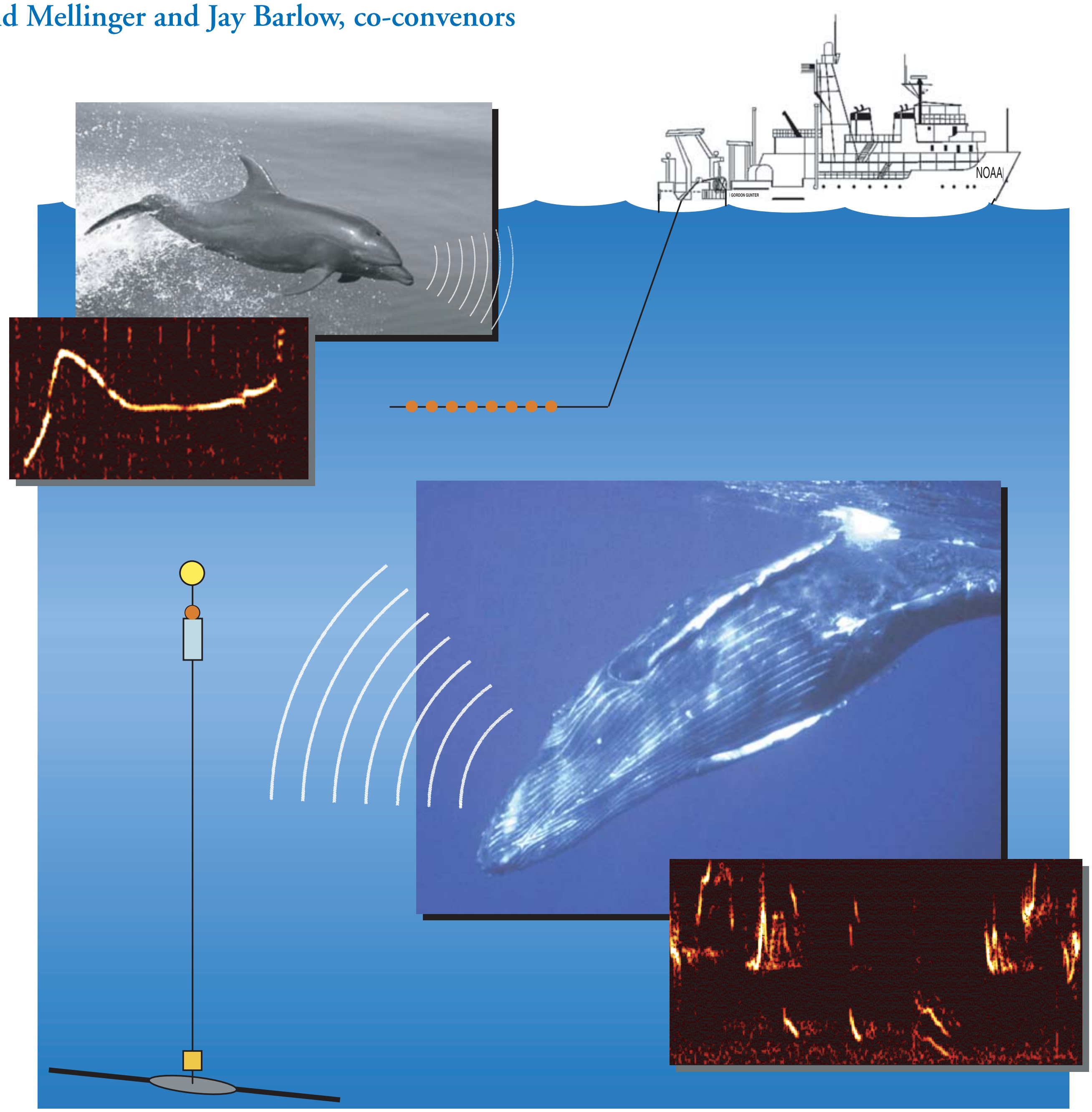
NOAA OAR Special Report

Future Directions for Acoustic Marine Mammal Surveys: Stock Assessment and Habitat Use

Report of a Workshop Held in La Jolla, California, 20–22 November 2002

David Mellinger and Jay Barlow, co-convenors



Contribution 2557 from NOAA/Pacific Marine Environmental Laboratory

On the cover: The bottlenose dolphin (photo: Jay Barlow) and humpback whale (photo: Barb Taylor) are known for their complex acoustic signals. Here their sounds are captured by instruments used for acoustic assessment: a hydrophone array towed behind a NOAA ship and a bottom-anchored autonomous hydrophone.

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David Mellinger[1] and Jay Barlow[2], co-convenors

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Future Directions for Acoustic Marine Mammal Surveys: Stock Assessment and Habitat Use

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Executive Summary

Current uses of acoustics: Acoustic survey methods are now used primarily to augment visual sighting methods. During line-transect surveys, acoustic observers who monitor towed hydrophone arrays routinely detect more groups of animals than visual observers. In some cases, acoustic detections are being used to make more accurate estimates of marine mammal populations than would be possible with visual methods alone. Autonomous recorders are cost effective for use in regions that are difficult or expensive to reach, such as Antarctica, the Indian Ocean, and areas far offshore in the Atlantic and Pacific Oceans, and they are effective for seasonal coverage when visual surveys are not feasible. They may also be useful to survey areas infrequently occupied by marine mammals, where routine visual surveys would have a very high cost per sighting.

Future uses of acoustics: Acoustics holds eventual promise of gathering information about marine mammals at very low cost. Research is needed in several areas to realize this possibility. Discussion at the workshop centered on these broad categories:

1. **Population structure.** If acoustic differences between populations of marine mammals are tied to genetic differences, then acoustics would offer a relatively fast and inexpensive method to assess population structure. The foremost research need is to determine the relationship between the population structures as indicated by acoustics and by genetics.

2. **Abundance and density.** Acoustic observation can complement visual observation to provide more accurate estimates of marine mammal populations. This has been done for some populations, as for example the Bering-Beaufort-Chukchi Sea stock of bowhead whales and the eastern Pacific stock of sperm whales, but it could be done more widely. For effective acoustic censuses, calibration methods must be determined by joint visual-acoustic studies; determining such factors offers the promise of low-cost surveys for many species of marine mammals using acoustic methods. Research is also needed in acoustic species identification, particularly for smaller odontocetes.

3. **Impacts of noise.** Responses of marine mammal to natural noise have not been well studied. Natural noise can include sounds of other ma-

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rine mammals, especially conspecifics, as well as physical noise sources such as from geological sound sources and wind. Responses of marine mammals to anthropogenic noise was seen as a topic well covered by other work; discussion here was limited to the contribution that passive acoustics can make. Assisting in the constructing of an "ocean noise map" was strongly supported, as was better public communication of information on ocean noise levels.

4. **Relative density, seasonal distribution, and trends.** For determining relative density or abundance, and trends in abundance, many of the same calibration factors are needed as for determining absolute abundance. But in the absence of those calibration factors, acoustic methods can offer estimates of minimum population size, and can be used to track large-scale movement patterns.

Workshop discussion culminated in a list of recommendations for management, research, and field operations.

Workshop Participants

Jay Barlow	NMFS Southwest Fisheries Science Center
Phillip Clapham	NMFS Northeast Fisheries Science Center
Chris Clark	Cornell University
Chris Fox	NOAA Pacific Marine Environmental Laboratory
Greg Fulling	NMFS Southeast Fisheries Science Center
John Hildebrand	Scripps Institution of Oceanography
Lance Garrison	NMFS Southeast Fisheries Science Center
Jeff Laake	NMFS Alaska Fisheries Science Center
Tony Martinez	NMFS Southeast Fisheries Science Center
Mark McDonald	Whale Acoustics, Inc.
Dave Mellinger	Oregon State University and NOAA Pacific Marine Environmental Laboratory
Sue Moore	NMFS Alaska Fisheries Science Center
Debbie Palka	NMFS Northeast Fisheries Science Center
Bill Perrin	NMFS Southwest Fisheries Science Center
Sarah Mesnick	NMFS Southwest Fisheries Science Center
Kate Stafford	NMFS Alaska Fisheries Science Center
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Observers

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Tom Norris	Science Applications International Corp.
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Background

Although acoustics has been used for studying marine mammals for decades, it has seldom been employed for assessing populations. The term assessment is used here to describe the process of evaluating the status of a population relative to some management goal. Assessment involves studies of the structure of populations, estimation of abundance and trends in abundance, and the evaluation of anthropogenic impacts. The best example of the use of acoustics in assessment to date is the long-term study of the Beaufort Sea bowhead whale population, where combined visual and acoustic methods have significantly improved the population estimate. The primary goal of this workshop was to explore how acoustic methods might be more fully exploited for marine mammal assessment—that is, how might acoustic methods provide assessment data unobtainable in other ways? In what ways might acoustic methods provide roughly equivalent data at less cost? A secondary goal was to explore how acoustic methods can be used to address the questions of how marine mammals respond to noise, especially anthropogenic noise, and how effective any mitigation measures might be.

Presentations (Wednesday, 20 November)

The workshop aimed to bring together two communities of marine mammal experts: those in assessment, and those in acoustics. The first day of the workshop included presentations by most of the attendees to establish a common base of knowledge. Assessment experts presented methods used in the field and projects that have used them, discussed statistical techniques for estimating populations from sets of observations, and covered the requirements needed for gathering necessary data to make statistically valid population estimates. Acoustics experts discussed projects they had participated in, outlined the methods used, and explained capabilities of the systems used and characteristics of data collected by these systems.

