Phi Beta Kappa.

Dr. Harry DeFerrari
University of Miami, RSMAS
4600 Rickenbacker Causeway
Miami FL 33149

phone: (305) 361-4644
fax: (305) 361-4701
e-mail: hdeferrari@rsmas.miami.edu

Dr. Gerald D'Spain
Marine Physics Lab
University of California, San Diego
Scripps Institution of Oceanography
9500 Gilman Drive, Mail Code 0701
La Jolla, CA 92093-0701

phone: (619) 534-5517
fax: (619) 534-5255
e-mail: gld@mpl.ucsd.edu

Dr. Charles R. Greene
Greeneridge Sciences, Inc.
1411 Firestone Road
Goleta, CA 93117

phone: (805) 967-7720
fax: (805) 967-7720
e-mail: cgreene@greeneridge.com

Charles R. Greene, Principal Scientist at Greeneridge Sciences, Inc., has S.B. and S.M. degrees in Electrical Engineering from the Massachusetts Institute of Technology and a Ph.D. in EE from the University of California at Santa Barbara. He has been working on underwater acoustics research and engineering since 1959. Much of his earlier work was supported by the U.S. Navy and involved underwater noise and acoustic transmission loss field experiments in the Arctic Ocean. Since 1980, he has worked with biologists studying the behavior of whales exposed to industrial noise. Since 1983 he has been conducting such work at Greeneridge Sciences, Inc. Projects have been supported by major oil companies (Shell Western, Unocal, Texaco, BPXA) and by Canadian and U.S. Government agencies. In 1995 he completed a project for the U.S. Minerals Management Service involving four field seasons at Barrow, Alaska, studying the influence of industrial sounds on migrating arctic whales in springtime. Dr. Greene is the author of three chapters on physical acoustics in the book *Marine Mammals and Noise* published by Academic Press in 1995. For the past three years he has been measuring and describing the pulsed sounds of airgun arrays operated in the Beaufort Sea in seismic surveys for hydrocarbon deposits. In support of this effort, he has developed and used autonomous seafloor recorders to store sound data for up to three weeks continuously during seismic surveys and bowhead whale migration.

Dr. John A. Hildebrand
Marine Physical Laboratory
Scripps Institution of Oceanography
9500 Gilman Drive, Mail Code 0205
University of California, San Diego
La Jolla, CA 92093-0205

phone: (619) 534-4069
fax: (619) 554-6849
e-mail: jah@mpl.ucsd.edu

Dr. John A. Hildebrand is a Professor at the Scripps Institution of Oceanography and an adjunct Professor in the Electrical and ComputerEngineering Department of the University of California San Diego. He obtained a B.S. degree in Physics and Electrical Engineering at University of California San Diego, and a Ph.D. degree in Applied Physics from Stanford University. His graduate studies were directed at the construction of an acoustic microscope and understanding of its imaging properties. He has been on the research staff at the Scripps

Institution of Oceanography for sixteen years. During this time he has been the chair or co-chair of six graduate Ph.D. thesis committees, and regularly teaches classes on marine geophysics, ocean acoustics, and experimental laboratory acoustics. He has contributed to more than 60 papers in referred publications, on topics ranging from studies of seismo-acoustic wave propagation in the the ocean basins, to sound production by large whales.

Dr. Darrell Jackson
Applied Physics Lab
University of Washington
1013 NE 140th St.
Seattle, WA 98105-6698

phone: (206) 543-1359
fax: (206) 543-6785
e-mail: drj@apl.washington.edu

Darrell Jackson received B.S. and M.S. degrees in Electrical Engineering from the University of Washington. He worked at Boeing as a Research Engineer and then received a Ph.D. degree in Electrical Engineering from the University of Washington in 1966. His thesis research was directed toward applications of magnetic resonance. This work was continued as a faculty member at the University of Massachusetts in Amherst. He returned to graduate school in 1972 and received a Ph.D. in physics from Caltech in 1977 with a dissertation on the extraction of experimental predictions from gluon theory.

Since joining the Applied Physics Laboratory of the University of Washington in 1976, Dr. Jackson's research has centered on underwater acoustics, with interests in both physics and signal processing. Reverberation modeling and measurement has been a dominant research topic. More recently, he has also worked on acoustic propagation as it affects matched-field processing and phase conjugation. Dr. Jackson is a member of the Acoustical Society of America and the American Geophysical Union.

Dr. Jeff Simmen
Office of Naval Research
Ocean, Atmosphere and Space, Code 321
800 North Quincy Street
Arlington, VA 22217-5660

phone: (703) 696-4204
fax: (703) 696-8423
e-mail: simmenj@onr.navy.mil

Dr. Jeff Simmen received his Ph.D. in applied mathematics from Caltech in 1984. After receiving his Ph.D., he worked for the following five years in the areas of underwater acoustics, search theory and operations research at the Center for Naval Analysis (which included a two-year assignment at the USN submarine command in Italy). In 1989 Dr. Simmen returned to academia where for the next few years he conducted research in fluid dynamics and ocean acoustics at the Naval Postgraduate School in Monterey and the University of California at Santa Cruz, respectively. Since 1993 he has managed a basic and applied research program in ocean acoustics for the Office of Naval Research (ONR). While at ONR, Dr. Simmen has established special programs in high-frequency acoustics, shallow-water acoustics, and long-range propagation. He has also encouraged international collaborations in ocean acoustics between the United States, Europe and Asia. Dr. Simmen continues to be an active researcher, investigating the propagation of sound through ocean internal waves and high-frequency acoustic fluctuations in shallow water. He is an assistant editor for the Journal of Underwater Acoustics and a member of the Acoustical Society of America, the American Geophysical Union, and the IEEE Oceanic Engineering Society.

