Final Report of the National Oceanic and Atmospheric Administration (NOAA) International Symposium:

"Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology"

18-19 May 2004
Arlington, Virginia, U.S.A.

Primary symposium sponsor:

NOAA Fisheries Acoustics Program,
Office of Protected Resources (OPR),
National Marine Fisheries Service (NMFS),
National Oceanic and Atmospheric Administration (NOAA)

Symposium report written by:

Dr. Brandon L. Southall (NOAA Fisheries Acoustics Program)

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Executive Summary

The first international symposium on "Shipping Noise and Marine Mammals" was held on 18-19 May 2004 in Arlington, Virginia, U.S.A. This meeting brought together representatives of various ocean industries, academia and other research organizations, government and military personnel, and non-governmental organizations. The main purpose of the meeting was to initiate discussion on what information is available and needed concerning sounds produced by large ships and other vessels and their potential impacts on marine mammals (and, to a lesser extent, fish and turtles). This collaborative forum begins a dialogue among various stakeholder groups on this emerging scientific question.

The National Oceanic and Atmospheric Administration (NOAA) Acoustics Program was the primary sponsor of this meeting. The Acoustics Program initiated the symposium to formally address the potential effects of sound from vessels on marine mammals, with specific technical emphasis on evaluating available data and planning future research efforts. Seven partners from segments of the commercial shipping industry, U.S. government, and academia aided in the planning and advertisement of the meeting. Approximately 200 people with a wide range of affiliations, including all of those given above, attended the meeting.

Introductory remarks were provided by a number of distinguished invited speakers. Technical sessions were conducted on issues ranging from sound produced by ships to the state of knowledge on possible acoustic impacts on marine animals to vessel quieting technologies and their possible commercial applications. Each of the technical presentations, as well as much more information regarding the meeting, are available at: **www.shippingnoiseandmarinemammals.com**

Many of the presentations and discussion in the symposium focused on large vessels, principally the largest ocean-going commercial shipping vessels (container and dry bulk ships and tankers). This emphasis, based on the fact that such vessels are specifically known to emit relatively high levels of low frequency sound capable of traveling long distances, is consequently largely reflected in the report of the symposium proceedings. As was acknowledged during the symposium, however, a wide range of human vessel types are not reflected by the term "commercial ships". The relative contribution of sounds from various vessel types to overall ambient noise and their possible impacts on marine life remain largely unknown. Symposium participants noted that emphasis should be expanded in future forums to the wide range of human vessel types: including recreational and fishing craft, cruise vessels, ferries, certain tankers, and other transport vessels.

An invited panel discussed various technical, legal, and economic issues and considered possible future actions. At the conclusion of the panel discussion, a steering committee was formed to plan aspects of a proposed follow-on symposium.

General Introduction

The first international symposium to investigate whether and how sounds from vessels may impact marine mammals, entitled "Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology" was held on 18-19 May 2004 at the Sheraton National Hotel in Arlington, Virginia, U.S.A. There were a total of 203 registrants for the symposium, including on-site and Internet registrations. The attendees had a range of affiliations, including government (40% of total), industry (22%), non-governmental organizations (17%), academia (13%), and other/non-affiliated (8%).

The National Oceanic and Atmospheric Administration (NOAA) Acoustics Program was the convener of this symposium. Seven partners from the commercial shipbuilding and operation industry, government, military, and academia collaborated in planning the meeting, announcing it to their members, and in some cases contributing technical presentations. Participants included the: U.S. Marine Mammal Commission (MMC), Chamber of Shipping of America (CSA), INTERTANKO, U.S. Navy, Society of Naval Architects and Marine Engineers (SNAME), University of Alaska Marine Advisory Program, and American Bureau of Shipping (ABS). The Statement of Purpose used in planning the symposium is appended to this report (Appendix 1), as is the final meeting agenda (Appendix 2).

Effects of Sound on Marine Animals

Currently, there is considerable interest in whether anthropogenic (human-generated) sound produced in the marine environment impacts animals and, if so, how. It is clear from scientific investigations of many marine mammals that the production and reception of certain sounds are critical in various aspects of life history. It is also evident that certain sounds (both natural and anthropogenic) have the potential to interfere with these functions.

Understanding appropriate terminology is essential in evaluating these questions. "Sound" is the term used to describe the effect a vibrating object has on the surrounding environment and may be scientifically defined as mechanical wave motion propagating in an elastic medium. "Sound" is a broad description of acoustic energy; there are two types of sounds from the perspective of receivers. "Signals" are sounds that contain biologically significant information (such as the location of a mate or predator). For marine animals as well as human underwater acoustic sensors, signals are quite rare in comparison to the wide range of extraneous sounds produced by both natural and anthropogenic sources. "Noise" is the term used to describe sound from a diffuse array of sources that does not convey biologically significant information. Nearly all natural and anthropogenic sound is in essence noise for receiving animals. Noise may be either benign background acoustic clutter or may in fact impede acoustic communication or have other adverse impacts. Use of the term noise presumes nothing about a sound's potential effect (neutral or negative) other than that the sound is not a meaningful signal for a particular receiver. In this regard, sounds produced by vessels may be viewed almost exclusively as noise for marine mammals (an exception would be an animal listening to an approaching vessel as a signal to avoid being struck by it). The term "vessel noise" may be used judiciously with respect to receiver effects, much in the same manner as "aircraft noise" is accepted verbiage by various stakeholders (industry, non-governmental organizations, scientists, and regulatory agencies) concerned with acoustic energy produced by aircraft. "Ambient noise" is a standard, scientifically accepted term used to describe, "the noise associated with the background din emanating from a myriad of unidentified sources" (National Research Council, 2003). Sounds from individual vessels contribute to overall ambient noise in some areas, greatly so in some areas such as in and around large harbors, although, as will be discussed, the extent of this is generally unknown.

The marine environment contains many natural sources of noise (*e.g.*, surf, wind, earthquakes, biological activity) that may impede acoustic communication and other vital functions, but which marine animals have presumably evolved to accommodate over the many millions of years they have existed in the marine environment. Human activities generate sound in the marine environment for a variety of reasons. There may be an explicit purpose, such as locating submerged objects or measuring environmental features. Additionally, sound may be produced as an incidental byproduct of industrial activities such as the construction of bridges or the transportation of cargo. Anthropogenic sounds are relatively new to the marine environment, having essentially begun with the advent of industrialization, and also have the potential to disturb behavior and/or interfere with important functions (Richardson *et al.*, 1995; National Research Council, 2003). Some of these effects may be somewhat obvious, such as breeding sea lions stampeding off a beach following an aircraft overflight or animals stranding following exposure to intense, discrete human sound sources. More subtle, though likely more widespread, effects may result from overall elevation in ambient noise levels due to human activities. Such changes in the local acoustic environment may result in reduced communication ranges for breeding marine mammals using sounds in reproductive interactions, interference with predator/prey detection relying on active or passive biosonar (the use of sound for biological purposes), or, in extreme cases, habitat avoidance. While relatively few empirical data on demonstrated communication ranges are available, calculations of detection zones in various conditions for some marine mammals demonstrate the potential for masking to substantially limit acoustic communication (*e.g.*, Janik, 2000; Southall *et al.*, 2003; Au *et al.*, 2004).

Much of the concern regarding potential impacts on marine mammals expressed by researchers, management agencies, and conservation groups has focused on the most obvious effects of human sounds produced intentionally for some purpose. Largely for this reason, oil and gas exploration using 'seismic' acoustic signals, military activities, and scientific research using acoustic sources have received the most attention in terms of assessing and mitigating noise impacts on marine mammals. Much of the research conducted on acoustic impacts has focused on these acoustic sources. Further, these groups tend to be the most advanced in terms of considering the environmental impacts of their acoustic activities. Recently, however, scientists have begun to consider how incidental sounds may affect marine mammal behavior, including acoustic communication. For instance, recent research has focused on various behavioral reactions of marine mammals to the presence of small vessels in coastal environments (*e.g.*, Buckstaff *et al.*, 2004; Foote *et al.*, 2004).

Specific knowledge is limited regarding the relative contributions of various anthropogenic sources to overall ambient noise in the marine environment, although a significant portion of human acoustic input in some ocean areas is apparently attributable to large vessels (see Wenz, 1962; Cato, 1976; Richardson *et al.*, 1995). In a single location off southern California, ambient noise levels in a frequency band consistent with sounds produced by large vessels have increased (along with vessel concentrations) at a rate of approximately 3 decibels (dB)/decade over the past thirty years (Andrew *et al.*, 2002). The potential for shipping noise to impact marine mammals by elevating ambient noise levels to the point of interfering with (or "masking") biologically important signals has been identified as an important consideration (Richardson *et al.*, 1995; National Research Council, 2003). To date, however, there has been fairly limited research and dialogue between the shipping industry, researchers, and government agencies regarding this acoustic environmental issue. These were largely the motivating factors for this international symposium.

Introductory and welcoming remarks

Speakers from a variety of organizations provided introductory comments prior to the technical sessions. These speakers highlighted the interests and commitments of their respective organizations to the identified goals of the symposium.

U. S. Representative Wayne Gilchrest (R-Maryland 1st District) provided the keynote address for the symposium, entitled "New Partnerships in Marine Conservation." This speech was framed around the following questions: "Who will benefit from what we do? Who will benefit from how we act?" Representative Gilchrest discussed some of the most important current issues the U.S. Congress is currently facing regarding marine mammals in general, and the marine noise issue in particular. These included ecosystem definitions, the FY2004 National Defense Re-authorization Act, re-authorization of the Marine Mammal Protection Act (MMPA) and the Magnuson-Stevens Fishery Conservation and Management Act, and the formation of a standing oceans committee (as recommended in the 2004 U.S. Commission on Ocean Policy Report). Representative Gilchrest stated that the U.S. Congress depends on this symposium report to provide detailed and current information regarding shipping noise and marine mammals and that the U.S. Congress might consider the adoption of a resolution on this issue.