I. Assessment: Abstracts of Presentations

SWFSC Acoustic Survey Research for Marine Mammal Assessment

Jay Barlow, Julie Oswald, Erin Oleson, Shannon Rankin

At the Southwest Fisheries Science Center (SWFSC) we have been experimenting with the incorporation of acoustics in line-transect surveys since 1995. The CADDIS survey in 1995 looked at the acoustic detectability of beaked whales and found that only Baird's beaked whales made sounds that could be readily detected (Dawson *et al.,* 1998). The SWAPS survey in 1997 was our first combined visual and acoustic survey and provided density estimates of sperm whales using detections from both methods (Barlow and Taylor, 1998). Starting in 1998, towed hydrophone arrays were used on dolphin line-transect surveys. We have worked with others (Thode *et al.,* 2000; Mellinger, 2001) to develop software to localize dolphins from their whistles. Results showed that dolphins could be detected at significantly greater distances using acoustics. However, the inability to look directly forward using a line array has hampered our ability to detect dolphins prior to their being detected by visual observers. In collaborations with Scripps scientists, sonobuoys have been used opportunistically on our surveys to make low-noise recordings of sounds from a variety of species. Most notably, we were the first to find that Bryde's whales make stereotypical low-frequency calls similar to blue whales and that the various call types show strong geographic patterns (Oleson *et al.,* in press). Recordings from sonobuoys and our towed array have been used to examine the feasibility of determining species from dolphin whistles. Using two different classification methods (DFA and CART), we have found that more than 50% of whistles from nine dolphin species can be correctly classified to species (Oswald *et al.,* in press), compared to an 11% correct classification by chance alone. Finally, in the last month, we have tracked the mysterious "boing" down to its source and have found that it is most probably a breeding call of the North Pacific minke whale. Future research will concentrate on estimating $g(0)$ for sperm whales, improving our ability to listen in a forward direction using a towed hydrophone, estimating

$g(0)$ for dolphins, and estimating the density of calling minke whales from their "boings" recorded on the 1997 sperm whale survey.

Barlow, J., and B.L. Taylor (1998): Preliminary abundance of sperm whales in the northeastern temperate Pacific estimated from a combined visual and acoustic survey. *Int. Whal. Comm. Working Paper SC/50/CAWS20,* 19 pp.

Dawson, S.M., J. Barlow, and D. Ljungblad (1998): Sounds recorded from Baird's beaked whale, *Berardius bairdi. Mar. Mamm. Sci., 14*(2), 335–344.

Mellinger, D.K. (2001): Ishmael 1.0 User's Guide. NOAA Tech. Memo. OAR PMEL-120, 26 pp.

Oleson, E.M., J. Barlow, J. Gordon, S. Rankin, and J.A. Hildebrand (in press): Low frequency calls of Bryde's whales. *Mar. Mamm. Sci.*

Oswald, J.N., J. Barlow, and T.F. Norris (in press): Acoustic identification of nine delphinid species in the eastern tropical Pacific Ocean. *Mar. Mamm. Sci.*

Thode, A., T. Norris, and J. Barlow (2000): Frequency beamforming of dolphin whistles using a sparse three-element towed array. *J. Acoust. Soc. Am., 107*(6), 3581–3584.

Distance Sampling and Marine Mammal Acoustic Surveys
Jeff Laake

Dr. Laake's contribution comprised significantly more than an abstract, and is included in this report as Appendix A.

Passive Hydroacoustic Detection of Marine Mammals at SEFSC
Lance Garrison (presenter), Steven Swartz, Anthony Martinez, Jack Stamates, John Proni, NOAA/NMFS/SEFSC and NOAA/OAR/AOML

The Southeast Fisheries Science Center (SEFSC), in cooperation with AOML and the U.S. Navy, has been actively developing passive hydroacoustic methods to enhance assessment surveys for marine mammals in the Atlantic Ocean, Gulf of Mexico, and Caribbean. The primary research vessel used on marine mammal surveys, the NOAA ship *Gordon Gunter*, is ideally suited for this task as it is acoustically quiet, provides ample space for acoustic data acquisition and recording equipment, and has an excellent platform for visual observations. Acoustic operations to date have primarily employed a five-element towed hydrophone array and a smaller two element array that can be deployed in shallower water. In addition, sonobuoys were deployed extensively during cruises targeting humpback whales in the Caribbean. Acoustic methods significantly enhanced the number of humpbacks detected during these surveys.

More recently, SEFSC conducted a joint visual and acoustic survey of the mid-Atlantic continental shelf. The hydroacoustic arrays were utilized simultaneously with the visual survey effort except where limited by water depths. The visual survey team operated independently of the acoustic effort and were not notified of acoustic contacts. There were numerous cases where acoustically detected marine mammals were not observed by the visual team. Visual sightings were noted in the acoustic data logs, and these records are currently being reviewed to match acoustic and visual detections.

The hydroacoustic program is still in development. Significant research challenges remain, such as developing and testing methods to calculate the distance to acoustic signals, estimate the number of animals detected, and verify species identifications. In addition, it is essential to develop a linked database program to reducing the processing time required to match visual and acoustic detections after the survey. During the next several cruises during 2003 and 2004, we will continue to evaluate the best survey and theoretical methods to integrate passive acoustic detections into marine mammal assessments.

Acoustic-Related Assessment Needs for Baleen Whales in the Waters of the Northeastern United States and Atlantic Canada
Phil Clapham

The waters off the northeastern coasts of the U.S. and adjacent areas of Atlantic Canada contain important feeding habitats for several species of mysticetes. These include North Atlantic right, humpback, fin, sei, minke, and blue whales. Current knowledge of the distribution and abundance of these species varies, and can be loosely categorized as follows: very good (humpback whales); reasonably good with major gaps (right and fin whales); fair (minke whales); and very poor (sei and blue whales). With some recent exceptions (notably work by Clark and colleagues), acoustic techniques have been used relatively little in studies of mysticete populations in this region.

Given that much of the distribution of mysticetes in the northeast is centered in coastal and shelf waters, remote monitoring of calling whales is constrained by shallow-water transmission loss. However, placement of pop-ups or similar devices in areas known or thought to represent habitats for mysticetes potentially allows for continual monitoring of the presence of (calling) whales over extended periods, including at night, during poor weather, and in locations that would be difficult to survey for much of the year. This technique could fill significant gaps in knowledge concerning the frequency with which certain species are found in more offshore areas. This would be particularly valuable for whales for which winter distribution is currently uncertain or unknown, which is an especially significant gap in our knowledge of right whales. In addition, acoustic monitoring might help to determine whether historically important but currently unsurveyed offshore habitats for right whales (or other species) are still utilized today.

Acoustically derived data on distribution (and, if practicable, on relative abundance) would be potentially important in assessment of risk in endangered populations. In particular, such data could help to determine the occurrence of right whales in areas subject to human activities such as shipping and fishing.

Problems with acoustic approaches to assessment include limited signal range, lack of information on call characteristics of some species, and the potentially low frequency with which individuals may vocalize. For relatively vocal species (such as right and humpback whales), additional research is required to establish whether correlations exist between calling rates and local abundance; this can potentially be accomplished by coordinating acoustic monitoring with aerial or shipboard surveys in the same areas.

Using Passive Acoustics during Cetacean Abundance Surveys in the Northwest Atlantic
Debra Palka

The Northeast Fisheries Science Center (NEFSC) estimates the abundance of many cetacean species in the Northwest Atlantic using shipboard and aerial line transect surveys. Abundance estimates derived from line transect surveys may be biased due to animal availability (i.e., animals never surface to be detected by visual observers), and human perception (i.e., observers visually detect fewer animals in inclement weather conditions). To account for these types of biases, the NEFSC has used the two "independent" team method. However, this method does not fully account for animals that remain mostly submerged and so are seldom seen. One way to account for this type of bias is to record the location of vocalizing animals in addition to recording the location of visually detected animals. To evaluate this approach, sightings of harbor porpoises were made by three teams on the R/V *Abel-J* in 1999 and simultaneously, harbor porpoises were acoustically detected using a high frequency hydrophone (125 kHz) trailed behind the ship. During the 2001 R/V *Delaware* survey, cetaceans were visually detected by two teams of observers and acoustically detected by a medium frequency hydrophone (100 Hz to 22 kHz) trailed to the side and behind the ship. Dr. David Borchers has developed a method to estimate abundance from combined acoustic and visual data. Applying Borchers' method to the 1999 harbor porpoise acoustic and visual data produced an abundance estimate about 2.5 times higher than that obtained from a conventional visual line transect analysis. These methods show promise but still need to be more fully developed and tested. To record vocalizations from a variety of species, a hydrophone system is now being constructed for use on NEFSC cetacean surveys that records both high and medium frequencies. In the future, we hope to use this hydrophone system and new analytical methods to produce less biased abundance estimates for many cetacean species.

II. Acoustics: Abstract of Presentations

Acoustic Assessment of Marine Mammal Populations
John Hildebrand

Passive acoustic monitoring may be a useful technique for assessing marine mammal populations, complementary to visual techniques. Acoustic and visual techniques have different strengths and weaknesses for marine mammal monitoring. Acoustic techniques fundamentally monitor submerged animals, whereas visual techniques monitor animals during periods of surfacing. Acoustic techniques have the ability to provide continuous temporal coverage and thus information on seasonal presence, providing data that are difficult or impossible to obtain with visual methods. Acoustic monitoring can be conducted relatively independent of daylight and weather, conditions that severely affect visual surveys.

