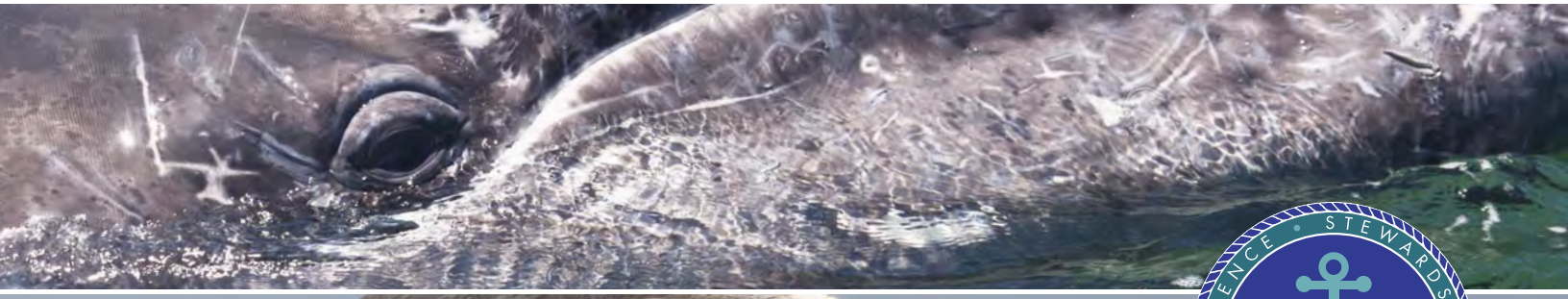
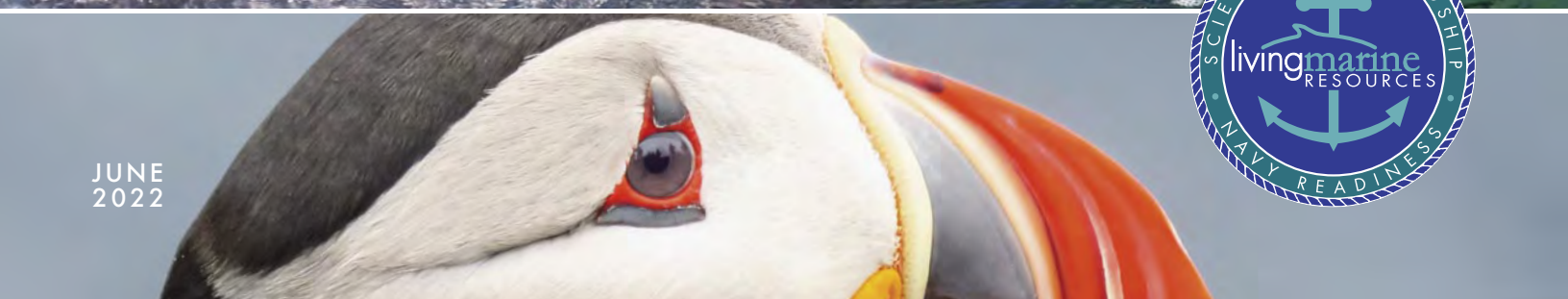
U.S. NAVY'S
LIVING MARINE
RESOURCES
PROGRAM
STATUS REPORT

LMR 2021





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JUNE
2022

LMR 2021

U.S. NAVY'S
LIVING MARINE RESOURCES PROGRAM
STATUS REPORT

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INSIGHTS

We are excited to share with you the 2021 Living Marine Resources (LMR) Program Annual Report. Throughout the past year, the program and all of its participants continued their valuable work to support the Navy's ability to train, test and be mission-ready. Please see the Environmental Compliance Overview section (page 10) to learn more about how the LMR program supports the Navy's at-sea environmental compliance process.

The LMR program was managing 30 projects during 2021, all carefully selected to meet specific Navy-defined needs and provide additional scientific credibility to the Navy's environmental compliance analysis. Of the 30 projects, we initiated seven new projects and had 17 ongoing. Six projects were completed during 2021 and are being transitioned to the end users.

> Throughout the past year, the program and all of its participants continued their valuable work to support the Navy's ability to train, test and be mission-ready.

In 2021 LMR continued to resourcefully address COVID-19 pandemic-induced obstacles. All of the LMR projects made significant achievements in 2021. Many of the projects with delayed field efforts in 2020 were able to resume fieldwork in 2021. We were excited that teams from 10 projects (projects 21, 22, 23, 26, 30, 35, 37, 38, 44 and 48) were all able to get out in the field again and collect data. We are proud of the project scientists' accomplishments and their continued determination to fulfill LMR's mission to address priority research needs.