Mr. Ted Kassinger, Department of Commerce General Counsel and Deputy Secretary Designate (since confirmed), opened the symposium by expressing appreciation for the "interest, time, and resources" of the symposium participants. He pointed to the anticipated doubling in the volume of marine cargo over the next several decades as one of many reasons for increasing scientific understanding of whether and the extent to which vessel noise impacts protected species. He identified three goals for the symposium: 1) generate a dialogue among stakeholders; 2) share current research and data; and 3) establish cooperative relationships and building on these meetings with the goals of safe commerce and marine stewardship.

Mr. James Walpole, NOAA General Counsel, acknowledged the significance of broad and proactive participation in the symposium across stakeholder groups. He emphasized that identifying and addressing solving the complex issues associated with vessel sounds and marine life is important to NOAA and that this effort must include a robust dialogue between vessel builders and operators, regulatory agencies, and scientists.

Dr. Roger Gentry, director of the NOAA Fisheries Acoustics Program, discussed the mandates of NOAA regarding anthropogenic noise under several federal statutes. He further chronicled the development of the Acoustics Program as well as the series of events leading to the hosting of this symposium. Dr. Gentry emphasized that this symposium was the first in a series of information-sharing meetings intended to form a community with regard to this issue among industry, government, and academia.

Ms. Kathy Metcalf, Chamber of Shipping of America (CSA), noted that noise, like other emissions from ocean-going commerce vessels, is an unintended consequence of normal operations. She particularly emphasized the transboundary nature of both shipping lanes and marine mammal distributions and stated that effectively mitigating shipping noise impacts on marine mammals will require international cooperation. Ms. Metcalf outlined the involvement of CSA in other environmental issues. She noted that currently, the shipbuilding industry does not consider noise emissions in the construction of vessels. Ms. Metcalf advocated doing what can be done now to mitigate this environmental issue, rather than waiting until everything is known about the range of possible impacts. She noted that industry action would be much more likely if collateral tangible benefits to ship quieting (*e.g.*, potential reduction in vessel operating costs related to reduction of propeller cavitation) could be identified.

Dr. John Hildebrand, Scripps Institution of Oceanography and U.S. Marine Mammal Commission (MMC), discussed the FY2003 U.S. Congressional appropriation directing the MMC to assess the current state of the issue of marine mammals and human noise impacts. He discussed the MMC's formation of a federal advisory committee, composed of individuals representing all stakeholder groups concerned with shipping noise impacts on marine mammals. Dr. Hildebrand outlined some of the technical aspects of sound emitted by vessels and some recent data suggesting possible compensatory reactions of whales to avoid masking from shipping noise off the Southern California Bight.

Ms. Laurie Allen, Director of NOAA Fisheries' Office of Protected Resources, expanded on Dr. Gentry's discussions of federal mandates regarding protected species and discussed certain relevant international organizations and treaties. She identified a significant NOAA priority as "maintaining the recovery and sustainability of protected species."

In addition to these introductory presentations, session chairs gave brief opening statements related to each technical session. These individuals, chosen for their involvement in various aspects of this environmental issue, provided remarks from their own perspectives, as well as those of their organizations. The session chairs included: CDR Paul Stewart (U.S. Navy, Director of the National Ice Center), Dr. Elena McCarthy

(Wood's Hole Oceanographic Institution), Dr. Richard Steiner (University of Alaska, Marine Advisory Program), Dr. Brandon Southall (NOAA Fisheries Acoustics Program and University of California, Santa Cruz), and CDR Karen Kohanowich (U.S. Navy, Office of the Assistant Secretary of the Navy for Environment).

Technical Sessions

Eighteen formal presentations were given in five technical sessions spanning the two-day meeting (for full agenda see Appendix 2). The technical sessions were titled:

I) Trends in the Shipping Industry and Shipping Noise
II) Effects of Noise on Marine Life
III) National and International Response to the Marine Noise Issue
IV) Developing Technologies for Monitoring Marine Noise, and
V) Vessel Quieting Technology: Application and Benefits.

Each presentation is available on the "materials" page of the official symposium website: http://www.shippingnoiseandmarinemammals.com/NOAAMaterials.cfm

Panel Discussion

Following the technical sessions, an invited panel consisting of subject matter experts, government personnel, and non-governmental organization representatives led a three-hour discussion in which comments and questions from the audience were considered. The general conclusions, needed research, and possible future actions for each technical session are summarized in the following sections of this report, followed by a synopsis of the panel discussion.

Session I – Trends in the Shipping Industry and Shipping Noise

The initial technical session of the symposium considered current information and predicted trends in the number, type, and routing distributions of large commercial vessels in the ocean. Also considered were measurements of radiated acoustic fields for certain vessel classes (predominately large ships) and trends in ambient noise levels potentially related to increased shipping density in various ocean areas.

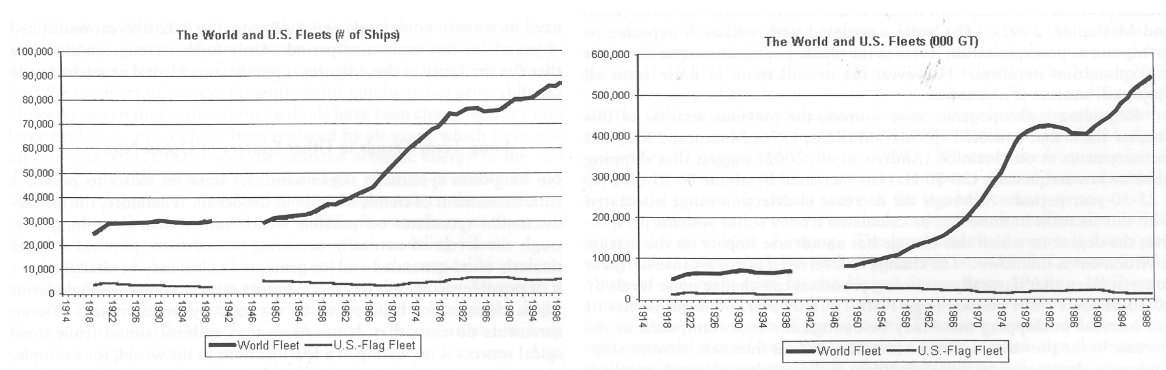
Commander Paul Stewart (U.S. Navy, National Ice Center) chaired this technical session. He discussed various projections being made by the National Ice Center indicating that the Arctic will be partially or largely ice-free in summers within 30-50 years. A clear result of such an environmental change will be a re-routing of commercial vessel traffic to and from Asia to take advantage of the Northwest Passage. CDR Stewart noted that the technical speakers would speak to the immediate need for passive acoustic monitoring in areas of anticipated increases in vessel activity, such as the Arctic.

Technical presentations were given by: Dr. George Frisk of Florida Atlantic University; Dr. Stephen Wales of Naval Research Laboratory; and Mr. Mark Womersley of British Maritime Technologies, Asia-Pacific. Specific conclusions regarding the most significant aspects of these presentations, needed research, and possible action items are summarized below. Although not a formal technical presentation, Dr. Edmund Gerstein presented some recent near-surface measurements he and others obtained of vessel sounds at very close ranges and various aspects during the panel discussion.

Conclusions

a) Commercial fleet: current and future numbers and trends

The worldwide commercial fleet (tankers, dry bulk vessels, container ships, and other large ocean-going vessels) grew from approximately 30,000 vessels (~ 85,000,000 gross tons) in 1950 to over 85,000 vessels (~ 525,000,000 gross tons) in 1998 (Fig. 1).



(a) (b)

Figure 1. World and U.S. shipping fleet trends during the 20th century in terms of total numbers of vessels (a) and thousands of gross tons (b). (Source: National Research Council, 2003)

Between 1950 and 1998, the U.S. flagged fleet actually declined from about 25,000 to under 15,000 and currently represents a small fraction of the world fleet.

From U.S. Department of Transportation Maritime Administration (MARAD) statistics presented by Mr. Womersley, foreign waterborne trade in the U.S. increased from 718 to 1,164 million gross metric tons over a 20-year period (1981-2001), a rate of 2.45% per year. Dr. Frisk provided statistics on increases in global commercial shipping over a similar period. From 1985 to 1999, world seaborne trade doubled to 5 billion tons (representing a 38% increase in gross tonnage), and currently includes 90% of total world trade (Westwood *et al.*, 2002). Container shipping movements represent the largest volume of seaborne trade. Uncertainty remains regarding precisely how international shipping volumes and densities will continue to grow in the future. However, the above statistics, as well as a recent federal report on U.S. transportation systems (U.S. Dept. of Transportation, 1999), support the general conclusion that the international shipping fleet will continue to grow at current or greater rates in the foreseeable future. An approximate doubling in the number of large vessels in the world's oceans over the next two to three decades is consequently expected.

Shipping densities in specific areas and trends in routing and vessel design are in fact as (or more) significant than the total number of vessels. International trade routes are transient and largely dependant upon global economic factors. World market variables are very important in terms of determining trans-oceanic vessel routing and densities. Coastal routes for large commercial vessels are relatively well defined, while offshore routes are much less predictable and dependant on a variety of environmental and economic factors. Densities along existing coastal routes are expected to increase to varying degrees both domestically and internationally. New routes are expected to develop as new ports are opened and existing ports expanded.