Long-term acoustic monitoring is best conducted from fixed sites, either from seafloor acoustic recording packages or cable-connected hydrophones such as the SOSUS arrays. Because of this, acoustic techniques are best applied to a small locale. Visual surveys are typically designed to cover a broad region, and thereby provide a synoptic assessment of the total population. The mismatch of these two scales, local for acoustic and regional for visual, must be reconciled before a good comparison can be made between these two techniques. Another important issue is whether whales detected visually can also be detected acoustically, and vice versa. There is some evidence that calling whales are stealthy (difficult to detect visually) and that easily seen whales are rarely vocalizing.

Examples are presented of acoustic monitoring for baleen whales in the southern California offshore region and in the Antarctic. Using automated call detection algorithms, blue whale calling seasonality at both sites can be described. In southern California, blue whale calling begins in early June, peaks from August through October, and decreases through the fall. Aerial visual survey data from southern California suggests that there is a mismatch in the seasonality of blue whales detected visually and those detected acoustically. More whales are visually detected early in the summer, while acoustic detections peak late in the summer. A diurnal calling pattern is observed with 30% more calls at dawn and dusk than at other times of the day. In the Antarctic, blue whale calling is detected year-round in a region where no visual sightings of blue whales have been confirmed for the past decade.

Status of NOAA/PMEL Acoustic Observing Systems
Christopher G. Fox

NOAA's Pacific Marine Environmental Laboratory (NOAA/PMEL) collects a variety of digital underwater acoustic recordings in support of NOAA's Vents Program. Since August 1991, NOAA/PMEL has collected continuous recordings from the U.S. Navy SOSUS arrays in the North Pacific, and this effort will continue into the foreseeable future with ten arrays currently collected. Numerous SOSUS arrays exist in the Atlantic which are not collected by PMEL, although the expertise exists to tap into those arrays. There are also several SOSUS arrays that have been abandoned by the Navy that could be occupied by NOAA. In May 1996, the Vents acoustic monitoring effort was expanded through the use of PMEL-developed autonomous hydrophones deployed in the eastern equatorial Pacific (8°S–8°N, 110°W–95°W), and later to the central North Atlantic between 15°N and 35°N (March 1999), the Gulf of Alaska (October 1999–July 2002), and the North Atlantic between 40°N and 50°N (June 2002). These arrays are generally deployed for seismic studies (with the exception of the Gulf of Alaska blue whale study) and are therefore collected in relatively low frequency bands (1–100 Hz) with some higher sampling (1–450 Hz). Natural seismicity in the

Pacific produces nearly 10,000 events per year with source levels exceeding 200 dB (re 1 μPa @ 1 m), with about 3,500 events per year exceeding this level in the North Atlantic. Significant contributions from manmade sources are present throughout the data but have not been quantified. Recordings from the North Atlantic arrays are dominated by noise from seismic airgun profilers working offshore Canada, Brazil, and West Africa. In September 2001, a cabled vertical hydrophone array was installed at Pioneer Seamount, offshore central California, which provided continuous, unclassified acoustic data (in the range of 1–450 Hz) to the research community in real time. Unfortunately, a cable break in Fall 2002 ended the experiment. Future plans call for the expansion of the NOAA monitoring effort to other opportunities worldwide and making the raw data available to the community via the internet. Areas being targeted for future monitoring include (1) the Eastern Tropical Pacific near 9–10°N, 104°W, with spacing of about 20 km, capable of tracking marine mammals through the area, (2) the Lau Basin region of the Southwest Pacific near 20°S, 180°W, and (3) the Marianas Islands region of the western Pacific. Currently, the inventory of portable hydrophones totals 35 units, some of which could be made available for marine mammal studies.

Seasonal Patterns of Large Whale Occurrence in the North Pacific
Kate Stafford (presenter), Sue Moore, and Chris Fox

In collaboration with the National Marine Mammal Lab, NOAA's Pacific Marine Environmental Lab has been supporting the study of low-frequency whale calls both through access to the U.S. Navy's west coast SOSUS data and through development of autonomous moored hydrophones (Fox *et al.,* 2001). Specific results include documenting seasonal and geographic variation in reception of fin whale calls from five sites in the North Pacific (Moore *et al.,* 1998); establishing the northern (Gulf of Alaska) and southern (equatorial eastern tropical Pacific) extents of northeastern Pacific blue whale calls and suggesting migratory patterns from these data (Stafford *et al.,* 1999a); documenting that there are at least two geographically distinct call types that may be attributed to blue whales in the North Pacific (Stafford *et al.,* 2001); showing that the eastern tropical Pacific is used by blue whales from both the southern and northern hemisphere and probably by fin whales (Stafford *et al.,* 1999b). Long-term monitoring of ambient noise in the ocean has shown that most large whale species produce calls year-round. Although the behavioral function of calling remains little understood for most species, this research shows that call reception can be used reliably to determine presence/absence of large whales across broad temporal and spatial scales. Remote monitoring of cetacean calls is clearly a powerful tool for monitoring macro-scale seasonal and geographic patterns of large whale occurrence.

Fox, C.G., H. Matsumoto, and T.K.A. Lau (2001): Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. *J. Geophys. Res., 106*(B3), 4183–4206.

Moore, S.E., K.M. Stafford, M.E. Dahlheim, C.G. Fox, H.W. Braham, J.J. Polovina, and D.E. Bain (1998): Seasonal variation in reception of fin whale calls at five geographic areas in the North Pacific. *Mar. Mamm. Sci., 14*, 617–627.

Stafford, K.M., S.L. Nieukirk, and C.G. Fox (1999a): An acoustic link between blue whales in the Northeast Pacific and the eastern tropical Pacific. *Mar. Mamm. Sci., 15*, 1258–1268.

Stafford, K.M., S.L. Nieukirk, and C.G. Fox (1999b): Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific. *J. Acoust. Soc. Am., 106*, 3687–3698.

Stafford K.M., S.L. Nieukirk, and C.G. Fox (2001): Geographic and seasonal variation of blue whale calls in the North Pacific. *J. Cetacean Res. Manage., 3*, 65–76.

Two Times the Trouble, Five Times the Fun: Using Two Towed Arrays for Dolphin and Sperm Whale Localization

Aaron Thode (presenter), Eric Howarth

Single towed arrays are typically used to estimate bearings during marine mammal survey work. The deployment of a second towed array, separated from the first array by 150 to 500 m, can yield range and even depth information, if surface reflections can be exploited. Two examples of such work will be shown, including 3D tracking of close-range sperm whales in the Gulf of Mexico, and automated bearing-range dolphin tracking using data from a February 2002 SE Fisheries survey cruise off the East Coast.

Acknowledgments: Tony Martinez, Jack Stamates, Steve Swartz, Matt Grund, Mark Johnson, Peter Tyack

Song of Blue and Fin Whales Applied to Population Identification, Distribution and Seasonal Movements

Mark McDonald (presenter), John Hildebrand, Sarah Mesnick

Blue whale song has been divided into nine types worldwide, excluding variations within some types. Seven of the nine song types have been recorded repeatedly over many years and are unchanging in character, though all have been shifting downward in frequency over the 40 years of recording. The frequency change may be related to recovery from whaling. There are presently three song types in the Indian Ocean, two in the North Pacific, one in the North Atlantic, one in the Antarctic, two in the South Pacific and no data in the South Atlantic. More song types will undoubtedly be discovered and some regions where blue whales are common lack acoustic recordings. Blue whales from some regions are known to sing year around, though the amount of singing for a given animal density is believed to vary by season. Approaches to estimating both minimum and absolute population density from recordings will be discussed.

Acoustic Surveys and Acoustic Detection Distance
David K. Mellinger

On recent sperm whale surveys in the Gulf of Mexico, towed hydrophone arrays and sonobuoys were used to gather data. The software used includes Ishmael, a multipurpose tool for recording, displaying, and analyzing sounds; WhalTrak, a program for plotting and logging bearings to vocalizing whales; RainbowClick, a powerful tool for locating sperm whales; and Matlab, a programming environment used for many purposes. Another acoustic technique is the use of autonomous hydrophone recorders, instruments that collect data for months to years at a time. The large quantity of data makes automatic call recognition an attractive option. A case study is presented in which sperm whale sounds in the Gulf of Alaska are automatically detected, with the detections used to show seasonal and geographic differences in calling.

A further step is to use acoustic data for assessment, for which we must estimate acoustic detection distances. This can be done by use of acoustic propagation models, which in turn need environmental information (sound speed profile, bottom characteristics, noise levels, etc.), whale depth, and information about whale calling behavior. The result of the propagation model—transmission loss as a function of range and depth—can then be used in a model of whale calling and diving behavior to estimate the probability of detection as a function of range.

Acoustics for Marine Mammal Surveys
Christopher W. Clark

The application of passive acoustic mechanisms for detecting and identifying marine mammals and the integration of visual and acoustic methods for population surveys are long overdue. Acoustic mechanisms are advancing rapidly and costs are decreasing continually. The breadth of engineering and oceanographic talent is steadily increasing. All the basic tools and talent are there. Visual survey methods have reached their limits. For many species known to be vocally active, the application of passive acoustics offers an immediate and obvious benefit at relatively modest cost. It is no longer a matter of proving the concept of dual-mode surveys, it is a matter of making them effective and pro forma. It is a matter of finding the right combination of people skills and technology and applying these to some real problems. The bowhead whale census is an excellent example of visual and acoustic techniques successfully merged for population assessment and trend analysis. The major challenge for application in other scenarios (e.g., vessel-based surveys) resides in (a) developing robust statistical methodologies to estimate abundance from vessel-based sightings and acoustic detections, (b) understanding levels of variability in acoustic behaviors, and (c) developing a suite of standardized tools for collecting, analyzing, and interpreting bioacoustic data. In cases where visual surveys are impractical, passive acoustic mechanisms offer ways of sampling large areas of the ocean for long periods of time at low cost. To better interpret such bioacoustic data we need to better understand the whys and hows of marine mammal vocal production and behavioral ecology. We need to integrate distributions and densities with ocean productivity.

