Report of the Joint Marine Mammal Commission – National Marine Fisheries Service Passive Acoustic Surveying Workshop

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Executive Summary

The National Marine Fisheries Service (NMFS) is responsible for gathering the information needed to support its stock assessments of marine mammals. The distribution and abundance of each stock is the core of those assessments. Data to support stock assessments are traditionally gathered by conducting visual observations during shipboard and/or aerial surveys. Increasingly, however, the agency is having difficulty provide abundance estimates and other data needed for marine mammal stock assessments. These challenges have spurred NMFS to increase its investment in alternative monitoring methods that may fill some critical data gaps more effectively and efficiently than large-scale ship and aerial surveys alone.

For the last several years, research teams across NMFS have been investigating the use of advanced survey techniques to fill the stock assessment data gap or to supplement traditional survey data. Passive acoustic monitoring (PAM) is a promising approach that can be pursued within the context of existing ship-based survey efforts or as part of an autonomous monitoring system. Research teams around the world are developing new vehicles, recorders, software and analytical techniques to study marine mammals. However, it is clear that one approach will not adequately address all NMFS science goals and research requirements for stock assessments. Technological, scientific and funding constraints are hindering the full and efficient use of passive acoustics by NMFS to inform its marine mammal stock assessments.

NMFS sponsored a previous workshop on stock assessment using passive acoustics (Mellinger and Barlow, 2003). Since then, however, there has been rapid growth in the hardware and software for collecting passive acoustic data and in the analytical approaches for processing these large datasets. In April 2015, the Marine Mammal Commission and NMFS convened a workshop to explore how passive acoustics may now best contribute to the significant challenges in surveying marine mammals and fulfilling stock assessment requirements. The workshop addressed the breadth and depth of passive acoustics development and use across the Science Centers in the context of its broader development and use throughout the marine mammal community. Workshop participants included researchers from all six Science Centers, a representative of NMFS's Office of Science & Technology (OS&T), a representative of the Marine Mammal Commission, and experts from academic institutions.

Science Center Resources

Information collected from NMFS's Science Centers before the workshop uncovered a number of important issues. The use of passive acoustics to gather critical data and to augment visual surveys of marine mammals is clearly growing in importance. Passive acoustics are used to augment ship-based, line-transect surveys; to contribute to stock delineation; to assess the occurrence and seasonality of marine mammals; and to estimate the density, abundance, and trends of marine mammals. However, limited resources have caused the Science Centers to rely primarily on outside organizations and researchers for support and expertise. Most NMFS staff members engaged in passive acoustics are temporary employees or students, making it very difficult to build the necessary in-house expertise and institutional knowledge. In addition, the availability of equipment is an issue for several Science Centers: often they do not have the resources to develop,

purchase or lease the equipment they require. An exception to this limitation is the Southwest Fisheries Science Center (SWFSC), which has led the Science Centers in a concerted effort to standardize the technology and increase the efficiency of NMFS in using and maintaining towed-array systems. Another issue affecting the Science Centers is that they do not have the information technology infrastructure to store and disseminate the vast quantities of digital data associated with passive acoustic studies.

Using Passive Acoustics in Stock Assessment

Occurrence and Seasonality

Deriving a list of species that occur in a management area is one of the most basic components of stock assessment. When it is not feasible to conduct regular surveys to evaluate species' seasonal occurrence in a region, passive acoustics has contributed significantly to marine mammal stock assessments. When a vocalization from a species is characteristic and well described, its detection in an acoustic recording can document occurrence of that species in a region. In addition, a collection of detections over a longer time series helps to determine whether the species is common or rare and whether it occurs year-round, seasonally or infrequently. There are many examples of PAM providing rich datasets from which species' occurrence and seasonality have been evaluated. However, there is more to be done in the field, especially as associations with habitat and environmental change become increasingly important aspects of stock assessment.

The assessment of occurrence and seasonality requires long-term monitoring, and for this, autonomous instruments are ideal. Such instrumentation can be deployed at relatively low cost, although the large volume of resulting data may require significant resources for analysis and storage. Increasing capacity in this area will require research in a number of areas, including establishing species/stock specific vocalization[1] repertoires; understanding the influence of ecological and social context on vocalization behavior; development of autonomous platforms that can be used over the vast pelagic ocean basins; and the development of much better automatic vocalization detectors and classifiers.

Stock Delineation

Distinguishing stocks and defining their boundaries is challenging, often requiring genetic or morphological differences between groups of animals to delineate putative stocks. There has been growing interest in using other lines of evidence for stock delineation, including differences in the characteristics of vocalizations. Geographic mapping of the vocalization characteristics for some baleen whale and delphinid species suggests differences in vocalizations may be a promising avenue of pursuit for identifying putative stocks for further study using other non-acoustic lines of evidence. Several factors can confound the apparent differences in vocalizations among putative stocks. Vocalization differences may reflect habitat, social or seasonal context, necessitating the delineation of differences in vocalizations that hold up over long periods and that encompass the full range of environmental and social contexts.

[1] In this report, the term "vocalization" refers to the wide range of sounds (songs, whistles, calls, clicks, etc.) made by marine mammals that may be recorded and analyzed in passive acoustic research and monitoring. We recognize that "vocalization" is somewhat of a misnomer because marine mammals may not use vocal cords to produce all sound types.

Differences in vocalization characteristics are most likely to indicate stock structure in cases such as baleen whales, where repetitive songs with stereotyped structures are used in reproduction. In other cases, acoustic differences alone are unlikely to provide definitive evidence of stock structure, but could be one piece of a multidimensional determination of stock delineation.

Trends in Relative Abundance

Estimates of cetacean population abundance are traditionally derived from data collected during visual sighting surveys. Although the assessment of trends does not require such intensive survey efforts, it is necessary to assume that detection probability and other absolute abundance parameters remain constant over time and space for abundance estimates to be comparable. Various measures derived from long-term passive acoustic recordings of specific species can provide relatively easily obtainable measures of relative abundance. For example, comparison of encounter rates or total acoustic energy from individual locations across many years can provide an indication of population growth or decline, under certain strict assumptions as mentioned above. Comparison of relative abundance estimates within and between locations and years can additionally reveal trends in distribution and seasonal presence over time. Like assessment of occurrence and seasonality, advancing the use of passive acoustics for assessing trends will require establishing vocalization repertoires that are species/stock specific, and understanding the influence of ecological and social context on vocalization behavior, though the latter is less of a concern if a large portion of the stock range can be monitored. A robust survey design is required to provide relative abundance estimates with sufficient precision and constant bias to detect trends over time.

Absolute Abundance

The estimation of absolute density (number of animals per unit area) and abundance (number of animals in a defined area) are among the most challenging uses of passive acoustic data. Although the use of acoustics for cetacean density and abundance estimation continues to grow, it is still not routine and is not likely to replace visual sighting surveys for most species within the next decade. Density and abundance estimation of marine mammals using passive acoustic detection is still in the early stages of development, although it is advanced in avian studies. In most cases, passive acoustic detection is not yet ready to be used alone to estimate stock abundance, because key parameters are either difficult to estimate (e.g., detection probability) or are unknown (e.g., vocalization production rates).

Most acoustic approaches to estimating density and abundance are based on methods related to distance sampling that have been adapted for acoustic data. The most significant challenges for using acoustics detection data in this context are central to the standard density-estimation framework used with line-transect or point surveys—knowing the relationship between the number of vocalizations received and the number of animals present, and locating those animals in three-dimensional space. In addition, the ability to classify vocalizations to species or stock and the influence of behavior on detection may influence whether estimation of density and abundance is feasible for a given species. Several of the limitations of using passive acoustics to estimate abundance can be overcome by combining ship-based, visual sighting and towed hydrophone surveys, which together can

overcome some of the shortcomings of visual surveys. However, in addition to technological advancements, additional behavioral data will be needed to apply distance-sampling-related methods to acoustic data.

Conclusions and Recommendations

Following the workshop, the Steering Committee met to develop general recommendations for future development of passive acoustics to support stock assessment efforts by NMFS. **Two primary areas for improvements were identified—infrastructure investment and research needs.**

Infrastructure Investment

Most of the development of passive acoustics capacity within NMFS has relied on peripheral funding and outside collaborations. Development of passive acoustic and related capabilities varies among Science Centers. Further, development of this technology generally lags behind the capacity of other research technologies that provide data used in stock assessments. The mature development of passive acoustics capacity within NMFS will require strategic and dedicated investment in infrastructure. A mature system will include state-of-the-art facilities and capacities for the development and testing of new technology (platforms, sensors, and analytic tools); maintenance of operational technology; training opportunities; deployment and retrieval of devices; storage of data; and processing and analysis of those data. These resources and capacities are often lacking. **The Steering Committee concluded that the full development of NMFS's passive acoustics initiatives would require increased and reliable federal and external funding streams.**

A larger force of bioacousticians is needed in general, but especially at the most under-staffed Science Centers. In order to provide consistent, long-term, in-house passive acoustics expertise and capacity, dedicated, full-time federal positions will need to be created to fill part of this gap. **The Steering Committee concluded that passive acoustics staffing is the first and most important issue that should be addressed.**

Access to ship time for the deployment and recovery of acoustic sampling devices is a critical factor limiting NMFS's ability to use passive acoustics to its fullest potential. Ship time is in short supply and expensive, meaning that the placement of acoustic sampling devices is dictated often by other priorities that determine the timing and track lines of NOAA research ships. **Achieving acoustic sampling designs that maximize statistical precision and minimize statistical bias (e.g., in estimates of the relative abundance of cetaceans) is critical and will require access to dedicated ship time.**

Almost all NMFS representatives from different Science Centers identified the storage, archiving, and security of large-volume, passive acoustic data as a critically important issue. **The Steering Committee concluded that in order to meet public access requirements, directed funding will be necessary. Also necessary is the development of standardized archiving protocols, collaboration with the National Centers for Environmental Information (NCEI), investment in storage devices and infrastructure, attention to security of sensitive (U.S. Navy) data, and efficient access to the data throughout the system.**

Research Needs

The use of passive acoustics to survey marine mammals is promising, but still requires considerable research effort in a number of areas. Fundamental to all acoustic research is the need to be able to identify the source of detected sounds. Although the repertoire of calls, songs, and clicks of a few species is well known, for many species repertoires are only partially known, and for some species we know very little. **The Steering Committee recommended the following: basic research to fill this gap, prioritizing focal species; the development of an accessible and centrally located catalog of marine mammal vocalizations that have been identified to species and/or stock; and additional investments in automated detection and classification algorithms and software.**

Many characteristics of marine mammal vocalizations are known or reasonably suspected to be highly dependent on environmental and social factors (e.g., season, depth, behaviors, sex, age, social context, group size, etc.), although these associations are not well understood for most species. Without such contextual information, severe biases may result in estimates of occurrence, seasonality, abundance, and trends. **The Steering Committee recommended a focus on "behavioral bioacoustics" research that will require integrated studies of vocal behavior of known animals. This research can be conducted by combining recordings with land-based observation, focal follows, or (especially) tagging, all of which are labor intensive and/or expensive.**

The estimation of the density of marine mammals recorded by acoustic monitors is highly complex and statistically difficult, primarily because it requires sophisticated equipment and processing capabilities, and because it depends on the accurate and precise estimation of several parameters. The estimation of the distance (range) to an animal that is vocalizing is a tractable problem when an array of recording devices (hydrophones) is used. However, in some important circumstances (e.g., surveying deep water), the most desirable monitoring configuration involves the use of single hydrophones. Methods have been proposed to estimate range in such situations (both actual range to identified vocalizations, and effective detection range or detection probability), but they will require considerable testing and validation. **The Steering Committee identified as a priority research goal range estimation from the data provided by a single hydrophone.**

Additional research priorities are identified throughout this report. Although it is likely that NMFS will never completely replace ships and piloted aerial platforms for marine mammal surveys, **it was clear to the Steering Committee that passive acoustics can play an important role in the cost-effective collection of data for marine mammal stock assessments.**

Contents

Figures

Tables

Chapter 1 Introduction and Background

Workshop Background

NMFS is responsible for gathering the information needed to support its stock assessments of marine mammals. Data on the pelagic distribution and abundance of each stock, which are the core of those assessments, are traditionally gathered by conducting visual observations during shipboard and/or aerial surveys, from which population estimates are derived. However, with the declining appropriations for its marine mammal conservation, management, and research, the agency is experiencing difficulty gathering those and other stock-assessment data that are necessary to fulfill its obligations under the Marine Mammal Protection Act (MMPA) and the Endangered Species Act (ESA).

For the last several years, research teams across NMFS have been investigating the use of advanced survey techniques to fill this data gap or to supplement traditional survey data. One promising approach is passive acoustic monitoring (PAM) using acoustic recorders that can be deployed from a variety of platforms, including a stationary (fixed) mooring, autonomous mobile vehicle (glider or floating buoy), or towed behind a ship.

Research teams around the world are developing new vehicles, recorders, software, and analytical techniques to study marine mammals. However, it is clear that one approach will not adequately address all science goals and research requirements for stock assessment. In addition, estimating abundance of animals using data gathered by passive acoustic approaches is proving to be a considerable scientific and funding challenge. Thus, technological, scientific, and funding constraints are hindering the full and efficient use of passive acoustics by NMFS to inform its stock assessments.

Because developments in this new and burgeoning area are moving fast, and because the technological and scientific challenges are substantial, in April 2015 the Marine Mammal Commission and NMFS convened a workshop to explore the use of passive acoustics for surveying marine mammals and fulfilling stock-assessment requirements. Progress on the development of passive acoustics for stock assessment is being made at each NMFS Science Center. The workshop addressed the breadth and depth of passive acoustic development and use across the Science Centers in the context of its broader development and use throughout the marine mammal community. Workshop participants included researchers from all six NMFS Science Centers, one representative of NMFS's OS&T, one representative from the U.S. Marine Mammal Commission, and several experts from academic institutions (Appendix A). In preparation for the workshop, several participants were asked to provide background documents (Appendix C through Appendix H) that were circulated among workshop participants prior to the meeting.

Workshop Focus

The goal of the workshop was to build a synoptic view of the development and use of passive acoustics to provide needed information for marine mammal stock assessments within NMFS. Information on planned, developing and implemented projects was gathered from each of the NMFS Science Centers (Appendix B). That information was assessed in the workshop with respect to performance and potential in the context of the general state of science and technology development. For each platform, the

workshop considered the key aspects of passive acoustic approaches to gather information for marine mammal stock assessments, including platform design; hydrophone/recorder design; software for detection, classification, and localization; data-stream handling; statistical density estimation; survey/monitoring design; and integration with traditional survey methods. The performance of various elements and whole systems was assessed relative to several factors such as: 1) the "state of the science"; 2) gaps and redundancies in NMFS's efforts; 3) constraints on development and use (e.g., regulatory hurdles, permitting, funding, platform availability, science/technology gaps, lack of available expertise, etc.); 4) expected cost-benefit ratios and actual performance in the field; and 5) needs (research, technology innovation/development, expertise, data standards, etc.). Finally, the workshop 1) contrasted "competing" technology options; 2) identified the most promising technologies for different situations and requirements; 3) identified opportunities for sharing, coordination, collaboration and synergy among regions; and 4) identified guidelines for planning, development, and use. The workshop focused entirely on cetaceans, for which passive acoustic methods are widely viewed to have the most potential. Currently, NMFS is doing little passive acoustic work on pinnipeds.

Passive Acoustics Overview

Visual survey techniques are limited when applied to marine mammals because many species are out of sight much of the time and surveying is not possible at night. However, because marine mammals generate sound to perceive their surroundings, find prey, and communicate with each other, researchers can use their sounds to detect their presence whether the animals are visible or not, as long as they are vocalizing. In addition, with the right technology and in the right circumstances, marine mammal vocalizations can be used to identify which species are present and to locate individuals.

Researchers use PAM approaches to study, monitor or survey marine mammals by deploying hydrophones in a variety of configurations and on a variety of platforms. Passive acoustics, in which researchers listen to the sounds produced by marine mammals, is different from active acoustics. In active acoustics, sounds are purposefully generated by the system, and the return signals (echoes) are recorded and analyzed to provide information on the locations and characteristics of objects in the water column. Active acoustics is typically used to create a picture of bathymetry, or to estimate the number or biomass of plankton or nekton (fish and squid) in the water column.

Using passive acoustics to survey marine mammals requires several steps. The acquisition of acoustic data begins with using a hydrophone that responds to sounds in the appropriate frequency range, depending on research goals and species of interest. Signals coming from the hydrophone are often conditioned to remove noise, filter out unwanted frequencies, and amplify desired frequencies. Often the signals are then digitized, recorded and stored for later analysis in the lab. However, in some situations, depending on the overall goals, signals are monitored and analyzed in real time and full recordings are not stored. In the lab or in real time, the signals may be further processed and analyzed to detect the clicks, calls, or songs generated by marine mammals. That analysis is often done with the assistance of computer software that detects signals in the data that match the characteristics of particular marine

mammal vocalizations. Next, analysts, often assisted by analytical and visualization software, attempt to classify vocalizations in terms of the type (e.g., echolocation clicks, whistles, songs) and source of the vocalizations (the species or population to which the vocalizing individuals belong). If the vocalizations were recorded from multiple hydrophones in an array, then arrival time differences or beam forming techniques can be used to determine the direction and/or distance to the individuals or groups that produced the vocalizations.[2] These processes are referred to as detection, classification and localization (DCL). Finally, the data from multiple recordings over time, or along a transect, can be used to estimate the density of vocalizations and, with some other information and assumptions, the density of animals (density estimation; Appendix F). If methods allow the determination of the total area within which those vocalizations occurred and the survey area was randomly sampled, then the abundance of animals in the area can be estimated.

PAM systems typically consist of the hydrophone array, a power source, pre-amplifier, recording and storage device, and sometimes a computer that pre-processes or filters the recordings. PAM systems can be combined as in the following configurations: 1) a single hydrophone or multiple elements in an array; (2) fixed or mobile; (3) monitored in real time and/or data recorded for post-processing; (4) autonomous or not. The hydrophones can be linked to a shore station or ship via cables, radio or satellite transmissions. In this case, the PAM system components are distributed, with the hydrophones, power source, and pre-amp in the water, and signals transmitted to the other components on land or a ship for recording and real-time processing.

A common mobile deployment is the towed array (Appendix D), which consists of a suite of hydrophones in a one- (linear), two-, or three-dimensional configuration that is towed behind a ship during a survey. Towed arrays often augment visual line-transect surveys to extend the range of detection, to extend surveys into nighttime hours, and to detect submerged animals that might be missed by visual survey methods. For some species (e.g., sperm whales, beaked whales, and harbor porpoises), towed arrays are often the primary survey method. Data collected from towed arrays are usually monitored in real time but are recorded for post-processing. Towed hydrophones can be severely affected by flow noise, ship noise and electrical noise, problems that are dealt with at least partially by amplifying and filtering signals. In general, towed arrays work best for species whose vocalizations are above 1 kHz because flow and ship noise mask low-frequency sounds in most situations.

Fixed autonomous acoustic recording systems, which typically contain all of the necessary components of a PAM system, are deployed at sea, where they record and store acoustic data that are later retrieved, processed and analyzed. Acoustic recording systems can be deployed as arrays of fixed units and positioned anywhere in the water column (Appendix C). Bottom-mounted acoustic recorders (BMARs) are set on the sea floor and are retrieved using a buoy line or acoustically triggered float. Surface-mounted acoustic recorders (SMARs) are positioned below the surface and held in place in the water-column by weights and floats, and kept in one location by bottom anchors. Both BMARs and SMARs store acoustic recordings captured over months or

[2] Direction alone can be determined with the use of DIFAR sonobuoys, and detection range alone can be determined from multipath signals under some conditions.

years to be off-loaded after the unit is retrieved. In some cases, data from a unit with a surface expression can be uploaded in near real time using very high frequency (VHF), mobile, or satellite networks.

Finally, mobile acoustic recorders can also be incorporated into drifting platforms or self-propelled vehicles (Appendix E). These deployments come in a few forms: buoyancy-driven autonomous underwater vehicles (AUVs); wind-/wave-powered unmanned surface vehicles (USVs); and free-drifting buoy recorders. AUVs, including both gliders and floats, can control the depth at which they move by altering their buoyancy. While floats can control only the depth at which they drift with the current, gliders use wings to generate forward velocity as well as vertical motion. Internal control and navigation mechanisms can change pitch and heading to allow a glider to "fly" a directed route. Typically, AUVs periodically surface to upload their location and data and to receive control instructions. These devices move slowly (average 0.5 kts) but can remain at sea for months during which time they can survey large areas. Because control-system noise is of concern with some mobile autonomous platforms, PAM systems are often disabled during buoyancy control operations in AUVs. Wave-powered USVs consist of two components: a surface float roughly the size and shape of a surfboard, and a subsurface unit that is winged and sometimes has a rudder. The subsurface unit is connected to the surface unit by a cable. Working in tandem, the two units use the energy of passing waves to propel the USV forward. USVs can move several times faster than AUVs. As with towed arrays, faster movement rates can create flow noise. In addition, moving components such as rudders or wave-guided surfaces can generate noise that can impede the detection of vocalizations.

Free-drifting buoys are designed to drift with surface currents or wind. The recorder can be packaged within a surface float with wired connections to subsurface hydrophones, or autonomous hydrophones can be attached to a rope line below a surface float. The sonobuoy is an example of a free-drifting buoy, although it is not considered autonomous because it lacks an onboard data-recording and storage device. Autonomous floating recorders are currently archival and must be recovered to retrieve full data files. However, processors within a surface float can send summary information via satellite or cell phones. Vertical hydrophone arrays can be used with drifting systems to allow range estimates.

Stock Assessment Requirements

The MMPA) was amended in 1994 to require stock assessment reports of marine mammals within U.S. jurisdiction (Appendix G). The requirements for stock assessment were further refined in the second Guidelines for Assessing Marine Mammal Stocks (GAMMS II; NMFS 2005). The purpose of stock assessment reports is to evaluate human impacts on marine mammal populations and to determine stock status. Similarly, the ESA requires periodic reviews of all endangered species to evaluate progress in meeting recovery goals and to re-evaluate their status under the ESA. The workshop considered the contribution of passive acoustics to both MMPA stock assessments and ESA status reviews conducted by NMFS.

The requirements for an MMPA stock assessment are clearly established, and include:

1) stock definition and geographic range (spatio-temporal distribution);
2) estimation of population size and trends in abundance, with emphasis on obtaining a "minimum population estimate";
3) estimation of current and maximum net productivity rates;
4) calculation of potential biological removal (PBR);
5) estimation of the rate of human-caused mortality and serious injury;
6) evaluation of whether a stock is "strategic"[3] under the MMPA; and
7) evaluation of other factors causing decline or impeding recovery for strategic stocks.

The requirements of ESA status reviews are not as clearly established, but certainly include many of the same elements as MMPA stock assessments. The main difference is that the standards for delineating management units under the ESA (called *distinct population segments*, or DPSs) are stricter than the standards for defining *population stocks* under the MMPA. The guidelines for delineating a DPS were established as a joint policy by NMFS and the U.S. Fish and Wildlife Service.[4]

Role of Passive Acoustics in Stock Assessment

Passive acoustics are best suited to address stock assessment requirements 1, 2 and 3 listed earlier. If there are consistent differences in vocalization structure between populations, this can aid in delimiting population stocks or DPSs using passive acoustics and may be helpful in subspecies designations. PAM can achieve broad temporal and spatial coverage, which can be useful in determining seasonal/temporal changes in geographic range. Long-term trends in detected vocalization rates can be used to infer rates of change in population sizes under certain strict assumptions, and these rates can help determine maximum net growth rates. Passive acoustic methods can be combined with distance sampling-related methods to estimate absolute abundance.

Passive acoustic research can be used in a wide variety of other contexts that are indirectly related to assessing human impacts on marine mammals (e.g., stock assessment requirement 7). These contexts include studies of ocean noise conditions and Behavioral Response Studies, which evaluate the behavioral impacts of specific noise sources on marine mammals.

[3] A stock is designated "strategic" under the MMPA if the level of direct human-caused mortality exceeds PBR and the stock is declining and likely to be listed as threatened under the ESA within the foreseeable future; is already listed as threatened or endangered; or is determined to be below its optimal sustainable population level as defined in the MMPA.

[4] Federal Register Notice: Policy Regarding the Recognition of Distinct Vertebrate Population Segments Under the Endangered Species Act. 61 FR 4722, February 7, 1996. Available at http://www.gpo.gov/fdsys/granule/FR-1996-02-07/96-2639

Chapter 2 Current Acoustic Assessment Capabilities within NMFS Science Centers

All NMFS Science Centers currently have some passive acoustic expertise and ongoing projects, generally within the branch or division that leads protected species assessments. The breadth of current work represents a significant advancement in passive acoustics capacity within NMFS since the original acoustics assessment workshop (Mellinger and Barlow, 2003). At that time, only the Southwest Fisheries Science Center (SWFSC) and Southeast Fisheries Science Center (SEFSC) had operational towed hydrophone arrays. Most other Science Centers had goals of incorporating passive acoustics into their ship surveys for long-term monitoring but had not implemented projects to do so. Since 2003, passive acoustics activities have expanded significantly within the protected species programs in NMFS. However, individual Science Centers find it challenging to maintain adequate staffing and other resources to use passive acoustics as a major element of the stock assessment process.

Staffing

Most NMFS Science Centers employ federal staff that spends some portion of its time conducting passive acoustic research projects or developing passive acoustic assessment technology (Table 1). The Southeast and Pacific Islands Science Centers do not currently have any full-time federal staff dedicated to passive acoustic research on protected species, although the Pacific Islands Fisheries Science Center (PIFSC) is pursuing the recruitment of a full-time federal bioacoustician. Only three Science Centers (Southwest, Northwest and Alaska) have more than one federal acoustician on staff.

Table 1. Number of current federal and contract staff full-time equivalents (FTEs) dedicated to passive acoustics assessment research within each NMFS Science Center, as well as the number of graduate students conducting research using passive acoustics for marine mammal assessments.[5]

Fisheries Science Center	Federal Staff	Cooperative Institute or Contract Staff	Graduate Students
Northeast	1	7½	-
Southeast	½	1	-
Southwest	3	1	3
Pacific Islands	¼	3	1
Northwest	1½	-	1
Alaska	2	5	-

Several Science Centers, especially Northeast and Alaska, rely heavily on staffing through cooperative institutes or contracting firms. They use this method primarily because most of the funds within the Science Centers for passive acoustic assessment projects are temporary, either from internal NMFS funding initiatives or from external sources, and cannot be used to support federal staff. Alternatively, the temporary nature of the funds requires temporary staff. There has been relatively little funding provided by NMFS to support passive acoustic assessment projects or staffing.