Trends in vessel propulsion systems are advancing toward faster ships operating in higher sea states for lower operating costs. In terms of other design features, ships are becoming narrower, and using medium speed diesels (as opposed to high speed diesel or gas turbine), with hull designs involving catamarans, trimarans, and pentamarans. Container vessels are expected to become larger along certain routes in the near future. This trend is not immediately expected for tankers, however.

b) Sounds produced by individual vessels

Large commercial vessels produce relatively loud and predominately low frequency sounds, the exact characteristics of which depend on vessel type, size, and operational mode. Most (83%) of the acoustic field surrounding large vessels is the result of propeller cavitation (when air spaces created by the motion of propellers collapse). When ships cavitate, relatively little acoustic energy is transmitted into the water from on-board machinery or movement of the vessel through the water. However, the respective contributions of various sources to radiated sound depend on the distance from the vessel at which measurements are made. This is because different vessel elements produce sounds of different frequencies, which are differentially transmitted in water (low frequency sound propagates most efficiently). These differences are more fully considered in the "Conclusions" section of technical session V.

Much of what is known regarding radiated sound fields for various large vessel types is summarized in Richardson *et al*., (1995). Dr. Wales presented recent data on acoustic source levels from individual commercial vessels (also see Heitmeyer *et al*., 2004). These data are generally consistent with previous results, but provide more comprehensive understanding of the similarities in radiated sound frequencies from large commercial ships and the range of variability in source levels than previously available. Their results also provide further indication that near-surface phenomena (Lloyd mirror effect) can significantly affect acoustic fields for receivers at shallow depths. In contrast to earlier data obtained for ships with largely obsolete propulsion systems, Heitmeyer *et al*. (2004) found that acoustic source levels are not a function of speed for modern diesel vessels across the majority of their nominal operations. There is significant aspect-dependence of radiated vessel sound fields – levels are approximately 10-15 dB lower off the bow and stern than sides. Source (propeller) depth is also important in terms of long-range propagation. This is a potentially significant historical factor in ambient noise trends due to shipping, as propeller depths have increased with increasing vessel size.

c) Trends in marine ambient noise: contributions from vessels

The sounds of individual vessels can contribute to overall ambient noise levels on variable spatial scales. Whether such contributions have adverse impacts on marine mammals, and their biological significance, is unknown. A critical consideration is how sounds from multiple vessels in an area contribute to the overall ambient noise, as well as changes on various temporal scales. Unfortunately, there are no empirical measurements of ocean ambient noise conditions prior to the introduction of human machinery into the marine environment. Dr. Frisk presented an estimate of nominal ocean ambient noise levels around 1900 (50 dB re: 1μPa in the 100-200 Hz band consistent with sounds produced by large commercial vessels) using current conditions in an area off Australia largely devoid of human activity.

In the 1950s, Ross (1976) estimated the ambient noise level in this frequency band to be about 72 dB (re: 1μPa) off the coast of California, while Andrew *et al*. (2002) later measured ambient noise in this area to be approximately 88 dB (re: 1μPa) (Fig. 2).

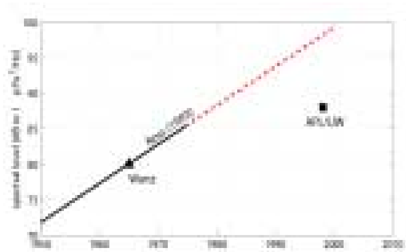


Figure 2. Ambient noise measurements in the 100-200 Hz band measured off California in the 1950's (Ross, 1976) and APL/UW noise measurements in the late 1990's (Andrew *et al*., 2002)

The combined data suggest an increase of approximately 3 dB/decade in this area. Over this period, commercial shipping density increased dramatically and is the most probable source of the increase, given that natural sound sources would be unlikely to change so dramatically over such a relatively short time (Andrew *et al*., 2002).

There appear to be mathematical relationships between various economic indicators of industry growth (*e.g*., gross shipping tonnage) and increasing ambient noise levels. These relationships may provide a basis for predicting increases in ocean ambient noise conditions in the future. However, a combination of empirical ambient noise measurements (extremely limited) and predictive modeling is needed to more fully develop these relationships and understand trends in ocean ambient noise.

Needed research and possible future actions

- Develop a global passive acoustic monitoring network to measure ambient noise levels in a variety of locations. This network should be flexible in terms of sampling regimes and include both relatively short term deployments as well as year round, long-term sensing capabilities. Assess the contributions of vessel sound to overall ambient noise relative to other anthropogenic sources and how this relationship changes over time. Baseline ambient noise measurements from relatively pristine acoustic environments likely to experience future industrial activity should be prioritized (*e.g*., the Arctic).
- Integrate empirical ambient noise data over time with detailed information on trends in vessel design and operation to assess the most appropriate global economic indicators in terms of shipping and other vessel noise.
- Determine how changes in vessel size, shape, and propulsion systems affect radiated noise levels for the next generation of large commercial vessels.
- Assess whether advances in propulsion systems for increased operating efficiency lead to reduced noise radiation (*i.e*., are there collateral benefits of noise reduction in terms of increased operating efficiency?).
- Determine (via some direct measurements followed by modelling) how increases in vessel routing density or the development of new routes (particularly coastal) will contribute to local ambient noise levels.
- Determine whether marine traffic impact assessments and risk-based methodologies offer opportunities to understand and potentially mitigate anthropogenic noise impacts on marine mammals.

Session II – Effects of Noise on Marine Life

The second technical session of the symposium included presentations on hearing and the effects of noise on various marine animal groups. Speakers particularly focused on what is known about the effects of vessel noise on behavior and hearing in marine mammals and fish.

Dr. Elena McCarthy (Wood's Hole Oceanographic Institution) chaired this technical session. She discussed the importance of having sufficient information regarding the possible effects of a specific noise source in considering guidelines or regulations on the operation of such sources.

Technical presentations were given by: Dr. Colleen Kastak of the University of California, Santa Cruz; Dr. Brandon Southall of the NOAA Acoustics Program and the University of California, Santa Cruz; Dr. Douglas Nowacek of Florida State University; and Dr. Mardi Hastings of the Office of Naval Research. Specific conclusions regarding the most significant aspects of these presentations, needed research, and possible action items are summarized below.

Conclusions

a) Underwater hearing in marine animals

Hearing capabilities have been studied for 22 of the approximately 125 species of living marine mammals and approximately 100 of the 25,000 species of bony fish (most of which are freshwater species). A significant limitation of the available data is that many of these studies, particularly for marine mammals, involve very small sample sizes (often a single individual). Thus, our knowledge of intra-specific variation in hearing capabilities is very restricted even for the species that have been tested. Based on these studies, some general observations regarding hearing capabilities in marine vertebrates are possible. Drs. Kastak and Hastings presented information on various techniques for determining or estimating hearing sensitivity in marine animals and the results obtained to date. Both speakers noted that variability in hearing characteristics has been observed at the level of individuals, sex and age classes, populations, and species. Given these considerations, marine mammals may be roughly segregated into functional hearing categories based on nominal auditory sensitivity.

Of the "cetaceans" (whales, dolphins, and porpoises), "mysticete" (or "baleen") whales are thought to be most sensitive to low frequency sounds (~ 0.01 kHz to 5 kHz) based on characteristics of their auditory morphology and sound production. No empirical data exist on mysticete hearing. Most "odontocete" (or "toothed") cetaceans that have been directly tested have relatively good hearing sensitivity across a broader range of mid to high frequencies (~ 4 kHz to 100 kHz). A few odontocete cetaceans, including harbor porpoises and river dolphins, hear relatively similarly in this broad range, but appear to be specialized for hearing very high frequency sounds (~ 4 kHz to 150 kHz or higher).

"Pinnipeds" (seals, sea lions, and walrus) are fundamentally different from other marine mammals in that they are amphibious mammals performing important life functions both above and below water. Consequently, they have a number of auditory adaptations enabling fairly sensitive hearing across fairly wide frequency bands both in air and water. They can be segregated into two functional underwater hearing groups. "Otariids" (sea lions and fur seals) have been shown to be sensitive to a fairly wide range of mid frequencies (~ 1 kHz to 30 kHz). "Phocid" (or "true") seals as well as walruses are generally capable of hearing across a wide range of low to mid sound frequencies (~ 0.2 kHz to 50 kHz), although there are some notable exceptions. The differences in hearing bandwidth in air are less striking between the phocids and otariids.

"Sirenians" (manatees and dugongs) appear to have a relatively narrower range of hearing sensitivity (~ 5 kHz to 30 kHz) based on the limited available data. Essentially nothing is known about hearing in polar bears and sea otters.

Fish may similarly be grossly categorized based upon auditory anatomy and function. Hearing "generalists" lack any sort of auditory mechanisms for improving hearing sensitivity. These species generally have relatively poor hearing sensitivity over a narrow band of low sound frequencies (~ 0.1 to 1.0 kHz). Hearing generalists are believed to comprise the majority of species. Hearing "specialists" have unique anatomical features that afford them greater hearing sensitivity over a relatively wider range of low sound frequencies (~ 0.1 to 3.0 kHz). Recent data indicate that some fish have specializations that allow them to detect ultrasonic sounds (~ 20 to 80 kHz) although only at relatively high sound pressure levels.

b) Effects of vessel noise on marine animal hearing

Noise exposure may result in a range of effects on auditory and non-auditory systems. Noise may be detectable, but have no effect on an animal's behavior, hearing, or physiology. Signals of interest may be "masked" (or interfered with) by the presence of noise. More intense or prolonged exposure may result in either temporary or permanent changes in hearing sensitivity. Noise may also induce direct physical trauma to non-auditory structures or, in fish, increase egg mortality.

Except for extremely busy shipping lanes or harbors, in which resident species could theoretically experience some hearing loss over long periods of exposure to industrial activity, Dr. Southall argued that the primary auditory effect of vessel noise on marine animals to consider is the masking of biologically significant sounds. Auditory masking occurs in marine mammals in a similar manner as terrestrial mammals. The fundamental consideration with regards to the potential for masking is the frequency relationship between signal and noise. Because most of the acoustic energy radiated from large commercial vessels is below 1 kHz, the greatest potential for masking exists for groups of marine animals that produce and receive sounds in this band for critical biological functions. In terms of communication signals, this primarily includes the mysticetes, pinnipeds (particularly the phocids), and fish.

c) Effects of vessel noise on marine animal behavior

A limitation in considering the effects of anthropogenic noise on marine mammal behavior is that most studies are observational rather than experimental. Thus, in many conditions, particularly with regards to the effects of noise from large vessels on marine mammal behavior, available data lacks appropriate controls. Dr. Nowacek indicated that this was an area of critical research need and discussed some progress that has been made in this area.