Cetacean Detection and Assessment via Passive Acoustics
Sue Moore

[This is the abstract of a significantly longer work, which is included as Appendix B.]

From 1999 through 2002, the National Marine Mammal Laboratory (NMML) conducted collaborative projects focused on the advancement of passive acoustics for detection of large whales. The NMML focused its efforts on long-term deployments of autonomous recording packages (ARPs) for detection of large whales in Alaskan waters. Four ARPs were deployed in the eastern Bering Sea in October 2000 to monitor waters where critically endangered North Pacific right whales (*Eubalaena japonica*) have been seen each July since 1996. Two other recorders, fabricated by NOAA/PMEL, were deployed southeast of Kodiak Island near an area where one North Pacific right whale was seen in July 1998. In addition, NMML collaborated with researchers using the U.S. Navy's SOund SUrveillance System (SOSUS) assets to locate blue whales in the North Pacific to conduct a provisional seasonal habitat analysis by integrating the call location data with bathymetry and remotely sensed data (i.e., sea surface temperature (SST), chlorophyll a, altimetry) using a geographic information system (GIS). Results of these analyses were presented at the 13th Biennial Marine Mammal Conference in 2000 and subsequently published in *Oceanography 15*(3), 2001.

Discussion (Thursday, 21 November)

The theme of this day of the workshop was "Directions for the Future." The day was organized as four discussion sessions on topics important to either performing assessment or understanding responses of marine mammals to noise. Each discussion session was moderated by a member of the workshop; the goal of the discussion was to determine what acoustics might contribute toward the topic at hand, and what the group might recommend toward that end. The recommendations were further discussed and refined on Friday.

Below is a summary of the day's discussion.

Discussion Topic I. Population Structure

Jay Barlow, moderator

Management aspects of population structure

The appropriate subdivision of a species into "management units" or "stocks" varies with different management frameworks and objectives. The U.S. Marine Mammal Protection Act (MMPA) has a requirement that species be maintained as functioning elements of their ecosystems, and this has been interpreted to mean that there should be no fragmentation or contraction of the range of any species. To meet this objective, a species would have to be managed on the basis of smaller units (to prevent local extirpation) than if the management objective were to prevent the extinction of the species. The Endangered Species Act (ESA) refers to Distinct Population Segments (DPS) of a species which are typically larger than the "population stocks" which are managed under the MMPA. The U.S. Fish and Wildlife Service and NMFS, which are responsible for enforcing the ESA, have interpreted these legal requirements to mean that a DPS must be genetically distinct and must occupy unique habitat. If conservation of populations is successful, the evolutionary potential of a species is preserved.

Studies of population structure for cetaceans have mainly used genetics, tagging, and photo-identification. To a lesser extent, gaps in distribution have been used as indicators of separate populations. It may be useful to use one technique—for example, differences in vocalization types—to form hypotheses about population structure, and another technique—say, genetics—to test the hypotheses.

Although the above principles have been widely discussed in the conservation biology community, there has been little uniformity in how the principles are applied across species. The International Whaling Commission (IWC) has a Working Group on stock identification. That group decided that the term "stock" was confusing because it means different things to different people; the IWC chose the term "unit to conserve" instead. Some examples:

- Under the U.S. ESA, gray whales are divided into eastern and western stocks, with the eastern stock considered recovered and the western stock still endangered.

- The appropriate population structure for Bryde's whales in the Pacific is unknown. Some within the IWC have suggested a structure with three populations: one near Japan, one made up of pygmy Bryde's, and the third encompassing all other Bryde's whales.
- The appropriate structure for Atlantic minke whales is likewise unknown. Separation into an oceanic population and a coastal Norway population has been suggested.

Time scale

Management typically operates on a time scale of years or decades. Traditional use of genetics to define populations has focused on differences between populations that build up on an evolutionary time scale and is inappropriate for defining management units. Genetics can now be used for estimating dispersal rates to answer the question, "If a species has been extirpated in one area, does repopulation happen in 10 years or 200?" As an example of this dilemma, the southern resident population of killer whales in the Puget Sound area has been declining. If this population dies out, will the northern residents repopulate the area? There is little to no genetic interchange between the southern and northern residents, but the northern residents do come into the southern area sometimes. Other examples include places where whaling eliminated a population, and re-population has not occurred: Spitsbergen bowhead whales, South Georgia blue whales, and South Georgia fin whales.

Acoustically defined populations

It may be reasonable to investigate populations as defined acoustically (Table 1), i.e., by vocalization characteristics. As an example, blue whale vocalizations in different areas appear to have different time/frequency contours. Such differences may sometimes be sufficient, for instance, for defining a Distinct Population Segment under the ESA. Acoustic differences have been used to define stocks by NMFS: the Eastern Pacific stock of blue whales was recognized because of its unique call type. At the same time, acoustic differences are not a necessary condition for defining a stock; humpback whale genetics has shown maternal fidelity to breeding sites—enough difference has been found to define separate stocks—but acoustically, these populations would be lumped into one stock. There is simply more difference in genetics than in song.

The amount of data available for investigating this question varies widely between species. For instance, Bryde's whale sounds have not been acoustically sampled throughout much of their range, and the variation in call types is not known. Taxonomists are now suggesting that Bryde's whale be split into at least two or three species, and perhaps more; the extent to which these species splits correlate with acoustic differences will remain unknown until more acoustic data can be collected.

It was strongly suggested that we think in terms of evolutionary biology

Table 1: Known acoustic population structures of some marine mammals.

Species	Geographic structure	Number of populations	Temporal stability	Citation
blue whale *B. musculus*	large fixed differences between populations	9–12	30–40 year	Stafford (1999, 2001); McDonald, pers. comm.
fin whale *B. physalus*	statistically detectable differences between populations	?	?	Thompson and Freidl (1982)
Bryde's whale *B. edeni*	large fixed differences between populations	8–?	≥2 year	Oleson *et al.,* to appear
common minke *B. acutorostrata*	fixed differences between populations	2–3	≥40 year	Winn and Perkins (1976); Mellinger *et al.* (2000); Gedamke *et al.* (2001)
humpback whale *M. novaeangliae*	within a season, fixed differences between populations	4–?	1–3 year	Payne and Payne (1983); Noad *et al.* (2000); Cerchio (2002)
right whales *E. glacialis, australis, japonica*	none?	?	?	Clark (1982); Clark *et al.* (2000); McDonald and Moore (2002)
bowhead whale *B. mysticetus*	none?	?	?	Clark and Johnson (1984); Würsig and Clark (1993)
gray whale *E. robustus*	?	?	?	Crane and Lashkari (1996); Moore and Ljungblad (1984); Dahlheim (1987)
sperm whale *P. macrocephalus*	statistically detectable differences between populations	?	?	Watkins and Schevill (1977); Weilgart and Whitehead (1993); Pavan *et al.* (2000)
orca *O. orca*	large fixed differences between populations	>>6	≥30 year	Ford (1991)
beluga *D. leucas*	unknown; some data exist	?	?	Sjare and Smith (1986); Angiel (1997)
other delphinids	statistically detectable difference between species	>>100	?	e.g., Steiner (1981); Rendell *et al.* (1999); Oswald *et al.* (2003)
bearded seal *E. barbatus*	unknown; some data exist	?	?	Ajmi (1996)
harbor seal *P. vitulina*	fixed differences	>>6	≥30 year	Hanggi and Schusterman (1994); Van Parijs *et al.* (2000); Van Parijs *et al.,* in press

about why there are acoustic differences, and about how fast vocalizations change.

It was reiterated several times during the workshop, and agreed by all or nearly all present, that a combined approach to studying populations (and assessment in general) is needed. By a combined approach, we mean using all appropriate methodologies, including but not limited to acoustics, visual surveys, genetics, behavior study, tagging, etc.

Discussion of population structure culminated in several recommendations, which are covered below as item R1 of Friday's topics.

Discussion Topic II. Abundance and Density

Phil Clapham, moderator

The estimation of marine mammal density or abundance using acoustics is similar to estimation by visual methods in several regards. The estimation methods for either are likely to involve the application of some form of "distance sampling": either line-transect or point-transect methods. These methods require the estimation of detection distances from either a moving platform or a single stationary point (respectively). For both, important factors include those that affect the production of cues (surfacings, blows, etc. for visual surveys; vocalizations for acoustic surveys) and those that affect the detection of cues (e.g., equipment used, sea state, etc.). For visual surveys, all individuals produce at least some cues at regular intervals (animals must surface to breathe); whereas, for acoustic surveys, there may be much more variation in the rate of cue production between different individuals (e.g., gender, age, and seasonal differences). Therefore, for acoustic surveys, there may need to be greater emphasis in the measurement of factors that are related to the production of cues. In contrast, the detection of cues is much more easily understood for acoustic detection methods than for visual methods. For visual surveys, detection distances are estimated empirically, and there has been very little progress in the mathematical modeling of visual detection distance. For acoustic detection methods, there is a much greater contribution that modeling can make to improve our understanding of detection distances.