[5] Table 1 does not show other federal staff that may support the theoretical framework behind the statistical treatment of passive acoustic datasets for use in quantitative assessments. Those staff typically do not require acoustics expertise and are mainly dedicated to other assessment projects. Also not included is temporary staff hired for field-data collection projects.

Some Science Centers have provided support for graduate students conducting research directly related to assessment of NMFS marine mammal stocks using passive acoustic techniques. Funds for student support are most commonly provided through partnerships and funding arrangements with external partners such as the U.S. Navy or Bureau of Ocean Energy Management (BOEM), although occasionally with some partial support from NMFS.

How NMFS Has Used Passive Acoustics for Assessment

Details on all NMFS acoustic assessment projects, at the time of the workshop, are provided in Appendix B. The majority of passive acoustics projects are externally funded or piggy-backed onto other assessment projects. The most common projects are those aiming to describe species or stock occurrence and seasonality, with relatively fewer projects designed for estimating abundance or assessing human impacts. Very few projects are designed specifically to collect the data required for stock delineation. Although data are often collected under a study design specific to assessing seasonality or occurrence, or for providing detection and localization capability during visual line-transect surveys, those data may also prove useful for other assessment projects. All Science Centers have collaborated with other academic, non-profit and industry researchers to accomplish passive acoustic assessment projects, with such collaborations often providing many of the staff and instrumentation required (Figure 1).

With the exception of incorporating passive acoustic detection with towed arrays into ship-based assessment surveys, most passive acoustic assessment projects are narrowly focused on a single priority species or species group. These assessments are generally limited to species that can be identified to species with high confidence.

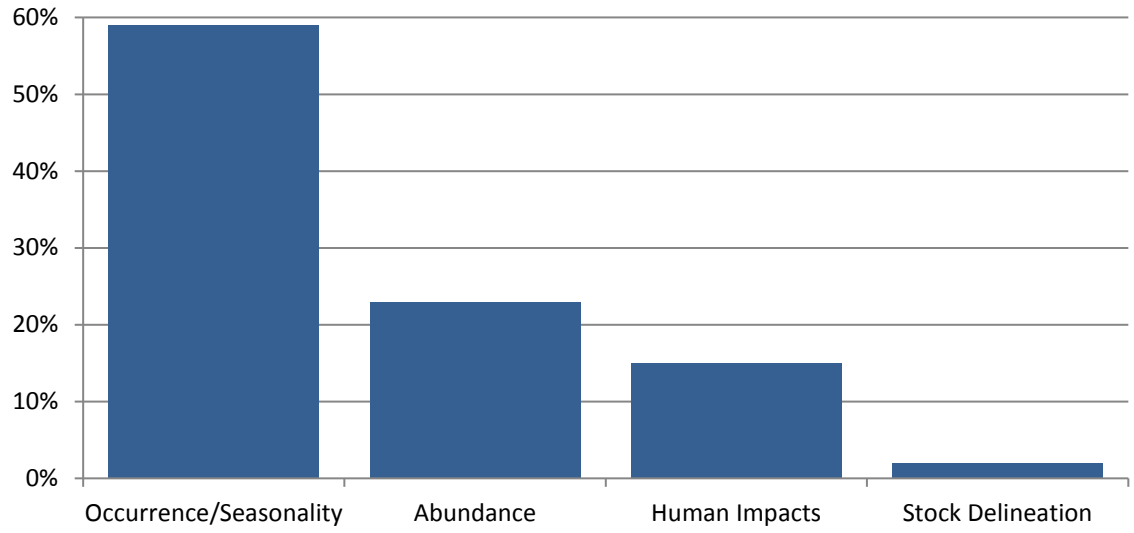

Figure 1. Proportion of NMFS passive acoustic assessment projects designed to address the different assessment components. Some projects may be designed to address more than one component.

Common Approaches

Most of the common technologies used for collecting passive acoustic datasets are described in the appendices of this report. Most of these technologies are widely available through academic or commercial sources, and some are being built in-house. Some technologies are more specialized and are used only by one or few Science Centers. Passive acoustics projects currently underway within NMFS, including the instrumentation used and the questions addressed using that technology, are described in Appendix B.

Detection, classification, and localization during ship-based surveys

All NMFS Science Centers conduct ship-based surveys for marine mammals, using line-transect methods either to assess abundance or to locate specific species for intensive sampling. Incorporation of passive acoustic monitoring during ship-based surveys provides an alternative method of detecting vocalizing groups and increasing encounter rates (e.g., Rankin et al. 2008). In some cases, this monitoring has provided an independent method to assess abundance (e.g., Barlow and Taylor, 2005).

All NMFS Science Centers currently possess towed multi-element hydrophone systems and the data acquisition equipment required to use these arrays on NOAA ships or other vessels. The SWFSC has been the primary driver of developing towed-hydrophone-array methods for use during ship-based, line-transect surveys for assessment of cetacean abundance. The Advanced Sampling Technology Working Group (ASTWG) funded a 2-week workshop in the fall of 2012 to bring together passive acoustics staff from each Science Center to build a hydrophone array for their own Science Center's use (Rankin et al., 2013). Since that workshop, all Science Centers acquired towed array systems that are interchangeable, creating redundancy within the agency and reducing the need for each Science Center to maintain several backup systems. Technology advances after the 2012 workshop mean that individual Science Center systems have since diverged somewhat, although the basic data-collection system remains the same or compatible with newer equipment. Follow-up workshops will likely be needed to enable all Science Centers to remain up-to-date on hydrophone and pre-amp technology, as well as new developments in acquisition hardware and software. Although the towed-array systems are owned by NMFS, some Science Centers provide their systems to bioacoustics contracting firms for use during ship-based surveys. This exchange occurs because the contractors do not have enough staff or adequately trained staff to conduct all towed-array operations at sea.

Sonobuoys are also commonly used during NMFS assessment surveys, and all Science Centers currently have access to these instruments through the U.S. Navy. These expendable monitoring devices transmit acoustic data over a VHF carrier frequency to a monitoring station on the ship or shore. Sonobuoys are capable of omnidirectional listening up to 24 kHz, or directional listening capability to about 4 kHz. Sonobuoys are most commonly used for recording sighted baleen whales during NMFS surveys to identify the vocalizations of a specific species or stock (e.g., Oleson et al., 2003; Rankin and Barlow, 2007) or for tracking vocalizations to find individuals or groups for sampling (e.g., Wade et al., 2006; Rone et al., 2012). Sonobuoys are provided at no charge by the U.S. Navy, but must be requested annually through a competitive process open to all passive acoustics researchers inside and outside the government.

Long-term monitoring

Autonomous long-term, passive acoustics systems are also used by most NMFS Science Centers for assessment of marine mammal occurrence based on detection of their vocalizations, as well as measurement and monitoring of ocean ambient and anthropogenic noise (e.g., Širović et al., 2013; Van Parijs et al., 2015). Although these systems may be used for assessing abundance or trends through deployment of autonomous recorders in an array, or by using modeling approaches to estimate detection distance based on the characteristics of the vocalization and the local environment, there has been relatively little effort toward this type of assessment within NMFS. Many different autonomous instruments are available for collecting passive-acoustic data, and no single instrument type can fit all research requirements. Each Science Center may use one or more autonomous recorder types depending on the recording duration and bandwidth required for the project. Some of the most commonly used autonomous systems within NMFS include Autonomous Underwater Recorders for Acoustic Listening (AURALs); Ecological Acoustic Recorders (EARs); High-Frequency Acoustic Recording Packages (HARPs); C-PODs; Marine Autonomous Recording Units (MARUs); and Hydrophones for Acoustic Research Underwater (HARU Phones). Some instruments are calibrated by the manufacturer, allowing for true measurement of ambient or anthropogenic noise amplitude and the received level of animal sounds. Many more types of autonomous instruments are not calibrated by the manufacturer and must be calibrated by NMFS staff, if calibrated measurements are required. Alternatively, these instruments are used only for relative measures of amplitude across the bandwidth of the recording. Many autonomous instruments used in NMFS projects are not owned by NMFS Science Centers, but instead are leased from the manufacturer or loaned from collaborating institutions for the duration of the project.

Two other instrument types used by some NMFS Science Centers are short-duration, free-floating or tethered recorders and acoustically equipped underwater gliders or profiling floats. These instruments are at seemingly opposite ends of the technological complexity scale, with most free-floating or tethered units being assembled from a commercially available recorder and hydrophone and deployed from small vessels to monitor sounds produced by a sighted species or stock. These types of data have proven particularly useful for developing automated classification algorithms and for assessing differences in vocalization characteristics among two or more stocks of the same species.

Autonomous underwater vehicles, including gliders and profiling floats, have more recently been outfitted with passive-acoustic sensors. This technology has recently received considerable attention from academic and industry researchers, but has been adopted to a lesser extent by NMFS scientists. Development of assessment capability for acoustically equipped gliders and profiling floats has been pursued within the Northeast Fisheries Science Center (NEFSC) and to a lesser extent PIFSC, primarily with funds from external sources or from the ASTWG. This technology has proven quite effective for detecting the sounds of vocalizing animals to assess geographic occurrence or habitat use. However, the theoretical framework for conducting abundance surveys from mobile autonomous platforms is still being developed. Mobile autonomous systems are generally leased from commercial or academic developers because operational and

maintenance costs, as well as staff-training requirements, have been prohibitively expensive for NMFS Science Centers.

Several other passive-acoustic devices have been used or developed by NMFS researchers. Acoustic recording tags, either the Woods Hole DTAG or the Greeneridge Sciences Acousonde, are commonly used for behavioral-response studies. Volumetric towed-hydrophone arrays are being developed by staff at SWFSC and PIFSC for use during line-transect surveys to increase localization accuracy and efficiency, and to reduce bias associated with measurement of sound location in only two dimensions (Barkley et al., in review). Current prototypes are not operational for large-scale surveys, although a Small Business Innovation Research (SBIR) grant issued through the OS&T Ocean Acoustics Program to two separate firms in 2015 should help overcome the technological and engineering challenges that remain. The Drifting Acoustic Spar Buoy Recorder (DASBR; Griffiths and Barlow, 2015) is an autonomous, long-term, floating recorder similar in its capability to various stationary, autonomous, long-term recorders, but not tethered to the sea floor. The drifting design is intended to allow passive-acoustic sampling in very deep water and in the open ocean, where it is typically logistically infeasible to deploy stationary recording devices. These units are currently being developed and used for assessment surveys on the West Coast by the SWFSC. Use in very distant or remote locations is somewhat hindered by lack of consistent and low-cost satellite service for tracking the drifting unit. Also impeding the use of these units is the expense of recovery for units that may have drifted far from vessels capable of or willing to assist with recovery.

Chapter 3 Stock Delineation

Distinguishing stocks and defining their boundaries is generally challenging, often requiring genetic or morphological differences among groups of animals to delineate putative stocks. Use of other lines of evidence for stock delineation has been gaining attention, including differences in vocalization characteristics among putative stocks. Geographic mapping of the vocalization characteristics for some baleen whale and delphinid species has suggested that differences in vocalizations may be a promising avenue of pursuit for identifying putative stocks for further study using other non-acoustic lines of evidence. The workshop focused on the current capabilities, impediments and improvements needed in order to further the use of passive acoustics in stock delineation. Toward this end, the workshop developed specific recommendations for advancing this field of research.

Data and Technical Requirements

The MMPA defines "population stocks" or "stocks" as "a group of marine mammals of the same species or smaller taxa in a common spatial arrangement, that interbreed when mature." The term "population stock" is not consistently defined within the scientific community, and the definition put forth in the MMPA leaves room for interpretation. NMFS has developed guidance for applying the MMPA definition (NMFS 2005). GAMMS II states that a marine mammal stock is a "demographically isolated biological population." The guidance notes that "reproductive isolation is proof of demographic isolation" and that "[e]vidence of morphological or genetic differences in animals from different geographic regions indicates that these populations are reproductively isolated." GAMMS II also recognizes that many types of information can be used to identify demographic isolation, including "distribution and movements, population trends, morphological differences, genetic differences, contaminants and natural isotope loads, parasite differences, and oceanographic habitat differences." GAMMS II does not provide further guidance on how to consider or weigh these lines of evidence.

A NMFS Working Group, the Stock Delineation Guidelines Initiative (SDGI), has explored the strength of using passive acoustic datasets for stock delineation by taxa (Martien et al., 2015). In addition, the forthcoming SDGI Handbook provides guidance on the use of acoustic differences versus other lines of evidence for delineating stocks. Although the focus of the current passive acoustic assessment workshop was not on the strength of acoustic differences versus other lines of evidence, many of the considerations identified in the SDGI Handbook are relevant here as well. The species data tables from the SDGI Handbook were presented to the workshop. Also, some key examples were discussed at the beginning of the Stock Delineation session to provide context for what is ultimately needed to delineate stocks using differences in vocalization characteristics or geographic patterns of vocalization occurrence. At a minimum, positive differences in vocalization characteristics among groups could be considered evidence for stock delineation if the differences are independent of geographic variation in prey preferences and other behavioral factors that may be mainly situational, and if vocalization characteristics are consistent over the stock range and through time. Changes in vocalization features through time may still be useful for delineating stocks. However, the change must be understood in the context of reproductive isolation, and comparisons between

putative stocks must be appropriate given the timing of changes in vocalization characteristics (i.e., comparisons across space at the same time, or during the same breeding phase).

The technical requirements for acoustic data collection for delineating stocks are no different than any other component of stock assessment — recordings must be of adequate bandwidth with sufficient signal-to-noise ratio to facilitate the detection and description of vocalizations. The geographic location and time of each recording is required, and the species from which the vocalizations are recorded must be known without error. It is advantageous to collect data with calibrated systems (known frequency response). Using these systems facilitates measurement of bandwidth and amplitude and reduces the effects of system variability on measured characteristics.

Stock delineation using acoustics is in its infancy, with few examples of geographic variation in vocalization characteristics among groups that can be reasonably concluded to be driven by demographic independence rather than other factors. These factors include prey differences, seasonality, or other environmental or behavioral differences. Most examples of differences in vocalization characteristics among groups serve primarily to bound hypothesis tests that may be addressed with other lines of evidence, including genetics, movements or a combination of factors. Several baleen whale species are known to have song characteristics that vary geographically. These differences map nicely to genetic differences where adequate samples are available for comparison (e.g., blue whales; McDonald et al., 2006).

To the extent feasible, genetic samples should be collected from individuals heard producing specific sounds so that stock delineation may be tested both genetically and based on the differences in vocalization characteristics among groups. Collection of tissue samples from recorded individuals is not trivial, because it is often difficult to confirm that samples came from the vocalizing animal or even to locate individual vocalizing animals for sampling. The success of this approach varies across taxa and specific field situations. For migratory baleen whales, acoustic vocalization characteristics need to be measured across the range of breeding and feeding grounds and from multiple years to ensure that the full song repertoire has been sampled and described. For delphinids, social and foraging vocalizations should be collected across a broad range of behavioral and environmental contexts to ensure variations are not related to prey preferences or other environmental conditions, such as geographic or seasonal variations in background noise. For all assessments of stock delineation using passive acoustic datasets, data collection must be of sufficient duration and across sufficient geographic range to identify variability among individuals and within groups.

Current Capabilities

The ability simply to collect passive acoustic data from marine mammal species is not sufficient to assess stock structure. Vocalization differences will likely need to be compared versus other lines of evidence to show that differences in vocalizations can be attributed to different stocks rather than related to geographic or behavioral differences within a stock. Most Science Centers have the capability to collect tissue samples and other environmental and behavioral data that may be required to use vocalization differences to delineate stocks. However, Science Centers vary in the degree to which passive acoustics programs and projects are linked to other data collection efforts. Assessment of stock structure

using passive acoustic data will be most successful when recordings are linked to other measures of behavior, prey, habitat, movements or genetic relatedness. Correlational studies may be feasible with sounds recorded on autonomous datasets, especially for those species whose sounds can be reliably identified to species despite regional variations in vocalization characteristics.

In general, stock delineation using passive acoustics occurs in an exploratory phase. The specific survey design requirements are not known and are likely to vary across taxa, depending on the plasticity of the vocalizations and the ecology of the species or stock. Differences in vocalization characteristics at the species- and/or population-level have been identified for several taxa, primarily pinnipeds, baleen whales, some dolphins and beaked whales (Table 2), while for others it is not yet possible to identify any vocalizations to the correct family. Those species that exhibit population-level differences in vocalization characteristics appear to be those with identified mating-related signals, or those with very distinct echolocation clicks, likely related either to prey differences or morphological characteristics of the melon (Soldevilla et al., 2008; Baumann-Pickering et al., 2013). Most population-level differences in pinnipeds have been observed through playback studies measuring response of males to territorial vocalizations of males from the same or other regions, or through the simple assessment of geographic variation across regions known to different populations based on other lines of evidence. Playback studies are more difficult to observe with cetaceans. Most assessments of stock delineation with cetacean populations have been correlational, typically relating changes in vocalization characteristics to the structure of the population measured using genetic analyses, or revealing potential structure that has not yet been tested with other lines of evidence.

Table 2. Capabilities and examples of acoustic differentiation of taxa, species, and populations.

Species / Group	Acoustically Identify Taxa?	Acoustically Identify Species?*	Examples / Exceptions	Acoustically Identify Populations?
Pinnipeds	Yes	Yes, generally, using mating-related vocalizations Greater uncertainty with social and foraging sounds	Several phocids can be identified to species Fewer robust studies on eared seals	Harbor seals: Van Parijs et al., 2000 Bearded seals: Risch et al. 2007; Charrier et al., 2013 Australian sea lions: Attard et al., 2010 Weddell seals: Pahl et al. ,1997; Abgrall et al., 2003; Terhune et al., 2008
Baleen Whales	Yes	Yes, generally, using mating-related vocalizations Greater uncertainty with social and foraging sounds	Bryde's and sei whale vocalizations not well characterized Overlap between bowhead and right whale sounds	Blue whales: McDonald et al., 2006. Fin whales: Hatch and Clark, 2004; Castallote et al., 2012; Delarue et al., 2009 Humpback whales: Cerchio et al., 2001; Garland et al., 2015; but cultural transmission complicates assessment: Noad et al., 2000 Bryde's whales: Oleson et al., 2003; Širović et al., 2014 Minke whales: Mellinger et al., 2000; Gedamke et al., 2001; Rankin and Barlow, 2005; Risch et al., 2014
Sperm Whale	Yes	Yes	Watkins, 1980	Unclear. Patterns of coda usage among groups do not correspond with genetic structuring or geography: Rendell et al., 2012.
Kogia	Not yet differentiated from porpoises and other narrow-band, high-frequency species[6]	Unknown		Unknown

[6] E.g., cephalorhynchids, lagenorhynchids, or river dolphins

Species / Group	Acoustically Identify Taxa?	Acoustically Identify Species?*	Examples / Exceptions	Acoustically Identify Populations?
Beaked Whales	Yes	Likely	Beaked whales: Baumann-Pickering et al., 2013, 2014	Unknown
Small Delphinds	Yes	Few. More sophisticated classifiers and incorporation of behavioral information required.	Tropical delphinids: Oswald et al., 2003; Azzolin et al., 2013 Risso's and white-sided dolphins: Soldevilla et al., 2008 Bottlenose and spinner dolphins: Baumann-Pickering et al., 2010	Some evidence for Risso's and Pacific white-sided dolphins: Soldevilla, unpublished Others unknown
Large Delphinids (Blackfish)	Yes	Most	Tropical blackfish: Oswald et al., 2003 Melon-headed whales: Baumann-Pickering et al., 2010 Short-finned pilot and false killer whales: Baumann-Pickering et al., 2015	Killer whales: Ford, 1991 Some evidence for false killer whales: Barkley, unpublished Others unknown
Porpoise	Not yet differentiated from Kogia and other narrow-band, high-frequency species	Unknown		Unknown

Impediments

Many species of marine mammals use stereotyped vocalizations. Although geographic variation in these characteristics has been suggested to correspond with population structure in some species, it can lead to erroneous conclusions about stock structure in others. For example, while differences in the acoustic properties of calls used for foraging could indicate local adaptation, they may also represent plasticity in response to habitat (e.g., Simard et al., 2010) or prey type (e.g., Johnson et al., 2007). Such plasticity could lead to incorrectly identifying multiple stocks in an area if animals that are part of the same stock use vocalizations with different characteristics when foraging in different regions within their range. Vocal characteristics have also been shown to change in response to the presence of boat traffic, differences in ambient noise, and/or interactions with other species (May-Collado and Wartzok, 2008; May-Collado, 2010; Tripovich et al., 2012; May-Collado and Quiñones-Lebrón, 2014). These changes suggest that variation in the social or physical environment can create differences in acoustic characteristics that are unrelated to stock structure.

The effectiveness of using passive acoustic datasets to define stocks may vary significantly among species (see Table 2), because particular differences in the purpose of produced sounds, and their plasticity across environmental and behavioral states, may determine whether variation in acoustic characteristics is truly representative of population segregation versus localized or seasonal differences in prey, sociality or other factors. The mechanism of vocal learning is not well understood for marine mammals. Whether vocalization characteristics are passed vertically (from mother to offspring) or horizontally (between unrelated individuals) may affect the utility of acoustic differences for assessing stock structure (Musser et al., 2014). Cultural transmission of songs of humpback whales (Noad et al., 2000) or codas of sperm whales have complicated the assessment of population structure using acoustic characteristics for those species (Rendell et al., 2012). However, using acoustic characteristics to delineate stocks is a powerful approach because population-specific differences in acoustic characteristics could develop rapidly, reflecting current movement patterns, or structure that has developed recently relative to the very long time scales required to evolve sufficient differences to be detected using genetic or morphological methods (Hatch and Clark, 2004).

To date, no stocks have been designated under MMPA based solely, or even primarily, on acoustic differences between groups. The utility of acoustic datasets for stock delineation is likely species-specific. For many species, we are currently unable to distinguish among species using acoustic characteristics, so that finer-scale assessment of stock-level differences is currently not possible. Workshop participants discussed this and a range of other impediments to using vocalization characteristics for stock delineation.

Species identification

Most species of baleen whales produce species-specific vocalizations, though not all vocalizations are species-specific. A combination of social and breeding display vocalizations may be required to find acoustic differences among stocks. However, social sounds in baleen whales are highly variable, and in some cases, multiple species make similar vocalizations, meaning that the vocalizations cannot be attributed to a specific species with certainty. Sperm whales and most species of beaked whales are also known to produce species-specific vocalizations, although for sperm whales, coda sharing across populations has been observed, suggesting these signals may be inappropriate for stock delineation. In contrast, many delphinid species cannot yet be reliably identified by their vocalizations. Although most are

known to produce some combination of echolocation clicks, tonal whistles, and pulsed sounds, in many cases characteristics of these classes of sounds have not been described. For the *Kogia*, porpoises, *Cephalorhynchus* dolphins, some *Lagenorhynchus* dolphins, and river dolphins, narrow-band, high-frequency echolocation clicks are distinct from other taxa, but have not yet been shown to be species-specific, so that additional research is needed to quantify whether species-specific vocalizations exist and then identify the variation in those sounds across stocks.

Behavioral information and seasonality

One of the most important aspects of using variation in vocalizations to assess marine mammal stock delineation is the behavioral context of the vocalizations. Vocalizations produced by males as a breeding display may play a large role in mate selection, and therefore may be more directly linked to population structure. However, male breeding displays are subject to learning and may be influenced by neighbors, so that an individual whale may change its song to align more closely with another male's. Such adaptation has been shown with humpback whales (Noad et al., 2000), and suggests that variation in song characteristics among humpback whale populations is likely meaningless for the purposes of assigning an individual whale to a specific population. Further, there appears to be seasonal and annual variation in song characteristics (e.g., McDonald et al., 2009; Oleson et al., 2014) or song production rates (Oleson et al., 2007) among some baleen whales. The drivers of these changes may be persistent enough to be accounted for and therefore are not an impediment to stock delineation. However, these drivers must be understood before differences in song can be attributed to stocks rather than changes induced by the environment (e.g., Parks et al., 2007) or other behavioral factors such as motivation to attract mates, defend territories, or search for food.

Conversely, foraging signals are more likely to be influenced by local prey resources and the need to adapt the echolocation signal to locate specific prey items most effectively. Clinal variation in prey availability that drives slight changes in echolocation characteristics may appear, if inadequately sampled, to be similar to differences between stocks. Understanding these behavioral questions is the most significant driver of data needs for the purposes of using vocalization data to delineate stocks.

Research Needs

Based on workshop discussions, the Steering Committee identified several recommendations for research that should advance delineation of stocks using passive acoustic datasets.

Data collection and archiving

Stock delineation studies in particular tend to rely on data from many locations and time periods, and potentially on data collected using different systems. To allow the comparison of such datasets, detailed metadata and system-calibration information is necessary to avoid conflating differences among vocalization characteristics and those among recording hardware.

Vocalization repertoire

Species identification is still challenging for many species, particularly for delphinids; however, for many baleen whales and beaked whales, multiple stereotyped vocalizations have been identified. For those species, attention to quantifying variability in vocalization repertoires in various environmental and behavioral contexts should be particularly valuable for future assessment of stock delineation using acoustic data. Defining a stock's vocalization repertoire will be important in many contexts, including stock delineation. Further, measurements of vocalization characteristics and their variability across all marine mammal species is a necessary

step to make progress toward assessment using passive acoustic datasets.

Further, building a library of sounds with extensive metadata will facilitate future research into population structure that uses vocalization characteristics. Such a library, which could be housed at a single institution or distributed among various online resources such as MobySound, could archive representative samples of sounds from specific times and places. Workshop participants discussed whether contribution of sounds to an online archive could be used to satisfy Public Access to Research Results (PARR) requirements, thereby making representative data available to the community, and facilitating comparison of sounds recorded from different populations or regions. Workshop participants felt that NMFS is especially well positioned to make a large contribution toward collecting and archiving the data required for examining stock delineation because all Science Centers have active passive-acoustic programs. Many of these programs work in tandem with other data-collection efforts (visual surveys that verify species, tissue sample collection for genetic analysis, collection of behavioral data for assessing context, and oceanographic sampling for assessing prey, etc.).

Behavioral studies

Understanding behavioral context of various sounds within a species repertoire is fundamentally important to determining which group or type of sounds will be most appropriate for stock delineation. For most baleen whales, it is likely that breeding displays are the best vocalization types for assessing stock structure; however, the plasticity and context of some of these sounds may change seasonally. The workshop identified the need for cheaper, more cost-effective studies of acoustic behavior in general. Focal-follow studies and studies using a combination of tagging and acoustic monitoring are likely to yield great insights into the behavioral context of vocalization and provide links to population structure through concurrent collection of movement or other data types.

Combined studies

It was widely recognized among workshop participants that the greatest role passive acoustics can play with regard to stock delineation is to identify differences in vocalization characteristics that may represent stocks, and to use those putative stocks to set up hypotheses about population structure that may be tested using other types of data. The SDGI Workshop (Martien et al., 2015) identified differences in morphology, genetics and movement as strong indicators of population structure; and distributional hiatuses, contaminants, habitat differences, and association data to be medium strength indicators depending on the specific taxonomic group under study. Acoustic stock-delineation data collection or data analysis projects should be designed so that the results may be tested using one or more of these other data types.