Much of the recent data on the effects of vessel activities on marine animals involve craft considerably smaller than tankers, container and dry bulk ships, and cruise liners. Some of these observations are presumably relevant to commercial shipping noise as well, though this remains largely an unanswered question. Dr. Nowacek presented data indicating that various dolphin and whale species exposed to close physical approaches as well as noise from different vessels may alter motor behaviors (Janik and Thompson, 1996; Nowacek *et al*., 2001; Williams *et al*., 2002; Hastie *et al*., 2003) as well as vocalization characteristics (Lesage *et al*., 1999; Au and Green, 2000; Van Parijs and Corkeron, 2001; Buckstaff, 2004; Foote *et al*., 2004). These changes in behavior have both direct energetic costs and potential effects on foraging, navigation, and reproductive activities.

Recently, studies have been conducted involving controlled sound exposure of animals fitted with specialized tags for monitoring movements, received sound fields, and, increasingly, physiological parameters. Using such techniques, manatees have been shown to respond to approaching vessels by changing fluke rate, heading, and dive depth (Nowacek *et al*., 2004a). Perhaps the most important experiment to date concerning the effects of shipping noise on marine mammal behavior involved the use of acoustic tags and controlled exposure experiments with north Atlantic right whales. Five of six individual whales responded strongly (interrupted dive pattern and swam rapidly to the surface) to the presence of an artificial alarm stimulus (series of constant frequency and frequency modulated tones and sweeps), but ignored playbacks of vessel noise (Nowacek *et al*., 2004b).

Needed research and possible future actions

- Improve estimates and obtain direct measurements (see next point) of hearing sensitivity in representative large whale species. Semi-aquatic species inhabiting coastal environments (*e.g*., sea otters) in which no auditory data exist are also areas of needed research.
- Continue to develop new technologies (auditory evoked potential (AEP) audiometry) to test hearing in marine animals that are more rapid, more objective, and can be used on more individuals than possible with current behavioral techniques. Simultaneously, continue research on basic acoustic functions in trained captive species for comparative purposes and to further understand higher auditory processing mechanisms.

- Measure detection thresholds for real-world acoustic signals (for natural as well as anthropogenic sources). Conduct these hearing studies in both silent conditions and using real-world masking noise (*e.g*., large vessel noise).
- Perform additional and more extensive controlled exposure experiments on behavioral reactions of marine animals to vessel noise. In other words, determine species-dependent dose/response relations for noise from various vessel classes.
- Continue to investigate behavioral responses of marine animals to periods of increased ambient noise levels (from both natural and anthropogenic factors), including changes in calling characteristics and other acoustic displays.
- Determine the biological significance of vessel noise exposure. Conduct comparative assessments of population demographic rates and other vital functions in areas of relatively high and low commercial shipping density. In order to avoid confounding results, careful attention should be paid to selecting comparative sites that have other critical environmental variables in common.
- Conduct habituation/dishabituation experiments on both captive and free-ranging marine mammals.

Session III – National/International Response to the Marine Noise Issue

The third technical session of the symposium included presentations on recent considerations of anthropogenic noise generally in an international regulatory context, how the environmental and research communities have responded to the marine noise issue, and what steps are needed in terms of research on marine mammals, specifically regarding shipping noise.

Dr. Richard Steiner (University of Alaska, Marine Advisory Program) chaired this technical session. He contended that commercial shipping represents one of the largest sources of environmental pollution in the world oceans. Dr. Steiner advocated not waiting until overwhelming evidence of possibly difficult to detect impacts is available before initiating proactive measures to minimize human sound production underwater and mitigate its effects on marine life.

Technical presentations were given by: Dr. Elena McCarthy of Wood's Hole Oceanographic Institution; Joel Reynolds of the Natural Resources Defense Council; Dr. Robert Gisiner of the Office of Naval Research; and Dr. Peter Tyack of Wood's Hole Oceanographic Institution. Specific conclusions regarding the most significant aspects of these presentations, needed research, and possible action items are summarized below.

Conclusions

a) Current status of international legal and regulatory considerations of underwater noise (as interpreted by session presenters)

Noise produced by vessels incidental to their operation has, under certain conditions, been interpreted as causing incidental harassment of marine mammals. There is general acceptance within the scientific, regulatory, and environmental communities that commercial shipping is one of the most significant anthropogenic sources of underwater noise, but there are currently no explicit guidelines or regulations in place in the United States or any other nation governing noise produced as a byproduct of commercial vessel operation vis-à-vis marine mammals. While there may be general consensus that vessel noise is fairly widespread, there is much less agreement regarding how this may be affecting marine mammal populations and the extent to which currently available data support the development of effective regulations. Several speakers postulated that more effective approaches at limiting or reducing vessel noise might involve economic incentives or collateral benefits of noise reduction to the industry (*i.e.*, noise reduction procedures may improve operating efficiency and thus reduce operating costs). It remains unclear, however, whether sufficient evidence exists to establish the need for vessel-quieting technologies.

Throughout this symposium the transboundary characteristics of both marine mammal distributions and noise generated from large, ocean-going vessels was identified. Dr. McCarthy and Mr. Reynolds focused on the international nature of anthropogenic noise issues, the ability of noise generated outside sensitive ecosystem areas to enter them, and current considerations of noise as a pollutant under international law and various agreements. Both speakers contended that certain statutes and conventions already in place (given below) may be applicable mechanisms for encouraging and/or enforcing noise reduction in future commercial operations.

Dr. McCarthy stated that vessel noise, as a form of incidental harassment of marine mammals, could be subject to the U.S. Marine Mammal Protection Act (MMPA), Endangered Species Act (ESA), and National Environmental Policy Act (NEPA) within the exclusive economic zone of the United States. This interpretation, however, has no precedent within the regulatory history of the responsible agencies of the U.S. government. Further, vessel noise could be interpreted, according to Dr. McCarthy and Mr. Reynolds, as either a particular environmental concern or specifically as a form of marine pollution under a variety of international agreements including: the United Nations Convention on Law of the Sea (UNCLOS); the Particularly Sensitive Sea Areas (PSSA) resolution of the International Maritime Organization (IMO); the International Convention for the Prevention of Pollution from Ships; the joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP), which includes IMO; and various European regional seas agreements. A divergence of opinions regarding this interpretation was expressed in the panel discussion. In the view of the presenters in this technical session, an ecosystem-based approach to conservation management regarding marine pollution appears to be emerging under IMO as well as other conventions and agreements. However, there are currently no explicit and binding international regulations regarding the impacts of anthropogenic noise sources, including vessels, on marine mammals.

b) Summary of recent and future research on marine mammals and noise

Three general areas of recent efforts within the scientific community were identified in Dr. Gisiner's presentation: empirical research; emerging technologies to improve research; and public/professional education on relevant issues.

Recent scientific research on marine mammals and noise, largely funded by the Office of Naval Research, include: estimating hearing capabilities using various behavioral and anatomical techniques; measuring sub-injurious impacts on hearing (temporary threshold shift, or TTS); estimating lethal and injurious effects of acoustic exposure; using controlled exposure experiments to quantify behavioral reactions; and improving information on animal abundance, distributions, and habitat use. Recent data have been obtained in each of these areas and are particularly useful when incorporated within risk assessment models for specific conditions.

Technological advancements allowing for some of the above advancements include: passive and active acoustic sensors; radar; infrared; lidar; satellites; improvements in tags and telemetry devices; new tools for anatomical and auditory investigations; measures of physiological stress; and advancements in databases and archival tools. Dr. Gisiner also emphasized the importance of the scientific community's continued involvement in both direct public and professional education.

Dr. Tyack reviewed some of the recent advances made in sensing technologies and their applications to address marine mammal behavioral reactions to noise, including vessel noise. He also identified some of the key research questions pending on this issue (see below).

c) Technologies for mitigating human acoustic impacts on marine mammals

Current technologies are implemented for sound sources other than vessels in order to minimize the potential for acoustic trauma or to exclude animals from certain areas. Their direct application in terms of mitigating the possible effects of vessel noise on marine mammals is unknown. However, they were discussed at the meeting in order to demonstrate some of the approaches taken regarding other anthropogenic sources and consider which, if any, may be applicable to vessel noise.

Certain techniques used in reducing impacts of some human sources on marine mammals involve detecting marine mammals around operations. Historically, visual surveillance techniques have been used, which have considerable limitations. More recently, both passive and active acoustic detection technologies as well as radar have been implemented with varying degrees of success in detecting and locating marine mammals. Efforts toward mitigation may also include modification or removal of source operations, avoiding animals and/or habitats, "ramping up" source operations, and using aversive acoustic alarms to remove animals from operation areas in which they might be negatively impacted.

Needed research and possible future actions

- Quantify the economic impacts of re-routing large vessels around certain areas and other sensitive habitats. Compare the advantages and disadvantages of such measures to incorporating quieting technologies on large vessels.
- Consider the typical movement patterns of commercial vessels into major global ports (generally east-west within waters of the continental U.S.) relative to the movement patterns of migrating marine mammals (generally north-south).
- Determine appropriate international institutional mechanisms to address spatial relationships and interactions between vessel noise and marine mammals.
- Consider the feasibility of effective enforcement if national or international regulations regarding vessel acoustic emissions were put into place. Compare this assessment with potential results of using economic incentives for quieter future vessels.
- Define ocean noise budget from the perspective of marine mammal hearing. Compare data obtained from the deployment of various noise monitoring networks using frequency-specific weighting networks developed for specific marine mammal groups.