To date, there has been greater emphasis on visual than acoustic methods of estimating marine mammal density or abundance. There are many abundance estimates based on visual methods alone, but none based solely on acoustic methods. However, there have been published estimates based on the integration of visual and acoustic methods (e.g., bowhead whales and sperm whales), and in these cases, the addition of acoustic methods have greatly improved the abundance estimation. Some members of the workshop envisioned a day when acoustic survey methods would completely replace visual methods; however, most participants felt that the greatest immediate benefits might be obtained by using the best attributes of each method in an integrated survey.

One key factor in the use of acoustic survey methods must be species identification. In this area, more progress has been made with baleen whales than with the toothed whales. There are many baleen whales for which species can be determined unequivocally from at least some call types (e.g., blue whales, fin whales, minke whales, humpback whales, and right whales); whereas there are few toothed whales for which this is true (e.g., sperm whales and killer whales). In a recent study of nine dolphin species, the percentage of correctly identified individuals (from a single whistle) was only about 50%, and, clearly, if acoustics are to be a valuable survey tool, methods should be investigated to improve this. A working group of Dave Mellinger, Kate Stafford, and Julie Oswald was identified to review the state of species identification from cetacean calls.

Another key factor in the use of acoustic survey methods is the need to estimate detection distances. For this, there are two general approaches: empirical and theoretical. The empirical approach involves measuring the actual location of vocalizing animals for a large sample and fitting some function to describe the probability of detection as a function of range. The localization of vocalizing whales can be purely acoustical using hydrophone arrays or by utilizing multi-path information (bottom/surface bounces) or other aspects of sound propagation. The theoretical approach involves modeling of detection distance using knowledge of source levels, propagation conditions, and ambient noise. It was pointed out that 20 dB variations in source level could have a 10-fold effect in detection distance, so additional efforts are needed to quantify source level variation. There is considerable variation in published estimates of source level for many species, and these need to be evaluated to determine whether this represents measurement error or natural variation. Chris Clark mentioned that he has data on variation in source level of right whales in the Atlantic. It was agreed that both empirical and theoretical approaches to estimating detection distance have merit, and that there should be efforts to validate the theoretical models using empirical methods.

The relative merits of moving platform (line-transect) surveys vs. fixed point surveys were discussed. In distance sampling, there is a common assumption that the speed of the survey platform is fast relative to the speed of the animals being surveyed. This is clearly violated for fixed-point surveys. In order for fixed-point surveys to work for estimating density, the residency time within the detection range needs to be addressed. Currently there is no well-defined method for doing this in a rigorous quantitative framework. It is possible that cue counting methods (a sub-set of distance sampling) can be used from fixed points, but cue rates would have to be well known and additional analytical developments are probably required. It is also possible that fixed-point surveys can be used in a narrow migration route to enumerate migrants, however this method is quite different. A common aspect of both line-transect and point-transect methods is that transects must be placed randomly with respect to the animals. The current array of fixed sampling points is probably inadequate to meet this assumption because they are placed in a physical environment that was chosen to optimize reception, and these physical factors are also likely to affect whale distribution. Also, a large number of fixed points would likely be necessary to adequately sample a species' range. For a mobile platform, it is easier to meet the assumption of randomness with respect to whale distribution, but if a systematic survey grid is used, care should be exercised to ensure a random starting point is selected. The strength of fixed point monitoring (e.g., bottom recorders) is the much greater temporal/seasonal coverage. The strength of mobile platform monitoring (e.g., ship line-transect surveys) is the broader geographic coverage. Participants agreed that there is value in both of these general approaches.

One area that clearly needs more work for the advancement of acoustic surveys is to understand variation in vocalization rates. Likely factors that affect vocalization rates are gender, age, seasonality, location, time-of-day, and associated behaviors (e.g., feeding vs. breeding). Fixed hydrophones or (especially) hydrophone arrays matched with detailed visual observations may also be extremely useful in quantifying vocalization rates. Oleson and Hildebrand described an experiment planned in association with FLIP and a moored hydrophone array to study blue whale vocalization rates in southern California next summer. The development of acoustic recording tags may allow great advances to be made in the near future. The information from acoustic tags can be greatly enhanced if the tag is designed to retain a small sample of skin for genetic analyses of gender and population structure. It was pointed out also that the value of acoustic tags is greatly enhanced if they can be applied to a random sample of the population; the deliberate sampling of vocalizing animals would result in a biased estimate of vocalization rates for the population as a whole.

Because methods for purely acoustic surveys are not well developed, emphasis should be placed on integrating visual and acoustic survey methods to improve estimates of abundance. Acoustic methods can provide improvements by extending search range, by allowing survey at night, by detecting submerged animals, and by estimating the fraction of animals missed by visual methods. If visual and acoustic detections can be considered to be independent, the fraction of animals missed can be estimated with mark-recapture methods. If there is a negative correlation between the probabilities of acoustic detection and visual detection, mark-recapture methods will result in an overestimation of abundance; in such cases it may be better to pool visual and acoustic detections to minimize the negative bias in either one without risking a positive bias in abundance estimates. However abundance is estimated, there is a need to match visual and acoustic detections to determine whether the animals seen are the same ones being heard. This is best done in the field, but analytical procedures that assign a probability of a match are also being developed. The purely acoustic estimation of the number of individuals in a large group remains problematic, and here visual methods are still essential.

Discussion Topic III. Responses to Noise

Sue Moore, moderator

How can acoustics be used to study responses of marine mammals to noise? One obvious answer is that one must measure the noise in order to understand any responses to it, but beyond that, acoustics may be useful in other ways as well.

Marine mammals may respond to both natural and manmade noise.

Natural Noise

There are several ways the issue of responses to natural noise can be viewed, depending on the type of noise and the response.

- Animals may respond to calling by conspecifics by changing their own vocalization behavior. If so, this bears directly on efforts toward an acoustic census, in which the number of individuals is to be estimated from acoustic data. Sometimes individuals of a species may respond by increasing their own rate of vocalizations; right whales, for instance, are known to increase their vocalization rates when other right whales are present and vocalizing. Another response could be decreased average call rates, such as when an individual needs to make fewer contact calls to a herd when other members of the herd are themselves calling nearby. This topic needs significantly more study before acoustics can become widely used for censuses.

- Animals may respond to increased noise by increasing the intensity of their vocalizations. This may happen regardless of whether the noise is from conspecifics, other natural sound sources, or manmade sound sources.

  One subject open to investigation is how whales respond to earthquake sounds, which are very low in frequency. This question could be studies using long-term recordings of SOSUS arrays, which are available at NOAA/PMEL, or using recordings from autonomous hydrophones that have been deployed by several researchers. It would probably make the most sense to investigate response to earthquakes in whale species that use very-low-frequency sound, such as blue and fin whales.

- An animal may respond to a noise source by moving toward or away from it. As an example, fin whales have been seen to move away from vessels emitting seismic profiling airgun sounds; similarly, seismic profilers operating off the coast of Africa have displaced some species. (These are obviously not natural noise sources, but they illustrate responses that could be studied using acoustic methods.) Again, data already exist from autonomous hydrophones and fixed arrays that could be used to address these questions.

In order to address the above questions quantitatively, it would help to have a prioritized listing including species, areas, and data sets.

Anthropogenic Noise

The topic of responses of marine mammals to anthropogenic noise is quite large, and is being addressed by a National Research Council panel. The relatively brief discussion at this workshop revolved around ways in which passive acoustics could be employed to address this topic.

One suggestion would be to use passive acoustics to quantify the noise field—to come up with a "noise budget" for the oceans. Constructing such a budget would necessarily be a huge undertaking, as the noise would need to be characterized by geographic location, time, and frequency (spectrum), and probably further by other properties such as duration of transients, variation over time, etc. Data sets already exist for constructing such a noise budget, but many more recordings will be needed.

As a first step toward creating such a budget, it was suggested that all passive acoustic recordings be made using calibrated equipment (hydrophones, amplifiers, etc.). This will, at minimum, make the collected data usable for analysis of noise budgets.

The suggestion was also made that it would help greatly to have some device to communicate to the public what ocean noise levels are like. For instance, this could be a graphic device like a thermometer showing averaged noise levels. It is also necessary to communicate to the public that the ocean is not a pristine sound environment; some level of natural sound is always present, and manmade sounds are present much of the time. The level of manmade sounds has been going up over the last several decades (see paper by Rex Andrews in JASA-Online).

Many workshop participants recognized that seismic airguns emit quite high levels of sound. For instance, seismic survey ships operating near Sable Island, Nova Scotia dominate the sound field recorded along the Mid-Atlantic Ridge thousands of miles away. There are alternatives to airguns (of unknown effectiveness and cost); marine vibro-seis technology was developed in the 1970's but has not been used widely. (Vibro-seis machines shake the ground, delivering a vibratory signal of longer duration but much lower peak intensity than an airgun.) If there is a large impact of airgun sounds on marine mammals, and people start asking whether there are alternatives, it helps to have "yes" as an answer.

Discussion Topic IV. Relative Density, Seasonal Distribution, and Trends

Jeff Laake, moderator

There is much interest in the use of "relative density" from vocalizations as a measure of trends in abundance or to infer seasonal movement pattern. Interpreting the number of calls or the summed intensity of calls as "relative density" requires that the factors that affect call production and call detection be the same in the two samples being compared. In most cases, this will not be known, and it would be extremely tenuous to make this assumption. The work to validate the assumptions required to interpret "relative density" is, in general, the same work that would be necessary to estimate absolute abundance, so there is seldom a compelling reason to concentrate research on relative density alone. The assumption that call rates are proportionate to animal density is likely to hold up best when comparing within one season and geographic area, such as for breeding-related calls made on the breeding grounds.