Dr. Robert C. Spindel
Applied Physics Laboratory
University of Washington
1013 NE 40th St.
Seattle, WA 98105-6698

phone: (206) 543-1310
fax: (206) 543-3521
e-mail: spindel@apl.washington.edu

Dr. Robert C. Spindel is the Director of the Applied Physics Laboratory of the University of Washington. Founded to aid the Navy during WWII, today APL consists of approximately 250 scientists and engineers, and 45 graduate students engaged in basic and applied research programs in ocean and polar science, meteorology, ocean technology and underwater acoustics. Primary sponsorship is from the US Navy the National Science Foundation and other federal agencies. Dr. Spindel's research specialty is underwater acoustics.

Dr. Spindel received his bachelor's degree in Electrical Engineering from the Cooper Union, New York, NY in 1965, and his M.S. and Ph.D. degrees from Yale University, New Haven, Connecticut, in Electrical Engineering, in 1966 and 1971, respectively. During 1971 he was a Postdoctoral Research Fellow at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. In 1972 he joined the Scientific Staff of the Institution in the Department of Ocean Engineering. He was appointed Chairman of the Department in 1982 and served in that capacity until 1987 when he joined the University of Washington as Director of the Applied Physics Laboratory. He holds professorships in Electrical Engineering and Oceanography.

His personal research specialty is underwater acoustics and he has authored or co-authored over 100 scientific and technical publications, and has served as Chief Scientist on

many research cruises. Dr. Spindel was awarded the A.B. Wood Medal by the British Institute of Acoustics in 1981, the Gano Dunn Award from The Cooper Union in 1988, and the IEEE Oceanic Engineering Society's Technical Achievement Award in 1990. He is a Fellow of the IEEE, the Acoustical Society of America, and the Marine Technology Society. He served as President of the latter organization from 1983-5. Dr. Spindel has served on many national advisory panels and committees. He is presently a member of the National Research Council's Naval Studies Board and the Naval Research Advisory Committee

HEARING PHYSIOLOGICAL EFFECTS TEAM

Prof. Arthur N. Popper (Team Leader)
Department of Zoology
Zoology - Psychology Building
University of Maryland
College Park, MD 20742

phone: (301) 405-1940
fax: (301) 314-9358
e-mail: popper@zool.umd.edu

Arthur N. Popper is professor in the Department of Biology (formerly Zoology) at the University of Maryland in College Park Maryland. He served as chair of that department from 1987-1997 and has recently assumed the role of the director of the campus Neuroscience and Cognitive Science (NACS) graduate program. He also serves as American editor of the journal Bioacoustics and on the editorial board of several other journals in the hearing sciences. Popper is also co-editor of the Springer Handboof of Auditory Research, a definitive series of books on hearing that now number 11 volumes and which will shortly include 18 volumes on various aspects of hearing.

Popper is interested in the structure, function, and evolution of the vertebrate auditory system. He has published over 100 scientific papers, most of which deal with the auditory systems of fishes. However, he has also investigated hearing mechanisms in marine mammals and is currently working with turtles. Most recently, Popper and his lab have been studying the evolution of vertebrate sensory hair cells and the ear, as well as mechanisms of sound source localization, ultrasound detection by fish, and aging in the auditory system. Popper is also interested applying knowledge of fish hearing to controlling fish behavior and protecting fishes in the vicinity of nets, power plants, and hydropower dams.

Popper's work is currently supported by NSF, NIH, and ONR.

Dr. Randy Brill
SPAWARSYSCEN San Diego, Code D351
49620 Beluga Rd.
San Diego CA 92152-1355

phone: (619) 553-0897
fax: (619) 553-1355
e-mail: brill@spawar.navy.mil

Prof. Robert Dooling
Department of Psychology
University of Maryland
Zoology-Psychology Building
College Park, MD 20742-4415

phone: (301) 405-5925
fax: (301) 314-9566
e-mail: dooling@bss3.umd.edu

Dr. Christine Erbe
Institute of Ocean Sciences
Acoustical Oceanography
9860 W Saanich Rd
Sidney, BC
V8L 4B2 Canada

phone: (250) 363-6587
fax: (250) 363-6798
e-mail: erbec@dfo-mpo.gc.ca

Dr. Christine Erbe

I'm a research scientist at the Institute of Ocean Sciences (Dept. of Fisheries and Oceans) in Sidney, British Columbia. I'm working in underwater acoustics focussing on ocean sound propagation, ambient and anthropogenic noise and noise-effects on marine mammals. I completed my Ph.D. in geophysics at the University of British Columbia in 1997. My thesis entitled "The Masking of Beluga Whale (Delphinapterus leucas) Vocalizations by Icebreaker Noise" was part of an environmental assessment for the Canadian Coast Guard. I received my M.Sc. in physics in 1993 from the University of Dortmund in Germany. After undergraduate studies in physics, maths and chemistry and graduate studies in physics and engineering, I specialized in accelerator physics and high-frequency engineering. For my M.Sc. I developed a beam position and a beam intensity monitor for an electron accelerator. This was great fun, but

ultimately, I decided that the prospects of life in an underground lab without even knowing what the weather upstairs would be like, were not for me.