Chapter 4 Occurrence and Seasonality

Deriving the list of species that typically occur in a management area is a basic component of stock assessment. Evaluating the seasonal occurrence of species in a region is more difficult without regular surveys, and this is one area in which passive acoustics has excelled in its contributions toward marine mammal stock assessments. When any sound from a species is characteristic and well-described, its detection in an acoustic recording can provide the first known occurrence of that species in a region. A collection of detections over a longer time series helps to determine whether the species is common or rare and whether it occurs year-round, seasonally or just infrequently. There are many examples of passive acoustic monitoring providing rich datasets from which species occurrence and seasonality have been evaluated, but there is more to be done in the field, especially as associations with habitat and environmental change become increasingly important aspects of stock assessment. The workshop participants discussed specific species or regional case studies that are ripe for assessment using passive acoustics. Participants also discussed the technological improvements and impediments that need to be overcome to further the use of passive acoustics toward assessment of occurrence and seasonality.

Data and Technical Requirements

Assessment of occurrence and seasonality using passive-acoustic datasets minimally requires knowledge of the sounds produced by the species of interest. Occurrence may be assessed using any type of passive-acoustic dataset collected at a known location and time and with sufficient bandwidth to encompass the sounds of interest. Assessment of seasonality requires longer-duration datasets spanning several months to years, and a complete understanding of a species repertoire to ensure that seasonal occurrence is described accurately and not biased by monitoring only those sounds that are produced seasonally or within specific behavioral contexts. It is often necessary to collect data using calibrated systems, especially when accurate species identification requires comparisons among spectral features.

Autonomous instruments excel at assessing occurrence and seasonality because they can be deployed at remote sites at relatively low cost. However, the hardware requirements for long-term monitoring are not trivial. In order to obtain an accurate representation of the recorded vocalizations, the sampling rate needs to be at least twice the highest frequency in the vocalization. At the low acoustic sampling rates that are sufficient for monitoring baleen whales (less than 5 kHz), there are many instrument types capable of multi-month duty cycling (turning recording on and off on a fixed schedule) or continuous recordings. However, at higher sampling rates (200 kHz) required for detection of sounds produced by delphinids and beaked whales or narrow-band, high-frequency species[7] (greater than 300 kHz), there are few instruments capable of multi-month recording. Continuous acoustic sampling at 200 kHz using a single sensor collects nearly 1 terabyte (TB) of data per month. Duty cycling can reduce data volume and allow longer overall monitoring duration. Duty-cycled recordings are typically required for year-round monitoring at remote locations, because currently available autonomous instruments are not capable of providing adequate power or data storage to support continuous operations for such a long period. Repeated recovery and deployment of devices during the monitoring period is generally needed when continuous recording is required for a year or more. Cabled or remotely powered systems, such as most Integrated Ocean Observing

[7] E.g., Kogia and porpoise species, *Cephalorhynchus* dolphins, some *Lagenorhynchus* dolphins, and river dolphins

System (IOOS) passive-acoustic sensors are not restricted by these power requirements. However, they are often constrained by transmission bandwidth, preventing or delaying transmission of high sample-rate data. A general overview of fixed autonomous systems is provided in Appendix C, and a detailed overview of the development and current diversity in autonomous systems available as of late 2012 can be found within Sousa-Lima et al., 2013. New autonomous systems regularly become available through the development efforts of industry, academia, and non-profit organizations focused on passive acoustic technology.

Long-term data require significant computer processing power to analyze the data, whether accomplished with a human analyst and/or an automated detector and classifier. Various types of automated detectors may be employed to reduce analysis time when the characteristics of the sounds are well known and have low variability. The performance of an individual detection algorithm must be well characterized to understand the potential bias it may introduce into assessments of seasonality. Human scanning and analysis of passive acoustic datasets are common when the signals of interest are not well described or are inconsistent. The development and implementation of automated detectors and classifiers are important components of all aspects of stock assessment using passive-acoustic datasets.

Measurement or estimation of the detection range of sounds of interest is not commonly part of passive-acoustic studies designed to elucidate occurrence or seasonality. However, variations in detection range can bias the assessment of seasonality if changes in detection rate are due to habitat differences or changing environmental conditions, rather than changes in the number of animals in the monitoring area.

Current Capabilities

All NMFS Science Centers own, or collaborate with partner institutions to use, various types of autonomous, long-term, fixed passive-acoustic recorders for the assessment of marine mammal occurrence. The list of ongoing projects within NMFS suggests assessment of occurrence and seasonality is one of the most common uses of passive acoustics within the agency. Many of these projects target specific species or locations, but few are capable of sampling the full range or seasonality of any species. Both archival and real-time systems are used within NMFS to assess occurrence and seasonality, although archival instrumentation is much more common given the challenges of maintaining real-time systems. Mobile autonomous sampling platforms such as acoustically equipped gliders and drifting recorders are being tested, a particularly important advancement for assessing occurrence in deep water where fixed moorings are difficult to deploy and maintain.

Within the wider acoustics community, many studies have employed passive acoustic technologies for assessment of occurrence and seasonality. These include a range of examples, from an assessment of seasonal occurrence of baleen whales in the Antarctic (Širović et al., 2009), to the occurrence and seasonality of up to 10 species of beaked whales across the Pacific (Baumann-Pickering et al., 2014). Occurrence and/or seasonality studies have been done using passive acoustic datasets for nearly every species of marine mammal that can be identified based on its sounds.

Impediments

Although passive acoustic monitoring has already played a significant role in the assessment of occurrence and seasonality of many marine mammal species, a number of issues remain that prevent the use of passive acoustic techniques for many species, locations or situations.

Instrumentation

The recording volume and battery capacity of available autonomous platforms often requires duty-cycled recording or regular instrument retrieval and redeployment to maintain the long-term time series of observations required to assess seasonality. Imposing a duty cycle increases monitoring duration, but comes at the cost of reduced detection probability, particularly for species that vocalize rarely or for very short periods. The impact of duty cycling will vary by species and situation, and passive acoustics studies requiring duty-cycled recording schemes must consider the impact on study design. Thomisch et al., 2015, found that subsampling of passive acoustic data could substantially bias acoustic presence estimates or affect the estimation accuracy for vocalization rates of focal species.

Maintaining continuous data collection through regular recovery and redeployment of instruments typically is feasible only when monitoring locations are close to shore or on regular vessel transit routes. Monitoring for assessing occurrence or seasonality across a management region or other area of interest might require monitoring well outside areas where regular instrument servicing is feasible. At present, most PAM platforms used for assessing seasonality are deployed as stationary moorings. The limits of such moorings may bias assessments of seasonality and range, because it is logistically difficult to deploy moorings in very deep water, under or near ice, or in high-current regions. Mobile sampling platforms will be required to sample some of these regions effectively. Alternative mooring designs may also be required for monitoring in some locations.

Species identification and vocalization repertoire

The most fundamental requirement for assessing species occurrence using passive acoustics is the ability to recognize the vocalizations of the species within the acoustic record. Detection of sounds during visual sighting surveys provides an opportunity to collect this information and to establish occurrence. However, most assessments of seasonality are carried out from autonomous instrumentation without the aid of visual observers. The vocalization repertoires of many species are known only partially, and many vocalization types are detected that cannot yet be reliably assigned to species. It is rare that all vocalization types produced by a species are known and can be reliably classified as being produced by that species. A lack of information about a species' vocalization repertoire limits the ability to draw conclusions about species absence, potentially even creating biases in the conclusions of a PAM study.

Behavioral context

Not understanding the behavioral context that guides the likelihood and rate at which sounds within a species repertoire are produced will also create bias in assessments of seasonality and range. When a species' use of different vocalization types changes seasonally, the use of single vocalization types to document the occurrence of the species may not be reliable. For example, Oleson et al., 2007, monitored the occurrence of two blue whale vocalization types in Southern California — a mating-related song produced only by males in the summer and fall, and a foraging-related vocalization produced by both sexes in the spring and summer. Monitoring of just call type would have suggested a seasonal occupation of the area, when in fact they were present nearly year-round. Similar biases will exist for all other species' vocalizations, so that knowledge of repertoire and context is required for the unbiased assessment of seasonality using passive acoustics detections of a species' vocalizations.

Automated processing and analyst variability

Seasonality studies often result in very large volumes of data that cover many months or years. Those data must be processed by humans, automated algorithms, or some combination of the two. Automated processing requires quantitative measurement of vocalizations of interest in order to create automated detection and classification algorithms. The challenges inherent in the development and use of automated detectors and classifiers are discussed several times within this report. The alternative is to have a human analyst scan the dataset or sub-samples of it. Even highly trained analysts are imperfect and will miss or misclassify sounds. Attaining an acceptable degree of certainty may require more than one analyst to scan the same dataset to quantify inter-analyst reliability.

Detection range

The monitoring range around an instrument can be very large (hundreds of kilometers) for low-frequency vocalizations heard across a flat-bottom, deep-water region. Or the range could be very short (hundreds of meters or less) when monitoring high-frequency directional sounds in dynamic bathymetry. Furthermore, within a maximum detection range, the probability of detecting a species' sounds may vary temporally or spatially, thereby creating a variable effective detection range (Buckland et al., 2001). The probability of detecting a species' sounds will vary according to the volume of ocean being monitored. If the size of a monitored area and any changes in its effective size is unknown, then it is difficult to assess whether seasonal changes in vocalization occurrence may be attributed to changes in the presence of animals producing vocalizations or changes in the monitoring area (as well as a number of other things discussed earlier). The choice of monitoring location may also bias seasonality assessments. Stationary moorings are often limited in their deployment depth so that they are inherently less likely to receive sounds produced by species that are found primarily or exclusively in deep pelagic waters.

Research Needs

The following are the highest priority research needs for robust assessment of marine mammal occurrence and seasonality using passive acoustics:

- To determine presence/absence or seasonality with certainty, unambiguous species-specific vocalizations are needed. Geographic and seasonal variability also need to be characterized. Vocalization repertoire libraries would facilitate needed research.
- A significant challenge to understanding seasonality is the need to disentangle the effects of seasonal vocalization behavior from seasonal occurrence, especially for baleen whales. Targeted behavioral studies are needed to understand seasonal changes in context or vocalization occurrence.
- The technology for long-term, bottom-anchored recording systems is well developed, but is not sufficient for acoustic studies in the ocean's vast pelagic basins. Additional development of mobile sampling technology is needed.
- Automated detectors and species classifiers are needed to effectively sort through vast quantities of acoustic data that can be collected with automated recording systems.
- Although species-specific vocalizations are well characterized for some species, little is known about the vocal repertoire of many others. Targeted sampling with visual verification of species ID is needed — especially for many *Mesoplodon* species, *Kogia* species, porpoise, Bryde's and sei whales, and many delphinids.

- Models and quantitative methods are needed for combining visual and acoustic datasets and thereby providing validation of purely acoustic methods of determining occurrence and seasonality.

Chapter 5 Long-Term Trends in Relative Abundance

Visual surveys have traditionally been the most prevalent method for obtaining abundance estimates in cetacean populations. Unfortunately, such visual surveys are conducted infrequently due to their high cost, and are restricted by their inherent methodological limitations (e.g., daylight, weather, sea ice, visual detection range, etc.; Thomas et al., 1986; Gillespie, 1997; Leaper and Scheidat, 1998). The acoustic techniques discussed at the workshop can overcome many of these limitations because data are relatively inexpensive to obtain and can be collected continuously for years on end, under ice cover and in any weather conditions or sea-states.

Obtaining accurate absolute abundance estimates from passive acoustic data is challenging at best. A suite of statistical methods has been developed (Marques et al., 2012) but absolute abundance estimation from passive acoustic data (Chapter 6) relies strongly on detailed knowledge about the acoustics and associated behavior of a given study species. For most cetacean species, these aspects are relatively poorly understood. Therefore, passive acoustic techniques are unlikely to replace visual surveys for obtaining accurate absolute abundance estimates in the near future.

Nonetheless, acoustic data can be consistently analyzed to give comparatively easily obtainable measures of relative abundance, under strict assumptions (see the next section). Thus, the workshop focused primarily on the use of acoustics for assessing long-term trends in population abundance. Comparison of relative abundance estimates from individual locations across many years, whether collected by visual surveys (e.g., Noad et al., 2008) or acoustic surveys similar to those discussed here (e.g., Stafford et al., 2009; Širović et al., 2015), can provide an indication of population growth or decline. Comparison of relative abundance estimates within and between locations and years can additionally reveal trends in distribution and seasonal presence over time (Širović et al., 2004; Stafford et al., 2009).

Data and Technical Requirements

Stock assessments under the MMPA include a requirement to provide for each stock, "the minimum population estimate, current and maximum net productivity rates, and current population trend." Although the use of passive acoustics to obtain estimates of actual population size is discussed in the next chapter, here we focus on the potential for NMFS to use passive acoustics to assess population trends, and to determine the rate at which a population is increasing or decreasing.

Towed hydrophone arrays have been used successfully to estimate relative density differences within a survey region (e.g., Gordon et al., 2000); to extrapolate relative densities from regions with concurrent visual and acoustic surveys to regions with solely acoustic surveys (e.g., Gerrodette et al., 2010); as well as to create habitat-based models of relative density (Fleming et al., 2013; Yack, 2013). One drawback of using mobile platforms for assessing long-term trends is the need to implement a large number of costly and logistically challenging repeat surveys to detect any larger population trends due to the inherent, potential short-term variability in population density (e.g., on the order of weeks to months). Although this may become more feasible in the future, in particular with the increased use of autonomous mobile platforms, workshop discussions focused largely on the more achievable near-term use of stationary data collection methods (e.g., moored, autonomous or cabled acoustic instruments). Stationary platforms are capable of collecting near-continuous or adequately sub-sampled long-term data over multiple years to assess trends in relative population abundance. The advantage of such

long-term datasets is that short-term variability can be averaged out.

The ability of passive acoustic approaches to detect trends in population abundance can vary widely. The resolution of detected trends can range from a very coarse estimation of whether a population is simply increasing, decreasing or remaining stable, to a much more refined quantification of the rate (e.g., percentage change) at which the change in relative abundance is occurring. The accuracy of any estimate of trend direction and rate will depend directly on survey design (number and placement of sensors); the validity of necessary ancillary data; and any associated assumptions made about the parameters required for absolute abundance estimation (e.g., the probability of acoustically detecting the focal species, the vocalization production rate of the focal species, and group size). If not explicitly estimated, the values of these parameters would have to be assumed (e.g., to be temporally and spatially constant) in order to infer animal abundance from the indices generated from the collected data.

A wide variety of methods is available to detect individual vocalizations, or "cues." A dedicated analyst can manually detect vocalizations over short time frames, but for longer periods, automated approaches such as spectral correlation, matched filtering, and energy summation methods (Mellinger et al. 2007) will be required. An alternative approach to detecting individual vocalizations is to measure the total amount of accumulated energy at whale vocalization frequencies through either power spectral density (PSD) or long-term spectral averaging (LTSA) analyses. Measures of individual detections and total accumulated energy at whale vocalization frequencies can independently provide an acoustic index related to the number of animals vocalizing. These measures have previously been used to assess changes in relative population abundance (e.g., Stafford et al., 2009; Širović et al., 2015). In its simplest form, vocalization counts or energy measures from a single sensor can be used to assess changes over time. Over long periods, consistent changes in this acoustic index can indicate relative changes in the number of vocalizing animals. This index can also give a basic indication as to whether the population is increasing, decreasing or remaining stable.

If these acoustic indices can be translated into a number of vocalizations or vocalizing individuals over a known area, more refined acoustic or vocalization density estimates can be calculated and compared. These estimates are preferred over simple vocalization counts or PSD values. In the case of vocalization or cue counts, they can be "distributed" over the known or likely detection range of the instrument by using sound-propagation modeling for a single instrument, or using the localization capability of an array of instruments. Here, the detection probability (a key parameter in a density-estimation framework) of cues can be estimated using a suite of statistical methods, most related to distance sampling (see Appendix F). In cases where energy measures such as PSD or LTSA are used, simulations can be run using a range of whale densities; information on vocalization parameters (typical source levels and repetition rates); and acoustic propagation modeling outputs to estimate how much energy would occur at the sensor. This exercise can then be reversed, using actual measured levels to predict inversely the number of vocally active whales present, which is still a relative abundance measure if non-calling animals in the population are not accounted for. It is critical to note that both techniques depend heavily on the precision and accuracy of required parameters, the validity of underlying assumptions, and the quality of associated data (see "Impediments" and "Research Needs," later in this section).

In order to conduct these analyses on the data collected, the most fundamental requirement is acoustically identifiable and regularly occurring vocalizations that are unambiguously species or

stock specific. For analyses using PSDs or other average energy measures, vocalizations must occur at a frequency where one can be relatively certain that most of the energy measured is from the focal species. If other species contribute significantly to the energy within the given frequency band during the analysis period, then it is difficult to assess how much each is contributing. For most species other than baleen whales, the small distances over which their sounds propagate likely limit their contribution to energy within a frequency band. Therefore, vocalization counts of individuals or groups will be a more effective metric to use, and the smaller detection ranges of these species must be accounted for in the survey design.

The requirements for data collection are straightforward. Recordings can be made from a variety of autonomous moored (e.g., HARPs, MARUs, or AUHs) or cabled platforms. In addition, data must be collected at a sampling rate sufficient to allow measurement of the vocalizations of interest. Alternatively, specialized instruments that perform on-board processing and signal detection are available and can be used directly to obtain cue counts (e.g., C-POD click detectors). However, the detection algorithms and parameters of these instruments should be more transparently available and ideally empirically verified. In addition, to assess large-scale trends, recordings must be made over long time frames (preferably many years) in the same location and ideally with the same instrumentation (or at a minimum, carefully calibrated) to allow for effective comparisons over the period of data collection.

Finally, there is a large amount of ancillary data which, when obtained, will allow for more refined estimates of relative abundance over time and ultimately absolute abundance, if all required parameters are estimated. These parameters include: background noise measurements; quantification of source levels and their variability; acoustic propagation conditions around the sensor(s); acoustic behavior (including vocalization rates) of the species; demographic differences in vocalizing animals; density-dependent acoustic behavior (individuals vocalizing more or less in the presence of other vocalizing individuals); detection probability at different ranges from the sensor (i.e., effective detection ranges); and group size associated with vocalizations. As discussed earlier, for assessments of relative abundance, some of these parameters can be dealt with through assumptions about their values (e.g., percentage of population vocalizing at any time or vocal behavior related to density), but as these assumptions stray further from reality, greater error is introduced into the estimates.

Current Capabilities

A wide range of existing instruments are available that could be used in passive acoustic studies of trends in abundance to collect the baseline acoustic data (e.g., a variety of autonomous moored acoustic recorders, C-PODs, cabled hydrophone arrays, towed hydrophone arrays, or autonomous mobile instruments). There is a need, however, for further technology and software development in order to more effectively conduct these studies (e.g., instruments with on-board detection and real-time reporting capabilities, automated detection software; see Impediments section, next). There has also been more focus on analysis techniques in recent years to allow the measurements of acoustic indices to be translated into measures of relative abundance, and eventually absolute abundance. Investigators at the University of St. Andrews, Scotland, have led this groundbreaking research into survey design and statistical analyses (e.g., Marques et al., 2012).

All NOAA Fisheries Science Centers have passive acoustic research programs and conduct passive acoustic research to varying degrees (Chapter 2, Appendix B). Science Centers use various autonomous moored instruments (e.g., HARPs, MARUs, AUHs and EARs), towed arrays, and most recently, autonomous mobile instruments such as

gliders or drifting buoys (see Appendix C through Appendix E). All Science Centers are currently capable of conducting the types of analyses of acoustic data that can be used for the assessment of trends in relative abundance (e.g., auto-detection of vocalizations of interest and PSD acoustic energy measures). However, an essential aspect of this type of study is an effective survey design that collects long-term, multi-year datasets from a sufficient number and appropriately placed set of stationary instruments (or systematic transect lines for mobile instruments). These studies must also use appropriate analyses to assess trends in relative abundance for the species of interest. Until these survey design and analysis techniques become more commonplace, researchers with this specific expertise, such as those at the University of St. Andrews, will likely need to be consulted.

Impediments

Cost and personnel

Acoustic trends in relative abundance can be assessed from single sensors, provided the dataset is of sufficient duration. In contrast, a carefully designed survey with multiple sensors that enable the localization of vocalizing whales, or an increase in the survey area, will likely have greater statistical power to detect trends and greater accuracy and precision of any subsequent estimate of the rate of change. The greatest impediment to conducting these expanded studies is the cost of instrumentation and associated deployment and recovery costs (i.e., ship-time and personnel), along with the considerable time required for NMFS personnel to conduct the analyses. Currently, there is very little dedicated funding for acoustic research at the Science Centers. Most of their work is conducted using funds from external sources (e.g., BOEM, Navy and industry), which can shape the objectives of the research. In addition, the Science Centers have different numbers of personnel to support passive acoustic research, ranging from only one-fourth to three FTEs, with additional contractor support dependent on funding. For passive acoustics to be more fully integrated into the stock assessment process, additional dedicated research funding and support for additional FTE personnel will be required.

Automated detection/classification routines

Directly related to the previous section in terms of personnel time required to conduct the analyses is the need for improved automatic detection algorithms. To assess trends in abundance, two levels of analyses must be conducted. The first is extracting an acoustic index in terms of vocalization/cue counts or measures of acoustic energy such as PSDs. The second level of analysis then takes these measures and uses them to make comparisons over time to assess trends. The first is the most labor intensive. An individual analyst can, in theory, go through the datasets visually logging the vocalizations of interest in long-term spectrograms. This, however, is simply not practical for the length of datasets that will be necessary to detect trends in abundance; therefore, automated detection routines will be necessary. These routines are currently being used at most of the Science Centers that collect long-term acoustic datasets. However, the Alaska Fisheries Science Center (AFSC) has had little success with automated detection routines and currently uses only manual scanning to detect marine mammal vocalization in the acoustic data it collects. However, there was consensus among workshop participants that running automated detection routines requires a high level of expertise and remains very labor intensive to minimize false detections. At the same time, it is important to maximize the ability to detect weaker vocalizations. These concerns, and the need to quantify false and missed detections, also apply to instruments with onboard detection and classification processing like the C-POD and DMON, and are particularly important for those instruments that do not retain

the raw acoustic data to ground-truth detections. Improved and consistently applied automated detection, classification, and localization routines will greatly increase the agency's ability to conduct these types of analyses.

Species-specific vocalizations

In order to detect vocalizations, or measure the energy present in a whale-vocalization frequency band, species-specific vocalizations must be present for detection, and ideally should be the primary contributor to energy above ambient levels. Many baleen whales have species-specific, if not population-specific, vocalizations (see Chapter 3). In addition, there is increasing ability to detect and discern those of various species of beaked whales. Therfore, the workshop noted the current difficulties in applying these passive acoustic techniques to most delphinid species.

Acoustic behavior

As with all other uses of passive acoustics examined at the workshop (absolute abundance, occurrence and seasonality, and stock delineation), well-defined, species-specific acoustic behavior remains one of the most consequential data gaps. Factors that can potentially introduce large errors into the interpretation of acoustic metrics include: 1) Lack of knowledge about vocal rates of individuals, density-dependent acoustic behavior, demographic variability in acoustic behavior, and the depths at which vocalizations are commonly produced; and 2) Changes in acoustic behavior over time (e.g., seasonal behavior) and space (e.g., for species with separate breeding and feeding areas) and in response to environmental changes (e.g., introduction of noise). Vastly simplified assumptions, such as assuming stable vocal rates over time or lack of density-dependence of acoustic behavior, can be used to obtain coarse relative abundance metrics that may indicate whether a population is increasing, decreasing, or remaining stable. However, even these basic metrics can be strongly influenced by the validity of underlying assumptions.

Research Needs

Although it is currently possible to coarsely estimate trends in abundance even from single-element, passive acoustic instruments (given known species-specific vocalizations), such estimates depend heavily on assumptions used to derive them. The following research needs were highlighted at the workshop as important data gaps to fill in order to reduce uncertainty, modify assumptions with empirical data, and ultimately increase NMFS's ability to provide reliable relative abundance trends over time.

The first requirement of any type of passive acoustic analysis is to have knowledge of species-specific vocalizations that will distinguish a given species from co-occurring species. Obtaining this knowledge requires sonobuoy and/or towed array surveys conducted concurrently with visual monitoring that allow vocalizations to be conclusively linked to a species or stock. Existing datasets examined for vocalizations or classes of vocalizations with distinguishing features (i.e., suitable for use in acoustic analyses such as these) that currently have an unknown source would be good candidates for further study.

Characterization of vocalizations, source levels, and directionality

An associated research need is the full characterization of identified species-specific vocalizations. In particular, a quantification of the range and distribution of source levels of vocalizations, and any directionality in these vocalizations, are important components that will allow for more accurate propagation modeling of these sounds. Effective propagation modeling, along with measurements of background noise and oceanographic parameters, such as sound speed profile and bottom composition surrounding deployment locations, will help refine estimation of

the probability of detection of these vocalizations at various distances from the acoustic instrument. Localization using multiple hydrophones (sonobuoys, towed arrays, or stationary instruments) with concurrent visual observations can be used to achieve these measures.

Acoustic behavior

A common theme throughout workshop discussions was the limited understanding of various behavioral parameters characterizing cetacean acoustic behavior, and the critically important ramifications these could have for results of passive acoustic analyses for stock assessment purposes. Essential data gaps include individual vocalization- or cue-production rates; density dependence of vocalization rates; context related to acoustic behavioral changes (e.g., breeding, feeding, and noise); variability in acoustic behavior related to age, sex, or population structure; and the relationship of group size to acoustic behavior.

In some instances, assessing trends in relative abundance (as opposed to absolute abundance) may not necessarily require data to fill these gaps. For example, an assumption could be made that the ratio of vocalizing individuals to total population size is constant, although unknown. With this assumption, understanding differences between the sexes in vocal production is not necessary to estimate changes in relative abundance over time. The results, however, then become fundamentally dependent on these assumptions, and testing their validity is essential.

Techniques to address these questions include 1) vessel-based sonobuoy and towed-array surveys conducted concurrently with visual surveys and observation; 2) shore-based visual observation with concurrent acoustic monitoring; 3) localization with passive acoustic arrays of vocalizing individuals to assess density dependence of acoustic behavior; and 4) long-term acoustic tags to document individual behavior (e.g., vocalization rates over time or depth of vocalization).