It was pointed out that acoustic surveys can provide additional information even when they are not able to provide unbiased estimates of density or abundance. For example, the density of calling whales may be estimated using a maximum estimate of calling rate and a maximum estimate of detection distances; such an estimate can be useful as a minimum estimate of density. Surveys of vocalizing animals also can be used to define the range of species and help define their breeding areas. Although it might be hard to use calls to quantify movement patterns, the geographic "big picture" of seasonal movements might be more obvious from acoustics than any other available method.

Management needs for acoustic surveys, especially to provide better knowledge of seasonal distribution, are shown in Table 2.

Table 2: Management-related needs for large whale populations that could be assisted by acoustic (point source) monitoring. In some cases, positive results from such monitoring could be used to focus dedicated surveys in the areas concerned.

Species	Location	Period	Issue	Notes	Priority
E. glacialis	Unsurveyed and/or historic habitats	Year-round	Are these habitats still utilized? Where does much of the population go in winter? Where do non-Fundy females go in summer?	In order of priority: Scotian Shelf (Roseway Basin, Emerald Basin), mid-Atlantic states, Flemish Cap, Cintra Bay, Labrador coast, Cape Farewell Ground, Hebrides, Maury distribution.	High
	Known major habitats	Seasonal	What is the occurrence and distribution of whales? What is the frequency of ship traffic?	Areas include Great South Channel, Roseway Basin, Bay of Fundy, Cape Cod Bay, U.S. mid-Atlantic states, southeastern U.S.	High
	U.S. mid-Atlantic states	Winter/spring	Movement and locations of migrating animals	Density may be low (so low call rates?) Important for ship-strike management.	High
E. japonica	Historic habitats, eastern North Pacific	Year-round	Are these habitats still utilized? Where are whales at any time?	Current distribution poorly known. Areas include: Bering Sea, Gulf of Alaska, Aleutians.	High
	Historic habitats, western North Pacific	Year-round	Are these habitats still utilized? Where are whales at any time?	Current distribution poorly known. Areas include: Kurils, Commanders, Okhotsk Sea (Sakhalin). Logistically and politically difficult.	Medium
M. novaeangliae	U.S. mid-Atlantic states	Winter	Frequency of occurrence	Area has high mortality and whales from at least two feeding grounds.	High
M. novaeangliae *B. musculus* *B. physalus*	South Georgia	Spring-fall	Has the area been recolonized?	All three species virtually extirpated in this area by whaling.	Medium
M. novaeangliae	New Zealand	Winter	Ditto	Ditto	Medium
B. musculus	Japan	Summer?	Ditto	Ditto	Medium
B. physalus	Gibraltar	Year-round?	Ditto	Ditto	Medium
B. mysticetus	Spitsbergen	Year-round	Ditto	Ditto	Medium
Any	Any marine mammal habitat in which noisy human activity is likely in the future	Year-round	What is the baseline ambient noise and distribution of whales in the area?	Collection of baseline data for assessment of impact of future industrial or other human activities (e.g., in lease-sale areas).	High

Recommendations (Friday, 22 November)

Discussion culminated in a set of recommendations for future research, survey methods, changes to marine mammal management policies, and changes to field operations procedures. Within each category (e.g., within *R1*), these recommendations are ordered from highest to lowest priority.

R1. Examine vocalization types as an indicator of population identity

In some species, there are identifiable differences between vocalizations recorded in different regions. For example, blue whales worldwide have several distinct vocalization types (e.g., Cummings and Thompson, 1971; McDonald *et al.,* 1995; Ljungblad *et al.,* 1998; Stafford *et al.,* 1999). To what degree are such differences useful as indicators of population identity—for example, do acoustic differences correlate well with genetic differences? If they do, it would facilitate determining the seasonal distributions of the various populations. In a small number of cases, acoustic differences have been found to be correlated with genetic differences; one such case is fin whales in the Mediterranean and in the North Atlantic. Some populations—for example, humpback whales breeding in different regions of the North Atlantic—evidence genetic differences but not acoustic ones.

R1a. **Literature Review Recommendation:** Compile example spectrograms of diagnostic species-specific or population-specific marine mammal sounds. Spectrograms need to be made at several time scales to ease comparison with sounds that may be observed later (and other spectrogram parameters need to be specified). This would be a research tool rather than a field guide for casual observers.

R1b. **Literature Review Recommendation:** Examine the time scales and geographic extent of vocalization types as shown by existing literature (and recordings?), with particular attention to identifiable categories that can be associated with certain species/areas (see Table 1). Identify gaps (many of them large) in knowledge.

R1c. **Management Recommendation:** Use evidence of diagnostic differences in vocalizations between areas as the null hypothesis for population structure instead of thorough mixing when making management decisions. However, lack of evidence of acoustic differences should not necessarily be interpreted to indicate a lack of population structure.

R1d. **Management Recommendation:** Recognizing that acoustics may be useful for only a subset of marine mammals, the pairing of acoustics with other indicators of population structure should be prioritized both by the conservation concerns and by the likelihood of success. The latter can be assessed using available data on whether species segregate by age and/or sex.

R1e. **Field Operations Recommendation:** Researchers deploying acoustic tags should collect skin samples from tagged animals, and process and store the samples in such a way that they can be analyzed genetically.

R1f. **Field Operations Recommendation:** When possible, obtain biopsy samples from targeted species when collecting data with ship-based acoustic systems, including towed arrays and sonobuoys.

R1g. **Research Recommendation:** Using the data collected from skin samples and biopsies, investigate genetic and acoustic population structures and the relationships between them. With skin samples from acoustic tags, differences between individuals making known vocalization can be compared; with biopsy samples, only comparisons between populations making different vocalizations are usually possible.

R1h. **Research Recommendation:** Because existing data indicate that some discrete populations mix either during migration or on feeding grounds, it is recommended that, when practical, data should be first collected on breeding grounds when genetic populations should be well segregated.

R2. Include acoustic monitoring on NMFS ship-based marine mammal surveys

R2a. **Survey Recommendation:** Routinely use acoustics on all NMFS ship-based surveys.

R2b. **Survey Recommendation:** Use calibrated hydrophones and amplifiers for all towed hydrophones.

R2c. **Survey Recommendation:** Establish and document recommended standards for the five NMFS regions for

- data collection tools and equipment (e.g., array connectors/pinouts, calibration standards),
- data collection methods (e.g., record and make static all amplifier/sample rate/filter configurations for calibration; collect data on sound speed profiles from CTD/XBT, data on behavior, estimates of group size, noise data from other sources),
- data collection software,
- data analysis methods (e.g., estimation of bearings and ranges to detected individuals; combination of successive locations into tracks; estimation of detection ranges).

R2d. **Survey Recommendation:** Develop a protocol for integrating visual and acoustic data from line-transect surveys (operational procedures, data recording, analysis).

R3. Investigate the acoustic detectability of vocalizing marine mammals. (Separate detection distance/source levels/depth/ orientation/beam pattern/environment from vocalization rates?)

What proportion of the time can different species of vocalizing marine mammals be detected using passive acoustics? While empirical field studies (e.g., Barlow and Taylor, 1998) and theoretical models (e.g., Mellinger *et al.*, 2002) have been used to study this question in a preliminary way, to date no directed investigations have been done for either towed-array systems, sonobuoys, or fixed acoustic sensors.

R3a. **Research Recommendation:** Study acoustic detection distance—how far away can a calling animal be heard?—and statistical modeling of calling and diving behavior, movement of animal and possibly of the sensor, environmental conditions, background noise levels, etc. Studies should be done both theoretically and empirically.

R3b. **Research Recommendation:** Determine the best (lowest-cost) way to localize whales at one site with the minimum number of hydrophones and recording devices.

R4. Study the relation between the number of vocalizations heard (or number of animals tracked) and the number present

How can acoustic data be used to estimate the number of animals present in a given area? One approach involves relating the number of calls received to the number of individuals estimated by visual surveys. This method requires estimates of calling rates, which can be derived from either acoustic tags or joint acoustic-visual surveys. Another approach involves acoustic tracking of individual animals; it requires estimating the proportion of individuals that produce sound.

R4a. **Research Recommendation:** Use acoustic tags to estimate calling rates of individual animals. Application of a tag to an animal should be done independently of the animal's acoustic behavior; in particular, these animals should not be located acoustically.

R4b. **Research Recommendation:** Use joint acoustic/visual surveys to estimate the proportion of animals that produce sound. This may vary with season, area, year, age, and sex of the animals, behavioral state, density of animals, and background noise, so all of these factors must at least be recorded.

R4c. **Research Recommendation:** Develop ways of estimating abundance from fixed autonomous recorders.

R4d. **Research Recommendation:** Develop and investigate statistical models for estimating detection probability from joint visual and acoustic surveys. Evaluate relationships between surfacing and calling from acoustic tag data.

R4e. **Research Recommendation:** Develop and evaluate methods for estimating group size from acoustic data. Where practical, deploy a second array in vicinity of large groups to enable precise tracking of individuals in groups.

R5. Use autonomous acoustic recorders to monitor trends in abundance

Although several researchers (e.g., Fox, Clark, Hildebrand, Moore) have deployed autonomous acoustic recorders for gathering data about cetacean occurrence, NMFS has yet to deploy these instruments systematically.