Dr. Darlene Ketten
Biology Department
Woods Hole Oceanographic Institution
Room 201-202 Shivrick/MS #36
Woods Hole, MA 02534

phone: (508) 289-2731
fax: (617) 573-4275
e-mail: dketten@whoi.edu

Dr. Darlene R. Ketten, Ph.D. is a marine biologist and neuroanatomist specializing in the sensory adaptations of marine mammals. She received a B.S./B.A. from Washington University (Biology and French, 1970), an M.S. from M.I.T. (Biological Oceanography, 1979), and a Ph.D. from Johns Hopkins University (jointly awarded by neuroanatomy, behavioral ecology, and experimental radiology, 1984). She currently holds a joint appointment as an associate scientist in Biology at Woods Hole Oceanographic Institution and as an assistant professor, Harvard Medical School, Department of Otology and Laryngology and serves as research director of the Three-Dimensional Imaging Service of the Mass. Eye and Ear Infirmary.

Her doctoral work explained the structural mechanisms behind differences in ultrasonic hearing ranges of echolocators. She did post-doctoral work on perception of signals in noise (MIT/Research Lab of Electronics) and on middle ear mechanics (Eaton-Peabody Laboratory for Auditory Physiology). Currently, her work is divided between sound reception and hearing mechanisms of marine mammals and developing in vivo micro-imaging and functional imaging techniques for assessing ear trauma and disease. She has completed medical specialty accredidation courses in Otopathology, Neuroradiology, and Forensic Pathology and is a lecturer on inner ear imaging and anatomy for specialty training courses for the Amer. Med. Assoc.- Head and Neck Surgery division. Dr. Ketten is a member of the Association for Research in Otolaryngology, J.B. Johnston Club, Neurosciences Society, International Society for Stereology, the Radiological Society of America, the Society of Marine Mammalogy, and the Acoustical Society of America. She is an active member of the ASA Bioacoustics Committee, is an associate editor for Marine Mammal Science, and has served on advisory boards on hearing, bioacoustics, and acoustic trauma for the National Institutes of Health, National Institutes of Deafness and Communication Disorders, NIH Consensus Development Conferences, the National Academy of Sciences Committee on Hearing and Bioacoustics, the Marine Mammal Commission, and National Marine Fisheries Service.

Dr. G. Richard Price
Army Research Lab
HRED, Bldg. 520
Aberdeen Proving Ground, MD 21005-5425

phone: (410) 278-5976
fax: (410) 278-3587
e-mail: dprice@arl.mil

Sam H. Ridgway
Navy Marine Mammal Program, D3503 (PLBS)
49620 Beluga Rd
San Diego CA 92152-6266

voice: (619) 553-1374
fax: (619) 553-1346
e-mail: ridgway@spawar.navy.mil

After earning a B.S. and DVM at Texas A&M, I was a veterinary officer in the U.S. Air Force. During this time I became associated with the U. S. Navy and was hired to be the first full time employee of the Navy Marine Mammal Program. As the first veterinarian to work exclusively with marine mammals I developed anesthesia techniques for dolphins and other monitoring methods allowing us to do experiments with trained animals in the open ocean. Because of these developments I was invited to collaborate with prominent scientists such as E. G. Wever of Princeton University, T. H. Bullock of Scripps Institution of Oceanography and John Kanwisher of Woods Hole. After several years of work including research on dolphin brain and ear, I got a fellowship to work with Sir Richard Harrison, FRS at Cambridge University where I earned a Ph.D in Neurobiology. I have been involved in about 200 scientific publications and currently have responsibility (as specified by SECNAVINST 3900.41D) for the medical care program for all Navy marine mammals world-wide, including biomedical research to support that program. I represent the Navy with other agencies such as the National Marine Fisheries Service, The U. S. Department of Agriculture, and the Marine Mammal Commission. Technical direction is provided for personnel that are civil servants, civilian contractors, U. S. Army officers and enlisted personnel, as well as uniformed U. S. Navy Personnel. I am principal investigator on projects involving marine mammal medicine, physiology and acoustics. [I was unable to attend the workshop but did comment on parts of the report]

Prof. Jeanette A. Thomas
Laboratory of Sensory Biology
Western Illinois University Regional Center
3561 60th St.
Moline, IL 61265

phone: (309) 762-9481, ext. 262
fax: (309) 762-6989
e-mail: mfjat@uxa.ecn.bgu.edu

Dr. William A. Yost
Parmly Hearing Institute
Loyola University Chicago
6525 N. Sheridan Rd.
Chicago, IL 60626

phone: (773) 508-2710
fax: (773) 508-2719
e-mail: wyost@luc.edu
www.parmly.luc.edu

William A. Yost, Ph.D., is Professor of Hearing Sciences and Director of the Parmly Hearing Institute Loyola University Chicago. He also is Adjunct Professor of Psychology, Adjunct Professor of Otolaryngology, and Director of the Interdisciplinary Neuroscience Minor at Loyola University Chicago. Dr. Yost received a B.S. in Psychology from The Colorado College in 1966 and a Ph.D. in Experimental Psychology from Indiana University in 1970. He was a National Science Foundation Postdoctoral Fellow at the University of California at San Diego, and served on the faculty at the University of Florida. He has had visiting appointments at Northwestern University and The Colorado College. His specialty within the area of hearing sciences is psychoacoustics. He has published 245 reports, articles, book chapters, and books. His research is funded has been funded by the National Science Foundation, National Institutes of Health, Department of Defense, and the Environmental Protection Agency.