Improvement in automated detection routines

Running auto-detection software currently requires an experienced analyst and a substantial effort to adjust detector parameters to maximize detections of actual vocalizations while simultaneously minimizing false detections. In addition, it is difficult to generalize processing from one region or dataset to another. These factors have likely limited the wider application of passive acoustics for stock assessments. Increased effort should be put into optimizing the detection algorithms for various vocalization types, making software more accessible to less experienced analysts, and ensuring future detector and configuration parameters are openly available for a range of researchers.

Simulations to assess performance of energy measures

The use of acoustic energy measures (e.g., PSDs or LTSAs) represents a promising and less labor-intensive option for the use of passive acoustics in assessing trends in abundance (e.g. Širović et al., 2015). These measures, however, do not detect individual vocalizations or animals. Rather, the total energy present in species-specific frequency bands is measured and then used to estimate the number of vocalizing animals required to produce the measured acoustic energy. Simulations can be run to test the ability of these metrics to detect changes in the relative abundance of the focal species. For example, simulations could include a range of densities of vocalizing individuals distributed around a passive acoustic sensor. Propagation loss from vocalizing individuals to the sensor can be modeled, allowing total received acoustic energy to be measured for each simulated density of the species, and the ability to measure changes with varying densities assessed. The relationship between density and received energy

can then be applied to empirical measurements of energy to back-calculate the relative density of vocalizing individuals.

Chapter 6 Absolute Abundance Estimation Using Passive Acoustics

Estimating absolute density (number of animals per area) and abundance (number of animals in a defined area) are among the most challenging uses of passive acoustic data. Although the use of acoustics for cetacean density and abundance estimation continues to grow, it is still not routine and is not likely to replace visual sighting surveys for most species within the next decade. The workshop reviewed the data and technical requirements, current capabilities, and impediments for density and abundance estimation using passive acoustics, from which the Steering Committee developed specific recommendations for advancing this field of research.

Data and Technical Requirements

Most acoustic approaches to density and abundance estimation are based on distance sampling methods adapted for acoustic data (Buckland et al., 2003; Marques et al., 2013). Distance sampling methods are so named because they depend on the estimation of detection probabilities as a function of distance from either a transect line (in line-transect surveys) or from a point (in point-transect surveys). The expectation is that the probability of detecting the acoustic signals made by an animal will decrease with its increasing distance from a detecting instrument (hydrophone). In distance sampling, distance is generally estimated for every detection, and the change in detection probability with distance is estimated empirically from these observations. Other methods, such as spatially explicit capture-recapture, have different data requirements (see Appendix F). There have been some attempts to analytically estimate acoustic detection probabilities from estimates of source levels and models of sound propagation when empirical estimates of detection distances are not available (e.g., Küsel et al., 2011). However, that approach depends on a large number of assumptions. For beaked whales, novel non-distance sampling methods have been developed to estimate abundance by counting all starts of foraging dives within a defined study area (Moretti et al., 2006). The latter approach appears limited to the situation within a Navy range with an extensive array of seafloor-mounted hydrophones. For this reason, the workshop concentrated on distance sampling-related methods, including spatially explicit mark-recapture.

Acoustic density estimation is typically based on detecting groups of animals, individual animals, or individual cues (in this case, vocalizations made by the animals). The data requirements and assumptions for each method differ, but a common requirement for use of distance sampling-related methods is the need to estimate detection probability as a function of distance, specifically horizontal distance from the hydrophone to the animal. Animal depth has to be estimated or assumed. Another common requirement for all density estimation methods is the ability to recognize species (or categories of species) from their vocalization types.

Group-based abundance estimation methods require an estimate of group size in order to estimate individual density or abundance (although group density can be estimated without this information). Purely acoustic methods to estimate group size are not currently available. As a result, group size information often comes from other sources such as visual sighting surveys. If distance sampling is used, the distance to groups should theoretically be the centroid of the group. However, for large, spread-out groups the centroid may be outside the acoustic detection range and therefore difficult to localize. The group-based approach also requires an estimate of the fraction

of time that at least one member of the group is making sounds.

Individual-based density estimation methods do not require group-size estimates, which might be viewed as an advantage for this method. However, the method does require information for each individual, such as horizontal range. For large groups, this added requirement is likely to make individual-based methods impractical. Software such as PAMGUARD (Gillespie et al., 2009) and its predecessor, RainbowClick, can be used to track individual odontocetes such as sperm whales, using consistent changes in bearing angles with ship movement and inter-click intervals. However, this approach breaks down for groups with more than 5 to 10 individuals. The individual-based approach also requires an estimate of the fraction of time that individuals are making sounds.

Cue-count distance sampling methods are based on estimating the density of cues per unit of time. In this case, cues are vocalizations made by the animals (e.g., clicks km^{-2} hr^{-1}). This estimate is converted to animal density by dividing by the cue production rate (e.g., clicks hr^{-1}). Unlike group- and individual-based methods, cue-count methods do not require an explicit parameter for the fraction of time spent silent, but do equivalently require estimates of the cue production rate (which must incorporate periods of silence).

In addition to purely acoustic methods to estimate cetacean abundance, passive acoustics can be used in conjunction with visual sighting surveys (Barlow and Rankin, 2007). Combined visual and acoustic surveys from the same vessel provide improved ability to detect cetaceans that are either visible at the surface or completely submerged. The two semi-independent modes of detection can be used to estimate the probability of detection by either method as well as the probability of being missed by both methods.

Current Capabilities

All six NMFS Science Centers have at least some capabilities for towed hydrophone line-transect surveys and fixed or free-floating point-transect surveys (Appendix B). All Science Centers standardized on the same modular towed hydrophone, cable, and connector design in 2013. Some Science Centers have made improvements in hydrophone and preamplifier design and array geometry, and it will probably be necessary to re-standardize occasionally to maintain inter-center compatibility and to facilitate equipment sharing. Towed hydrophone surveys are typically conducted in conjunction with visual sighting surveys from the same ship, greatly decreasing the cost of surveys that use towed hydrophones. Autonomous hydrophone recorders (anchored instruments, drifters, and gliders) currently being used at the Science Centers have not been standardized. The field is changing rapidly, and currently there is no single device that can meet the various needs of each Science Center.

Outside NMFS, most research on passive acoustic abundance estimation in the United States is sponsored by the U.S. Navy and is carried out at its research facilities and by researchers at the University of California at San Diego, Oregon State University (OSU), Cornell University, and others. Elsewhere in the world, the center for research on the use of passive acoustics for cetacean abundance estimation is at the Centre for Research into Ecological and Environmental Modelling of the University of St. Andrews in Scotland. The largest absolute abundance estimation project in Europe using passive acoustics is the multinational Static Acoustic Monitoring of the Baltic Sea Harbour Porpoise project, which used C-PODs to estimate the abundance of harbor porpoises in the Baltic Sea.

Impediments

Currently, acoustic abundance estimation for cetaceans is in its infancy. This approach is not currently used for stand-alone abundance estimates in U.S. Marine Mammal Stock Assessment Reports. However, in a few cases acoustic methods are used in conjunction with visual surveys to estimate abundance. Most studies that have produced acoustic abundance estimates to date have typically involved small areas and can be viewed as pilot or demonstration projects. Greater spatial coverage is needed to provide representative samples of larger study areas in order to provide abundance estimates on an appropriate scale for stock assessment. The situation is similar in the rest of the world. Workshop members recognized this as a problem and identified a number of impediments to advancement in this field.

Behavioral information

All acoustic abundance estimation methods described here require additional information on cetacean acoustic behavior. The required behavior information includes estimates of the fraction of time that groups and individuals are acoustically active; the rate at which acoustic cues are produced; and the seasonal, social, geographic, and depth- or density-dependent variability in cue production rates. However, this information has proven difficult to collect. For some cetacean species greater than approximately 4 meters in length, acoustic recording tags can be attached by suction cup to provide this data. For some cetaceans, focal follows may provide some of the needed information, at least during daylight hours. Direct observation may produce biased representations of typical behavior because animals are easier to follow when they are in particular behavioral states, and because the observation vessel can affect their behavior. Acoustic-only tracking studies may also give a biased representation of behavior because they require the tracked animals to be acoustically active. Because animal behaviors vary with location, time of day, season, activities, and among individuals, behavioral studies must obtain large sample sizes to characterize acoustic behavior adequately. Such studies are expensive. Density-dependent vocalization rates are particularly vexing for abundance estimation because abundance may not be linearly related to vocalization rates. Group-based abundance estimation may be a more robust method for highly vocal delphinid species. Although individual behavior is variable, at least some group members may be vocally active at any given time, eliminating the need to estimate the fraction of time that individuals are vocalizing.

Species identification

All abundance estimation methods also depend on accurate species identification based on acoustic vocalizations. Prior research indicates that baleen whale species produce species-specific vocalizations, but not all of their vocalizations are species-specific. In addition, for some species, only males may produce species-specific vocalizations. Sperm whales make very distinctive echolocation clicks that can be easily recognized. All beaked whales that have been studied appear to have species-specific echolocation clicks. A few delphinids have species-specific vocalizations or echolocation clicks. However, species identification for most delphinids is problematic, with computer algorithms producing high classification error rates. Some taxonomic groups (porpoises, *Cephalorhynchus*[8], and *Kogia*[9]) produce similar narrow-band, high-frequency clicks that are distinguishable from those of other odontocetes. Although this is an area of active research, little has been published on distinguishing among these high-frequency species.

[8] Commerson's, Heaviside's, Chilean, and Hector's dolphins

[9] Pygmy and dwarf sperm whales

Group size

The group-based abundance estimation methods require estimates of mean group size. Group size cannot be effectively estimated from acoustics alone, and the use of group sizes from visual surveys negates some of the potential advantages of acoustic surveys. Group sizes may vary geographically, diurnally, and seasonally, making the extrapolation from one visual survey to another acoustic survey difficult. The extrapolation of visually estimated daytime group sizes to nighttime acoustic detections is a particular concern. Although visual estimates from ships may be the only available group-size information, these estimates are typically imprecise and may be biased (Gerrodette and Forcada, 2005).

Distance estimation

The estimation of the distance from a vocalizing individual to a transect line or point is a critical element of all abundance estimation methods based on standard distance sampling. For towed hydrophone arrays, perpendicular distance to the trackline can be estimated accurately for a stationary sound source using changes in bearing angle, but distances may be biased if animals are moving. This is a particular problem for towed hydrophones because animals may be detected after they have reacted to the presence of the vessel. The perpendicular distances estimated from typical linear towed arrays cannot distinguish between horizontal distances (needed for abundance estimation) and vertical distances. Assuming that an estimated perpendicular distance is a horizontal distance results in a significant bias when estimating density of species that vocalize at depth (e.g., beaked and sperm whales). The development of towed tetrahedral arrays may eliminate this problem and resolve the left/right ambiguity of localizations by towed arrays. Vertical hydrophone arrays can be used to estimate distance to a vocalizing animal, but this approach has seldom been implemented to date. Large spatial arrays of time-synchronized autonomous hydrophones can be used to localize vocalizing animals and thereby estimate detection distance. However, the array spacing must be sufficiently dense to ensure that animals are recorded on at least three hydrophones. Clock drift in autonomous recorders is an impediment for accurate localization, and very accurate clocks may double the cost of autonomous recorders. Directional Frequency Analysis and Recording (DIFAR) sonobuoys and other types of pressure-vector sensors can determine the bearing angle to a sound source with a single sensor, and thus can be used to localize animals and estimate distance if a signal is received on two receivers. Clock drift is not a significant problem for this method because it does not require accurate measurements of time difference of arrival. Currently, however, vector sensors are limited to low frequencies (less than 2 kHz), and their use is therefore limited to studies of baleen whales. Most methods of distance estimation require multiple hydrophones, which increases costs. Some research has been done on estimating detection distances for a single hydrophone based on sound propagation theory (Küsel et al., 2011; Bonnel et al., 2014). This approach requires many assumptions or external measurements of sound-source levels and their variation, sound propagation conditions, directionality of the sound source, and distributions of animal orientation. These theoretical approaches are likely to be of limited value until they are empirically validated.

Combined visual and acoustic surveys

Although there are clear benefits of combining visual sighting surveys with towed hydrophone surveys, this approach is not without compromises. From a visual survey perspective, a towed hydrophone array reduces vessel maneuverability, which is a particular concern as the ship approaches cetaceans for species identification and group size estimation (in a “closing mode” survey). In some cases, the array must be retrieved before other studies such as photo-identification and

biopsy sampling can begin, resulting in lost time and potentially lost opportunities. From an acoustic survey perspective, visual surveys in closing mode are not optimal. The orientation of the ship toward a group of cetaceans after a sighting is made (again in "closing mode") limits acoustic detection range (acoustic reception is low along the axis of the array) and prevents acoustic estimation of range using changes in bearing angles. These conflicting needs often put visual and acoustic teams into conflict and result in poor cooperation between teams.

Research Needs

Considering the impediments to acoustic abundance estimation, described previously, the workshop identified research to help fill these gaps.

Behavioral studies

There is a need for more behavioral studies of vocalization rates; the fraction of time that individuals and groups are silent; and the seasonal, social, geographic, depth-dependent, and density-dependent variability in both the vocalization rates and periods of silence. More studies with acoustic recording tags on a wider assortment of cetaceans would be helpful, but such studies are very expensive and sample sizes are typically limited. The workshop identified the need for less expensive, more cost-effective studies of acoustic behavior. Focal-follow studies and land-based observations, in conjunction with acoustic monitoring, were identified as potentially valuable for estimating the parameters needed for abundance and density estimation.

Species classification

Species identification is most challenging for small delphinids and porpoises. Additional information is needed on these species as well on under-researched beaked and baleen whales. Most species-classification algorithms have been based on tonal calls, pulsed calls, or clicks. Better species classification might be obtained by combining information from all three types of vocalizations, especially in the case of small delphinids.

Group size estimation

Members of the workshop did not identify clear alternatives to using mean group size estimates from visual sighting surveys. Nonetheless, additional research is needed to quantify temporal (diurnal, seasonal, and annual) and spatial changes in group size to determine the validity of extrapolating group-size estimates from one study to another. Visual estimates of group size can be improved by aerial photogrammetry from helicopters (Gerrodette et al., 2002) or unmanned aircraft.

Distance estimation

Range estimation typically requires localization of the sound source with respect to the hydrophone. This topic has been an important research focus in the last decade. Many methods are available for different configurations of hydrophone arrays. However, with a single hydrophone, this empirical approach is generally not practical and theoretical models are needed. There is a need to validate such models with empirical observations.

Spatial extent and randomized survey design

Acoustic surveys need to be spatially extensive to provide abundance estimates for management. Broad-scale surveys are likely to require mobile hydrophones—towed arrays, gliders, or drifting arrays. Surveys should be designed with an equal probability of sampling every point within a study area. This method is a design-based survey approach that typically is based on a systematic survey grid with a randomly chosen starting point.

Combined visual and acoustic method

Because towed hydrophone arrays are already being used in conjunction with many visual sighting

surveys, there is undeveloped potential for using both sources of information for improved abundance estimates. The most direct approach might be to use an independent acoustic detection platform to help estimate the track-line detection probability (g(0)) for visual observers. Additional analytical developments are needed to deal with the potential negative correlation between acoustic and visual detection. Acoustic detections and localization can also be used in real time to increase the number of detections for abundance estimation, particularly for rare species like false killer whales (Bradford et al., 2014). Clearly, combined surveys are the best way to obtain acoustic recordings from known species for developing better species-classification algorithms.

Chapter 7 Conclusions and Recommendations

Following the workshop, the Steering Committee met to discuss findings and to develop general recommendations for future development of passive acoustics to support stock assessment efforts by NMFS. Two primary areas for improvements were identified—investment in new or improved infrastructure and the need for additional research and development (R&D). Encompassing the issues of infrastructure and R&D is the need for the strategic development of this technology and its resourcing. A strategic approach to developing and using the technology needs to be integrated across NOAA, involving each NMFS Science Center, Leadership, OS&T in NMFS headquarters, and the Office of Marine and Aviation Operations. In addition, the Steering Committee suggested that the development of the technology could be facilitated by a new working group within NMFS that would serve a similar role as the ASTWG; that is, by coordinating and supporting research into advanced survey and sampling technologies for marine mammals.

Infrastructure Investment

As with many research areas within NMFS, passive acoustics requires investment in infrastructure. Passive acoustics research and the use of passive acoustics to support marine mammal stock assessment requires access to equipment, lab facilities, software, field research platforms, training, data archiving resources, and computational capacity. Most of the development of passive acoustics capacity within NMFS has relied on peripheral funding and outside collaborations. Development of those capabilities varies among Science Centers and lags behind the capacity of other research technologies that provide data used in stock assessments. The mature development of passive acoustic capacity within NMFS will require strategic and dedicated investment in infrastructure. A mature system will include state-of-the-art facilities and capacities for the development and testing of new technology (platforms, sensors, and analytic tools); maintenance of operational technology; training opportunities; deployment and retrieval of devices; storage of data; and processing and analysis of those data. Some of the most important elements necessary to achieve this vision are discussed in the next section. However, it is important to recognize that NMFS's primary focus is on the implementation of the technology, and secondarily on its development. Currently, most of NMFS's development activities are undertaken in collaboration with universities and industry. It will be important for NMFS to balance its internal development investments with external investment activities.

Recognition of importance of passive acoustics

Passive Acoustics FTEs. Across NMFS, approximately 31 individuals are involved in passive acoustics research. However, just over eight FTEs are dedicated to this area. The SWFSC has three FTEs, the AFSC has two FTEs, and the Northwest Fisheries Science Center (NWFSC) has one and one-half FTEs, but two Science Centers have less than one each. Most passive acoustic "personnel" are contractors, graduate students, or affiliates paid with external funds. One Science Center, NEFSC, has seven and one-half individuals working on passive acoustics, but the average is just under four, and one Science Center, NWFSC, has only one. In most cases, the temporary employees conduct the majority of passive acoustics research, making it difficult to build capacity and knowledge within NMFS and to retain institutional knowledge of the technology and research. In addition, NMFS personnel are not able to spend enough time on passive acoustics development and research to build their expertise in the field fully. The mature development of passive acoustics capacity within NMFS will require

a substantially larger force of NMFS personnel primarily tasked with the development, testing, and operationalization of passive acoustics for stock assessments.

Development of New Funding Sources. The lack of sufficient dedicated passive acoustic FTEs reflects to some degree a still developing recognition of the importance of passive acoustics within the agency, but also a shortage of funding for stock assessments in general. For passive acoustics capacity to grow to meet its demand, substantially increased funding is required. Funding is required to fill the additional FTEs with highly qualified bioacousticians, pay for the development of the next generation of passive acoustics technology, secure and equip the bench and testing space for that development, and to build/lease/purchase the platforms necessary to collect the acoustic data needed for stock assessments and related research.

Funding currently comes from a variety of internal and external sources. Internally, resources are provided primarily by the Science Centers, OS&T, and the Office of Protected Resources (OPR). Within the OS&T, the Oceans Acoustics Program and the ASTWG are particularly important. Improved funding for the Oceans Acoustics Program would foster the proposed development and capacity-building. Although the ASTWG has provided a number of grants that have supported the development of passive acoustics for marine mammal research, their primary focus has been on new technology to sample fish. Increasingly advanced survey technology is needed to support the assessment of marine mammal populations and research into the impacts of human activities. In addition to passive acoustics, the development of unmanned aerial vehicles, genomics, hormone analyses, and habitat modeling are just a few of the advanced survey/sampling technologies that are growing rapidly.

External funding comes primarily from the Department of the Navy and the Bureau of Ocean Energy Management (BOEM). The reliance of the different Science Centers on the various Navy commands (e.g., Office of Naval Research (ONR), Living Marine Resources, or the Fleets) varies among the centers. NMFS's partnerships with these agencies are very important to advancing the development of passive acoustics and its application to marine mammal research and monitoring. The Navy and BOEM bring substantial resources to these partnerships, with the Navy also bringing expertise in passive acoustics, and NMFS bringing bioacoustics and biological expertise. Although the Navy and BOEM provide large sums of critically needed funding for passive acoustics, two problems need to be addressed. First, fund transfers can be complicated and carry a heavy administrative load, which could be addressed by streamlining the memorandum of understanding process. Second, the funds are understandably focused on the needs and challenges faced by the Navy or the energy industry. Because those needs and challenges can change frequently over time, it can be difficult for NMFS to sustain technology development and research efforts when relying on these fund sources. Additional strategic effort is needed to establish partnerships with the Navy and BOEM that will support long-term efforts in technology development that will meet the needs of all of the partners.

NMFS acoustic research receives little direct funding from non-governmental sources, in part because of the administrative difficulty in transferring private funds to the government. The oil and gas Exploration and Production Sound and Marine Life Joint Industries Program (JIP) has funded the private and university-based development of software tools for cetacean surveys and species recognition, most notably the software platform PAMGUARD. This indirect support has benefitted NMFS acoustic assessment research. NMFS should consider developing collaborative relationships with organizations such

as the National Fish and Wildlife Foundation (NFWF) and Small Business Innovation Research (SBIR) program, and with private sector organizations, where a conflict of interest can be avoided, to promote the further development of passive acoustics for marine mammal research.

Improving infrastructure

Technology Development Partnerships. Because the field of passive acoustics is relatively young, new technologies and methods are being proposed and tested regularly. As the use of passive acoustics matures and transitions from pilot projects to implementation, there is a need to assess different approaches and invest in the subset of possible methods that show the most promise. Standardization has a number of benefits for NMFS, including economies of scale, building equipment pools, equipment and expertise sharing, and ensuring comparability and compatibility of datasets. Investment in some technologies (e.g., sophisticated gliders) can exceed the resources of individual Science Centers and might be managed more efficiently by a centralized group within NMFS. Alternatively, various Science Centers could be made the home for development, training, and maintenance of particular technologies (e.g., towed arrays, fixed moorings, gliders, etc.).

The development of passive acoustics technology and uses in the field has proceeded at different paces and in somewhat different directions at the various NMFS Science Centers. This non-uniformity has impeded the sharing of equipment, information, and knowledge among Science Centers. In 2012, the SWFSC sponsored a workshop on the development of standardized methods for the construction and use of towed arrays. The workshop proved very successful at equalizing knowledge and experience across Science Centers and at establishing an equipment standard that has enhanced sharing among Science Centers. Other areas of technology development could similarly benefit from workshops designed to share knowledge and standardize equipment and field methods. Examples are glider technology, data archiving, and DCL analyses.

Raw Data Archiving Support. The use of passive acoustics results in the collection of large amounts of digital data that need to be stored for later analysis and archived. For example, a 4-hydrophone array monitoring dolphin vocalizations over a 400 kHz bandwidth could generate 1 TB of data every 2 days. Currently the Science Centers generally use external hard drives to store and archive their acoustic data using local protocols. That system leaves data vulnerable to loss and impedes the sharing of data and combining of data sets. NMFS should develop a standardized protocol for storing passive acoustic data and support the distributed infrastructure required to securely store and archive those data. This capacity should be standardized and developed in-house and in collaboration with the NCEI. The pilot study undertaken by the Alaska and Northeast Science Centers and NCEI will provide standards, guidelines, and important process lessons.

Secure Data Access and Serving. In response to a request from the U.S. Navy, NOAA Fisheries has agreed to follow several data-handling protocols to ensure that acoustic data that may contain sensitive information is not released publically. These protocols include the secure, locked storage of potentially sensitive data until the Navy reviews those data and approves them for public release. This step requires NMFS researchers to copy all requested data and securely transport the datasets to Navy facilities for review. If some data are deemed sensitive, these data must be maintained separately in a secure, locked facility and cannot be released.

The Federal Government is also required by the new PARR policy to make all data publically available. Both of these requirements are

unfunded and require staff time and new facility/hardware capabilities.

Random Deployment Capacity. The estimation of the population/stock sizes of marine mammals requires surveys of large areas because the ranges of most species are extensive. Unbiased sampling requires the randomized placement of sampling locations or, when environmental features significantly affect abundance, randomized placement within strata. For efficiency, systematic sampling grids, transect lines, or sampling stations can be used if their placement is randomized. Although this is standard protocol for towed acoustic surveys conducted in conjunction with visual sighting surveys, the random placement of autonomous acoustic recorders within a large study area will require additional resources. These resources include dedicated NOAA or charter vessel time, mooring with acoustic releases, drifting recording systems, broad-scale glider surveys, etc.

Targeted Studies

The use of passive acoustics to survey marine mammals is promising but still requires considerable research in a number of areas. Based on the workshop discussions, the Steering Committee identified the need for research studies targeted on particular science gaps or needs.

Classification—species/stock identification capability

Detecting acoustic signals from marine mammals is of limited utility if they cannot be classified to species or stock. The capacity to identify the vocalizations of a species or stock varies taxonomically. Careful research that pairs visual identification with acoustic detections, or the placement of recording tags on marine mammals, has allowed researchers to identify the vocalizations of many species and stocks. Most species of baleen whales produce species-specific vocalizations, although not all vocalization types are species-specific. However, the distinctiveness of a vocalization may be environmentally or socially dependent or linked to gender. Sperm whales and most species of beaked whales produce species-specific echolocation clicks, but many delphinid species cannot be reliably identified by their vocalizations. The narrow-band, high-frequency echolocation clicks of *Kogia*, porpoises, *Cephalorhynchus* dolphins, some *Lagenorhynchus* dolphins, and river dolphins are distinct from other taxa, but have not yet been shown to be species-specific.

Classification relies on the ability of an analyst or computer algorithm to identify a vocalization as coming from a particular species or stock. This identification can be made by pattern matching or the statistical comparison of acoustic features of the signals. However, as just described, only some vocalizations have been associated with particular species or stocks, and for many species, species-specific vocalizations have yet to be identified. In addition, vocalizations that an analyst can identify may defy automatic classification by computer algorithms. These problems currently limit the usefulness of passive acoustic data for stock assessment. The ability to distinguish species by a single vocalization type varies among vocalization types and species.

Because NMFS is responsible for conducting stock assessments of every species and stock of cetaceans and most pinnipeds in the U.S., comprehensive knowledge of their vocalizations is required. NMFS should take a leadership role in developing a comprehensive catalog of marine mammal vocalizations and species/stock repertoires. That development would encompass several elements, such as the specification of vocalization types, guidelines for obtaining full repertoires, specification of the metadata to be kept, and the construction of the infrastructure necessary to house the catalog and to make it easily accessible to researchers. The catalog could be housed at a single institution or distributed

among several, with a website that would allow researchers to access the data. Such a repository of acoustic data should, at least partially, satisfy PARR requirements for passive acoustic research.[10]

Researchers, statisticians, and mathematicians are always exploring new and promising algorithms for the automatic and real-time classification of marine mammal vocalizations. Because of the very large time commitments needed to analyze passive acoustic data, the full integration and use of passive acoustics to support stock assessment will require the development of efficient automatic detection and classification algorithms. NMFS should identify and contribute to the development of the most promising algorithms. Finally, NMFS should further focus on signal classification in particularly high-need cases, such as the classification of delphinid whistles, beaked whale echolocation signals, and the differentiation of similar vocalizations in closely related species (e.g., the gunshot calls of bowhead and North Pacific right whales).