R5a. **Research Recommendation:** Pick areas in which some species of interest occur (see Table 2), make several successive 1-year deployments of arrays of recorders, and analyze the results for trends in number of vocalizing animals or the number of vocalizations detected. Knowledge of acoustic detection distances is a prerequisite to estimating trends in abundance.

R5b. **Field Operations Recommendation:** Use calibrated hydrophones for all deployments. Re-calibrate regularly.

R5c. **Recommendation:** Share and compare information on automatic signal detectors. Published descriptions of detectors should be as explicit as possible.

R6. Fill in gaps in knowledge about unknown sound types and unknown cetacean populations

R6a. **Field Operations Recommendation:** Collect acoustic and visual data in such a way that definitive identification of animal(s) making unknown or poorly-known vocalizations is possible. (Primarily this means that visual observers need to record animal location as frequently as possible.)

R6b. **Literature Review and Research Recommendation:** Determine the significant gaps in knowledge about distribution and seasonality of marine mammal populations; go to suspected or likely locations and obtain recordings. Conversely, investigate some of the unknown sounds that are recorded.

R7. Study responses of marine mammals to natural noise

Marine mammal species may respond acoustically to natural noise sources, including wind/wave noise, earthquakes, and sounds from conspecifics. They might, for instance, increase or decrease the rate or intensity of their vocalization. Existing data sets, principally from cabled arrays and autonomous recorders, could be used to investigate these responses.

R7a. **Literature Review Recommendation:** Develop a list of species, existing data sets, and geographic areas in which responses to natural noise could be investigated.

R7b. **Research Recommendation:** Choose one or more items from this list and do the study.

R8. Support efforts to quantify the noise field

Recognizing that ambient noise is an important part of marine mammal environment and is an essential component of assessing marine mammals by acoustic methods....

R8a. **Management Recommendation:** Support efforts to map ambient noise fields throughout the world.

R9. Assess the effects of seismic airgun surveys and mitigation measures on marine mammals

The International Association of Geophysical Contractors (IAGC) and Minerals Management Service are looking for research recommendations on reducing the potentially harmful effects of airgun emissions (which may be funded by oil companies).

R9a. **Research Program Recommendation:** Assess the potentially harmful effects of airgun emissions on marine mammal populations.

R9b. **Recommendation:** Contribute to monitoring the effects of mitigation measures on ambient noise levels.

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Appendix A: Distance Sampling and Marine Mammal Acoustic Surveys

Jeff Laake

Estimation of animal abundance or density, in its simplest form, requires correctly counting the number of animals in a sample region of known size. For example, n animals could be counted within a strip of length L and width $2w$ and the density (D) for this strip transect sample would be

$$D = \frac{n}{2wL}$$

Typically, the effectiveness of methods to detect animals, whether they are visual, auditory, or otherwise, declines as the distance between the animal and receiver (e.g., observer, acoustic receiver, etc.) increases. Thus, if an observer traversed the rectangular region by traveling down the centerline and could not detect all animals within a lateral (perpendicular) distance of w, animals would be missed and the density estimator would be negatively biased. One option would be to make the strip more narrow such that no animals were missed. However, this would exclude many potentially useful observations detected beyond the strip boundary and would require a strip that was sufficiently narrow such that the assumption of perfect detection was satisfied for all conditions that would be encountered.

A more complete use of the data is accomplished with distance sampling (line and point) (Buckland *et al.,* 2001) which originated with visual surveys of animals but has been extended into numerous other applications (e.g., sonar, underwater video) due to the generality of the underlying concept. The fundamental construct of distance sampling is the detection function, $g(x)$, which is the probability of detecting (e.g., visual or auditory) an animal that is at a lateral (perpendicular) distance x from the centerline or at a radial distance x from a point (e.g., sonobuoy). If $g(0) = 1$ (all animals on the line or at the point close to the receiver are detected), lines or points are selected independent of the animal distribution and animals do not move prior to detection, then the expected proportion of animals detected within a strip is

$$p = \frac{\int_0^w g(x)dx}{w}$$

and the abundance estimator is

$$D = \frac{n/p}{2wL}.$$

Likewise, for point (circular) samples,

$$p = \frac{\int_0^w xg(x)dx}{w^2}$$

and for k points the abundance estimator is

$$D = \frac{n/p}{k\pi w^2}.$$

Acoustic (auditory) sampling is often used in bird sampling, and in forest habitats it is the primary mechanism for locating birds that are not visible or difficult to see. Thus, it is quite natural to consider applying distance sampling to acoustic surveys of marine mammals or joint acoustic and visual surveys. The acoustic and visual sampling methods are complementary because marine mammals are available for acoustic sampling when they vocalize and are not visible beneath the surface and they are available for visual sampling when they are at the surface and they are not vocalizing.

Standard distance sampling is only unbiased if all marine mammals on the line or at the point are detected ($g(0) = 1$). In visual surveys, marine mammals are detected if they are at the surface (available) when in view of the observer and they are observed (perceived) and identified by the observer. In acoustic surveys, marine mammals are detected if they vocalize (available) and the vocalization is within the detection range of the acoustic receiver (perceived) and identified based on its vocalization. Thus, it is unlikely that $g(0) = 1$ for either method for many marine mammals and large whales in particular. The expected value for the abundance estimator is $g(0)$D, which is negatively biased unless $g(0) = 1$.

Several alternatives are possible to remove or minimize the bias due to $g(0) < 1$. One approach used with visual surveys is to develop an estimate of $g(0)$ based on a model for availability (e.g., surfacing interval) and the observation process (Barlow, 1999) or incorporating surfacing interval data within an estimation model from the observed data (Schweder, 1999). Similar approaches could be used with acoustic surveys if data on the vocalization process were available. These approaches assume that the externally derived process data (e.g., surfacing interval) applies to the survey data that are typically collected at a different time and place. Another approach that avoids that assumption uses survey data collected from "independent observers" (IO) during the course of the survey (Buckland and Turnock, 1992; Borchers *et al.,* 1998; Laake, 1999). The independent observers can be on the same survey platform (e.g., ship or plane) or on different platforms (e.g., one on a ship and the other on a helicopter in front of the ship). The analysis is a form of mark-recapture (sighting and re-sighting) and requires knowing which observations are detected by both observers or that assessment must be incorporated into the likelihood (Hiby and Lovell, 1998). If the timing for the observations is nearly coincident (e.g., two observers in the same aircraft) then the IO method will not correct for "availability bias" (e.g., whales beneath the surface) but can correct for reductions in $g(0)$ due to "perception bias" (e.g., visible whales that are missed) as long as there is a non-zero probability that one of the observers can detect every whale. In some situations (e.g., high Beaufort states) it is not possible to correct entirely for "perception bias" because neither observer has a non-zero probability of detection and the estimator will remain negatively biased under those circumstances. If observers are in separate platforms that survey sequentially and separated sufficiently in time (Buckland and Turnock, 1992; Laake *et al.,* 1997; Hiby and Lovell, 1998; Carretta *et al.,* 1998), both "availability" and "perception" bias can be eliminated. Similar approaches could be used with "independent" acoustic surveys, but a better approach would be to combine visual and acoustic surveys as the "independent" sampling methods. A joint visual/acoustic survey would enable estimation of $g(0)$ for both methods as long as the availability processes (surfacing and vocalizing) were independent. In general for two sampling methods, the expected value of the conditional probability of detection of one method (1) given an observation from another (2) can be expressed as:

$$E[\text{Pr(detected by 1} \mid \text{detected by 2)}] = \frac{\text{cov[Pr(detected by 1), Pr(detected by 2)]}}{p_2} + p_1$$

If the process covariance is 0, the correct answer (p_1) is obtained. If the covariance is positive, detection probability will be over-estimated and abundance will be negatively biased. But, if the covariance is negative, abundance will be positively biased. When the same survey method is used for both "independent" observers the covariance is typically positive because what affects the visibility for one observer affects the other in the same way. However, with visual and acoustic sampling methods the covariance is not necessarily positive and may be negative depending on the surfacing and vocalizing processes. If whales vocalize at depth and vocalizing whales are unlikely to be at the surface within the field of view of the visual observer and surfacing whales were unlikely to vocalize within the range of the receiver, the processes would be negatively correlated and abundance would be positively biased, possibly severely so. A better understanding of the relationship between surfacing and vocalization is needed before any confidence is placed in $g(0)$ estimates derived from joint visual and acoustic sampling. An alternative approach for a joint visual/acoustic survey is to pool the unique observations from the sampling methods. This will reduce but not eliminate the bias due to $g(0) < 1$. If $g_v(0)$ and $g_a(0)$ are the $g(0)$ values for the visual and acoustic methods, respectively, then $g(0)$ for the pooled data would be bounded between max $[g_v(0), g_a(0)]$ and 1. The former would occur if the observations from one method were a subset of the other and the latter could occur if there was no overlap between the observations of the two methods.