NON-HEARING PHYSIOLOGICAL EFFECTS TEAM

Dr. Edward Cudahy (Team co-chair w/ Popper)
Research Audiologist
Naval Submarine Medical Research Laboratory
Naval Submarine Base New London Box 900
Groton, CT 06349-5900

phone: (860) 694-3391
fax: (860) 694-4096
email: cudahy@nsmrl.navy.mil

Dr. Edward Cudahy, Research Audiologist at the Naval Submarine Medical Research Laboratory, has over 25 years of experience in psychoacoustic and audiological research. He has published extensively in the areas of the effects of sound on divers, psychoacoustics, cochlear implants, speech perception and production, and hearing aids. Dr. Cudahy has over 75 published abstracts from national and international meetings on topics such as diver hearing, bioeffects of underwater sound on divers, otoacoustic emissions, masking, cochlear implants, and temporal aspects of sound and speech perception. In addition, he has published a book on audiological and speech instrumentation.

Along with his scientific activities, Dr. Cudahy provides on-going expert consultation to operational components of the US Navy regarding permissible underwater noise exposure limits for divers. Recently, he and his colleagues directed a research program that generated guidance regarding permissible exposure limits for low frequency underwater sound (100 – 500 Hz). This was done as part of their input into the US Navy's draft environment impact statement for a low frequency sonar system. Other current projects include developing underwater sound measurement instruments and investigating means of protecting divers from underwater sound.

John Sims, LT USNR
Diving Medical Officer
Naval Submarine Medical Research Laboratory
Naval Submarine Base NLON Box 900
Groton, CT 06349-5900

phone: (860) 694-4680
fax: (860) 694-4809
email: sims@nsmrl.navy.mil

LT John R. Sims, MC, UMO, USNR: Principal Investigator for the Psychological and Physiological Effects of Low Frequency Water-Borne Sound at the Naval Submarine Medical Research Laboratory, Groton, Connecticut. He received a M.D. degree in 1994 as a graduate of Dartmouth Medical School. He was awarded the Stanley J. Sarnoff Cardiovascular Research Fellowship in 1991-1992 to study the cellular and cytoskeletal dynamics of angiogenesis at Harvard Medical School. After medical school he completed an internship in Internal Medicine at the National Naval Medical Center, Bethesda, Maryland, in 1995. Prior to his current position, he trained at the Naval Undersea Medical Institute, Groton, Connecticut, in Diving and Submarine Medicine.

Robert Kull
Geo-Marine Inc.
610 Thimble Shoals Blvd, Suite 302B
Newport News VA 23606

phone: (757) 873-3702
fax: (757) 873-3703
e-mail: bkullgmi@usa.net

Robert Kull currently works for Geo-Marine, Inc. where he is program manager for their environmental noise program. Mr. Kull recently retired from the Air Force. His last assignment was at the Headquarters Air Force Center for Environmental Excellence (AFCEE) where he was chief of the Resource Conservation Division (AFCEE/ECR). Mr. Kull has a Bachelor of Arts degree in Biology (1972) from the University of the Pacific and a Masters of Science degree in Biology (1976) from the University of North Carolina at Charlotte where he specialized in Ornithology. His Air Force career included tours on the Bird/Aircraft Strike Hazard (BASH) Team at the Air Force Engineering and Services Center, Tyndall AFB (1981-1985), four years teaching biology at the AF Academy (1985-1988), program manager of the Noise and Sonic Boom Impact Technology (NSBIT) Advanced Development Program Office, Wright-Patterson AFB (1989-1993), chief of the Environmental Noise Branch, Armstrong Laboratory, Wright-Patterson AFB (1993-1994), and chief of Programs and Operations Division, Occupational and Environmental Health Directorate, Armstrong Laboratory, Brooks AFB (1995-1996). The wide range of experience afforded him the opportunity to work closely on research projects with the US Fish and Wildlife Service and state fish and game agencies to reduce noise impacts on bighorn sheep, caribou, desert kit fox and small mammals, pronghorn, raptors to include Peregrine Falcons, and domestic animals. He has also managed multimillion research projects with various universities in the US and Europe. Mr. Kull was Team Chair of Noise and Animals subcommittee of the International Committee on the Biological Effects of Noise (ICBEN) until he relinquished that seat in 1998. His current duties include project oversight for a study on the effects of aircraft overflights on birds in the southwest.

Dr. Teri Rowles
NOAA/NMFS
F/PR
1315 East-West Highway
Silver Spring, MD 20910

phone: (301) 713-2322
fax: (301) 588-4976
e-mail: Teri.Rowles@noaa.gov

BEHAVIOR TEAM

Dr. Roger Gentry (Team Leader)
National Marine Mammal Laboratory

NOAA/NMFS
7600 Sand Point Way NE
Seattle, WA 98115

phone: (206) 526-4032
fax: (206) 526-6615
e-mail: Roger.Gentry@noaa.gov

Dr. Roger Gentry is presently the acoustic coordinator for the National Marine Fisheries Service's Office of Protected Resources, Silver Spring, MD. Dr. Gentry is trained as a zoologist. Early in his career Dr. Gentry worked in vision, acoustics, and learning under Ron Schusterman and did an MA thesis on underwater directional hearing in sea lions. He continued to read in acoustics, but he did a Ph.D. in animal behavior under Burney LeBoeuf at UC Santa Cruz. For the past 30 years Dr. Gentry has conducted field research in behavior and ecology of pinnipeds. He was never bitten more than once by any species. He worked a bit on penguins and whales, and a bit in physiology. He helped develop the Time Depth Recorders that are now widely used to measure foraging ecology of marine mammals. For the past three years Dr. Gentry has worked with the NMFS acoustics team in Silver Spring as it tries to develop agency policy on noise, marine mammals and endangered species. Dr. Gentry also acts as a liaison between NMFS and other agencies (governmental and nongovernmental) on acoustic issues.