Behavioral acoustics

The detection, classification, and localization of marine mammal vocalizations depend on those signals being consistent and predictable. However, it is well known that the types of vocalizations and their characteristics can change significantly in different circumstances. For example, received-level can change depending on the type or directionality of the vocalization and the orientation of the animal with respect to the hydrophone. In addition, vocalization types and rates can change in different social contexts, locations, depths, ecological situations, or seasons. Vocalizations can be sex-specific and can be affected by anthropogenic noise. The rate at which individuals vocalize can be a critical variable in estimation of density, but that rate can vary by orders of magnitude depending on a range of social and environmental factors. One of the most vexing problems stems from the fact that vocalization rates can depend on the density of animals (density-dependent vocal behavior), which can lead to severe biases in abundance estimates if it is not corrected for.

Research is critically needed to understand how ecological and social environments can affect marine mammal vocalizations, if those data are to prove useful in stock assessments. The research required depends on the aspect of stock assessment being addressed. For example, determining which vocalizations within a repertoire are most characteristic of a population is important for stock delineation. However, identifying a species' repertoire is not essential for abundance estimation. Conversely, vocalization rates are critical to estimating absolute abundance but less so for stock delineation. Understanding the role factors such as vocalization rate play in the variance and bias of measures such as population density is critical. Studies that link behavioral observations, the collection of ecological data, and the recording of vocalizations of tagged marine mammals are necessary to provide the required information. However, studies that require tagging animals are expensive and generate relatively small sample sizes. Alternative research approaches, such as focal follows and land-based observations paired with acoustic monitoring, require investigation.

Range estimation

Estimation of the distance from the hydrophone or a transect line to the source of a vocalization (i.e., the range) is critical to the estimation of density. When multiple hydrophones are used in linear, two-dimensional or three-dimensional arrays, then differences in the timing of the arrival of signals at the hydrophones can be used to estimate the bearing angle. With multiple vocalizations over

[10] In 2013, the White House Office of Science and Technology Policy released a memorandum requiring federal agencies to develop plans for public access to research results (PARR).

time, the convergence of bearing angles in a moving array can be used to estimate the range. However, other techniques must be used when single hydrophones or stationary small-aperture arrays are used, as with autonomous floating PAM systems. One approach in this situation is to model sound propagation based on assumptions about the source levels of the signal and physical characteristics of the water and bathymetry. Another approach is to use multipath signals such as those from surface/bottom reflections and sound refraction. Both approaches have promise, and additional testing and validation is required before these methods can be used in practice.

Detection probability and validation

The application of distance-based sampling theory to the estimation of marine mammal densities from acoustic data collected along transects often requires the estimation of detection probabilities that are specific to particular taxa and situations. Research effort is needed to estimate detection probabilities for most taxa and to understand how those probabilities vary in time and space, and in response to different environmental, ecological, and social factors. Further research is needed to validate those estimates using tagged animals, where all vocalizations from an animal are logged and animal position from the hydrophone is measured at each vocalization, so detection probability can be estimated empirically.

Automated analyses and quantitative performance measures

Several researchers have developed software packages that automate the analysis of acoustic data, particularly the detection and classification of signals. However, detection and, especially, classification can be very difficult. Distinguishing coherent signals from background noise is problematic in many situations. In addition, the identification of the species or stock that produced the signal can be highly error-prone for a variety of reasons explained earlier in the stock delineation chapter (Chapter 3). It is difficult to know, however, when a classifier is good enough to use. Research that would establish performance measures and guidelines should improve the usefulness of many classifiers. In addition, research is needed to assess whether those performance measures could be used to compensate for the error rates experienced by some classifiers.

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Acknowledgements

We want to express our heart-felt thanks to the workshop participants who gave freely of their time and expertise, and in some cases traveled a long distance to attend. NMFS's Southwest Fisheries Science Center provided excellent facilities for holding the workshop, and the Center's Marine Mammal and Turtle Division Director, Dr. Lisa Ballance, kindly opened the workshop and provided the participants with background and context. Several individuals at the Southwest Fisheries Science Center contributed their time and effort to make the workshop a success. Shannon Rankin put in an amazing amount of work, even while sick with the flu, to organize all of the local meeting logistics. In implementing the plans for and running the workshop, Shannon had considerable help from Jennifer Keating and Emily Griffiths, who made sure that everything we needed was available when it was needed. Ravi Shiwmangal was quite helpful in setting up the audio and making sure that everything electronic within his control ran perfectly. In addition, we had the assistance of four graduate students (Amy Van Cise, Anne Simonis, Eiren Jacobson, and Eric Keen) who volunteered to take notes.

Appendix A Participants

Note: An asterisk after a participant's name indicates that he/she is on the Steering Committee.

Jay Barlow, Ph.D.*

NOAA Fisheries – Southwest Fisheries Science Center – Marine Mammal and Turtle Division – EEZ Mammals and Acoustics Program

Expertise: Population dynamics

Taxa/species: Marine mammals and sea turtles

Dr. Jay Barlow is a research scientist within the EEZ Marine Mammals and Acoustics Program at the Southwest Fisheries Science Center (SWFSC), La Jolla, CA, where he has worked for 33 years. Jay received his Ph.D. from Scripps Institution of Oceanography (SIO) in 1982. He is also an Adjunct Professor at SIO. Dr. Barlow's research is directed primarily at assessing human impacts on marine mammal populations, estimating their abundance and dynamics, understanding the role of mammals in marine ecosystems, and developing survey methods that use passive acoustics to detect and localize cetaceans.

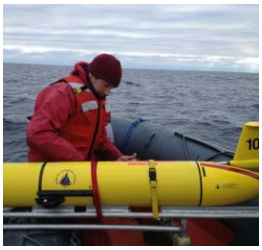
Simone Baumann-Pickering, Ph.D.

University of California at San Diego – Scripps Institution of Oceanography – Behavioral Acoustic Ecology Lab

Expertise: Long-term PAM, signal description and classification

Taxa/species: Odontocetes

Dr. Simone Baumann-Pickering is an Assistant Research Scientist at Scripps Institution of Oceanography. Her focus is on the behavioral ecology of marine organisms using passive acoustic methods. Dr. Bauman-Pickering has experience in signal description, acoustic species discrimination, and automatic signal detection and classification, particularly of odontocete echolocation signals. Recently, she has been involved in improving and comparing methods for density estimation of beaked whales using stationary long-term passive acoustic sensors in the Gulf of Mexico.



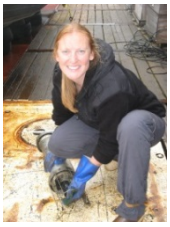
Mark Baumgartner, PhD

Woods Hole Oceanographic Institution – Biology Department

Expertise: Biological oceanography, ecology of cetaceans and zooplankton

Taxa/species: Cetaceans, particularly baleen whales

Dr. Mark Baumgartner is a scientist at the Woods Hole Oceanographic Institution (WHOI) specializing in top predator ecology and the physical and biological oceanographic processes that allow those predators to survive in the ocean. He focuses much of his research on baleen whales and their zooplankton prey as a tractable system in which questions can be addressed about how prey behavior, life history, and aggregation mechanisms can influence top predator distribution and behavior. Mark has been using passive acoustics from autonomous platforms to assess whale occurrence in his studies, and has recently developed a capability to report in near real time the calls of several baleen whale species for both scientific and conservation applications.



Jessica Crance, M.S.

NOAA Fisheries – Alaska Fisheries Science Center – National Marine Mammal Laboratory

Expertise: Acoustic detection, classification, localization of marine mammals

Taxa/species: Marine mammals (emphasis on Arctic species)

As the lead research assistant and project manager for the acoustics program at the National Marine Mammal Lab, Jessica is involved in all aspects of data collection, management, and analysis for several projects. She has experience in the deployment and analysis of three acoustic platforms (moored recorders, sonobuoys, and towed arrays), and has acted as Chief Acoustic Scientist on field surveys in the Alaskan Arctic. Through her analysis of long-term passive acoustic recorders, she helps provide information on the seasonal distribution of marine mammals in the Arctic and sub-Arctic. She also has extensive experience in fine-scale acoustic analysis of call characteristics and call patterns.

Karin A. Forney, Ph.D.

NOAA Fisheries – Southwest Fisheries Science Center – Marine Mammal and Turtle Division – EEZ Mammals and Acoustics Program

Expertise: Marine mammal ecology and population assessment

Taxa/Species: Marine mammals

Since 1987, Dr. Karin Forney has conducted research on the abundance, distribution, ecology, fishery bycatch, and status of more than 20 species of cetaceans and pinnipeds in the eastern and central North Pacific Ocean, with special emphasis on harbor porpoise, false killer whales, and other small cetaceans. Her research interests include: 1) ocean variability and its effect on marine mammals and other marine vertebrates; 2) habitat-based predictive models of cetacean distribution and abundance; 3) assessment and mitigation of human-caused mortality and injury of protected species; and 4) the development of improved methodology for estimating marine animal abundance and evaluating population trends. Dr. Forney co-authors annual stock assessment reports for the Pacific marine mammal stocks under NMFS's jurisdiction.

Jason Gedamke, Ph.D.*

NOAA Fisheries – Office of Science and Technology – Ocean Acoustics Program

Expertise: Marine bioacoustics

Taxa/Species: Marine mammals

Dr. Jason Gedamke manages the Ocean Acoustics Program within NOAA Fisheries' Office of Science and Technology. Jason completed his Ph.D. in 2004 at the University of California, Santa Cruz, studying minke whale acoustic behavior and acoustically tracking singer movements. Following that, he worked for the Australian Antarctic Division conducting acoustic research on cetaceans in the Southern Ocean and providing scientific advice on the potential impact of anthropogenic sound on marine mammals. The Ocean Acoustics Program aims to increase understanding of how animals use sound, how underwater acoustics can be used to assess marine animal populations, the degree to which anthropogenic activities are changing the underwater soundscape, how these changes may potentially impact marine animals, and what measures can be taken to mitigate these potential impacts.

Douglas Gillespie, Ph.D.

University of St. Andrews – School of Biology – Scottish Oceans Institute – Sea Mammal Research Unit

Expertise: Algorithms and software tools for the detection, classification, and localisation of marine mammal vocalisations

Taxa/species: Many species including North Atlantic right whale, sperm whale, harbour porpoise, and dolphin species

Dr. Douglas Gillespie is a physicist by training. Since 2005, he has been developing algorithms and software tools for the detection and tracking of marine mammals using passive acoustics. He currently manages and is a key developer of the PAMGUARD PAM software. Other research interests include the development of embedded low-power PAM systems for use in remote buoys and autonomous vehicles. Dr. Gillespie is based at the Sea Mammal Research Unit at the University of St. Andrews, Fife, Scotland.

Danielle Harris, Ph.D.

University of St. Andrews – Centre for Research into Ecological and Environmental Modelling (CREEM) and Sea Mammal Research Unit

Expertise: Abundance/density estimation of marine mammals using acoustic data

Taxa/species: Cetaceans

Dr. Danielle Harris is a post-doctoral research fellow at CREEM with a multi-disciplinary background involving biological, statistical, and acoustical analyses. Her research focuses on cetacean density estimation using acoustic data, particularly investigating cost-effective approaches by exploring existing opportunistic data sets and new technologies. Most of her work has focussed on blue and fin whales, although she has also worked on projects involving deep-diving odontocetes and harbour porpoises.

Dennis Heinemann, Ph.D.*

U.S. Marine Mammal Commission

Expertise: Marine ecology

Taxa/species: Pinnipeds, seabirds

Dr. Dennis Heinemann is the Science Director at the Marine Mammal Commission. Dennis was the lead organizer of the workshop. He does not have a background in marine bioacoustics, but is a statistician and is experienced with stock assessment, population dynamics, and the design of shipboard and aerial surveys for seabirds and marine mammals.

John Hildebrand, Ph.D.

University of California, San Diego – Scripps Institution of Oceanography – Scripps Whale Acoustic Lab

Expertise: Underwater sound and marine mammals

Taxa/Species: Marine mammals

Dr. John A. Hildebrand is a Professor at SIO at the University of California at San Diego. He obtained a B.S. degree in Physics and Electrical Engineering at the University of California, San Diego, and a Ph.D. in Applied Physics from Stanford University. He has been on the research staff of the Scripps Institution of Oceanography since 1983. He regularly teaches classes on bioacoustics, experimental laboratory acoustics, and marine mammal biology. Dr. Hildebrand has contributed to more than 165 referred publications on topics ranging from underwater noise to sound production by marine mammals. His recent research has focused on ambient noise and acoustic techniques for marine mammal population census.

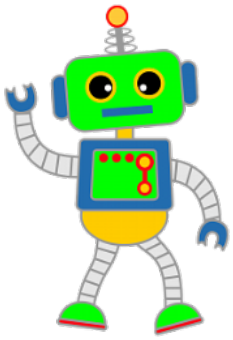
Marla Holt, Ph.D.

NOAA Fisheries – Northwest Fisheries Science Center – Conservation Biology Division

Expertise: Bioacoustics (including sound production, acoustic communication, noise effects, acoustic risk factors, sensory ecology, and PAM)

Taxa/species: Marine mammals

Dr. Marla Holt is a Research Wildlife Biologist for the Marine Mammal and Seabird Ecology (MMSE) Team. She received her Ph.D. in Ocean Sciences at the University of California, Santa Cruz; her dissertation focused on directional hearing and acoustic communication in pinnipeds. Dr. Holt joined the NWFSC as a National Research Council Postdoctoral Associate in October 2006. Marla's current research focuses on cetacean acoustics including Southern Resident killer whales' (SRKW) use of sound, noise and vessel effects on their behavior, mechanisms and energetics of sound production in odontocetes, and passive acoustic monitoring of marine mammals. Current PAM investigations of the MMSE Team include work using towed arrays and sonobuoys for the Pacific Orcinus Distribution Survey (PODS) cruises, EARs for documenting SRKW winter coastal distribution, DTAGs for understanding vessel noise exposure and effects on behavior in SRKWs, and C-PODs for detecting porpoise clicks in Puget Sound.



Holger Klinck, Ph.D.

Cornell University – Cornell Lab of Ornithology – Bioacoustics Research Program, Oregon State University (OSU) – Department of Fisheries and Wildlife and National Oceanic and Atmospheric Administration – Office of Oceanic and Atmospheric Research – Pacific Marine Environmental Laboratory

Expertise: Passive acoustic monitoring, autonomous platforms, detection and classification

Taxa/species: Marine mammals

Dr. Holger Klinck was recently appointed as the Technology Director of Cornell University's Bioacoustics Research Program. He also holds an appointment as Assistant Professor at OSU and is affiliated with OAR's Pacific Marine Environmental Laboratory (PMEL). His current research at Cornell and OSU focuses on the development of hardware and software tools for passive acoustic monitoring of marine life. This work includes the use and modification of autonomous underwater vehicle (AUV) and unmanned surface vehicle (USV) systems to study and monitor marine mammals. In collaboration with researchers from the University of Washington, NOAA, and the Austrian Society for Innovative Computer Sciences, he has used AUVs and USVs to monitor and study marine mammals in remote regions throughout the world. He is also involved in ocean noise studies and is currently leading a collaborate effort with PMEL, all the NMFS Science Centers, National Marine Sanctuary System, and the National Park Service to establish a large-scale Ocean Noise Reference Station (NRS) network to monitor long-term changes and trends in the underwater ambient sound field in U.S. waters.

Tiago André Marques, Ph.D.

University of St. Andrews – Centre for Research into Ecological & Environmental Modelling, and Universidade de Lisboa

Expertise: Animal density estimation, distance sampling, passive acoustic density estimation

Taxa/species: Mostly marine mammals

Dr. Tiago Marques is a Senior Research Fellow at the University of St. Andrews, although permanently residing in Lisboa, Portugal. He was the main postdoctoral researcher in the Density Estimation for Cetaceans from passive Acoustic Fixed (DECAF) sensors project, during which methods for estimating animal density from passive acoustic data were developed and implemented in a variety of case studies. Most recently, he has been working on the Linking Acoustic Tests and Tagging using Statistical Estimation program, evaluating the impact of navy sonar on marine mammals. Tiago is a biologist (1998) with M.Sc. (2002) and Ph.D. (2007) degrees in statistics. His M.Sc. and Ph.D. research was on extending distance-sampling methods for estimating animal abundance in situations where conventional assumptions do not hold, namely non-random transect placement and error in distance measurements.

David K. Mellinger, Ph.D.

Oregon State University – National Oceanic and Atmospheric Administration – Office of Oceanic and Atmospheric Research – Cooperative Institute for Marine Resources Studies (CIMRS)

Expertise: Software and hardware for detecting, classifying, and locating animals acoustically and application of these methods to research and conservation

Taxa/species: Cetaceans, pinnipeds, fishes

Dr. Dave Mellinger is the program leader for the CIMRS Bioacoustics Lab. The lab develops new tools for studying marine mammals acoustically: algorithms for detection, classification, localization, and density estimation; and user-friendly software to make these algorithms easily accessible by people everywhere. The lab develops these methods for new hardware platforms such as ocean gliders, robotic sailboats, and fixed pop-up sensors. In addition, the lab applies these new technologies for research and conservation of marine species throughout the world.

Jeff Moore, Ph.D.

NOAA Fisheries – Southwest Fisheries Science Center – Marine Mammal and Turtle Division – EEZ Mammals and Acoustics Program

Expertise: Population dynamics, statistics, survey design and modeling

Taxa/species: Marine mammals and sea turtles

Dr. Jeff Moore is a population-assessment scientist within the SWFSC Marine Mammal and Sea Turtle Division, joining the group in 2010. His expertise and responsibilities include developing methods for quantifying population impacts of bycatch on sea turtles and marine mammals; risk assessment; Bayesian statistics; developing quantitative decision tools for policy and management; estimating cetacean abundance, trends, and population dynamics parameters; designing marine mammal abundance surveys; and analysis. Jeff serves on advisory committees such as the Biological Review Team for assessing the status of northeastern Pacific white sharks, and the International Union for Conservation of Nature's Cetacean Specialist Group. He regularly contributes to protected species management processes such as Take Reduction Planning and activities related to the Pacific Fishery Management Council.

Erin Oleson, Ph.D.*

NOAA Fisheries – Pacific Islands Fisheries Science Center – Protected Species Division – Cetacean Research Program (CRP)

Expertise: Marine bioacoustics

Taxa/species: Cetaceans

Dr. Erin Oleson has been the leader of the CRP at the Pacific Islands Fisheries Science Center since 2009. Erin received her Ph.D. from the Scripps Institution of Oceanography. She has conducted acoustic tagging of humpback, blue, and fin whales off California and in the eastern tropical Pacific; conducted shipboard and acoustic surveys for cetaceans; and used long-term autonomous acoustic recorders to assess seasonal species occurrence off the U.S. West Coast, Alaska, Hawaii, Mexico, and the Antarctic. As leader of the CRP, Erin oversees field investigations, conducts statistical analyses, provides scientific advice, and prepares status reports and manuscripts on research to assess cetacean populations in the Pacific Islands Region.

Julie Oswald, Ph.D.

Bio-Waves, Inc.

Expertise: Acoustic species identification

Taxa/species: Cetaceans

Dr. Julie Oswald is Vice President and Senior Scientist at Bio-Waves, Inc., a small bioacoustic research and consulting firm located in Encinitas, California. Her main area of expertise is the development of classification methods for sounds produced by odontocete species. She is also involved in the analysis of acoustic data collected using towed hydrophone arrays and seafloor-mounted acoustic recorders. These projects include examinations of species occurrence and distribution patterns, acoustic behavior, and impacts of anthropogenic sound on marine mammals.

Shannon Rankin
NOAA Fisheries – Southwest Fisheries Science Center – Marine Mammal and Turtle Division – EEZ Mammals and Acoustics Program

Expertise: Bioacoustics

Taxa/species: Cetaceans

Ms. Shannon Rankin is a wildlife research scientist specializing in passive acoustic monitoring of marine mammals. Specifically, she is interested in using passive acoustics as a tool for monitoring marine mammal populations through systematic surveys. Shannon works primarily with towed hydrophone arrays and Navy sonobuoys on shipboard surveys throughout the Pacific Ocean, as well as the Gulf of Mexico and the Antarctic.

Professor Marie A. Roch, Ph.D.
San Diego State University – Computer Science Department

Expertise: Bioacoustics, classification

Taxa/species: Marine mammals

Dr. Marie Roch is an interdisciplinary computer scientist who works on the classification of marine mammal vocalizations as well as methods to integrate marine mammal call detections with environmental measurements and anthropogenic acoustic sources for data exploration and habitat modeling. Her work ranges from species identification to extraction of call parameters and the recognition of call component archetypes. Recent classification work has focused on quantifying and mitigating the effects of site and equipment variability for fixed PAM units deployed within a geographic region.

Ana Širović, Ph.D.

University of California at San Diego – Scripps Institution of Oceanography – Marine Physical Laboratory

Expertise: Passive acoustics, ocean ambient sound, long-term time series analysis

Taxa/species: Cetaceans, with a focus on mysticetes and fishes

Dr. Ana Širović is a researcher at the Scripps Institution of Oceanography. She has been working on the use of passive acoustic tools to answer population-level questions relevant to the management of animal resources since 2000, and during this time has analyzed many decades' worth of passive acoustic data. She is currently working on projects relating to estimation of baleen whale call rates as they pertain to density estimation. She is also interested in ambient noise and the effects human activities have on marine organisms.

Melissa Soldevilla, Ph.D.

NOAA Fisheries – Southeast Fisheries Science Center (SEFSC) – Protected Resources Division – Marine Mammal Program

Expertise: Echolocation, bycatch, stock assessment
Taxa/species: Delphinids, North Atlantic right whales

Dr. Melissa Soldevilla is a Research Fishery Biologist at NOAA's SEFSC. She received her Ph.D. at SIO where she developed methods to identify delphinid echolocation clicks to species and applied this work to study Risso's dolphin and Pacific white-sided dolphin ecology from fixed passive acoustic sensors in the Southern California Bight. Currently, her work at the SEFSC includes fishery bycatch estimation and data-gap evaluations; developing passive acoustic methodologies to enhance stock assessments, including acoustic abundance estimation of deep diving cetaceans and odontocete click-classification techniques; and developing surveys and analyzing PAM and mitigation studies for conservation of North Atlantic right whales on their southeast calving grounds, including evaluation of survey method effectiveness, localization and estimation of detection distances, and characterization of shipping noise.

Sofie van Parijs, Ph.D.*

NOAA Fisheries – Northeast Fisheries Science Center (NEFSC) – Resource Evaluation and Assessment Division – Protected Species Branch – Passive Acoustics Research Group

Expertise: Marine bioacoustics
Taxa/species: Marine mammals, fish

Dr. Sofie Van Parijs has worked on passive acoustic research from the poles to the tropics for more than 20 years. She has undergraduate and master's degrees from Cambridge University and a Ph.D. from Aberdeen University in the U.K. She worked as a postdoctoral scientist at the Norwegian Polar Institute, James Cook University in Australia, and Cornell University before moving to the NEFSC in Woods Hole in 2004. At NMFS, she leads the passive acoustic research program within the Protected Species Branch, which consists of postdoctoral scientists, Ph.D. students, research analysts, and summer interns. Her expertise in marine bioacoustics has addressed questions on behavioral ecology, distribution, abundance, long-term monitoring, mitigation, and effects of ocean noise on marine mammals.

Appendix B Science Center Passive Acoustics Research Programs (Prepared by Erin Oleson)

Northeast Fisheries Science Center Passive Acoustic Research Group[11]

NEFSC is responsible for cetacean stock assessments in the northeast U.S. Atlantic waters. The Passive Acoustic Research Group within the Protected Species Branch at NEFSC extensively uses well-proven and new technology to monitor and understand the occurrence and abundance of, and human-impacts on, large whales and other cetaceans in the region.

Passive Acoustics Personnel:

- 1 FTE (Van Parijs)
- 1 senior scientist
- 1 postdoctoral researcher (shared by NEFSC and Stellwagen Bank National Marine Sanctuary (SBNMS))
- 1 data manager
- 4 research assistants
- ½ field work manager

Other than 1 FTE, all others are temporary contractors paid through competitive external funds/grants.

Instrumentation Available:

- 2 linear towed hydrophone arrays
- 8 leased HARPs (with SEFSC in West Atlantic through BOEM)
- Leased MARUs (~20 per year for large whale work; various external funding sources)
- 2 ocean NRSs (1 for NE Atlantic, 1 for SBNMS through NOAA)
- 1 leased AMAR (U.S. Navy)
- 2 Liquid Robotics Wave Gliders, 1 Slocum glider, 2 EOM surface real-time moorings (owned and maintained by WHOI) for real-time monitoring (ESTCP/LMR U.S. Navy)
- 50 sonobuoys (donated by U.S. Navy)
- Leased MARU or MiniHARPs; ~15 upcoming for migration corridor work (Atlantic Marine Assessment Program for Protected Species (AMAPPS))

Data Management Support:

- In-house data manager (contractor) and NEFSC IT support for archiving and managing all passive acoustic data
- Backup data housed at NEFSC and with collaborators
- Metadata management database in progress (Tethys through M. Roch at San Diego State University (SDSU))
- Long-term archiving pilot project in progress (with NCEI and AFSC)

[11] Website: http://www.nefsc.noaa.gov/psb/acoustics/

Ongoing projects

1. Long-term archiving of assessment PAM data:
   - National Oceanographic Partnership Program (NOPP) funding for development of metadata base
   - Ongoing pilot project with NGDC to archive PAM data and understand full cost/effort involved per TB of data with National Marine Mammal Laboratory (NMML) and NGDC
     - *Partners:* SDSU, SIO, NMFS Science Centers, NGDC
     - *Funders:* NOPP (ONR), PIFSC, NMML, OS&T, NMFS Ocean Acoustics Program

2. Autonomous technology projects:
   - Demonstration project to show feasibility of integrating autonomous and real-time passive acoustic monitoring into assessment and mitigation needs throughout the northeast U.S. (Gulf of Maine and N.Y. Bight) using Slocum gliders, Wave Gliders, and fixed real-time moorings with WHOI
     - *Partners:* WHOI
     - *Funders:* ONR, ASTWG, ESTCP, LMR
     - *Website:* http://dcs.whoi.edu/

3. Fish Acoustics:
   - Using archival acoustic recorders, gliders, and acoustic telemetry to find, define, and protect spawning areas for fish (especially Atlantic Cod)
     - *Partners:* Massachusetts Department of Marine Fisheries, University of Massachusetts School of Marine Science and Technology, The Nature Conservancy, SBNMS, WHOI
     - *Funders:* NMFS Co-Operative Research Grant Program, NOAA Saltonstall-Kennedy Grant Program

4. Marine Mammal Acoustics:
   - Seasonal occurrence, distribution, and migration patterns for baleen whales in the Western Atlantic using historic (2005 to present) and new data for large whales
     - *Partners*: Dave Mellinger and Sharon Nieukirk, Hilary Moors-Murphy, Erin Summers, Maine Department of Marine Resources, College of the Atlantic, New England Whale Center, JASCO Ltd., Cornell University, SEFSC, Duke University, Naval Facilities Engineering Command, Kate Stafford, Ana Širović, Scripps, Susan Parks, Syracuse University, NEFSC, Gary Buchanan, New Jersey Department of Environmental Protection, Helen Bailey, University of Maryland, Catherine Berchok, NMML
     - *Funders*: BOEM, GAFRO, OPR
   - Towed array for stock assessment (mainly sperm and beaked whale) as part of AMMAPS
     - *Partners*: SEFSC
     - *Funders*: BOEM
   - Integrating PAM and visual data (density estimates from long-term array data for right whales, new integration methods for fixed sensors and visual)
     - *Partners*: SBNMS, SEFSC, University of Maryland, others
     - *Funders*: U.S. Navy

5. Northeast Passive Acoustic Network (NEPAN)
   - Combining projects 2 and 4 above with Canadian partners to produce an integrated monitoring and mitigation network throughout the northeast
     - *Partners and Funders*: See above

6. Noise Impacts
    - Shelf-break monitoring throughout the Western Atlantic as part of a Before-After Control-Impact (BACI) design for full range of species before and during seismic exploration
        - *Partners:* SEFSC, Duke University, SIO
        - *Funders:* BOEM

Southeast Fisheries Science Center Passive Acoustic Assessment Program

SEFSC is responsible for cetacean stock assessments in the southeast U.S. Atlantic waters, the northern Gulf of Mexico, and the Caribbean. Passive acoustics are used currently for ship-based stock assessments in the Gulf of Mexico and southeast U.S. Atlantic. In the same locations, passive acoustics are also used for seasonal assessments of cetacean occurrence from fixed platforms.