- Conduct medium-scale studies mapping underwater noise from vessels and other sources, along with marine mammals and factors affecting distribution.
- Determine the ranges over which large whales use communication signals in reproductive contexts (comparative studies in variable noise conditions).
- Continue and accelerate the development of acoustic tag technologies and deployments. Determine the relationship between acoustic dosage and behavioral response both within and between species in a variety of environmental conditions.
- Develop innovative methods to reduce the risk that vessels injure or kill whales by collision. However, the use of active acoustic alarms on vessels in efforts to prevent or minimize ship strikes should be carefully considered in relation to this issue of noise and its impact on marine mammals in general and more specifically in the context of apparent habituation to vessel sounds that has been observed. The fact that these alarms contribute to overall ambient noise and/or may disturb other species should be considered.
- Consider the potential conflicts/trade-offs between quieting vessels to mitigate communication masking and the potential that quieter vessels may be more difficult for marine mammals to detect and thus avoid. Consider effects of speed restrictions enacted to prevent ship strikes in the context of noise pollution (slower ships take longer to transit through a specific area emitting noise for a longer period of time within it; however slower transit speeds may reduce cavitation noise).

Session IV – Developing Technologies for Monitoring Marine Noise

The fourth technical session of the symposium included presentations on current and proposed passive acoustic monitoring networks on local, regional, and global scales. Additionally considered were new techniques for assessing trends in ocean ambient noise and estimating vessel densities in ocean areas of specific interest.

Dr. Brandon Southall chaired this technical session. At the outset, he discussed the logic for having a technical session on existing and emerging sensing technologies. Dr. Southall argued that our future ability to adequately consider anthropogenic noise impacts on populations of animals and ultimately ecosystems depends critically on the amount and quality of information on trends in ambient noise in different marine areas. He indicated that speakers for this technical session were selected for the purpose of addressing current data bearing on these questions and emerging technologies to improve it in the future.

Technical presentations were given by: Dr. Christopher Clark of Cornell University; Dr. David Mellinger of Oregon State University; Dr. Anthony Eller of Scientific Applications International Corporation; and Mr. Jonathon Mintz of the Center for Naval Analyses. Specific conclusions regarding the most significant aspects of these presentations, needed research, and possible action items are summarized below.

Conclusions

a) Past and current passive acoustic ocean monitoring

Many of the efforts to monitor ambient noise in the oceans conducted to date were discussed in this technical session. Dr. Eller discussed detailed ambient noise measurements made at a specific site in the Gulf of Mexico and outlined specific methods for comparing and interpreting noise data. Dr. Mellinger discussed ambient noise monitoring data from several discrete sites in the context of integrating efforts into larger acoustic observation systems. Dr. Clark outlined the challenges to and technological advances in monitoring ocean ambient noise over a regional area, with specific discussion of relevant spatiotemporal variables.

The speakers considered underwater acoustic monitoring, with varying degrees of detail and effort, conducted in various locations. In the north Pacific, sources include the: U. S. Navy's Church Opal and Church Anchor projects; unclassified U.S. Navy SOSUS data from undisclosed locations; NOAA/Pacific Marine Environmental Laboratory (PMEL) measurements off the East Pacific Rise; and measurements separated by 30 years off southern California (Andrew *et al*., 2002). In the north Atlantic, ambient noise data have been obtained with: U.S. Navy SOSUS monitoring stations; regional monitoring networks of "pop-up" acoustic recorders operated by Dr. Clark and others around Cape Cod and Great Britain; and NOAA/PMEL hydrophones on the mid-Atlantic ridge. Recent data on local noise monitoring efforts were also reported from studies in the Gulf of Mexico (Dr. Eller's presentation), Sea of Cortez, Mexico (Dr. Clark), and

Ligurian Sea (Dr. Clark). Additional noise measurements have been conducted at discrete locations around the world, but were not discussed during this technical session.

Ocean acoustic measurements conducted to date clearly indicate diurnal and seasonal patterns in both natural and anthropogenic sound sources in most environments. Also noted were the large deviations from nominal ambient noise conditions that may be observed during a large discrete disturbance such as the passage of a large storm or a very nearby vessel. Measuring deviations from mean or median ambient values is useful in describing noise variability in an area. The presence of such variability points to the possibility of obtaining very skewed information about typical noise parameters in an area if sampling is not sufficiently frequent or prolonged.

While speakers acknowledged that current data on ambient noise are highly limited, patterns are emerging. The available ambient noise data support the conclusions presented in technical session I by Dr. Frisk that noise levels in areas of increased industrial activity are higher (and rising) than those in more pristine areas.

b) Proposed ocean acoustic monitoring network

There was agreement among the technical speakers with the specific statements made in the NRC (2003) report (quoted in Mellinger's presentation) regarding the need for passive monitoring of ocean sound from all sources. The presenters additionally concurred on the need for comparative measurements in locations of variable industrial activity across seasons over multiple years.

Dr. Mellinger described emerging plans for a global acoustic monitoring network based on a March 2004 NOAA planning workshop on this issue held in conjunction with the University of Rhode Island. In designing a global system, relevant questions must be considered regarding marine mammal distributions and critical habitats, industrial activity densities, and system design element and sampling regimes, all of which may vary considerably.

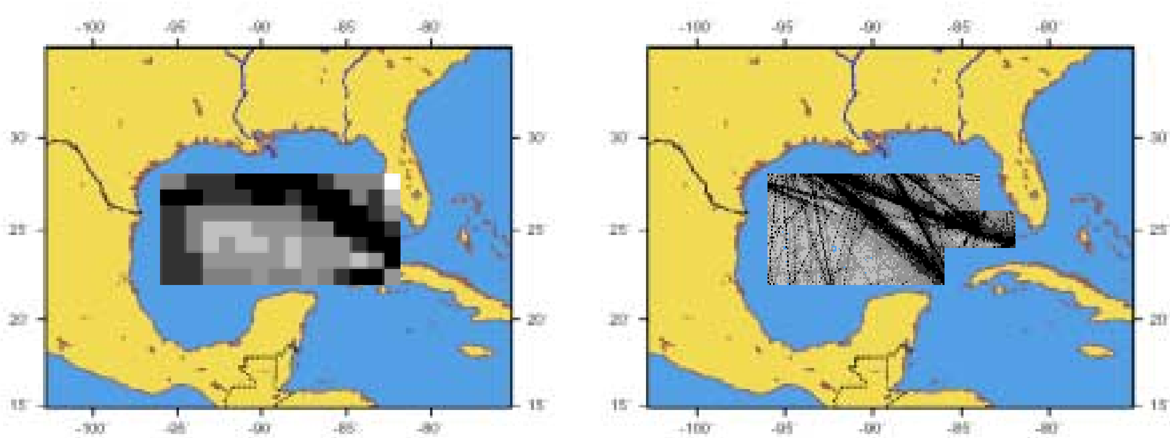
In terms of monitoring sites, Dr. Mellinger proposed measurement locations around the world that would be needed to specifically address vessel noise. These included sites in areas of variable vessel densities (*e.g.* known shipping lanes vs. areas less frequently transited) across ocean basins of variable industrial activity (*e.g.*, North Atlantic vs. Indian Oceans). The latter of these comparisons is needed to assess adequately the apparent trend that ocean ambient noise conditions are 10-20 dB lower in the southern hemisphere than the northern hemisphere (Cato, 1976). Dr. Mellinger additionally proposed particularly focusing on ports and harbors of various sizes, which would provide comparisons based on differences in vessel classes, including measurements of noise directionality over a relatively wide bandwidth. He reiterated concerns regarding potential increases in vessel traffic in the Arctic and proposed a number of monitoring locations that the global observing system should include (beginning immediately) in order to track related changes in Arctic ambient noise conditions.

Various monitoring platforms must be used in the global noise-monitoring network. These will likely include autonomous devices (single or arrays of hydrophones for archiving data intermittently sampled) as well as integrated cabled arrays. Each has advantages and disadvantages in terms of cost, data quantity and quality, and flexibility. A flexible approach, relying on a combination of data acquisition platforms and sampling regimes taking advantage of existing ocean observing systems, is called for. Additionally, there is a need to coordinate to the greatest extent practical with existing ocean observing systems (*e.g.*, the Integrated Ocean Observing System (IOOS), or the NSF ORION project) implemented for other purposes). Placing passive acoustic sampling capabilities on platforms intended for other sensing purposes will likely be much cheaper and easier than developing autonomous acoustic sampling systems independently. Further, integrating passive acoustic sampling with sensors measuring other oceanographic features will enhance data collected for both purposes.

c) Determining vessel densities in specific ocean areas

Knowing with reasonable precision the nominal vessel densities in regions of the ocean is a prerequisite for accurately designing effective passive acoustic monitoring with regards to vessel noise. The current standard for estimating vessel traffic in specific regions of the ocean is the Historical Temporal Shipping (HITS) database. HITS uses data on port calls and known vessel routes to produce estimates of vessel densities in 1°-longitude by 1°-latitude sectors. This degree of precision is insufficient for certain considerations.

Mr. Mintz described a new technique developed by the Center for Naval Analyses (CNA) that increases the resolution of vessel density estimates by an order of magnitude, providing densities in 0.1° degree areas (Fig. 3).



(a) (b)

Figure 3. Example of vessel density estimates in the Gulf of Mexico using HITS method (a: 1° degree resolution) and advanced techniques developed by CNA (b: 0.1° degree resolution) (Source: J. Mintz and R. Filadelfo presentation at the symposium).

This new approach uses sporadic vessel positions, interpolations, and other information from U.S. Navy and Coast Guard positional databases. Temporal resolution is also enhanced so that hourly outputs of the database are possible. Using the CNA database, relatively clear commercial shipping patterns emerge compared with the coarse HITS data. This developing methodology allows for consideration of vessel routes relative to military training areas, marine sanctuaries, and migratory corridors with much greater accuracy than previously possible.