Dr. Daryl J. Boness
Dept. of Zoological Research
National Zoological Park
Smithsonian Institution
Washington D.C. 20008

phone: (202) 673-4826
fax (202) 673-4686
e-mail: dboness@nzp.si.edu

Dr. Daryl J. Boness is Head of the Department of Zoological Research at the Smithsonian Institution's National Zoological Park. He received a B.A. in psychology and biology from Cornell College in 1972, a M.A. in human psychophysiology from Hollins College in 1973 and a Ph.D. from Dalhousie Univeristy (Canada) in behavioral ecology. He has been studying the reproductive behavior of pinnipeds (seals, sea lions, & walruses) for 25 years and has published over 70 papers on the subject. His main interests are in understanding how ecological and social factors affect the mating and parental care strategies of males and females. He uses an integrative (combining behavioral, physiological and genetic methods) and comparative approach to determining fitness costs and benefits to individual animals of the same species in different populations and of different species to make inferences about the adaptiveness and evolution of behavior. While two species, grey and harbor seals have been the focus of long-term research, he has 11 of the 31 species of pinnipeds, in parts of the world ranging from nearly one end of the globe to the other. More recently he turned his experience in

studying pinniped behavior to important issues concerning interactions between humans, marine mammals, and the ocean environment. In this regard his efforts have included: 1) conducting studies to investigate the possible effects of sonic booms on the reproductive behavior of grey and harbor seals, 2) serving on the U.S. Marine Mammal Commission's Committee of Scientific Advisors for the past four years, and 3) serving on program review and evaluation panels for the National Marine Fisheries Service or the Fish and Wildlife Service.

To study some aspects of reproduction in pinnipeds, one must often supplement direct observations with special technology, especially because seals spend part of their lives at sea. Thus much of the work has involved using or helping to develop state-of-the-art technology. This includes the use of molecular DNA techniques to assess paternity or genetic relationships, non-radioactive isotopes to measure energy flow, satellite telemetry to obtain location data, time-depth recorders to investigate diving and foraging, a video camera system that can be attached to a free ranging seal (called the Crittercam), and Geograhpical Position System (GPS) tags to obtain fine-scale movements of individual seals.

Dr. Ann E. Bowles
Senior Staff Biologist
Hubbs-Sea World Research Institute
2595 Ingraham Street
San Diego, CA 92109

phone: (619) 226-3870
fax: (619) 226-3944
e-mail: annb1@san.rr.com

Dr. Ann E. Bowles is a Senior Research Biologist at the Hubbs-Sea World Research Institute. She obtained a B.A. in Linguistics from the University of California at San Diego, graduating Magna Cum Laude, and a Ph.D. in Marine Biology from the Scripps Institution of Oceanography for studies of vocal communication in the Emperor Penguin (*Aptenodytes forsteri*). Under contract to agencies such as the U.S. Air Force, National Park Service, and NASA, she has spent over 18 years studying the effects of human-made noise and disturbance on a wide range of taxa, including pinnipeds, odontocete and mysticete cetaceans, small mammals, terrestrial carnivores, birds, reptiles, and farm animals. Included among these efforts are of potential effects of human-made impulsive noise on marine mammal hearing, behavior, and non-auditory physiology. She maintains adjunct lecturer and research positions at Scripps Institution of Oceanography, San Diego State University and the University of San Diego, advising intern and graduate students. She was co-chair of the Acoustical Society of America's Animal Bioacoustics Technical Committee during the period when it became a full technical committee and is now the committee's representative to the ASA Committee on Standards. She is also a team member for the International Congress on the Biological Effects of Noise.

Dr. Stephen Insley
Dept. of Zoological Research
National Zoological Park
Smithsonian Institution
Washington D.C. 20008

phone: (202) 673-4748
fax (202) 673-4815
e-mail: sinsley@nzp.si.edu

Dr. Stephen Insley's perspective and interest in animal behaviour combines the areas of behavioural ecology, bioacoustics, and conservation biology. He is particularly interested in the factors that affect communication and how communication in turn affects other evolutionary processes. Dr. Insley received an Honours B.A. in Biological Sciences and Communications at Simon Fraser University in 1984. He then took a position at Barron and Associates, Acoustical Consultants, in Vancouver, B.C., where he specialized in environmental noise and also managed projects in architectural, mechanical, and industrial noise control. Dr. Insley returned to graduate school at the University of Victoria where he completed an M.Sc. with Dr. E.H. (Ted) Miller in 1990. Dr. Insley's thesis compared individual distinctiveness in two pinniped species, northern elephant seals and northern fur seals, and demonstrated that selection on recognition ability can shape vocal morphology. He went on to a Ph.D. in Animal Behavior at the University of California, Davis, with Dr. Peter Marler, which he finished early in 1996. His Ph.D. research looked at the details of maternal vocal recognition in the northern fur seal, and among other things, demonstrated the ability of this species to remember individual identities for time periods greater than a year.