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Appendix B: Cetacean Detection and Assessment via Passive Acoustics

Sue E. Moore

Abstract

From 1999 through 2002, the National Marine Mammal Laboratory (NMML) conducted collaborative projects focused on the advancement of passive acoustics for detection of large whales. The NMML focused its efforts on long-term deployments of autonomous recording packages (ARPs) for detection of large whales in Alaskan waters. Four ARPs were deployed in the eastern Bering Sea in October 2000 to monitor waters where critically endangered North Pacific right whales (*Eubalaena japonica*) have been seen each July since 1996. Two other recorders, fabricated by NOAA/PMEL, were deployed southeast of Kodiak Island near an area where one North Pacific right whale was seen in July 1998. In addition, NMML collaborated with researchers using the U.S. Navy's SOund SUrveillance System (SOSUS) assets to locate blue whales in the North Pacific to conduct a provisional seasonal habitat analysis by integrating the call location data with bathymetry and remotely sensed data (i.e., sea surface temperature (SST), chlorophyl a, altimetry) using a geographic information system (GIS). Results of these analysis were presented at the 13th Biennial Marine Mammal Conference in 2000 and subsequently published in *Oceanography, 15*(3) 2001.

Introduction

Since 1999, the National Marine Mammal Laboratory has collaborated with scientists at the NOAA Pacific Marine Environmental Laboratory (PMEL) and Oregon State University (OSU) in Newport, OR, Scripps Institution of Oceanography (SIO), La Jolla, CA, and Woods Hole Oceanographic Institution (WHOI), Woods Hole, MA, and to leverage their expertise in underwater acoustic techniques and analysis. The focus of acoustic studies at NMML was on long-term deployment of autonomous acoustic recorders to monitor the SE Bering Sea and waters offshore Kodiak Island for mysticete whale (especially, North Pacific right whale) calls.

North Pacific right whales were a species of particular focus due to their status as a critically endangered species and the on-going photo-identification studies conducted by the Southwest Fisheries Science Center (SWFSC) in the eastern Bering Sea. The sighting of a lone right whale among humpback whales southeast of Kodiak Island in 1998 provided impetus for placement of two recorders there also. In addition, NMML was able to collaborate on an on-going acoustic study of blue whales in the North Pacific basin using the U.S. Navy's SOSUS, and to augment that work though application of GIS technology. A brief synopsis of each collaborative project is provided below.

Acoustic Monitoring for Right Whales in the Eastern Bering Sea: Collaboration with SIO

Four autonomous recorders were deployed on 1 October 2000 in the eastern Bering Sea at locations where SWFSC researchers have photographed North Pacific right whales (*Eubalaena japonica*) during aerial surveys each July since 1998 (Fig. 1: NMML/SIO). The ARPs sample acoustic data at 500 Hz and have 36 Gbytes of data storage capacity. Two of the four ARPs were recovered and two replacement recorders deployed in late August 2001. Of necessity, this was a particularly shallow-water deployment (~70 m) and it was uncertain if storms or drag by fishing gear had caused the "loss" of two of the instruments. Subsequently, both "lost instruments" were recovered; one on the beach at Nelson Lagoon (Alaska Peninsula) and one by a fisherman working near the IDL in the central Bering Sea. So, although 2 ARPs were recovered in an unconventional way, data from four instruments are now available for analysis. Data analysis is ongoing, via contract to Dr. Mark McDonald, and SIO graduate student Lisa Munger (under the direction of Dr. John Hildebrand). Dr. McDonald is using calls recorded from North Pacific right whales in 1999 (McDonald and Moore, 2002) to aid in the detection and enumeration of recorded calls.

North Pacific Right Whales in the Gulf of Alaska: Collaboration with NOAA/PMEL

After a North Pacific right whale was sighted off Kodiak Island in July 1998, an acoustic search for right whales was conducted (Waite *et al.,* 2002). In May 2000, an autonomous recorder, similar to instruments used by PMEL for seismicity detection (Fox *et al.,* 2001), was placed on the seafloor at the location of the sighting, 57° 08.20′N and 151° 51.00′W. A second recorder was deployed farther offshore to listen for right whales and to complement a broad array of six recorders deployed in the Gulf of Alaska by PMEL (Fig. 1: NMML/PMEL). The first instrument was recovered in early September 2000, but sea conditions have thus far prevented recovery of the second recorder. The first instrument recorded sound continuously to a magnetic disk from 26 May to 11 September 2000. After recovery of the instrument, all sounds that could potentially be right whale calls were detected by a computer. This was done by measuring energy in the frequency band of right whale calls, 50 Hz to 400 Hz. Whenever the total energy was above the background noise level for at least 0.6 sec (so short thumps and clicks would not be detected), but not more than 3 sec (so long tones would not be detected), the sound was extracted and saved as a separate sound file.

A total of 10,729 potential right whale sounds were detected and extracted using this method. Next, a spectrogram of each sound file was examined visually to determine whether it was similar to other up-type calls that have been recorded from North Pacific right whales (McDonald and Moore, in press). Upon examination, 6,364 (59%) were found to be humpback whale (*Megaptera novaeangliae*) sounds, with most of the rest being various sounds from fish and other, unknown sources. A few sounds were

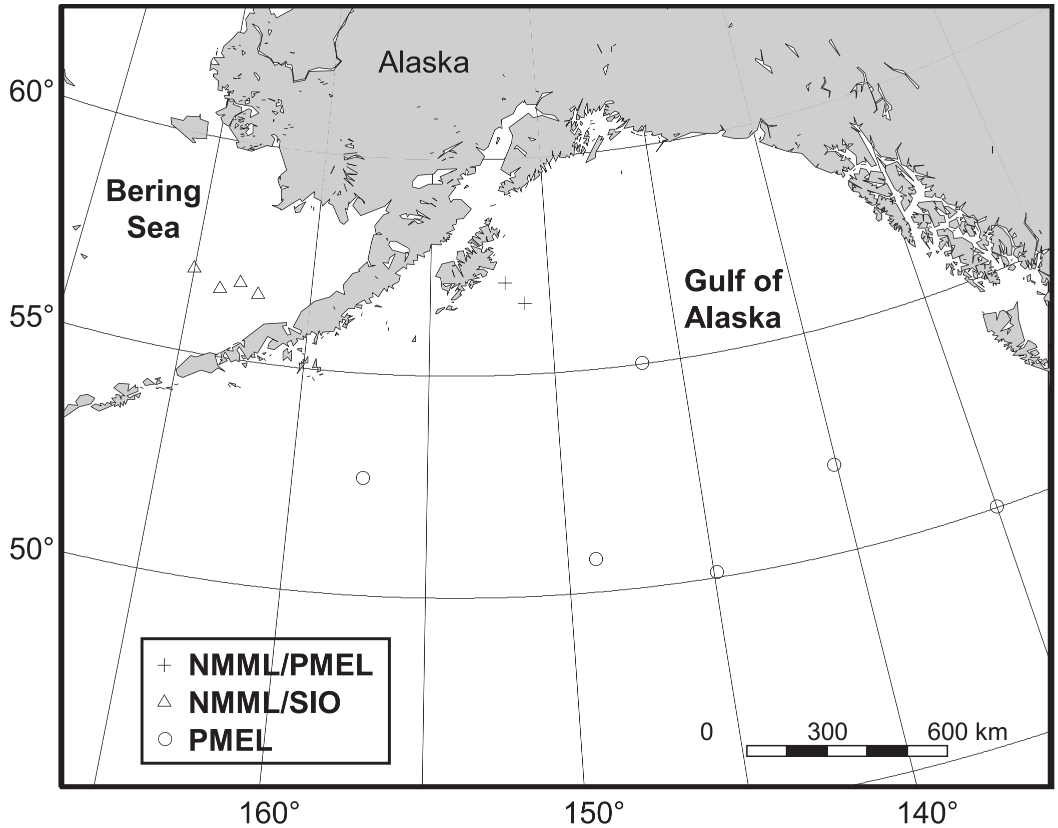

Figure 1: Locations of autonomous acoustic recorders deployed to monitor areas for North Pacific right whale (and other mysticete whale) calls in the eastern Bering Sea (NMML/SIO) and in the northern Gulf of Alaska (NMML/PMEL). The two recorders in the Gulf of Alaska complement six recorders deployed by PMEL to monitor deep-water areas for blue whales.

somewhat similar to right whale calls but could not be identified with certainty because some of the calls made by humpbacks that summer were very similar to right whale up-type calls. This made it difficult to determine with certainty what species produced these calls—especially since the right whale seen in 1998 was among humpbacks. Improvements to the algorithm used to detect right whale calls in 2001, resulted in 10s of calls, recorded during the last week of deployment being identified as being from right whales. While calls were few, it is cause to re-double efforts to find right whales near Kodiak Island, a former "key" whaling ground for the species.

Blue Whales in the Northwest Pacific Ocean: Collaboration with WHOI

Dr. Bill Watkins at WHOI heads an on-going study (since 1995) of mysticete whale calls in the North Pacific, based upon SOSUS signal reception at the U.S. Navy NAVFAC/Whidbey Island (Watkins *et al.,* 2000a, b). In FY00, NMML contracted with GIS-analyst Jeremy Davies to construct call-maps for blue whales in the North Pacific and collate call location and seasonal occurrence with bathymetry and remotely sensed data (e.g., SST, chlorophyl a). Preliminary results of this analysis were first provided in an oral presentation at the 13th Biennial Marine Mammal Conference, December 1999, with final results presented in *Oceanography* (Moore *et al.*, 2002). Here, the focus was on blue whale call detection in the Northwestern Pacific, an area of the ocean virtually unsurveyed for large whales since the era of commercial whaling. The strong seasonal signal of blue whale calling corresponds with seasonal changes in SST and chlorophyl a, although it is the association with ocean height (altimetry) and eddys that appear the strongest. This paper is designed to augment an earlier presentation of seasonal occurrence of blue, fin, and humpback whales in the North Pacific, as derived by SOSUS reception of calls (Watkins *et al.*, 2000a).

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