Needed research and possible future actions

- Replicate local and regional underwater acoustic monitoring efforts in untested ocean areas as a means of more fully understanding variability in both natural and anthropogenic sources on daily, seasonal, and annual timescales.
- Develop a comprehensive global passive acoustic observing network consisting of integrated local and regional elements. A high degree of technical and interpretive consistency is needed in the various system elements. The network should be designed to maximize the comparative power of acquired ambient noise data in addressing specific questions. As advocated by the 2003 National Research Council report, the global acoustic monitoring system will ideally be integrated into national and/or international ocean observing systems designed to sense other environmental parameters.
- As included in needed research following technical session III, speakers in this session identified the need to more fully understand how large whales use low frequency sounds in social and other contexts. Determine the range over which large whales communicate, and whether shipping noise in certain areas is reducing or otherwise affecting these ranges.
- Integrate CNA database results on shipping density in specific areas with empirical ambient noise measurements to determine appropriate proxies for estimating noise from shipping in untested areas.
- Assess available information in classified military databases that can be used in developing noise budgets and investigating temporal trends in ambient noise at specific locations.

Session V – Vessel Quieting Technology: Applications and Benefits

The final technical session of the symposium considered current information and predicted trends in vessel quieting technologies. Detailed technical information on both commercial and military vessel quieting technology was discussed as well as some of the possibilities and limitations to the commercial shipping industry.

Commander Karen Kohanowich (U.S. Navy, Office of the Assistant Secretary of the Navy for Environment) chaired this technical session. She explained the Navy's interest in ocean sound in the context of two ingredients of the sonar equation: source signal strength and ambient (masking) noise. The Navy strives to reduce the vulnerability of their ships to submarine attack, and therefore has become a leader in ship quieting technology. High ambient noise levels can be both advantageous if one is avoiding detection and disadvantageous if one is attempting to detect another vessel. Therefore, the Navy's interest in ocean noise is primarily focused on a tactical level of ambient noise measurement and prediction. CDR Kohanowich added that for this reason, and because of resource limitations, the U.S. Navy does not hold large volumes of temporal records of ambient noise across wide areas of oceans. She stated that SOSUS data is tactical and so was not archived systematically. She also stated, however, that the U.S. Navy stands ready to assist as possible in providing information on ship noise quieting and ambient noise characterization techniques.

Technical presentations were given by: Mr. Willem Verboom of TNO TPD, Delft University, The Netherlands and Mr. Gary Jebsen of the Naval Sea Systems Command (NAVSEA). Dr. Neal Brown (NAB and Associates) was scheduled to present "Vessel Quieting Technologies: Cost/Benefit Considerations." He was unable to attend the meeting, but some of the material that would have been presented is included in this report. Specific conclusions regarding the most significant aspects of these presentations, needed research, and possible action items are summarized below.

Conclusions

a) Commercial and military vessel quieting technologies

The military has a relatively long history of quieting vessels to reduce their acoustic signature and thus vulnerability to detection by enemy passive acoustics. Commercial applications of ship quieting technology are more recent and less widespread, though growing in such areas as cruise ship and acoustic research vessel design. There are some commonalities in both military and civilian contexts to reduce radiated vessel noise based purely on the physics of sound and constraints of vessel design. Efforts at reducing noise are most effective when incorporated into the design of ships, though retrofitting of vessels may also be successful to varying degrees, but certainly at relatively high cost.

For any vessel, commercial or military, propeller motion, onboard machinery, and turbulence around various external ship elements generate sound through direct and secondary paths. "Flanking" or indirect (secondary) paths (such as sound transmission from engine mounts through power cabling or emission ducts and ultimately into the hull) may be as effective in terms of transmitting acoustic energy into the environment as direct paths (from engine block directly to hull). Failure to mitigate sufficiently transmission via all flanking paths may result in acoustic source levels comparable to those obtained with no quieting technologies at all. At low ship speeds, machinery noise dominates and is characterized primarily as being low in frequency, although main gearboxes and gas turbines may produce tones in the 1-4 kHz range. As vessel speed increases, both flow and propeller noise increase, with the former producing very low frequencies. These differences are considerably important in considering relatively long range propagation (again, low frequencies propagate most efficiently in water).

As discussed in earlier technical sessions, the majority of radiated sound from large vessels is the result of propeller cavitation. Therefore, not surprisingly, much of the effort in quieting vessels focuses on propeller design and operation that limit or reduce cavitation. Propellers designed to minimize cavitation may have: tips without added weight, large diameters, low RPMs, long blade lengths, bulbs on the tips, and/or refined trailing edges. Additionally, variable pitch propulsion systems will produce (very) high sound levels when used outside their design pitch. Optional configurations of propellers, such as placing them deeper in the water column through the use of propeller pods, are also used to varying degrees in designing quiet vessels.

For minimizing mechanical acoustic radiation from vessels, in addition to developing quieter equipment, a number of sound isolating and absorbing techniques are employed. Modern diesel electric engines may be fitted with resilient isolation mounts (in some cases double mounts), flexible hoses, and pipe hangers to minimize radiated sound. Acoustic filters, desurgers, and flow control valves may also be used to minimize sound emanating from fluids flowing to and from engine equipment. Dr. Brown cautioned against efforts to use vibration-isolation mounting for direct-drive main diesel engines, due to the fact that these huge engines are so heavy that their ship's hulls are in fact effectively "softer" than the resilient mounts required to isolate them. Flexible connections in the propeller shaft and in piping and ducting are problematic and maintenance-intensive. Dr. Brown, however, indicated that smaller, diesel-generators can be effectively vibration isolated. The smaller engines may be ganged on a single "raft" which is then isolated on resilient mounts from supporting hull foundation structures. This arrangement enlists the mass of all the engines and generators, as well as that of the raft, to reduce "above-mount" vibration levels, particularly at less than full power, when several engines may be shut down. Even very large, direct drive motors are quiet when compared to reduction gears and piston engines. They need not be isolated. Fuel efficiency at less than full vessel speed can be maintained by shutting down some of the engine-generator units while running the remaining units at full power.

Electric drive propulsion may result in relatively low machinery radiated noise for those ship types where it is economically feasible, provided the system has a high-quality acoustic power supply. Electric (DC) drive has always been used on diesel-electric submarines where silencing is very important. Electric (AC) drive is being increasingly used in cruise ships and is being considered for large, high-speed container ships. Electric drives may have a greater initial cost than mechanical or direct drive propulsion, but for some applications provide greater overall fuel economy. One type of electric drive, called podded propulsion, employs a submerged electric motor directly coupled to the propeller, without gearing. This provides not only excellent maneuvering and backing power, but also a minimum of disturbed flow to the propeller, which greatly reduces propeller cavitation. While some podded propulsion systems may consequently have lower radiated underwater noise levels, this depends strongly on the type of power supply involved. A significant limitation of podded propulsion systems is that they in fact result in higher fuel usage for hydrodynamic reasons. As such, they have largely been employed thus far only on cruise ships where internal noise is a greater consideration than for other large vessels carrying non-human cargo, without specifically considering minimizing underwater noise emission.

Flow noise around the hull is generally minimal compared to that generated by propeller cavitation and machinery noise, but plays an increasingly significant role at low frequencies as vessel speed increases. Distributed hull treatments including damping, decoupling, and lagging devices may reduce flow noise. However, this is most effectively dealt with at the design phase in which flow measurements and engineering are conducted.

Many of the above quieting technologies require some degree of maintenance to ensure continued performance at optimal quieting levels. Maintenance of all propulsion generating elements is needed to ensure continued quiet operations. A corollary benefit of such on-going maintenance is ensuring that propulsion systems are operating at peak performance. Continued maintenance of isolation mounts and flexible hoses and pipes also ensures quiet performance as well as minimizes stress-related failures of rigid devices. Optimally, vessel acoustic signatures are monitored diagnostically through empirical measurements of radiated noise.

b) Potential applications of quieting technologies to commercial industry

Through advances in both military and commercial uses of vessel quieting, the technology by which commercial vessels could be significantly quieted already exists. Again, optimal quieting is achieved when this goal is incorporated into the design of vessels and strictly adhered to during construction. Given the long duration between the design and operational phases of large vessels, this option, while one that the speakers felt should be considered, is a long-term solution to minimizing the contribution of large vessels to overall ocean ambient noise. Retrofitting of existing ships, with particular attention to the installation of non-cavitating propellers, is a more feasible short-term solution, although this is also an expensive and possibly cost-prohibitive procedure. However, given that acoustic energy radiated into water by transiting ships represents wasted energy that could be used to more efficiently propel the ship forward, making such modifications may have the dual benefit of reducing radiated noise and reducing vessel operating costs. Further, vessels fitted for reduced radiation of underwater sound also tend to be quieter onboard, which is desirable for both crew and passengers.

c) Cost/benefit analysis for the application of vessel quieting technologies

While there is no debate as to whether large commercial ships could be quieted with the application of mature vessel quieting technologies, there is no consensus as to whether the need for this is clear, based on our current understanding of impacts, or when this is likely to occur. A critical factor is, of course, economics. Presenters and several symposium participants identified having a thorough and proper cost/benefit analysis of the application of various quieting technologies to commercial industry as a very important needed action. While this was beyond the scope of the presentations given at the symposium, presenters identified some key considerations and areas for further investigation.

There are considerable costs associated with the application of these technologies either in the construction of new vessels or in retrofitting existing ones. Mr. Verboom estimated that achieving maximal noise reduction (20-40 dB) on new commercial vessels will result in approximately 10-15% of additional building costs in case model experiments. Vessel quieting with 'standard' reduction measures will likely require only a small increase in cost. He added, however, that the costs associated with noise-reduction efforts might be partially or fully balanced by reduced maintenance costs and increases in vessel efficiency over the approximately 20-30 years of average commercial vessel service. Mr. Jebsen additionally noted that moderate levels of silencing are possible for large commercial vessels, but pointed out that owners and operators will have to be convinced that silencing is in fact necessary and that such costs will be partially or fully recovered by increases in efficiency and reduced maintenance costs.