Dr. Insley is now doing Post Doctoral research at the Smithsonian Institution's National Zoological Park with Drs. Daryl Boness and Robert Fleischer. His main project focuses on adult male northern fur seals and combines behavior and molecular techniques to investigate the feedback between factors such as competitive, cooperative, and recognition behavior. His goals are to test for long-term recognition among territorial neighbours, to see if there is evidence for cooperation during the acquisition of breeding territories, and to show the pattern of relatedness among these males. He also has three ongoing projects in addition to this study. He is investigating the underwater display behaviours of breeding adult male harbour seals at Sable Island, Nova Scotia. He is beginning a project in Peru with South American fur seals which looks at how environmental catastrophes, such as the 1997/8 El Nino, affect breeding social behaviour. And finally, Dr. Insley is directing a collaborative effort to refine the use of GPS technology to answer more detailed questions in behavioural ecology.

Dr. Roger Payne
Whale Conservation Institute
88 Crescent LN
London SW4 9PL
U.K.

phone: 9-011-441-714-980-320 or (802) 457-4450
fax: 9-011-441-714-983-184 or (802) 457-4095
e-mail: 74201.247@compuserve.com

Dr. Roger Payne has a B.A. degree from Harvard University where he studied hearing of bats under the direction of Donald R. Griffin, and a Ph.D. in biology from Cornell, where his dissertation was a demonstration that barn owls can locate prey in total darkness based on hearing alone. He also did a post doc at Tufts University with insect physiologist Kenneth Roeder on the directional sensitivity of the ears of moths. He was on the faculty of Rockefeller University for 19 years and at the New York Zoological Society for 16 years. Payne is best known for his discovery (with Scott McVay) that humpback whales sing songs, and for his theory (with Douglas Webb) that the sounds of fin and blue whales can be heard across ocean basins. He has studied the behavior of whales since 1967 and is founder and President of the Whale Conservation Institute (originally the Long Term Research Institute).

Dr. Payne has led over 100 expeditions to all oceans and has studied every species of large whale in the wild. He pioneered many of the benign research techniques now used throughout the world to study free-swimming whales, and has trained many of the current leaders in whale research, both in America and abroad. He directs long term research projects on the songs of Humpback whales, and on the behavior of 1300 individually known Argentine right whales (the longest such continuous study).

Payne has published extensively both technical papers (including editing a volume for the A.A.A.S. entitled "Communication and Behavior of Whales") and for a more general audience (including the book "Among Whales," '1995'). He has produced four recordings of whales for popular audiences (including "Songs of the Humpback Whale," the best-selling natural history recording ever released). Payne has lectured at most major universities in the U.S. and England, and has been a writer and presenter for television documentaries, as well as a co-writer and director of the IMAX film "Whales"

Payne's honors and awards include: a knighthood in the Netherlands, a MacArthur Fellowship, the similar Lyndhurst Prize Fellowship, the Joseph Wood Krutch Medal of the Humane Society of the U.S., The Albert Schweitzer Medal of the Animal Welfare Institute, and a United Nations, UNEP, "Global 500" Award. His films have received seven awards including two Emmy nominations and an Emmy for best interview (with Charlie Rose).

Dr. Ronald J. Schusterman
Long Marine Laboratory
University of California
100 Shaffer Road
Santa Cruz, CA 95060

phone: (408) 459-3345
fax: (408) 459-3383

e-mail: rjschust@cats.ucsc.edu

Ronald J. Schusterman is an Emeritus Professor of Psychology and Biology at California State University at Hayward. He is also a Research Biologist in the Institute of Marine Sciences at the University of California at Santa Cruz, and he does the majority of his research there, at Long Marine Laboratory. He has held an adjunct appointment in Biology at the University of California at Santa Cruz, and currently has an adjunct position in Ocean Sciences there, as well as with the Biology department at Oregon State College. Schusterman currently is a Visiting Scientist in Psychology at Columbia University, and is a Senior Scientist at the Osborne Lab at the Aquarium for Wildlife Conservation in New York. Educated at Brooklyn College and Florida State University, Schusterman took his first research position at the original Yerkes Laboratory of Primate Behavior in Orange Park, Florida, where he investigated the cognitive and social behavior of chimpanzees, gibbons, and monkeys. He then acquired a full-time position doing research in 1963 at Stanford Research Institute where he helped develop the first laboratory in North America primarily devoted to the study of the behavior and physiology of pinnipeds. He moved his operation to the Ecological Field Station at Cal State University at Hayward in 1971, and again moved his research program with sea lions and seals in 1985 to Long Marine Laboratory.

For the past 35 years, his major research interests have been in sensory systems, perception, cognition and communication of marine mammals. Schusterman's field work has been done on the communicative behavior of California sea lions and harbor seals off the coast of California. In the lab, he has used behavioral techniques to study perception and cognition, and he is currently researching the effects of noise on hearing in pinnipeds. When he is not researching or teaching courses such as animal behavior and evolutionary psychology, Schusterman likes to swim, see sporting events live or on TV, travel, read Elmore Leonard mysteries, schmoose with old friends from the Bronx or with fellow animal behaviorists, taste wines, dance, listen to jazz, see movies and play with his grandchildren.

Dr. Peter Tyack
Woods Hole Oceanographic Inst.
Dept. of Biology, Mail Stop 34
Redfield 1-32
45 Water Street
Woods Hole, MA 02543-1049

phone: (508) 289-2818
fax: (508) 457-2134
e-mail: peter@cetacea.whoi.edu

Dr. Peter Tyack is an Associate Scientist in the Department of Biology at Woods Hole Oceanographic Institution. He received his Bachelor of Arts degree in Biology from Harvard University in 1976 and his Ph.D. in Animal Behavior from Rockefeller University in 1982. His

research interests are centered on the social behavior and acoustic communications of cetaceans, with specific research emphases on the reactions of cetaceans to playbacks of their own sounds, effects of manmade noise on cetaceans, and the role of individually distinctive signature signals, vocal learning and mimicry in bottlenose dolphins and sperm whales. Dr. Tyack is the author of over 30 scientific papers and is a co-author of the 1994 National Research Council report "Low-frequency sound and marine mammals: current knowledge and research needs." Dr. Tyack is a member of the American Academy for the Advancement of Science (AAAS), the Acoustical Society of America, Sigma Xi, and the Animal Behavior Society. He is a charter member of the Society for Marine Mammalogy and serves on the Advisory Board for the ATOC Marine Mammal Research Program, and is a Trustee of the Center for Coastal Studies.