Passive Acoustics Personnel:

- ½-time FTE (Soldevilla; other ½ time on take reduction team support)
- 1 full-time contractor (externally funded)
- Occasional volunteer student help

Instrumentation Available:

- 3 linear towed hydrophone arrays
- 2 dedicated HARPs (BOEM, Dry Tortugas)
- Leased MARUs (~12 per year for right whale work through the Southeast Implementation Team of the North Atlantic right whale recovery plan)
- 2 NRSs (1 for Gulf of Mexico, 1 for southeast Atlantic through NOAA)
- Leased MARUs or MiniHARPs (~8 upcoming for migration corridor work (AMAPPS))
- Leased HARPs (~3 for upcoming BOEM pre-seismic study)

Data Management Support:

- Limited – Serial Advanced Technology Attachment (SATA) disks in office, backup disks with collaborators
- Metadata management database in progress (Tethys through M. Roch at SDSU)
- Long-term archiving project in progress (NGDC and NEFSC collaboration)

Primary Research Partners:

- SIO
- Cornell University
- NEFSC, PIFSC, SWFSC, PMEL
- Duke University
- Bio-Waves, Inc.
- SDSU

Primary Near-Term Goals:

- Shelf-break monitoring throughout the western Atlantic as part of a BACI design for full range of species before and during seismic exploration
- Seasonal occurrence, distribution, and migration patterns for right whales in the western Atlantic using historic (2005 to present) and new data for large whales
- Towed array surveys in the Atlantic for stock assessment (sperm whale abundance estimation and delphinid species classification) as part of AMMAPS
- Localization and tracking of North Atlantic right whales on calving grounds for detection distance estimation and PAM effectiveness evaluation

- Ship noise characterization on North Atlantic right whales calving grounds
- Gulf of Mexico towed array surveys for stock assessment (sperm whale abundance estimation and delphinid species classification)
- Dry Tortugas sperm whale monitoring for assessment of seasonal occurrence and habitat use
- NOAA's Noise Recording Station (NRS) network in the Gulf of Mexico and southeast U.S. Atlantic

Southwest Fisheries Science Center Passive Acoustics

The SWFSC EEZ Mammals and Acoustics Program (EMAP) is responsible for monitoring marine mammal populations off the West Coast of the United States. The Program has been developing methods for using passive acoustics as a tool for population estimation of sperm whales, beaked whales, and porpoise. The acoustics program has been actively involved in the research and development to improve detection, localization, and classification of cetaceans using passive acoustic monitoring for other cetaceans.

Passive Acoustics Personnel:

- 1 FTE senior scientist (Barlow)
- 2 FTEs (Rankin, Keating)
- 1 research assistant (contractor)

Other than Program Director, all personnel are paid through competitive external funds/grants.

Instrumentation Available:

- 5 linear towed hydrophone arrays, 2 experimental tetrahedral arrays
- Various over-the-side and free-floating recorders for short-duration recordings
- 4 DASBRs
- 1 NRS (PMEL)

Data Management Support:

- Limited – SATA disks in office
- Small server for network access to subset of data

Primary Research Partners:

- Other Science Centers
- Bio-Waves, Inc.
- SIO
- Cascadia Research Collective
- Southall Environmental Associates
- PMEL

Primary Funding:

- LMR
- OS&T (Ocean Acoustics Program, ASTWG, Cooperative Research Program)
- BOEM
- SBIR

Acoustic Projects and Goals:

The bulk of SWFSC acoustic efforts are focused on hardware development and implementing towed-hydrophone-array data collection for combined visual/acoustic line-transect cetacean surveys. Our extensive shipboard surveys (10 years of 4- to 5-month surveys in addition to other smaller projects) have led to an extensive data archive but few remaining resources to analyze this data. Most data collection includes simultaneous visual observation (confirmation of species) and ecosystem sampling. All funding to

support the program comes through external grants/funds; we make a strong effort to identify funds that overlap with NMFS priorities. One of our greatest hurdles is addressing our great need for improvement in hardware/software/analysis with limited piecemeal funding. We have been successful in obtaining NOAA Cooperative Research Program funds to obtain moderate amounts of vessel time (fishing vessels) for hardware testing.

Ongoing projects

- California Current Cetacean Ecosystem Assessment Survey (CalCurCEAS): Combined visual/acoustic line-transect shipboard cetacean surveys off the West Coast of the United States. Towed hydrophone arrays collected recordings for detection, localization, and classification of odontocetes and minke whales. U.S. Navy surplus sonobuoys were used to obtain recordings of baleen whales. This survey was conducted from August to December 2014. Possible repeat of this survey from August to December 2015.
- Southern California Behavioral Response Survey: Use towed arrays to identify potential target species for controlled experiment exposures to study response of cetaceans to navy sonar.
- Development of volumetric towed hydrophone arrays: Research and development to date has been performed in-house or in conjunction with SIO. Future development will include collaboration with business partners funded by NOAA's SBIR (in process).
- Development of Drifting Autonomous Spar Buoy Recorders (DASBRs): Research and development of drifting buoys as an alternative means of estimating cetacean density and for measuring ocean noise.
- Development of a compound acoustic classifier for odontocetes: Incorporating whistles, echolocation clicks, and burst pulses to improve classification. We are in the final testing phase using towed array data collected during CalCurCEAS survey.
- Acoustics as a tool for stock structure in fin whales in the North Pacific.
- Passive acoustic density estimation of baleen whales: Using sonobuoys to estimate vocalization-rate correction factors. Project start date July 2015.
- Development of methods to calibrate hydrophones at the SWFSC Technology Tank.
- NRS Network in Channel Islands, CA.

Pacific Islands Fisheries Science Center Passive Acoustics

The PIFSC CRP is responsible for cetacean stock assessments in the Pacific Islands Region, including Hawaii, American Samoa, Guam, and the Northern Mariana Islands, as well as the Pacific Remote Islands and Atolls. Passive acoustics are currently being used for ship-based stock assessments in Hawaiian waters and for year-round assessments of cetacean occurrence and ambient noise from fixed platforms throughout the central and western Pacific.

Passive Acoustics Personnel:

- ¼ FTE (Oleson; other 75% of time as CRP Leader)
- 1.5 Cooperative Institute staff (Joint Institute of Marine and Atmospheric Research)
- 1.5 contract staff (externally funded)
- 1 Ph.D. student
- Field assistants for cruises as needed
- 1 new FTE anticipated in late FY2015

Instrumentation Available:

- 4 linear towed hydrophone arrays, 1 experimental tetrahedral array
- 8 HARPs (1 capable of 320 kHz acoustic sampling)
- 5 mini-HARPs

- Various over-the-side and free-floating recorders for short-duration recordings
- 1 NRS (PMEL)
- Seaglider with integrated DMON (owned by University of Hawaii, used for cooperative projects)

Data Management Support:

- Limited – SATA disks in office, backup disks with collaborators
- Metadata management database in progress (Tethys through M. Roch at SDSU)
- Long-term archiving project in progress (NGDC and NEFSC collaboration)

Primary Research Partners:

- SIO
- University of Hawaii
- SWFSC, SEFSC, PMEL
- Cascadia Research

Primary Funding:

- PIFSC, PIRO, OS&T (Ocean Acoustic Program, Advanced Sampling Technology Working Group, Bycatch Reduction Engineering Program)
- U.S. Navy Pacific Fleet

Projects and goals

The bulk of PIFSC's acoustic efforts are focused on various aspects of false killer whale assessment (detection, classification, tracking, and mitigation of fisheries interactions); long-term monitoring for cetaceans at various sites in the central and western Pacific (Hawaii, Wake, Commonwealth of the Northern Marianas, Palmyra); and development and use of towed hydrophone arrays for abundance estimation. Significant hurdles to our work include lack of robust delphinid species-classification algorithms for many species; lack of support for post-processing towed array data collected at sea; and theoretical hurdles related to estimation of group size, subgroup structure, and robust estimation of group location. PIFSC and its partners have invested heavily in the integration of the DMON into the Seaglider and are now working on testing onboard detection and classification algorithms for efficient data collection from the glider. Technical issues still plague glider deployments, including inconsistent communications between the DMON and glider infrastructure, and insufficient battery and data storage for missions longer than 1 month.

Other projects include:

- Acoustic characterization and geographic and temporal occurrence trends in Kogia and beaked whales
- Monitoring longline fisheries for evidence of false killer whale depredation and other interactions
- Ambient noise monitoring and characterization
- NRS Network in Hawaii

Northwest Fisheries Science Center Passive Acoustics

Passive acoustics research plays a prominent role within the MMSE Team's research into Southern Resident killer whales and other Puget Sound and Pacific Northwest cetaceans.

Passive Acoustics Personnel:

- 1.5 FTE (Holt, Emmons; other ½ dedicated to non-PAM projects)
- Research assistants primarily for field work, as needed
- University of Washington graduate student

Instrumentation Available:

- 2 linear hydrophone arrays
- 17 leased EARs
- Sufficient inventory of surplus sonobuoys
- 3 owned C-PODs
- 2 leased DTAGs

Data Management Support:

- Limited – hard drives in office, backups through in-house services (NWFSC IT data retention/storage) and some data sets with collaborators
- Metadata management – custom databases (limited); Tethys potentially
- Long-term archiving – either through project with NGDC and other NMFS Science Center collaborations, or NWFSC IT data retention/storage

Primary Research Partners:

- Bio-Waves, Inc.
- Cascadia Research Collective
- University of Washington
- University of California, Davis
- University of Hawaii

Primary Funding:

- NMFS Ocean Acoustics Program
- U.S. Navy
- ASTWG

Current projects

- PODS cruise
  Orcinus "species" occur in the Pacific Ocean throughout the West Coast of North America. Data concerning their precise locations and abundance are critical to understanding their population trends and movement patterns. PODS provide such data, allowing scientists and managers to better understand and manage Orcinus "species." Passive acoustic monitoring provides the means for detecting, localizing, and tracking groups of killer whales when visual observations are not possible (e.g., tracking through night/inclement weather to get photo IDs and prey/fecal/biopsy samples, satellite tag deployments when possible).

- Coastal distribution of Southern Resident killer whales (SRKWs) using PAM recorders
  SRKWs are listed as a Distinct Population Segment of killer whales under the Endangered Species Act (ESA). Their distribution varies by season according to a variety of factors. Determining the patterns of SRKW occurrence provides understanding of the factors that contribute to their seasonal distribution. Their winter distribution is an identified data gap. A series of passive acoustic recorders moored in various locations on the coasts of Washington, Oregon, and California are being used to determine the seasonal occurrence of SRKWs.

- Passive acoustic monitoring of Puget Sound harbor porpoise
  Drs. Marla Holt, Brad Hanson, and Candice Emmons of the NWFSC, along with efforts from the NWFSC dive team (coordinated by Nick Tolimieri), are currently conducting PAM of harbor porpoises in Puget Sound. The occurrence of harbor porpoises is being acoustically documented using porpoise detectors (C-PODs, made by Chelonia, Ltd), which detect and log harbor porpoise

echolocation clicks and store the data on flash memory cards. C-PODs are deployed on the sea floor by scientific divers, and must be recovered every 3 months to replace batteries and memory cards. The project, which is ongoing, will document the occurrence and habitat use of this protected species. The project is a well-defined component of a larger study that addresses harbor porpoise occurrence and habitat use in the Salish Sea.

- Using DTAGs to study acoustics and behavior of SRKWs
  Drs. Marla Holt, Brad Hanson, and Candice Emmons of the NWFSC, along with collaborators from Cascadia Research Collective, University of Washington, and UC Davis, are conducting a study using digital acoustic recording tags (DTAGs) to examine sound exposure, sound use, and behavior of SRKWs in their core summer habitat. The DTAG is temporally attached with suction cups and consists of a number of different sensors that record sound, pitch, roll, heading, and depth. Prey samples and vessel data are also concurrently collected relative to tagged whales in a manner similar to previous work (Giles and Cendak, 2010; Hanson et al., 2010). The project research goals include: (1) measure noise levels in biological-relevant frequency ranges that are received by individual SRKWs; (2) quantify the relationship between received noise levels and detailed vessel traffic variables obtained from precise geo-referenced data collected concurrently; (3) investigate whale acoustic and fine-scale movement behavior during various activities, including foraging, to understand sound use and behavior in specific biological and environmental contexts; and (4) determine potential effects of vessels and associated noise on behavior. The results of this study will provide pertinent data to address multiple risk factors of SRKWs, including vessel disturbance, noise exposure, effects on foraging, and cumulative effects.

Alaska Fisheries Science Center Passive Acoustics

The acoustic group led by Catherine Berchok and affiliate researcher, Manuel Castellote, undertakes passive acoustics research at AFSCs NMML. Berchok's acoustics team works as part of large-scale, multi-disciplinary projects, of which the primary research goals are three-fold: 1) assess the long-term, year-round seasonal occurrence and distribution of marine mammals (with a focus on baleen whales) in Alaskan waters; 2) evaluate how environmental conditions and prey abundance influence these distributions; and 3) monitor ambient noise levels in the Arctic. Castellote focuses primarily on behavioral ecology questions and the effect of anthropogenic noise on cetaceans. His primary species of focus are beluga, killer whale, porpoises, and fin whales.

Passive Acoustics Personnel:

- 2 FTEs (Berchok, Crance)
- 2 research assistants
- 2 junior analysts (all except FTE externally funded)
- 1 affiliate researcher (Castellote)

Instrumentation Available:

- Berchok Acoustic Team
  - 50 AURAL recorders
  - Sufficient inventory of surplus sonobuoys
  - Towed array
- Castellote
  - Moored recorders (owned by ADFG)
  - Leased DTAGs (WHOI)

Primary Research Partners:

- Berchok Acoustic Team:
  - PMEL
  - AFSC/Resource Assessment and Conservation Engineering Division
  - Cornell University
  - APL
- Castellote:
  - ADFG
  - APL
  - Oceanwide Science Institute (Lammers)
  - WHOI
  - Department of the Army
  - Alaska Boroughs (Yakutat, Kotzebue, North Slope)
  - Alaska Marine Ecosystem Research (Frost and Lowry)

Primary Funding:

- Berchok Acoustics Team:
  - *BOEM*
  - *OS&T*
  - *International Fund for Animal Welfare*
- Castellote:
  - *ADFG*
  - *Department of Defense*
  - *U.S. National Park Service*
  - *Alaska Boroughs*
  - *OS&T*
  - *Alaska Regional Office (NMFS)*

The most important limitation for the Berchok team is analysis time. Currently, we do not have any auto-detectors or classifiers for our Arctic species. The team has tried to incorporate auto-detectors in the past, but with no success. One team member has been working on implementing Mark Baumgartner's (WHOI) low-frequency detection and classification system on the team's Arctic dataset, with limited success. There are still too many errors (both false positives and false negatives) to consider it a viable option for anything other than fin whales. As a result, we manually analyze 100 percent of our data using a program written by Dr. Berchok (SoundChecker). It takes one analyst approximately 75 days to analyze one recorder for all species (cetaceans and pinnipeds). Problems that we have encountered by subsampling our analyses include losing contextual clues to species identification.

The second most important limitation is an inability to obtain abundance estimates from a single hydrophone. The team now has a methodology to overcome this limitation based on the MMC-sponsored workshop on density estimation led by Len Thomas and Tiago Marques of the University of St. Andrews from January 2015. By including dedicated focal follows using sonobuoys during the field season, we can collect simultaneous acoustic/visual data to obtain vocalization rates on visually detected individuals, and then apply those vocalization rates to our acoustic data.

The third problem is the large number of unknown vocalization types detected on our long-term recorders. If we are able to conduct more focal follows with concurrent visual/acoustic data, we can begin to attribute some of the unknown vocalizations to certain species, and possibly clear up some confusion regarding shared vocalization types. Additional problems include the high cost of sea time (due to vessel size requirements, the size of the survey area, and the remote location), moorings being fished up, and a lack of any significant NOAA funds, despite the Arctic being an area of concern/interest.

Dr. Castellote conducts research primarily using moored autonomous recorders deployed for the long term, although shorter deployments, with the use of acoustic tags and associated sampling (e.g., trawling, visual observations) are common in his projects. Another technique used in his research is collecting hearing sensitivity. In collaboration with Dr. Aran Mooney (WHOI), Dr. Castellote has also been investigating hearing sensitivity in wild and captive belugas.

The biggest limitations faced by Dr. Castellote are the analysis demands, inefficient automated detection tools for large datasets, and a lack of funding for long-term research programs. In addition, he would benefit from an advancement in noise analysis tools (e.g., support in developing new Matlab codes) to streamline his analyses. A general challenge for coastal studies has been the difficulty deploying and maintaining long-term acoustic moorings in typical beluga habitats—shallow, high-current areas exposed to ice interaction in winter (e.g., Cook Inlet, Kotzebue).

Appendix C Fixed Autonomous Acoustic Platforms (Prepared by Sofie Van Parijs)

General Overview

Figure 2 illustrates several fixed acoustic recorders that have been, and currently are, used by NOAA for PAM research of marine mammals. For more technical details about and in-depth specifications for these and other recorders, see a recent review by Sousa-Lima et al., 2013.

Figure 2. Fixed autonomous recorders for passive acoustic monitoring of marine mammals.

Bottom-Mounted Acoustic Recorders (BMARs)

- **Mode of operation**: BMARs are bottom-mounted recorders that collect acoustic data and archive data on internal hard drives.
- **Anchorage**: BMARs are anchored to the sea floor using various anchorage mechanisms that may have a surface expression in the form of a line and float. Systems with no surface expression are mostly retrieved by using an acoustic release system.
- **Duration**: Several months to years of continuous and/or duty-cycled acoustic recordings are possible.
- **Deployment**: Deployment has become a relatively routine process for most sensors. Depending on the system, a unit can be deployed by hand using an A-frame or crane from a wide variety of vessels. BMARs require little further investment after deployment because they can be left at sea for long periods until the time of recovery.
- **Cost**: The purchase or lease price for commercially available BMARs ranges widely from approximately $2,000 to $80,000 USD. Purchase or lease can include the anchorage and/or an acoustic release system. If you purchase a BMAR, then you need to include the technical capability and the personnel to service, refurbish, and maintain these recorders.
- **Frequency range**: Individual recorders vary widely in frequency range and capabilities, from low-frequency recorders (~10 Hz to 5 kHz) to those that completely cover the marine mammal frequency spectrum (~10 Hz to 200 kHz). The higher the frequency range required, the more data storage capacity needed, resulting in shorter deployment duration or the need to duty cycle the recorders.
- **Configuration**: BMARs are highly versatile and can be deployed as single fixed-point sensors, in lines at set distances apart or in array configurations allowing for the localization of signals. This allows for data collection of long-term seasonal presence and distribution covering large spatial scales, monitoring of migration routes, estimation of relative (and sometimes absolute) abundance of species, and trends in ocean noise.
- **Other considerations**: A wide range of options is available for shallow and deep water deployments. The cost and recording duration of BMARs is framed by the location, depth, and frequency range of the requirement. In order to meet the widely varying depth, species, and frequency requirements of each project, it is important to have a range of options to suit each goal.

Surface-Mounted Acoustic Recorders (SMARs)

- **Mode of operation**: SMARs are surface-mounted recorders that collect acoustic data and can both archive data on internal hard drives and relay data back in near real time through a VHF, mobile, or iridium connection. Several acoustic recording packages can be installed onto a SMAR (see the PAM systems options in Appendix E). In addition, an SMAR can be equipped with

a detection and classification software package so that it relays specific vocalizations/events that are of interest, or a series of detections of multiple species. Continuous data streaming is expensive and often not vital to a real-time operation.

- **Anchorage**: SMARs are anchored to the sea floor using various anchorage mechanisms but can suffer from "self noise" due to wave action on the surface buoy. EOM Offshore Pte Ltd has created an anchorage system that buffers the wave action with a stretch hose and isolates unwanted "self noise" from the recordings. These types of anchorage systems are essential but require custom building.
- **Duration**: A single deployment can yield several months to years of continuous real-time and continuous or duty-cycled archived data.
- **Deployment**: Deployment is relatively routine and can be done using an A-frame or crane from a wide variety of vessels. After deployment, SMARs require little further investment and can be left at sea with minimal maintenance for long periods until the time of recovery.
- **Cost**: The lease price for commercially available SMARs ranges from approximately $60,000 to $80,000 USD and can include the anchorage system. If a purchase is considered, then having the in-house technical capability and personnel to service, refurbish, and maintain these recorders is essential.
- **Frequency range**: Individual recorders vary in the frequency range at which they can record. The higher the frequency range required, the more data storage capacity is required, resulting in shorter deployment duration or the need to duty-cycle recordings.
- **Configuration**: SMARs can be deployed as single fixed-point sensors, in lines at set distances apart, or in arrays allowing for the localization of signals. SMARs are starting to be used for data collection similar to that described in the BMAR section (Appendix C). Additionally, they are a valuable tool for directed mitigation requirements aimed at reducing the impact of ship strike and other anthropogenic risks.
- **Other considerations**: A wide range of options is available for shallow and deeper water deployments. The cost and recording duration of SMARs is framed by the location, depth, and frequency range of the requirements. In order to meet the widely varying depth, species, and frequency requirements of each project, it is important to have a range of options to suit each goal.

Existing Hurdles

- **Leasing versus owning**: The costs of leasing and owning can vary significantly. However, leasing is advantageous in that it does not require in-house qualified personnel to service, refurbish, and maintain the equipment. In addition, leasing prices tend to include the anchorage and acoustic release system. When purchasing, all of these requirements—personnel time, refurbishment materials (batteries, hard drives, etc.), costs of a new anchorage and acoustic

release system required at each new deployment—need to be included in the running costs. Of course, at the end of a lease, you no longer have in-house passive acoustic recording capacity.

- **Dedicated vessel time**: NOAA usually conducts stock assessment surveys for marine mammals in blocks of time during one particular season. However, the deployment and retrieval of passive acoustic sensors at sea requires vessel availability for short periods to deploy, service, and recover/swap recorders. The current process for requesting NOAA vessel time does not lend itself to passive acoustic data collection and needs to be adjusted to incorporate these requirements.
- **Data processing and analysis**: A large suite of software exists for processing and analyzing archival acoustic data for detection, classification, and localization of signals. However, improvements are still needed in terms of specific species detections and classifications. Additionally, using localization software is time consuming and could be improved to meet requirements, such as the tracking of multiple species and extracting information for the purposes of density estimation. Only a few software options exist for real-time relaying of specific acoustic signals back to shore (e.g., Spaulding et al., 2009; Baumgartner et al., 2013).

Uses of Bottom- and Surface-Mounted Acoustic Recorder Data

- **Description of species- and population-specific vocalization**: As described in the towed array section (Appendix D): "Species-specific vocalization characterization is not, by itself, an important component of stock assessment. However, it is a necessary precursor to any other use of acoustics for stock assessment." Recordings from arrays of BMARs can provide information on new species vocalization types by overlaying tracks of known species vocalizations with unknown vocalization types to demonstrate their co-occurrence (such as the recent description of several new sei whale vocalizations, Tremblay et al., 2015). Additionally, both opportunistic and planned visual surveys conducted concurrently with BMAR and SMAR deployments are proving fruitful in their ability to identify species vocalizations, evaluate species behavior, and improve our understanding of visual and acoustic biases.
- **Stock delineation and distribution**: Currently, recordings collected using BMARs and SMARs provide large-scale information (e.g., along an entire coast line) on long-term (e.g., decadal) occurrence and distribution, as well as the delineation of migration corridors of key species (still poorly understood for nearly all western Atlantic baleen whale species, for example). These data provide the timely assessment of changes in population distribution and improve stock delineation. SMARs are currently providing highly valuable real-time information on shifts in species habitat usage. An example of this are the rapid changes noted in large whale distributions in the northeast U.S. SMARs in this case provide critical information on the whales' habitat changes as well as help direct photo-ID surveys to assess population abundance and individual health status. We foresee that the combination of BMARs and SMARs will enable an improved and responsive understanding of changes in species distribution, given the rapid changes in species movements that are observed in the western Atlantic.

Further use of these large spatial-scale data will help further delineate stocks using similar methods as those being used with towed arrays in the Pacific Ocean. Acoustic identification of species such as Risso's dolphins and pilot whales, improved identification of sei whales, and breeding ground delineation of humpback whales are just some of the possible applications that require further study during subsequent years in the western Atlantic.

Abundance Estimation

- **Absolute abundance**: As mentioned in Appendix D, "[t]he use of passive acoustics to estimate absolute abundance (number of animals within a defined study area) has and continues to be a great challenge." Arrays of BMARs are currently deployed to evaluate the feasibility of using these techniques for large whales, especially North Atlantic right whales. However, these techniques require realistic data on animal vocalization rates. Obtaining this information remains a challenge to the implementation of this methodology for non-odontocete species.
- **Relative density**: BMARs and SMARs can be used readily to estimate relative density of vocalizing animals. The integration of this information with the extensive large-scale visual data that is collected has the potential to provide valuable insights for the stock assessment of species such as large whales.