Dr. Brown concurred that advanced propeller design may represent one of the more economically feasible options in terms of vessel quieting. Propellers modified to minimize cavitation may be applied as original equipment on new-build ships at little cost increase, and may reduce operating costs due to increased efficiency. They may also be substituted for otherwise acceptable propellers on existing ships during overhaul, although at more substantial cost. Dr. Brown also noted the potential correlation between lower noise output for vessels outfitted with electric drives and increased fuel efficiency as one possibly fruitful area, provided those vessels have special electric power supplies. Modifications he feels are less likely to be cost-effective for commercial applications include many naval and research vessel silencing techniques and podded electric propulsion.

Needed research and possible future actions

- Based on the results of research identified elsewhere in this report, determine whether there is sufficient evidence of adverse impacts of vessel noise on marine animals to justify advancing voluntary and/or regulatory efforts at quieting large commercial vessels.
- Initiate discussion between commercial ship designers and operators to determine the extent to which reducing noise and/or vibration-related structural stress is currently being considered within the industry.

- Conduct a complete cost/benefit economic analysis of the application of various vessel-quieting techniques to large commercial ship design and operation.
- Hold a technical workshop, coordinated by the planning committee, in which vessel quieting experts from military and private sectors meet shipping industry representatives, including the shipbuilding industry. The meeting would consider the potential applications, timelines, and cost/benefit analyses of applying vessel-quieting technology to commercial ships.
- Compare the advantages and disadvantages of retrofitting existing ships versus concentrating on the design and construction of new vessels.
- Consider the potential trade-offs between quieting vessels to minimize interference with hearing versus the potential increases in vessel strikes that might result in quieting them. This consideration should include marine mammal scientists with expertise in ship strike issues.
- Consider the potential applications of existing quieting technology to commercial shipping and the costs and potential benefits of doing so in white papers or technical reports.
- Consider trade-offs between various quieting techniques and ship operations. For example, reducing propeller cavitation at normal operating speeds may produce substantial quieting with minimal effort.

Panel Discussion

An invited panel consisting of several of the technical speakers and additional participants led a discussion on the final afternoon. Panel members included: **Dr. Roger Gentry** (NOAA Acoustics Program), **Dr. Edmund Gerstein** (FAU), **Dr. Richard Heitmeyer** (Naval Research Laboratories), **Dr. Ron Kastelein** (SEAMARCO), **CDR Karen Kohanowich** (Navy Central Command -- SECNAV), **Kathy Metcalf** (Chamber of Shipping of America), **Joel Reynolds** (Natural Resources Defense Council), **Dr. Brandon Southall** (NOAA Acoustics Program), **Dr. Peter Tyack** (Wood's Hole Oceanographic Institution), **Mark Womersley** (BMT Asia-Pacific).

The panel was asked to answer questions from the audience and discuss various issues. Dr. Southall moderated the panel discussion and directed questions to specific panel members. The following is a general summary of notes taken on the panel discussion including opinions expressed by panelists and audience participants during this portion of the meeting. None of these necessarily reflect the opinions of invited panel members, NOAA, or any of the symposium co-partners.

- **Vessel noise impacts on marine mammals** – There was general consensus that we lack a full understanding of how shipping noise may affect marine mammals. Numerous speakers indicated that advances toward such an understanding would be critical in justifying a response. Others felt that there was already sufficient evidence suggesting a likelihood of impacts that actions (either cooperative or regulatory) are warranted before the severity of the problem is entirely identified. Some of the specific research needed in various coastal and pelagic environments was discussed in greater detail. Several participants stated that research needs should not be considered prerequisites to initiate collaborative action to minimize anthropogenic contributions to ocean ambient noise. A planning committee should be established to help identify key questions, pursue scientific answers, and act on those items deemed necessary.
- **Cruise industry participation** - The cruise ship industry has distinct environmental priorities that differ from, for instance, container shipping. The Chamber of Shipping of America and INTERTANKO represent commercial associations whose participation could hopefully have a "snowball effect" within the industry and lead to broader engagement, including the cruise ship industry. The Chamber of Shipping of America will re-approach the International Council of Cruise Lines (ICCL) and the Baltic and International Maritime Council (BIMCO) about participation in future efforts.
- **Short sea shipping** – This represents an emerging concern in terms of increased shipping traffic and the increased potential for sound impacts and strikes. This industry trend should be particularly considered regarding marine mammals and noise because the routes involved in this emerging market are almost exclusively in near shore environments. Thus the potential overlap between short sea shipping lanes and marine mammal distributions may be considerably higher than for ocean-going vessels.

- **Types of ships –** Existing and new ships must be addressed separately. In considering application of vessel quieting technology to large commercial vessels, particular attention should be paid to the lag time between design and implementation. There are certainly trade-offs associated with overall noise reduction efforts and environmental benefits between focusing on either existing or new vessels.
- **Solutions must target industry stakeholders –** Costs and benefits should be clearly defined to engage such entities as ship builders, owners and operators, as well as international organizations and other industry segments.
- **Measurements of radiated sound from vessels –** Continued efforts to assess and classify acoustic energy radiated by various vessel types are needed. Vessel sounds (point source) and ambient noise resulting from vessels (multiple diffuse sources) are distinct focal points of study. Cavitation should remain a primary focal point for mitigation options, but alternative sources should not be ignored, particularly for long-range considerations. Standards for measurements could facilitate assessment of the feasibility of noise reductions.
- **Ambient noise measurements –** The development of a global passive acoustic monitoring network should begin immediately. There appeared to be greater agreement among the panel and audience members on this point than perhaps any other. This recommendation has been made clearly in a number of reviews and panel reports (most recently NRC, 2003). There was discussion about how to bring together some of the various local and regional efforts into a global monitoring network, with NOAA taking a leadership role. There was a comment made that the ongoing planning meetings on the formation of a global noise monitoring network should provide progress reports or meeting notes to the shipping noise planning committee.
- **Sensitivity of individual species** to masking and/or behavioral disturbance from vessel noise can vary based on acoustic parameters, distance from the source, operational environment, and a wide variety of receiver characteristics, including both sensory and behavioral parameters. Sound "dosage" may be a convenient conceptual packaging of the two factors.
- **Ferries, fishing vessels, and recreational watercraft** also warrant evaluation, especially in regards to coastal marine mammal populations. Long distance, low-frequency noise generated by large ships should not be the only focus area. Smaller vessels may be the predominant anthropogenic source of ambient noise and/or disturbance of marine mammals in some areas.
- **Masking** is a key focus area with regards to potential effects of vessel noise. Masking effects are difficult to measure empirically in the field. Thus, the selection of laboratory test stimuli, particularly the use of "real-world" stimuli is a very important research need. Measurement methods of stress or other adverse reactions also require further development. Another approach to managing unknowns would be to assume the "cause" is present, and create models and matrices to elucidate the "effect". Acoustic playback experiments may be undertaken concurrently to quantify a range of behavioral and physiological reactions to noise in natural environments.

- **High traffic areas** (*e.g.,* coastal regions and shipping routes) should be studied in regards to *physiological* and *behavioral* effects within marine animal populations. Further research could, in the long-term, elicit recommendations for potential changes to vessel routes based on affected areas. Specifically, stranded animals resident in high traffic areas should be investigated for evidence of permanent hearing loss that may be attributable to noise exposure.
- **Command-and-control** can take time, especially with regard to international law and political complexities of this subject. Common objectives should be developed, as well as a strategic plan to achieve these objectives. Interagency group discussions should be initiated for the development of an information paper on this subject (perhaps via a sub-group of the planning committee).
- **Regulation** of shipping noise was discussed extensively throughout the panel discussion. Some individuals indicated that regulation was needed immediately. Others, including representatives of the shipping industry, felt that proactive collaboration would be more likely to provide both short and long-term results. Guidance in terms of implementing cost-effective quieting technologies rather than developing standards or regulations may be a more effective approach in engaging the shipping industry. A regulatory structure may be counter-productive to developing a collaborative working relationship between the industry, regulators, and scientists on this environmental issue. Those either in favor or opposition of future regulations on commercial shipping concur that this would be a process that would take many years.
- **Industry motivation** may be harnessed through attention to engineering gaps and practical considerations. If the shipping industry is provided information regarding how to minimize noise from vessels, they may devise engineering solutions that have acceptable associated costs. Cost/benefit assessment about quieting technologies is critically needed. Information sharing from the U.S. Navy or private sector technical experts to industry about design advances would be welcome. Provision of specific design, maintenance, and operational means for noise reduction, with adequate consideration of economic impacts, would be ideal for the shipbuilding industry. Trade associations can serve as valuable conduits for information of this type to the industry.
- **Alliances** must be created – particularly on the international stage. Greater awareness via collaborative associations and dissemination of meeting documents will elicit a broader transfer of awareness and implementation of mitigation efforts. Alliances should be forged on this issue between various industry, government, non-government, and environmental organizations. The formation of the planning committee should be the first step in this process.
- **MARPOL** may not be the most appropriate instrument of future regulation of ocean noise. Of the IMO instruments, the Safety of Life at Sea Convention might be more appropriate since it addresses ship design. It may also be appropriate to look at regional instruments and fora such as the Arctic Council and the Arctic Environment Protection Strategy. It was recognized that there might be political, procedural, and substantive hurdles to overcome in proceeding in international

fora and under international instruments with regard to this issue. If a decision is taken to proceed, a strategy for doing so should be developed.