MONITORING AND MITIGATION TEAM

Dr. W. John Richardson (Team Leader)
LGL Ltd. Environmental Research Associates
22 Fisher St.
P.O. Box 280
King City, ON L7B 1A6
CANADA

phone: (905) 833-1244
fax: (905) 833-1255
e-mail: wjrichar@idirect.com

W. John Richardson is Executive Vice President of LGL Ltd., environmental research associates, of King City, Ontario. He is an animal behaviorist by training (Ph.D., Cornell Univ., 1976). Since 1980, he has worked on field studies, reviews and environmental assessments of noise effects on marine mammals, working closely with physical acousticians. Much of this work has concerned reactions of bowhead whales, beluga whales and seals to underwater noise from offshore oil exploration in the Alaskan and Canadian arctic. This work has included monitoring of reactions to actual industrial activities plus controlled tests of reactions to simulated industrial activities. Dr. Richardson has also prepared impact assessments concerning effects of acoustic disturbance by military test activities. He is senior author of the book "*Marine Mammals and Noise*", published in 1995 by Academic Press. In 1992-94 he was a member of the U.S. National Research Council's Committee on Low-Frequency Sound and Marine Mammals. Since 1993 he has chaired an advisory board for the ATOC Marine Mammal Research Program. He also works on birds, especially bird migration and bird hazards to aircraft.

Dr. Raymond C. Cavanagh
Science Applications International Corporation

1710 Goodridge Dr.
McLean, VA 22102

phone: (703) 448-6562
fax: (703) 821-3576
e-mail: raymond.c.cavanagh@cpmx.saic.com

Raymond Cavanagh works as a senior scientist for Science Applications International Corporation (SAIC) in McLean, Virginia. For almost 30 years, he has been almost exclusively involved in the study of underwater sound, with an emphasis on sound propagation, ambient noise, and sonar system performance.

His educational background is in mathematics (numerical methods), with a Ph.D. degree from the University of Maryland in 1970.

Beginning in 1969 at Bolt Beranek and Newman, Inc., he worked under ONR sponsorship on SOSUS system performance, submarine sonars, and ambient sea noise. He joined ONR in 1972 to pursue research in ambient noise modeling, data analysis for major sea tests, and adiabatic transmission-loss modeling. From 1975 to 1979, he worked for SAIC, where his projects included directional noise modeling, acoustic fluctuation research, and performance of torpedoes in shallow water.

He spent the next nine years at Planning Systems Incorporated, where he managed a large Arctic acoustic research project for ONR, including field tests and predictive modeling. The project addressed acoustic model development and major on-ice experiments. Since returning to SAIC in 1989, he has worked on a variety of R&D projects for DOD, including: the Navy's Fixed Distributed System, low-frequency active acoustics (LFAA), environmental assessments (effects of sound on marine life), propagation-model and reverberation-model compendia, and atmospheric acoustics.

Dr. Cavanagh is a member of the Acoustical Society of America and the author of a number of reports and publications.

Dr. Christopher Clark
Bioacoustics Research program
Cornell lab of Ornithology
159 Sapsucker Woods Rd.
Ithaca, NY 14850

phone: (607) 254-2405
fax: (607) 254-2415
e-mail: cwc2@cornell.edu

Christopher W. Clark is the I.P. Johnson Senior Scholar in the Section of Neurobiology and Behavior at Cornell University and Director of the Bioacoustics Research Program at the Cornell Laboratory of Ornithology. He received his Master's in electrical engineering and Ph.D. in Biology from the State University of New York at Stony Brook under Charles Walcott and Roger Payne and completed an NIMH Post-doctoral Research Fellowship on avian song learning with Peter Marler at the Rockefeller University. As part of his Ph.D., he conducted the first successful playback to a baleen whale and described the functions of sounds in southern right whales. He has devoted a great deal of effort to developing methods for quantitative analysis and comparison of animal sounds, and the potential impact of human-made sounds on whales. He is best known for his research using passive acoustic techniques for research on baleen whales, including the acoustic behavior and census of bowhead whales off Barrow, Alaska; the acoustic behavior, seasonal distribution and environmental monitoring of balaenopterids using Navy IUSS assets; and the behavior and census of whales in the open ocean through the combination of towed arrays and visual survey techniques.