Limitations and Impediments in Stock Assessment

BMARs and SMARs can detect the full range of species effectively; however, logistical and financial decisions are often made that restrict the data collection to low-, mid-, or high-frequency species. BMARs have been used extensively to detect the occurrence and distribution of many species on an ocean-basin-wide scale. They can therefore provide detailed information on species presence, their relative abundance, and the timing of their movements, but cannot provide information on absolute abundance. Currently, BMARs/SMARs cannot provide information on individuals or health status in a population. However, SMARs and AUVs can direct and optimize time spent collecting visual data on specific endangered species where this information is of essence.

As is true for towed arrays, "Species classification in this case for all cetaceans has seen rapid improvement in recent years; however, significant hurdles remain in acoustic species classification (Appendix D)."

Localization using BMARs/SMARs can be very informative and useful in improving the understanding of vocalization types and behavior for a given species. However, it remains a very time-consuming and laborious undertaking.

Future efforts will focus on continuing to expand the use of fixed platforms to: a) monitor changes in marine mammal populations during long periods and spatial scales; b) estimate population densities; c) integrate acoustic information from long-time series across large spatial scales with available visual and other ecological data; and d) reduce the risk of human impacts.

Other Considerations

Fixed bottom-mounted recorders are widely used by many NMFS Science Centers for data collection. However, these groups do not have sufficient financial and personnel resources to maintain an active program. Funding currently comes from external sources or from sporadic and unpredictable internal funds. Due to the varying needs for both BMARs and SMARs among regions, the primary way to integrate this technology into NOAA's current technology would be to provide a set line item funding directed at acoustic equipment. This approach would allow the lease or purchase of the BMAR, SMAR, or other technology that is most appropriate for the regional goal and species.

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Appendix D Uses of Towed Hydrophone Arrays for Cetacean Stock Assessment (Prepared by Jay Barlow and Shannon Rankin)

Introduction

Towed hydrophones have been used to collect data for cetacean stock assessment (Appendix G) for more than a decade. Arrays of towed hydrophones are often added to visual line-transect surveys of cetaceans to extend the range of detection, to extend surveys into nighttime hours, and to detect submerged animals that might be missed by visual survey methods. For some species (e.g., sperm whales and harbor porpoises), towed arrays can be the primary survey method. In general, towed hydrophones are best for species whose sounds are above 1 kHz because flow noise and ship noise mask low-frequency sounds in most situations. Although very low frequency baleen whale calls can be detected at very low tow speeds (Clark and Fristrup, 1997), this is not practical in most applications. For this reason, towed arrays are most useful for detecting odontocetes and minke whales.

In this report, we briefly review the hardware and software systems that typically are used with towed hydrophone surveys, and discuss the primary uses of the resulting acoustic data in stock assessments. We also summarize the limitations of towed hydrophone arrays and discuss the practical impediments to increasing their contributions in cetacean stock assessment.

Hardware and Software Used

Towed hydrophone arrays

Towed hydrophone arrays are usually constructed using a series of two or more hydrophones distributed linearly along a cable. The hydrophone elements are encapsulated in polyurethane nodes (Barlow et al., 2008) or contained within an oil-filled tube (Rankin et al., 2013a). The hydrophones within a single array are typically close enough (30 to 300 cm separation) to receive the same coherent signal and to estimate a conical bearing angle to that signal using time-difference-of-arrival (TDOA) methods. The convergence of several bearing angles over time are needed to identify the location of the sound source (with a left-right ambiguity). These localization methods are successful for single animals or tight schools that are close to the surface and moving slowly relative to the vessel speed (Rankin et al., 2008). However, these methods break down for groups that are large and spread out, swimming fast (greater than ~half the survey speed), or when there are multiple distinct groups with overlapping vocalizations. Likewise, the time required to obtain a location using these methods potentially violates a key requirement for line-transect surveys: that the location of the initial detection occurs before the animals have responded to the vessel.

Improved localization performance can be attained using more complicated array configurations, such as multiple in-line arrays, dual towed hydrophone arrays, spatial arrays, towed vector sensors, and long arrays with many elements (Norris et al., 2007; Hanson et al., 2010; Thode et al., 2010; Rankin et al., 2013a, 2013b; Zimmer, 2013; Tran et al., 2014). Current spatial array configurations are limited to tow speeds below that required for shipboard line-transect surveys of most cetacean species; however, we expect that design modifications will rectify these issues within a few years.

Hydrophones are usually towed 200 to 300 meters behind a research ship (to decrease radiated ship noise and cavitation bubbles) using a multi-conductor cable with an internal strength member made of Kevlar or similar material. The tow cable provides power to the hydrophone pre-amps and any other sensors within the array (e.g., depth or directional sensors) and carries signals from the hydrophones to the ship. Shorter tow cables (approximately 100 m) can be used on smaller or quieter research ships. A modular design with underwater connectors can allow substitution of different hydrophone arrays with a single tow cable. State-of-the-art components such as digital hydrophones, vector sensors, and fiber optics cable could vastly improve the quality of the data collected (and therefore expand the possible uses of the data). However, to date these technologies have exceeded the financial resources available to NMFS.

The tow cable can be weighted using a spiral of lead wire to increase the tow depth. Shorter (less than 200 m) and smaller diameter (less than 13 mm) tow cables can be deployed by hand and stacked on the deck, but the deployment of longer and thicker cables is greatly facilitated by use of a winch. When a winch is used, a waterproof connector is needed to disconnect a "deck cable" from the tow cable when the winch is turning.

Signal conditioning, array power, and noise considerations

Flow noise, ship noise, and electronic noise are significant concerns for towed hydrophone arrays. To reduce their effects, amplification and filtering are typically applied within the hydrophone array. Pre-amps amplify the signals by boosting them and thereby making them less susceptible to electronic noise after they reach the ship. Recent testing by the SWFSC showed that a two-stage amplification design, which provides differential output and gains up to 60 dB, improved signal quality by reducing susceptibility to radiated electronic noise and cross-talk between different hydrophone signals. A high-pass filter (approximately 1 to 2 kHz) is typically built into the hydrophone pre-amp to prevent low-frequency flow noise from clipping the signal and to allow passage of higher frequency signals. Because ship power frequently introduces noise, an independent 12 V battery bank typically powers all components of the array.

On the ship, signals are converted from analog to digital signals for real-time processing and storage. In some cases, additional signal-processing hardware receives the hydrophone signals and provides additional amplification and filtering. High-quality commercial audio digitizers can

provide additional analog amplification and digital conversion at rates of 192 k samples per second on four or more channels. For very high-frequency signals, scientific analog-to-digital converters can digitize four or more signals at greater than 500 k samples per second.

Software and recording

Recent developments in computer hardware and software allow for full bandwidth recording of multiple channels for relatively low cost. There are a large number of software programs available for stereo audio recordings. These can run on off-the-shelf digital signal processing devices that can provide high-quality recording up to 96 or 192 kHz sampling rates for up to two channels (varies by device). Recording a larger number of channels at higher sampling rates requires software that can interface with the scientific analog-to-digital converters (of which there are several options). Specialized software programs allow for real-time detection, classification, and localization of some sounds, as well as integration of this information with recordings, streaming GPS input, and other metadata. A trained field technician facilitates real-time detection and tracking. However, rapid improvements in all aspects of software development will enhance automation in both real-time and post-processing of data collected using towed hydrophone arrays.

Species- and Population-Specific Vocalization Description

Towed hydrophone arrays have been used to document the sounds made by different cetacean species and to determine whether sound types differ among populations. Species-specific vocalization characterization is not, by itself, an important component of stock assessment. However, it is a necessary precursor to any other use of acoustics for stock assessment. Recordings from towed hydrophones have been the primary source of information for building many vocalization-classification algorithms (Oswald, 2006; Oswald et al., 2007b).

The combination of expert visual observers and towed hydrophone arrays on line-transect surveys has been especially helpful in documenting vocalization characteristics. Hydrophone arrays provide directional information that is critically important in determining that a sound is coming from a specific identified individual or group. Species for which towed hydrophone arrays have contributed significantly to vocalization characterization include: minke whales (Rankin and Barlow, 2005); false killer whales (Oswald, 2006); Fraser's dolphins (Oswald et al., 2007a); striped dolphins (Papale et al., 2013); northern right whale dolphins (Rankin et al., 2007); Sowerby's beaked whale (Cholewiak et al., 2013); Longman's beaked whale (Rankin et al., 2012); Baird's beaked whale (Baumann-Pickering et al., 2013); and rough-toothed dolphins (Rankin et al., 2015). The vocalization types of many cetacean species still have not been documented, and we anticipate that towed hydrophone arrays will play a significant role in filling these knowledge gaps.

Stock Delineation and Distribution

Recordings collected using towed hydrophone arrays can contribute to stock delineation and distribution for those species that can be reliably detected using a towed array (odontocetes and minke whales). Given that shipboard surveys that use towed arrays typically have experienced marine mammal observers on board, towed arrays may be most useful for providing distribution information for cryptic species (such as minke whales) or during nighttime and poor weather conditions.

Identification of the minke whale "boing" using towed hydrophone arrays also provided information of geographic variation in vocalization structure that may indicate different stocks in the North Pacific Ocean (Rankin and Barlow, 2005). Acoustic identification of stocks has been suggested for Risso's dolphins and Pacific white-sided dolphins (Soldevilla et al., 2008). However, application of this for towed hydrophone arrays (or other hardware methods) requires further research and testing.

Abundance Estimation

Absolute abundance

The use of passive acoustics to estimate absolute abundance (number of animals within a defined study area) has been a great challenge. This activity requires not only the random or systematic coverage of a study area, but also requires range estimation, accurate species identification, group size estimates (for group-based estimation methods), cue production rates (for cue-based estimation methods), and the fraction of animals on the trackline that are missed (for group- and individual-based estimation methods).

Using group-based estimation methods, towed hydrophone arrays have been used to estimate sperm whale abundance in the eastern tropical Pacific (Barlow and Taylor 2005); however, that study relied on group sizes estimated from the visual sighting survey conducted on the same ship. Group size was estimated acoustically in abundance estimates of sperm whales in the Ionian Sea (Lewis et al., 2007). Sperm whales are ideal for acoustic density estimation because they make sounds (echolocation clicks) that are readily identifiable, frequently produced (typically 1 to 2 per second for 80 percent of the day), and propagate long distances. Bearing angles are accurately estimated for these types of impulsive signals, which allows distance from the transect line to be estimated (Barlow and Taylor, 2005). Because echolocation clicks are produced in regular sequences, different bearing angles can often be estimated for multiple individuals, allowing use of individual-based abundance estimation methods (Gillespie and Leaper, 1996), although these methods may not work when group sizes exceed 5 to 10 individuals.

Cue-based methods hold some potential for estimating absolute abundance for sperm whales, beaked whales, and other species that produce very regular echolocation clicks. Click rates and

silent times have been relatively well quantified for these species. To date, however, these methods have not been applied to estimate abundance from towed array data.

Relative density

Using towed hydrophones to estimate relative density can be easier than estimating absolute abundance. Gordon et al. (2000) used acoustic detections as a measure of relative density for striped dolphins in the Ligurian Sea. Gerrodette et al. (2010) used data from a towed hydrophone to estimate relative density for vaquita and thereby extrapolate vaquita density to areas that could not be covered by the visual sighting survey (which was used to estimate absolute abundance). Fleming et al. (2013), Leaper and Gordon (2015), and Yack (2013) use acoustic detections from towed arrays to create habitat-based models of relative density for Dall's porpoise, harbor porpoise, and beaked whales, respectively.

Estimation of fraction missed by visual observers

Cetacean line-transect surveys typically employ visual observers to detect animals when they are at the surface. To estimate density or abundance, corrections are needed to account for cetaceans that never surface within the range of visual observers or are otherwise not seen. One method to estimate the fraction missed is to use one or more independent visual observers recording sightings that were missed previously by the primary team. However, this approach cannot account for animals that never surface within visual range. Acoustic methods can detect submerged animals and thereby provide a more complete accounting of animals missed by visual observers. This approach has been used for false killer whales (Barlow and Rankin, 2007); rough-toothed dolphins (Rankin et al., 2009); and harbor porpoises (Gordon et al., 2011). If visual and acoustic methods are independent, this dual-platform approach can estimate both the fraction missed visually and the fraction missed acoustically (Leaper and Gordon, 2015).

Limitations and Impediments to the Wider Use of Towed Arrays in Stock Assessment

Towed hydrophone arrays are particularly effective for detecting odontocetes but have limited ability to detect mysticetes (except minke whales). Species classification for many odontocetes has seen rapid improvement in recent years; however, significant hurdles remain in acoustic species classification for many delphinids.

Localization has typically relied on the convergence of vocalizations from a group based on differences in arrival time. The best location using these methods is obtained after the group has passed the beam (90^{o}) of the ship. If animals react to the vessel by moving toward or away from the transect line, acoustic localizations using towed arrays are likely to occur after this reactive movement, a factor that may bias line-transect density estimates. With the exception of porpoise, group size estimation of cetaceans using towed hydrophone arrays has made very little progress. Acoustic behavior is variable based on a large number of factors—one of which

is group size. Disentangling these variables presents one of the hurdles to estimating group size based on acoustic detections. There is a spatial and temporal disconnection between visual sightings ahead of the ship and acoustic detections, which are typically behind the ship. For some species, it can be very difficult to match visual and acoustic detections due to the time delay. This is especially true for species for which the acoustic detection range is extremely short (porpoise and beaked whales). This is an impediment to the use of combined visual and acoustic surveys to estimate the fraction missed by both methods.

Towed arrays perform best when the ship maintains a constant course and speed. Inopportune changes in course or speed can negatively affect localization and recording quality by increasing the noise. Also, changes in course and speed make it extremely difficult to effectively use towed array data as an independent "observer" to estimate the fraction of animals missed by the visual observation team.

Collection of data from towed arrays requires trained field personnel and extended periods. It is difficult to train and retain field personnel. Ideally, NMFS Science Centers could have a trained pool of experienced acoustic field technicians. This approach would improve the quality of data collection and continuity between surveys.

Effective analysis of towed array data requires additional software improvements to improve post-processing of acoustic data. Currently, PAMGUARD provides good visualization, data processing, and analysis for echolocation clicks. Expansion of these modules to include detection and analysis of other vocalization types would vastly improve post-processing of towed array data. In addition, improved synchronization of data from different vocalization types with each other and with data obtained from a visual observation platform would improve matching of acoustic and visual detections.

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Appendix E Mobile Autonomous Platforms (Prepared by Holger Klinck and Jay Barlow)

General Overview

This appendix focuses on buoyancy-driven, autonomous underwater vehicles (AUVs), wind/wave-powered unmanned surface vehicles (USVs), and free-drifting buoy recorders. Vehicles featuring electric or combustion engines are outside the scope of this white paper. Figure 3 illustrates several AUVs and USVs that have been used for passive acoustic monitoring (PAM) of marine mammals.

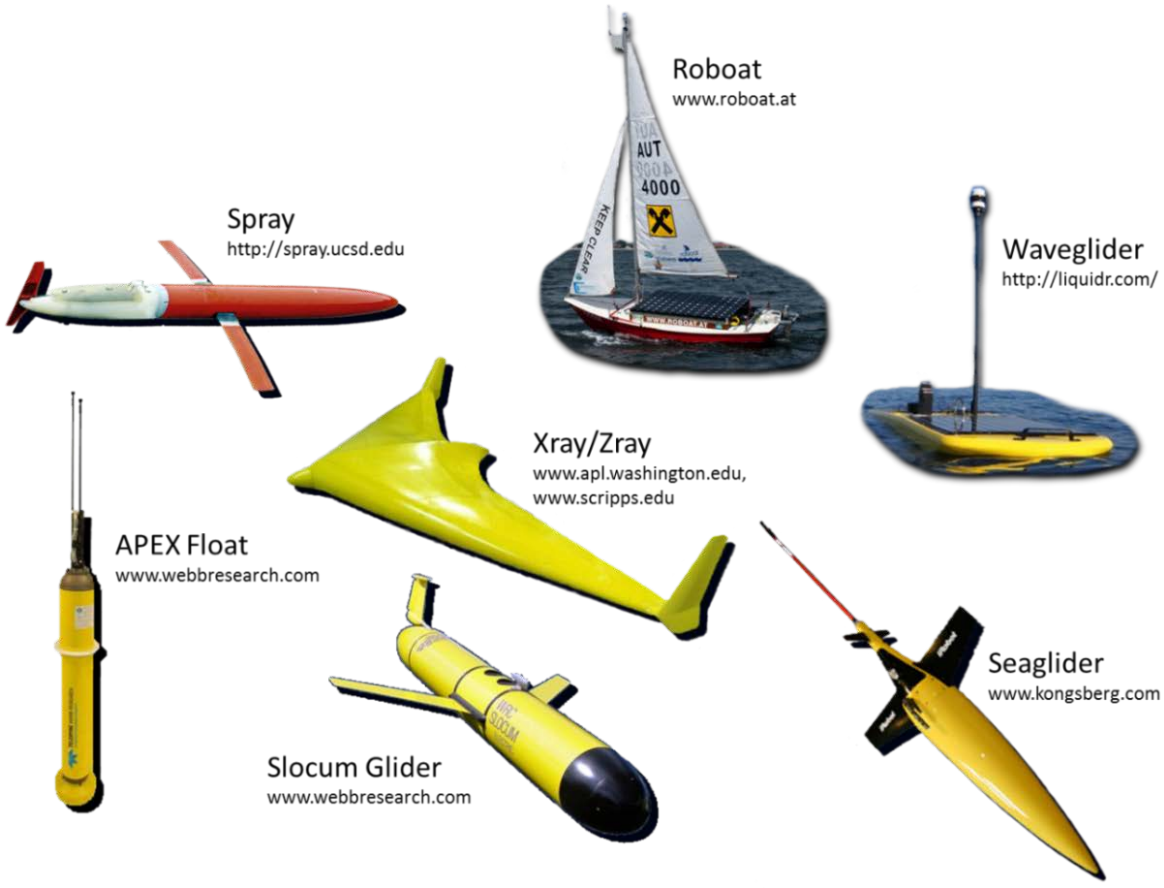

Figure 3. Autonomous mobile platforms for passive-acoustic monitoring of marine mammals.

Autonomous Underwater Vehicles

- *Mode of operation*: Buoyancy-driven AUVs, such as gliders and floats, use changes in volume (usually generated by pumping oil back and forth between a reservoir and an external bladder) to create positive and negative buoyancy. Although floats can control only the depth at which they drift with the current, gliders utilize wings to generate forward velocity as well as vertical motion. Additional internal control and navigation mechanisms to change pitch (e.g., by changing the center of gravity) and heading (e.g., by using a rudder) allow a glider to fly in a saw-tooth pattern from waypoint to waypoint. When the glider reaches the surface between dives, a bidirectional satellite link allows remote communication with the device.
- *Speed/Depth*: Gliders are slow-moving vehicles. Average speed is approximately 0.5 knots. Floats drift at the speed of the current. The maximum operating depth of the available gliders/floats varies from a few hundred meters to 2 km.
- *Duration (including PAM)*: Several weeks to a few months.
- *Cost:* The purchase price for commercially available floats (without a PAM system) ranges from $15,000 to $20,000; gliders cost approximately $100,000 to $150,000.
- *Other considerations*: The internal glider control and navigation mechanisms can hinder acoustic observations (e.g., saturating the PAM system). In the case of the Seaglider, the related acoustic data loss during a typical 1,000 m dive is approximately 5 to 10 percent. In addition, some gliders are and some are not well suited for operation in areas with strong ocean currents.

Unmanned Surface Vehicles

- *Mode of operation*: Wind/wave-powered USVs have not been used extensively for passive acoustic monitoring of marine mammals. Wind-powered USVs (a.k.a. robotic sailboats) such as the Roboat and Saildrone are prototype vehicles and not commercially available at this point. The wave-powered Wave Glider is composed of two components: a surface float that is roughly the size and shape of a surfboard and a subsurface unit that is equipped with wings. The surface and subsurface units are connected by a 7 m umbilical tether. A rising wave lifts the float, causing the tethered subsurface unit to rise. The articulated wings on the subsurface unit are pressed down, and the upward motion of the subsurface unit becomes an up-and-forward motion, in turn pulling the float forward and off the wave. This causes the subsurface unit to drop, the wings pivot up, and the subsurface unit moves down-and-forward.
- *Speed*: Wind-powered USVs can reach speeds of several knots (depending on the size of the boat and sails). The Wave Glider SV3 reaches speeds up to 2.5 knots.
- *Duration (including PAM)*: In principal, months to years.
- *Cost*: The purchase price (for academic institutions) for the Wave Glider SV3 (without the PAM system) is approximately $250,000. Wind-powered USVs are not commercially available at this time.

- *Other considerations*: Compared with AUVs, USVs provide an increased payload capacity (e.g., for additional environmental sensors), the capability of harnessing solar power to extend the survey duration, real-time data access, and increased speed. However, increased speed can hinder the detection of low-frequency vocalizations because of increased flow noise. This is especially an issue for the fast-moving, wind-powered USVs. The Wave Glider, too, has been reported to make the detection of low-frequency vocalizations challenging due to noise caused by the subsurface unit. USVs are generally not well-suited for towing long hydrophone cables because the cables reduce their maneuverability and speed (drag). Consequently, the acoustic sensors are restricted to the upper water column. Depending on local sound-propagation conditions, this can reduce the detection range for marine mammal vocalizations.

Free-Drifting Passive Acoustic Monitoring Systems

- *Mode of operation*: Free-drifting PAM systems are designed to drift with surface currents or the wind. The recorder can be packaged within a surface float with wired connections to subsurface hydrophones, or autonomous hydrophones can be attached to a rope line below a surface float. Recorders must be recovered to retrieve full data files, but processors within a surface float can send summary information via satellite or cell phones. Retrieval can be facilitated with satellite locators and VHF beacons.
- *Speed*: Drift rates depend on ocean currents but are typically 0.2 to 0.5 knots. Drifts cannot be controlled directly, but can be influenced by using windage or subsurface drogues at different depths to take advantage of predominant wind and current directions.
- *Duration (including PAM*): Several months.
- *Cost*: Costs for a simple 2-element vertical hydrophone array, 100 m of conducting cable, and a surface recording package with GPS synchronization is approximately $4,000 to $5,000 excluding labor. Complete systems may be commercially available soon.
- *Other considerations*: Vertical hydrophone arrays are easy to incorporate in drifting systems, and these can be used to help approximate detection ranges for cetacean density estimation. Vertical hydrophone arrays at 100 m have been found to detect surface reflections of beaked whale echolocation signals that can be used to improve range estimation. The effect of surface waves on hydrophone noise can be mitigated by using elastic cords and dampener disks, thus allowing free-drifting systems to record ambient sound levels with little self-noise. Being at the surface allows the use of GPS signals to precisely synchronize clocks in multiple units and allow localization by time difference of arrival (TDOA). Payload is limited only by the size of the surface buoy. Long-duration deployments may be able to utilize solar or wave energy for power.

Passive Acoustic Monitoring Systems

There are many different PAM systems available for use with mobile autonomous platforms. For AUVs and USVs, systems fall into two general categories:

- Integrated PAM systems are fully incorporated into the platform of choice. Most of these systems utilize the main vehicle battery for power. Integrated PAM systems feature real-time detection and reporting capabilities and can be controlled remotely throughout a mission.
- Piggyback PAM systems (mostly recording only) are completely independent systems (including a battery) that utilize the AUV/USV as a carrier with no communication between the PAM system and the AUV/USV or a shore station.

Each system has advantages and disadvantages. For short-duration surveys (1 to 2 weeks) without real-time detection requirements, piggybacked PAM systems work well. One advantage of these systems is that they do not share any electronic connections with the AUV/USV, reducing the risk of potential electronic noise issues. For repeated long-duration surveys, a full integration of the PAM system into the AUV/USV is preferable. Fully integrated PAM systems allow for remote and flexible programming (turn off passive acoustic monitoring during transits; record only every other dive, etc.); utilization of the AUV/USV main vehicle battery (extended operation); and GPS time synchronization (e.g., accurate time stamping of files). Free-floating PAM systems are currently independent systems that may include their own processing and communication system.

The recommended vehicle-PAM combination largely depends on four factors: 1) the species of interest (e.g., low- vs. high-frequency vocalizations, shallow vs. deep diver); 2) the environmental conditions in the study area (e.g., shallow vs. deep water, weak vs. strong current); 3) your research question; and 4) your budget.

Developers/users

Following is a list of individuals who have been involved in passive acoustic monitoring of marine mammals using mobile autonomous platforms (in no specific order):

- Erin Oleson (NOAA/PIFSC), Bruce Howe and Lora Van Uffelen (University of Hawaii)
  Platform: Seaglider
  PAM: DMON
  Status: Active

- Martin Siderius, Lisa Zurk, and Elizabeth Kuesel (Portland State University)
  Platform: Slocum Glider
  PAM: DMON
  Status: Active

- David Mellinger (OSU, PMEL), Haru Matsumoto (OSU, PMEL), Holger Klinck (Cornell University), OSU, PMEL), Jim Luby (University of Washington)
  Platforms: Seaglider, Slocum Glider, APEX autonomous profiling float, Roboat
  PAM: Various proprietary systems, Songmeter SM2+
  Status: Active
- John Hildebrand, Sean Wiggins and Gerald D'SPain (SIO), Marie Roch (SDSU)
  Platforms: Wave Glider, ZRay Glider
  PAM: Various proprietary systems
  Status: Unknown
- Aaron Thode (SIO)
  Platforms: Spray Gilder
  PAM: Acousonde
  Status: Unknown
- Harold Cheyne (Cornell University)
  Platform: Wave Glider
  PAM: Proprietary system
  Status: Not active
- Mark Baumgartner and David Fratantoni (WHOI)
  Platform: Slocum Glider, APEX autonomous profiling float, Wave Glider
  PAM: DMON
  Status: Active
- Phil Abbot (Ocean Acoustical Services and Instrumentation Systems)
  Platform: Slocum Glider, Remus AUV
  PAM: Proprietary systems
  Status: Active
- Doug Nowacek (Duke University)
  Platform: Seaglider
  PAM: DMON
  Status: Not active
- David Mann (Loggerhead Instruments)
  Platform: Slocum Glider
  PAM: Proprietary system
  Status: Not active
- Doug Gillespie and Mark Johnson (University of St. Andrews)
  Platform: Seaglider, Slocum Glider, Wave Glider
  PAM: Proprietary systems
  Status: Active

- Alberto Dassatti and Walter Zimmer (NATO Undersea Research Centre)
  Platform: Slocum Glider, Spray Glider
  PAM: Proprietary system (PAMBuoy, Decimus)
  Status: Unknown
- Jay Barlow (NOAA/SWFSC)
  Platform: DASBR free-drifting buoy recorder (custom)
  PAM: Wildlife Acoustics SM2BAT+ w/GPS
  Status: Active

The most active groups in the U.S. are currently WHOI (Baumgartner); OSU/APL/PMEL (Mellinger, Matsumoto, Klinck, and Luby); and SWFSC (Barlow). Although WHOI's efforts focus primarily on mysticetes in coastal waters using the Slocum glider, OSU/APL targets mostly odontocetes in offshore waters using the Seaglider and APEX float. The SWFSC targets beaked whale and sperm whale density estimation with free-drifting systems.