- **Ship strike** issues relative to noise concerns must be addressed. There must be a consideration of the potential conflicts/trade-offs between quieting vessels in minimizing masking and the potential that quieter vessels may be more difficult to detect and thus avoid. The effects of speed restrictions enacted to prevent ship strikes should be considered relative to potential increases in ambient noise.
- **Traditional knowledge** can be a key resource for the technical community to integrate into future regulatory decision-making and/or ship routing. Subsistence issues may include marine noise issues, but may be outweighed by other subjects (*e.g.* ice thinning, ice breaking activities) in relative urgency.
- IMO's **Marine Electronic Highway (MEH)** initiative considers environmental and safety information regarding marine transportation. Noise could potentially be added or incorporated under the existing scope.

Steering Committee for Follow-On Symposium
~ Timeline of Proposed Actions ~

Based on the dialogue initiated at this symposium, an *ad hoc* steering committee was formed following the meeting to cooperatively plan aspects of a proposed follow-on symposium to be held in 2006. The steering committee consists of representatives from the shipping industry, government agencies, academia, and environmental organizations. The steering committee will engage in discussions of the most critical elements identified in the initial symposium that should be considered in greater depth in the follow-on meeting. The steering committee will agree on the sessions for the follow-on symposium and will assist in the planning, including identifying and engaging participants from various fields. Participation in the steering committee is open to anyone who wishes to participate. The following is a tentative timeline of events at the time of the release of the final report.

- Draft symposium report distributed (*July 2004*).
- Planning committee members submit reviews of draft report (*September 2004).*
- Final symposium report released (*April 2005*).
- Steering committee dialogue on possible technical sessions and working groups for follow-on symposium initiated through e-mails and/or conference calls (*Spring/Summer 2005*)
- Possible meeting of steering committee (*Fall 2005*)
- Follow-on Symposium (*Winter/Spring 2006*)

The steering committee currently consists of the following 18 individuals:

Dr. Neal Brown (NAB Associates)
David Cottingham (U.S. Marine Mammal Commission)
Dr. George Frisk (Florida Atlantic University)
Dr. Roger Gentry (NOAA Acoustics Program)
Dr. Edmund Gerstein (Florida Atlantic University)
Dr. Colleen Kastak (University of California, Santa Cruz)
Dr. Ron Kastelein (SEAMARCO)
John Mayer (Marine Acoustics, Inc.)
Kathy Metcalf (Chamber of Shipping of America)
Dr. Douglas Nowacek (Florida State University)
Joel Reynolds (Natural Resources Defense Council)
LCDR Mary Sohlberg (U.S. Coast Guard)
Dr. Brandon Southall (NOAA Acoustics Program, UC Santa Cruz)
Tom Stirratt (British Maritime Technologies, Designers and Planners)
Dr. Peter Tyack (Wood's Hole Oceanographic Institution)
Willem Verboom (TNO TPD Delft University)
James Walpole (NOAA, Office of the General Counsel)
Mark Womersley (British Maritime Technologies, Asia-Pacific)
Sharon Young (Humane Society of the U.S.)

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Appendix 1: Statement of Purpose

Noise generated by human activities is an emerging issue in our oceans. It can interfere with marine animal hearing of important natural signals. Conservationists, government agencies, navies, researchers, and industry are striving to understand the effects of sounds and explore technologies that could mitigate potential impacts. Management strategies for marine noise continue to emerge as policymakers consider noise exposure guidelines in light of existing airborne noise regulations. Another developing issue is the potential treatment of marine noise as a pollutant relative to the Law of the Sea and MARPOL. Meanwhile, ocean noise levels continue to rise in some areas and the effects of noise on ocean ecosystems remain largely unknown.

A collaborative forum is needed to discuss state of the art research and technology and establish a dialogue among participants toward future cooperative efforts. The event's partners have come together to provide an open symposium for all interested parties-biologists, ship owners and designers, oceanographers, regulators, developers of ship quieting technology, and more-who are exploring this important subject. Each perspective will provide a different view of human noise in our oceans and the need, costs and benefits of reducing it.

Symposium speakers have been chosen for their expert knowledge on selected topics. Several U.S. government agencies will discuss how considerations of noise impacts on protected species affect their mandated efforts. Scientists will report on trends in ocean noise, the need to monitor it, physical and behavioral effects of sound on various kinds of animals, and what is known about the effects of shipping noise. Members of the shipping industry will discuss trends in the number, design, and operation of large vessels. The legal and political implications of marine noise pollution will be discussed, including reviews of national and international regulations and treaties. Both commercial and U.S. Navy speakers will discuss the effectiveness and benefits of ship-quieting technologies. The symposium will conclude with a panel discussion that synthesizes the material presented and identifies future steps including prioritized research needs, increased collaboration mechanisms, and possible follow-on symposia.

Attendance is open to the public and is free with advance registration. The partners particularly welcome representatives of commercial shipping and ship building organizations.

Appendix 2: Meeting Agenda

Tuesday 18 May 2004 (Morning)

0700-1700	**Registration**
0700-0830	**Continental Breakfast**

Welcome to Symposium		
0830-0845	Ted Kassinger U. S. Department of Commerce General Counsel & Deputy Secretary (Designate)	"Department of Commerce Welcome to the First International Symposium on Shipping Noise and Marine Mammals"
0845-0900	James Walpole National Oceanic and Atmospheric Administration (NOAA) General Counsel	"NOAA Welcome to the First International Symposium on Shipping Noise and Marine Mammals"

Introduction to Concerns About Noise and Marine Life		
0900-0915	Dr. Roger Gentry NOAA Fisheries Acoustics Program	"Development of the Symposium: NOAA's Views on Marine Noise Issues"
0915-0930	Kathy Metcalf Chamber of Shipping of America	"Shipping Industry Perspective on Shipping Noise and Marine Mammals"
0930-0945	Dr. John Hildebrand Marine Mammal Commission and Scripps Institution of Oceanography	"Marine Mammal Commission Perspective on Shipping Noise and Marine Mammals"

0945-1000	**Break**

Session I: Trends in the Shipping Industry and Shipping Noise Chair: CDR Paul Stewart, U.S. Navy, National Ice Center		
1000-1030	Dr. George Frisk Florida Atlantic University	"Historical Trends in Shipping Noise"
1030-1100	Dr. Stephen Wales Naval Research Laboratories	"Merchant Ship Radiated Noise Source Levels"
1100-1145	Dr. Mark Womersley BMT, Asia-Pacific	"Shipping Volumes, Routings, Propulsion Systems, and Associated Trends"

1145–1245	**Lunch**

Tuesday 18 May 2004 (Afternoon)

Session II: Effects of Noise on Marine Life Chair: Dr. Elena McCarthy, Woods Hole Oceanographic Institution		
1245-1315	Dr. Colleen Kastak University of California, Santa Cruz	"Marine Mammal Groups: Typical Hearing Capabilities"
1315-1345	Dr. Brandon Southall NOAA Fisheries Acoustics Program, University of California, Santa Cruz	"Anthropogenic Noise Masking of Marine Mammal Hearing"
1345-1415	Dr. Douglas Nowacek Florida State University	"Effects of Shipping Noise on Marine Mammal Behavior"
1415-1445	Dr. Mardi Hastings Office of Naval Research	"Hearing in Fish and the Effects of Noise"

1445–1500	**Break**

Session III: National and International Response to the Marine Noise Issue Chair: Dr. Richard Steiner, University of Alaska, Marine Advisory Program		
1500-1530	Dr. Elena McCarthy Woods Hole Oceanographic Institution	"International Regulation of Underwater Sound: Implications for Shipping"
1530-1600	Joel Reynolds Natural Resources Defense Council	"Environmental Community Perspective on Shipping Noise and Marine Mammals"
1600-1645	Dr. Robert Gisiner Office of Naval Research	"Noise Impacts on Marine Animals: Advances in Research and Mitigation Measures"
1645-1715	Dr. Peter Tyack Woods Hole Oceanographic Institution	"Research Needed on Shipping Noise and Marine Mammals"

1715-1730	Dr. Brandon Southall NOAA Fisheries Acoustics Program	Discuss Agenda for Wednesday

1730-1930	**Informal Reception**

Wednesday 19 May 2004

0700-1200	**Registration**
0700-0830	**Continental Breakfast**

Introductory Remarks		
0830-0840	Laurie Allen, NOAA Fisheries, Office of Protected Resources	
Keynote Speaker		
0840-0900	Hon. Wayne T. Gilchrest, U.S. Representative (R-MD)	"New Partnerships in Marine Conservation"

Session IV: Developing Technologies for Monitoring Marine Noise Chair: Dr. Brandon Southall, NOAA Fisheries Acoustics Program, U. of California, Santa Cruz		
0900-0930	Dr. Christopher Clark Cornell Laboratory of Ornithology	"A Regional Noise Monitoring Network"
0930-1000	Dr. David Mellinger Oregon State University	"A Global Observatory for Studying Marine Noise"
1000-1030	Dr. Anthony Eller Scientific Applications International Corporation	"Temporal Trends in Ambient Noise Measurements in the Gulf of Mexico"
1030-1100	Jonathon Mintz Center for Naval Analyses	"Estimating Vessel Traffic in Ocean Areas of Interest"

1100–1115	**Break**

Session V: Vessel Quieting Technology: Applications and Benefits Chair: CDR Karen Kohanowich, Office of the Assistant Secretary of the Navy for Environment		
1115-1145	Willem Verboom TNO TPD - Delft University	"Radiated Ship Noise Reduction: Case Study of a Fishery Research Vessel"
1145-1215	Dr. Gary Jebsen NAVSEA, U.S. Navy	"U.S. Navy Ship Quieting Technology"
1215-1245	Dr. Neal Brown NAB and Associates, Inc.	"Vessel Quieting Technologies: Cost/Benefit Considerations"

1245-1345	**Lunch**

1345-1515	**Discussion and Planning Next Steps:** Invited Panel, Speakers, and Attendees

1515–1530	**Break**

1530-1700	**Discussion and Planning Next Steps:** Invited Panel, Speakers, and Attendees