Dr. William Ellison
Marine Acoustics Incorporated
809 Aquidneck Ave.
Middletown, RI 02842

phone: (401) 848-2995
fax: (401) 847-7864
e-mail: wemai@aol.com

Dr. Christopher Fox
NOAA PMEL
2115 Southeast OSU Drive
Newport, OR 97365

phone: (541) 867-0276
fax (541) 867-0356
e-mail: fox@pmel.noaa.gov

Christopher G. Fox has served as a Principal Investigator within the VENTS Program of NOAA's Pacific Marine Environmental Laboratory since June, 1985. He leads a diversified program in marine mapping, geophysics, and underwater acoustics. The project is located at NOAA's laboratories within the Hatfield Marine Science Center in Newport, Oregon. Dr. Fox is also an Associate Professor (Courtesy) at Oregon State University's College of Oceanic and Atmospheric Sciences. His background is in marine geophysics (Ph.D., Columbia University, 1984), and interest in marine mammal acoustics only began with the first viewing of acoustic data collected for geophysical studies from the Pacific in 1991. In recognition of his efforts in developing the U.S. Navy's Sound Surveillance System for environmental applications, Dr. Fox

was awarded the U.S. Department of Commerce Gold Medal in 1994. Prior to his service with the National Oceanic and Atmospheric Administration, Dr. Fox worked for the Advanced Technology Staff of the U.S. Naval Oceanographic Office in Bay St. Louis, Mississippi, where he participated in a wide variety of studies including the numerical modelling of seafloor microtopographic roughness for acoustic bottom interaction prediction and the development of automated cartographic mapping from multibeam sonar systems. Prior to joining NAVOCEANO, he worked within the U.S. Geological Survey developing numerical simulations of geothermal reservoir dynamics. Dr. Fox currently serves on the U.S. delegation to the International Whaling Commission Scientific Committee, where he chairs a working group on marine mammal acoustics, and he has served in various advisory capacities for the U.S. Navy and the National Science Foundation.

Dr. Robert Hofman
Marine Mammal Commission
4340 East-West Highway, Room 905
Bethesda, MD 20814

phone: (301) 504-0087
fax; (301) 504-0099
e-mail: rhofman@mmc.gov

Dr. Robert Hofman is the Scientific Program Director of the U.S. Marine Mammal Commission. He received his Ph.D. from the University of Minnesota in 1975. The topic of his dissertation research was the distribution patterns and population structure of antarctic seals. He served as a sonarman in the Navy from 1955 to 1959, and taught Biology and Physics at Warren G. Harding High School in Warren, Ohio, from 1962 to 1967. He was a member of the U.S. delegations that negotiated the Convention for the Conservation of Antarctic Marine Living Resources (1978-1981) and the Protocol to the Antarctic Treaty on Environmental Protection (1989-1991), and was the first U.S. representative to the Scientific Committee for the Conservation of Antarctic Marine Living Resources and the Antarctic Treaty Committee for Environmental Protection.

Dr. Hofman was a charter member of the Society for Marine Mammology and the Unusual Marine Mammal Mortality Working Group established by the National Marine Fisheries Service as directed by Marine Mammal Health and Stranding Response Act of 1992. He was a member of the program board of the 1978 U.S. Tuna Foundation dedicated vessel research program, and one of the co-conveners of the 1981 Workshop on Identification and Assessment of Possible Alternative Methods for Catching Yellowfin Tuna. He has been convener or co-convener of other workshops on a broad range of issues, including the effects and effectiveness of acoustic devices for deterring harmful marine mammal-fishery interactions. He is the Marine Mammal Commission's representative on the Interagency Coordinating Group on Ocean Noise.

Sue Moore, Ph.D.
Cetacean Assessment and Ecology Program Leader
NOAA/NMFS/AFSC
National Marine Mammal Laboratory
7600 Sand Point Way, N.E.
Seattle, WA 98115

phone: (206) 526-4021
e-mail: sue.moore@noaa.gov

Sue Moore received a Ph.D. in Biological Oceanography from Scripps Institution of Oceanography (SIO) in 1997, and a Master of Science degree from San Diego State University (SDSU) in 1979. Her research focus at SIO was cetacean habitat selection in the Arctic, while studies at SDSU were directed at bio-acoustics and behavioral ecology of tree frogs. Dr. Moore completed her Ph.D. while working full-time for Science Applications International Corporation, where she was Progam Manager for a variety of marine mammal survey and mitigation projects. Dr. Moore is currently the Cetacean Assessment and Ecology Program Leader at the NMFS/National Marine Mammal Laboratory, overseeing a variety of survey, assessment and bio-acoustic projects. Dr. Moore is a member of the Acoustical Society of America, Association of Women in Science, and a charter member of the Society for Marine Mammalogy.

HOST/ SUPPORT

Dr. Robert Gisiner
Office of Naval Research
BCT-1, Code 335
800 North Quincy Street
Arlington, VA 22217-5660

phone: (703) 696-2085
fax: (703) 696-1212
e-mail: gisiner@onr.navy.mil

Dr. Gisiner received his Ph.D. in Biology in 1985 from the University of California at Santa Cruz. Following a post-doctoral research stint at the UC Santa Cruz Long Marine Lab from 1985 to 1990, Dr. Gisiner joined the Navy's marine mammal research program located at Kaneohe, Hawaii, and moved with that program to San Diego in 1993. In 1994 Dr. Gisiner joined the Office of Naval Research as program manager for marine mammal science programs. His research interests include social behavior with emphasis on the role of learning in social relationships, complex learning and cognition, and bioacoustics. His two most recent research projects have been a multiple methods study of the migratory patterns of Hawaiian humpback

whales and studies of the role of "signature" calls in Steller sea lions. Dr. Gisiner currently manages basic research programs on biosonar and biolocomotion, in addition to research related to the effects of manmade underwater noise on marine mammals. Dr. Gisiner also serves as a member of the Steller sea lion Recovery Team and works closely with the Northern Right Whale Implementation Teams. He is a member of the Animal Behavior Society, International Society for Behavioral Ecology, the Psychonomic Society, and a charter member of the Society for Marine Mammalogy.