Existing hurdles

- Initial cost: The initial costs to buy mobile autonomous platforms are high. Most models cost more than $100,000 (without PAM) and often require an additional investment in training (piloting, maintenance, etc.) and infrastructure (base station, Iridium contracts, etc.). Costs are considerably less for free-drifting systems. Kongsberg Inc. now offers an acoustics package (originally developed by OSU and EOS, Inc.) as an option when buying a Seaglider. This is currently—to our knowledge—the only available off-the-shelf AUV featuring a PAM system.
- Deployment duration: The duration of most AUVs is limited to a few weeks (4 to 8 weeks when recording continuously). USVs can, in principal, operate for months. However, such long-duration PAM surveys have not been conducted yet. Free-drifting systems have been deployed for months.
- Liability: USVs are potential navigational hazards and can cause liability issues when operated in areas with high recreational and commercial shipping activity (collisions).
- Data analysis: The acoustic data recorded with mobile autonomous platforms often contains electronic and mechanical noise that is caused by the vehicle itself. Noise sources include the buoyancy pump, rotating battery packs, rudder movements, etc. Therefore, the data analysis with automated detectors and classifiers can be challenging (false positives). Free-drifting systems can record with very low levels of self-noise, and standard software (e.g., PamGuard) has been used to analyze their WAV files.
- Density estimation: A statistical framework for estimating marine mammal densities using data collected with (slow moving) mobile autonomous platforms has not been developed yet. However, the ONR recently funded (FY2015 funding cycle) such an effort lead by Danielle Harris, University of St. Andrews. This project is intended to be completed by 2017.
- Slow development: The number of users is still very limited, and we just started to use AUVs regularly for long-duration (longer than 1 month) surveys. The lessons learned from these survey efforts are critical for improving the systems (reliability, data quality, etc.). However,

because the deployments are sparse, the "maturing process" takes a long time. Funding is, of course, also a limiting factor.

Future directions

There is no doubt that mobile autonomous platforms will play a major role in future marine mammal monitoring efforts, especially considering the reduced availability and high cost of ship time for traditional marine mammal surveys and the deployment of stationary recorders.

Future efforts will focus on using mobile autonomous platforms to: 1) monitor marine mammal populations in remote and inaccessible areas; 2) estimate population densities; and 3) conduct holistic ecosystem studies by utilizing additional biological and chemical oceanographic sensor packages.

Other considerations

It is obvious that most groups interested in collecting data with these instruments do not have the proper financial and personnel resources to establish and maintain an AUV/USV program. As indicated earlier, several AUV/USV efforts are currently not active likely because of the lack of funding.

This lack of funding raises the question of how to make this technology available to the broader community. One solution could be the establishment of a few centers, which provide AUVs/USVs as a service. External (project) funding would help these centers to maintain the personnel and infrastructure necessary to operate and maintain the vehicles. This funding would also ensure a certain degree of uniformity of data products across the surveys, which would be extremely useful when pooling multiple surveys data sets for large-scale studies.

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Appendix F Absolute Density and Abundance Estimation from Passive Acoustic Data (Prepared by Danielle Harris, Tiago Marques, and Len Thomas)

General Overview

The aim of this document is to provide a broad overview of the topic of animal density and abundance estimation using passive acoustic data, examples of applications, and a summary of associated challenges. We encourage readers to refer to a comprehensive review paper (Marques et al., 2013) for more detail on the information presented here, as well as the cited literature. We also note that while the focus of this white paper will be on marine mammal studies, passive acoustic density/abundance estimation is applicable to a wide range of both aquatic and terrestrial taxa (see Marques et al., 2013, and Stevenson et al., 2015, for more details and references).

Traditionally, marine mammal density and abundance estimates have been derived from ship-based visual sightings surveys. However, the potential to use acoustic data to estimate marine mammal absolute density or abundance has been recognized for several years (e.g., McDonald and Fox, 1999). During the last decade or so, research efforts into the topic of density/abundance estimation from passive acoustic data has grown. Both fixed passive-acoustic instruments and ship-towed instruments have been used for marine mammal studies (e.g., fixed: Marques et al., 2009; towed: Barlow and Taylor, 2005). More recently, density/abundance estimation from mobile autonomous platforms has become an active research topic.

Absolute density and abundance estimators

Visual or acoustic encounters of animals are sometimes presented as relative indices of density or abundance. However, in order to interpret spatial and temporal patterns in such indices as changes in the underlying density or abundance of the study species, it must be assumed that the same proportion of animals are always detected across all surveyed sites and time periods. There are often many reasons such an assumption would be violated, leading to the need for absolute density and abundance methods. A fundamental concept of absolute density or abundance estimation is that animals missed in a surveyed area must be accounted for. This task is accomplished by estimating the probability of detecting an animal during the survey.

A typical density estimator, which estimates absolute density from animals observed during a survey, is as follows:

$$\widehat{D} = \frac{n}{\hat{p}a} \qquad \text{(Eqn. 1)}$$

where $\widehat{D}$ is the estimated density, n is the number of observations made during the survey, $\hat{p}$ is the estimated average probability of detecting an animal, and a is the total surveyed area.

If the survey has been designed so that the surveyed area represents the whole study area, *A*, then absolute abundance, $\widehat{N}$, can be estimated as:

$$\widehat{N} = \widehat{D} \times A \qquad \text{(Eqn. 2)}$$

In passive acoustic monitoring, individual animals often cannot be easily counted. However, acoustic "objects," such as individual vocalizations or vocally active groups, can. Furthermore, automated routines, which can generate false detections, are often used in acoustic data processing. Therefore, density estimators linked to acoustics are often based on the following:

$$\widehat{D} = \frac{n(1-\hat{f})}{\hat{p}a\hat{r}} \qquad \text{(Eqn. 3)}$$

where *n* is now the number of observed objects, *f* is the proportion of false detections generated by the detection routine, and *r* represents the appropriate multiplier(s) that will convert the object density to animal density. For example, if individual vocalizations are counted, the required multipliers will include the average vocalization rate and the amount of time spent monitoring (in addition to the probability of detection, which is also a multiplier).

Methods to estimate animal density and abundance

Although an entire population can rarely be censused, it may be possible to detect all animals within monitored lines or points. These survey types are known as strip-transect sampling (using lines) or plot sampling (using points). Given an appropriate survey design (i.e., a sufficient number of survey lines or points have been randomly placed with respect to the underlying distribution of animals), then the density in the lines or points can be used as a representative estimate for the rest of the study area.

Strip-transect or plot sampling are examples of design-based surveys, where the surveyed areas can be assumed to be a random sample of all the possible survey lines or points. Resulting density estimates are applicable to the wider study area. Conversely, if a standard survey design has not been followed, then inference about density and abundance in the wider study area is made using a statistical model. The model links density or abundance to covariates, which can be used to predict numbers of animals in the unsurveyed regions of the study area.

In cases where animals are missed within surveyed areas, several methods can be used to estimate the probability of detection. These include traditional, commonly used methods, such as distance sampling and mark-recapture (Buckland et al., 2001; Borchers et al., 2002). Distance sampling can be conducted from surveyed lines (line-transect sampling) or points (point-transect sampling). An extension of mark-recapture is spatially explicit capture-recapture (SECR), which is also related to distance sampling (Borchers, 2012; Borchers et al., 2015). The advantage of SECR over mark-recapture is that density, as well as abundance, is easily inferred. In mark-recapture methods, it is difficult to estimate the size of the surveyed area, making it possible to estimate abundance; however, density estimation becomes non-trivial. Other "non-standard" methods to estimate detection probability also exist that often rely on auxiliary information (e.g., Marques et al., 2009). Many of the non-standard methods were developed specifically for use with passive acoustic data; some examples are given later in this section.

Each method requires different information to be recorded about the observations. Distance sampling requires horizontal ranges to each detection be estimated. Spatially explicit capture-recapture (originally developed for trapping small terrestrial mammals) requires detections to be identifiable across "traps" and knowing the location of the "traps." In passive acoustic surveys, this means that the same acoustic event must be identifiable across multiple instruments in an array (where the location of the instruments is known). Non-standard methods generally require less information about the detections, but rely on more assumptions and modeling to compensate for the lack of empirical data. It is important to note that most of the methods discussed earlier have associated assumptions, which, if violated, can result in biased estimates of the detection probability and, ultimately, density or abundance.

Variance estimation

Estimating the uncertainty in a density or abundance estimate is a crucial part of an analysis. It is important to generate estimates that are as precise as possible so that they can be useful in, for example, management and mitigation decisions. The coefficient of variation (CV) is often reported as a measure of uncertainty of density or abundance estimates. The CV of an estimated parameter is calculated as the standard error of the estimate, divided by the estimate. This is a useful measure because levels of uncertainty can then be compared between estimated parameters that have different measurement units. The overall CV of a density or abundance estimate can be estimated by combining the CVs associated with all the estimated parameters in the estimator, using the delta method (Seber, 1982).

Examples and Case Studies

All methods described earlier (except mark-recapture, for the reasons cited) have been implemented in marine mammal studies using acoustic data. Examples are given here, but it should be noted that this is a non-exhaustive list.

Census/strip transects

Moretti et al. (2010) estimated Blainville's beaked whale density at the Atlantic Undersea Test and Evaluation Center (AUTEC). The dense array of fixed hydrophones at AUTEC allowed the number of diving beaked whale groups to be detected with certainty, and there was no need to estimate the probability of detection. Therefore, this analysis was essentially a census of diving beaked whale groups. Other multipliers (mean group size and an average rate of diving) were required to estimate the density of animals from the density of diving groups.

Ward et al. (2012) also estimated sperm whale density at the AUTEC range using a plot sampling approach. However, in this case, the number of sperm whales in specific time bins was counted, leading to a different density estimator than the one used in Moretti et al. (2010). The differences in the two analyses provide a good demonstration of the flexibility of density or abundance estimation methods; the estimators can be adapted to suit a given vocalization type or a particular signal-processing scheme.

Distance sampling

Distance-sampling approaches have been used with both towed and fixed acoustic instruments. Ship-based surveys using towed hydrophones can determine distances to vocalizing animals, which can then be analyzed using distance-sampling methods. For example, sperm whale abundances have been estimated from such data (e.g., Barlow and Taylor, 2005; Lewis et al., 2007). Lewis et al. (2007) counted individual vocalizing animals, whereas Barlow and Taylor (2005) counted the number of vocalizing groups and therefore required an average group-size multiplier in their estimator, as in Moretti et al. (2010). Distance sampling requires the horizontal distance from the line or point to the animal. However, distances estimated using towed instruments are often the direct distance to the vocalizing animal. Without an estimate of the depth of the animal and the angle of detection from the transect line, the horizontal distance cannot be estimated. This fact can pose a potential issue because using direct distances in the analysis may cause bias in the probability of detection estimate. Recently, methods to extend standard distance sampling that consider the potential depths of vocalizing animals have been developed and implemented (Yack et al., 2015).

Marques et al. (2011) used point-transect sampling to estimate North Pacific right whale density from three HARPs deployed in the Bering Sea. Normal-mode propagation could be used to estimate the range of right whale calls using separate sensors. The number of calls was counted and an average vocalization rate, which converts estimated call density to estimated animal density, was used from combined visual and acoustic focal follows of right whale groups. Harris et al. (2013) also used point-transect sampling to estimate the density of fin whale vocalizations recorded on Ocean Bottom Seismometers in the Atlantic Ocean. No suitable vocalization rate was available, and therefore the estimation of animal density was not possible.

Spatially explicit capture-recapture

Marques et al. (2012) estimated the density of minke whale vocalizations at the Pacific Missile Range Facility using SECR. This analysis was extended using more data in Martin et al. (2013) to estimate minke whale density. The number of minke whale vocalizations was counted, and a vocalization rate was estimated from acoustically tracking a suspected single whale on the hydrophone range for several hours.

Detection probability from auxiliary data

There are several different ways in which the probability of detection can be estimated using auxiliary data. Marques et al. (2009) used acoustic tag data to estimate the detection probability of Blainville's beaked whales on the fixed hydrophones at AUTEC. The location of the tagged animal when it was clicking was known, and its clicks could be matched to those received on the fixed hydrophones. Click detectability could then be modeled as a function of distance using a logistic regression analysis. A similar approach was taken by Kyhn et al. (2012) to estimate harbour porpoise density. As an alternative to using acoustic tags to conduct the trial to assess detection probability, porpoises were visually tracked from a land vantage point. The distances from the fixed instruments at which the animals were acoustically detected could then be estimated.

Finally, a simulation-based method has been developed that mimics animals around a single instrument and predicts the average probability of detecting their vocalizations based on information about vocalization source level, sound propagation, ambient noise levels, and the efficiency of the automatic detection process. This approach was first used to estimate beaked whale density (Küsel et al., 2011) and has been subsequently used for blue and humpback whales (Harris, 2012; Helble et al., 2013a, b).

Challenges of Passive Acoustic Density Estimation

A suite of statistical methods now exists to estimate absolute density or abundance using passive acoustic data. As more case studies use these methods, the research should focus on three key areas: 1) survey design; 2) the accuracy and precision of multipliers; and 3) understanding animals' acoustic behavior.

Survey design

The way that a survey is designed will affect not only the precision and accuracy of the density or abundance estimate, but also the applicability of those estimates to the wider study area of interest. Many of the density-estimation methods discussed earlier were first developed or implemented for marine mammals using hydrophone arrays that were not optimized for marine mammal monitoring (e.g., military hydrophone ranges). In cases where hydrophones were deployed to monitor marine mammals, only a few sensors were available (e.g., Marques et al., 2011). In these cases, methods could be demonstrated as a proof of concept, but it was acknowledged that survey design needed improvement. Therefore, focus should now be placed on implementing robustly designed acoustic surveys that have enough instruments to provide the required spatial and temporal coverage. In addition, at the survey-design stage, consideration must be given to how the detection probability will be estimated (preferably using a "standard" method such as distance sampling or SECR), because this will also affect instrument configuration.

Multipliers

Multipliers of any kind (e.g., vocalization rates, group size, or detection probability) will add additional uncertainty to the overall density or abundance estimate. Therefore, survey designs that do not require such multipliers are preferred. However, should multipliers be required, and they are often unavoidable, they ideally should be estimated using data collected from the study animals at the same time and place of the acoustic survey. This approach ensures that any given multiplier will be the correct average for those animals at the time of the survey, helping to achieve unbiased density or abundance estimates. Where multipliers can be estimated from collected data, such as false positive proportions, systematic random-sampling schemes will ensure that an appropriate sample of the data is taken to estimate the required parameter.

Behavioral information

Finally, it is clear that for passive acoustic monitoring of marine mammals to be successful, a good understanding of the acoustic behavior of the study species is required. This is true not only for density and for abundance estimation, but also for other research questions that can be answered using

acoustic monitoring. For many cetacean species, little is known about the full repertoire of their vocalizations and the contexts in which vocalizations are made. Such information is vital to plan efficient passive acoustic surveys; therefore, continued research focus on cetacean vocal behavior is required. Furthermore, for density or abundance estimates, fine-scale behavioral studies are essential for the estimation of multipliers such as vocalization rates and group sizes, and should also be included as part of the survey design process.

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Appendix G Marine Mammal Stock Assessment Requirements (Prepared by Jay Barlow)

The Marine Mammal Protection Act (MMPA) was amended in 1994 to require stock assessment reports for marine mammal stocks within U.S. jurisdiction (Appendix H). The requirements for stock assessment are further refined in the GAMMS II (NMFS 2005). The purpose of stock assessment reports is to evaluate human impacts on marine mammal populations and to determine their status under the MMPA. Similarly, the Endangered Species Act (ESA) requires periodic reviews of all endangered species to evaluate progress in meeting recovery goals and to reevaluate their status under the ESA. The contribution of passive acoustics to both MMPA stock assessments and ESA status reviews conducted by NMFS were considered at the MMC/NMFS Workshop. The requirements for an MMPA stock assessment are clearly established and include the following:

1. Stock definition and geographic range (including seasonal/temporal variation)
2. Estimation of population size and trends in abundance (with emphasis on approximating a "minimum population estimate")
3. Estimation of current and maximum net productivity rates
4. Calculation of PBR
5. Estimation of annual human-caused mortality and serious injury
6. Evaluation of other factors causing decline or impeding recovery for strategic stocks
7. Evaluation to determine whether a stock is "strategic" under the MMPA

The requirements of ESA status reviews are not as clearly established, but certainly include, many of the same elements as MMPA stock assessments. The main difference is that standards for delineating management units under the ESA (called distinct population segments, or DPSs) are stricter than the standards for population stocks under the MMPA. The guidelines for delineating a DPS were established in 1996 as a joint policy by NMFS and the U.S. Fish and Wildlife Service.[12]

Passive acoustics can help most directly in meeting stock assessment requirements 1, 2, and 3. Consistent differences in vocalizations between populations can aid in delimiting population stocks or DPSs and may be helpful in subspecies designations (as is common for birds). Passive acoustic monitoring can achieve broad temporal and spatial coverage that can be useful in determining seasonal/temporal changes in geographic range. Long-term trends in vocalization rates can be used to infer rates of change in population sizes, and these rates can help determine maximum net growth rates. Passive acoustic methods can be combined with distance-sampling methods to estimate absolute or minimum population size.

Passive acoustic research can be used in a wide variety of contexts that are indirectly related to assessing human impacts on marine mammals, including studies of ocean noise and behavioral response studies. It is not the intent of this workshop to include the potential application of all such acoustic

[12] 61 Federal Register 4722, *Policy Regarding the Recognition of Distinct Vertebrate Population Segments Under the Endangered Species Act*.

research. Rather, the workshop narrowly focus on providing information currently needed for MMPA stock assessment reports and ESA status reviews.

References

Federal Register. 1996. Policy regarding the recognition of distinct vertebrate population segments under the Endangered Species Act. http://www.nmfs.noaa.gov/pr/pdfs/fr/fr61-4722.pdf

NMFS. 2005. Revisions to Guidelines for Assessing Marine Mammal Stocks. 24 p. http://www.nmfs.noaa.gov/pr/pdfs/sars/gamms2005.pdf

Appendix H Marine Mammal Protection Act—Stock Assessment Requirements

Stock Assessments

16 U.S.C. 1386

Sec. 117. (a) IN GENERAL. — Not later than August 1, 1994, the Secretary shall, in consultation with the appropriate regional scientific review group established under subsection (d), prepare a draft stock assessment for each marine mammal stock which occurs in waters under the jurisdiction of the United States. Each draft stock assessment, based on the best scientific information available, shall—

I. describe the geographic range of the affected stock, including any seasonal or temporal variation in such range;

II. provide for such stock the minimum population estimate, current and maximum net productivity rates, and current population trend, including a description of the information upon which these are based;

III. estimate the annual human-caused mortality and serious injury of the stock by source and, for a strategic stock, other factors that may be causing a decline or impeding recovery of the stock, including effects on marine mammal habitat and prey;

IV. describe commercial fisheries that interact with the stock, including—

A. the approximate number of vessels actively participating in each such fishery;

B. the estimated level of incidental mortality and serious injury of the stock by each such fishery on an annual basis;

C. seasonal or area differences in such incidental mortality or serious injury; and

D. the rate, based on the appropriate standard unit of fishing effort, of such incidental mortality and serious injury, and an analysis stating whether such level is insignificant and is approaching a zero mortality and serious injury rate;

V. categorize the status of the stock as one that either—

A. has a level of human-caused mortality and serious injury that is not likely to cause the stock to be reduced below its optimum sustainable population; or

B. is a strategic stock, with a description of the reasons therefor; and

VI. estimate the potential biological removal level for the stock, describing the information used to calculate it, including the recovery factor.

Acronyms and Abbreviations

ADFG – Alaska Department of Fish and Game

AFSC – Alaska Fisheries Science Center (NMFS)

AMAPPS – Atlantic Marine Assessment Program for Protected Species (NOAA, BOEM, U.S. Fish and Wildlife Service, U.S. Navy)

APL – Applied Physics Laboratory (University of Washington)

ASTWG – Advanced Sampling Technology Working Group (OS&T)

AUV – Autonomous underwater vehicle

BACI – Before-After-Control-Impact (experimental design)

BMAR – Bottom-mounted autonomous recorder

BOEM – Bureau of Ocean Energy Management (Department of the Interior)

CalCurCEAS – California Current Cetacean Ecosystem Assessment Survey (SWFSC)

CREEM – Centre for Research into Ecological and Environmental Modelling (University of St. Andrews)

CRP – Cetacean Research Program (PIFSC)

CIMRS – Cooperative Institute for Marine Resources Studies (OAR/OSU)

CV – Coefficient of variation

DCL – Detection, classification, and localization

DECAF – Density Estimation for Cetaceans from Passive Acoustic Fixed Sensors Project (JIP)

DIFAR – Directional Frequency Analysis and Recording sonobuoy (US Navy)

DPS – Distinct population segment

EMAP – EEZ Mammals and Acoustics Program (SWFSC)

EEZ – Exclusive Economic Zone

ESA – Endangered Species Act

ESTCP – Environmental Security Technology Certification Program (Department of Defense)

FR – Federal Register

FTE – Full-time equivalent

GAMMS – Guidelines for Assessing Marine Mammal Stocks

GPS – Global Positioning System

ID – Identification

IOOS – Integrated Ocean Observing System (NOAA)

IT – Information Technology

JIP – Exploration and Production Sound & Marine Life Joint Industry Programme

LMR – Living Marine Resources program (Department of the Navy)

LTSA – Long-term spectral averaging

MMPA – Marine Mammal Protection Act

MMSE – Marine Mammal and Seabird Ecology Team (NWFSC)

NCEI – National Centers for Environmental Information (NOAA)

NEFSC – Northeast Fisheries Science Center (NMFS)

NEPAN – Northeast Passive Acoustic Network (NEFSC)

NMFS – National Marine Fisheries Service[13] (NOAA)

NMML – National Marine Mammal Laboratory (AFSC)

NOAA – National Oceanic and Atmospheric Administration (Department of Commerce)

NOPP – National Oceanographic Partnership Program (independent federal program)

NRS – Ocean Noise Reference Station network (NOAA)

NWFSC – Northwest Fisheries Science Center (NMFS)

OAR – Office of Oceanic and Atmospheric Research[14] (NOAA)

ONR – Office of Naval Research (Department of the Navy)

OPR – Office of Protected Resources (NMFS)

OS&T – Office of Science & Technology (NMFS)

[13] Also known as NOAA Fisheries
[14] Also known as NOAA Research

OSU – Oregon State University

PAM – Passive acoustic monitoring

PARR – Public Access to Research Results (federal policy)

PBR – Potential biological removal

PICEAS – Pacific Islands Cetacean Ecosystem Assessment Survey (SFSC)

PIFSC – Pacific Islands Fisheries Science Center (NMFS)

PMEL – Pacific Marine Environmental Laboratory (OAR)

PODS – Pacific Orcinus Distribution Survey (NWFSC)

PSD – Power spectral density

SBIR – Small Business Innovation Research (NOAA)

SBNMS – Stellwagen Bank National Marine Sanctuary (NOAA)

SDGI – Stock Delineation Guidelines Initiative (SWFSC)

SDSU – San Diego State University

SEFSC – Southeast Fisheries Science Center (NMFS)

SIO – Scripps Institution of Oceanography (UCSD)

SMAR – Surface-mounted autonomous recorder

SRKW – Southern Resident killer whale

SWFSC – Southwest Fisheries Science Center (NMFS)

TB – Terabyte

TDOA – Time difference of arrival

USV – Unmanned surface vehicle

VHF – Very high frequency

WHOI – Woods Hole Oceanographic Institution

Devices

Acousonde – miniature, self-contained autonomous acoustic/ultrasonic

AMAR – Autonomous Multichannel Acoustic Recorder (underwater acoustic and oceanographic data recorder)

APEX Float – Autonomous Profiling Explorer (autonomous drifting profiler used to measure subsurface currents and make profile measurements)

AURAL – Autonomous Underwater Recorder for Acoustic Listening (underwater equipment for continuous recording)

C-POD – Cetacean and Porpoise Detector (PAM instrument that identifies toothed whale, dolphin, and porpoise clicks)

DASBR – Drifting Acoustic Spar Buoy Recorder (drifting autonomous passive acoustic monitoring buoy system)

Decimus – passive acoustic monitoring system

DMON – Digital acoustic MONitoring instrument (low-power digital acoustic monitoring instrument)

DTAG – archival behavior monitoring tag

DSG-ST – long-term acoustic data logger

EAR – Ecological Acoustic Recorder (long-term, low-power digital acoustic recording system)

EOM Offshore, Ltd Mooring System – auto-detection mooring system that reduces high-flow, noise-to-signal ratios in passive acoustic applications

HARP – High-frequency Acoustic Recording Package (long-term, high-bandwidth acoustic data recorder)

HARU Phone – Hydrophone for Acoustic Research Underwater (long-term autonomous hydrophone system)

MARU – Marine Autonomous Recording Unit (small, portable, bottom-mounted pop-up buoy)

MobySound – website that hosts a database for research in automatic recognition of marine animal vocalizations

PAMBUOY – now Decimus

PAMGUARD – open-course, integrated PAM software infrastructure

RainbowClick – analytic program designed for the detection and analysis of sperm whale and other odontocete vocalizations

Remus – Remote Environmental Monitoring UnitS (low-cost AUV)

Roboat – small, automated sailboat that can carry a variety of PAM equipment

Song Meter – long-term PAM system

Spray Glider – small, long-range autonomous glider

Seaglider – AUV glider developed for continuous, long-term measurement of oceanographic parameters

Slocum Glider – versatile, long-endurance AUV glider driven by buoyancy change

Sonobouy – expendable, free-floating PAM buoys obtained from the U.S. Navy that transmit acoustic data over a VHF carrier frequency to a monitoring station on the ship or shore

SoundChecker – Matlab-based, multi-species passive acoustic analysis program

Tethys – knowledge management system that actively gathers, organizes, and provides access to information on the environmental effects of marine energy, offshore wind energy, and land-based wind energy development

Wave Glider – wave- and solar-powered AUV linked to a surface float that is capable of directed movements

Wildlife Acoustics SM2BAT+ w/ GPS – see Song Meter

XRay/ZRay – high-performance, long-distance, high-speed, wing-shaped AUV gliders