Anu Kumar
Program Manager

Mandy Shoemaker
Deputy Program Manager

This year we continued to broaden collaboration with other research programs. We maintained our partnership with the Interagency Task Force on Ocean Noise and Marine Life (ITF-ONML), which was established by the Subcommittee on Ocean Science and Technology (SOST) to leverage other agencies' common interest in mysticete hearing to invest in research projects (page 18). Additionally, the Small Business Innovative Research (SBIR) program selected one Phase II technology development project (page 18). This project is focused on expanding the technical capabilities of unoccupied underwater vehicles (UUV) to detect marine mammals in waters difficult to reach and survey. If successful, this will allow the monitoring program to extend its reach and survey larger areas in a cost-effective manner.

Some other 2021 highlights include a new start project (Project 48) that was accelerated to collect the first ever, comprehensive acoustic measurement of a full ship shock trial (FSST) of the new Navy aircraft carrier, USS *Gerald R. Ford* (CVN-78).

We also want to share highlights from one of our completed projects to provide a sense of the scope of our work. One of these, 3S3: Behavioral Responses of Cetaceans to Naval Sonar (Project 29, page 33), obtained critical data on the behavioral response of sperm whales to Navy sonar signals.

These data compared responses from two types of sonar sources (traditional pulsed sonar and continuously active sonar). The project also investigated the role of range versus received level on animal response. This work will help the Navy to develop a more robust scientific basis for estimating the effects of Navy training and testing on marine mammals. In addition to the great scientific value, this project was a good example of a leveraged opportunity funded in partnership with the LMR program and the United Kingdom, French, Norwegian and Dutch naval authorities.

For information on our many other projects, which cover a wide range of Navy needs—marine mammal tag technology, hearing and behavioral response research, acoustic recording devices and processing tools, and scientific standards for collecting and managing the data—see the Program Portfolio section (beginning on page 22).

Results from all of these current and past projects continue to contribute to the scientific literature that provides critical, well-founded scientific information needed by the Navy's Fleet and Systems Command (SYSCOM) environmental planners, regulators, scientists and other stakeholders. Fourteen publications and technical reports, resulting directly from LMR-supported projects or using data from LMR projects, were published in 2021, with several more to be released in 2022. To facilitate access to the citations, we have a downloadable list under the Publications tab on our public website. This list, updated quarterly, provides Navy environmental planners with the latest science coming from LMR funded research.

> As the Navy continues to restructure and realign to become more efficient, so too does our program.

As the Navy continues to restructure and realign to become more efficient, so too does our program. We now have a new website address, exwc.navfac.navy.mil/lmr, where you can find

MC3 Javier Reyes

MC Seaman Matthew Bakerian

information on the program, including the previously mentioned publication list. We encourage you to visit the website to learn more about the unique ways in which the LMR program serves as the Navy's only marine species applied research program.

> Your participation and support keep the program focused on priority needs and well-coordinated with other Navy efforts.

This work could not happen without our resource sponsor, the Chief of Naval Operations Installations Division (OPNAV N4I, formerly OPNAV N45), and all the members of our management team, including the Fleet and SYSCOM representatives on the Living Marine Resources Advisory Committee. Your participation and support keep the program focused on priority needs and well-coordinated with other Navy efforts. Thank you for all your work. The program continues to be relevant and foundational to the current and future Navy mission because of your involvement.

Anu Kumar, Program Manager

Mandy Shoemaker, Deputy Program Manager

OVERVIEW

Mission

The Living Marine Resources (LMR) program's fundamental mission is to support the Navy's ability to conduct uninterrupted at-sea training and testing, which preserves core Navy readiness capabilities.

The U.S. Navy supports both basic and applied research to improve the understanding of marine species in regard to occurrence, exposure, response and consequences. This research is needed to help reduce potential impacts to marine species and to bolster the Navy's at-sea environmental compliance and permitting processes.

The LMR program is responsible for the applied research and works both to address the Navy's key research needs and to transition the results and technologies to end users. LMR meets its mission and responsibilities by

- Improving the best available science, regarding the potential impacts to marine species from Navy activities, available for use in at-sea environmental compliance documentation
- Demonstrating and validating basic research projects that are ready for applied research investment
- Broadening the use of or improving the technology and methods available to the U.S. Navy Marine Species Monitoring program.

PROGRAM HISTORY

The LMR program traces its history back to the Navy's earliest efforts to better understand the impact of anthropogenic sound on marine mammals. In 1997, the scientific knowledge needed to establish an appropriate marine mammal monitoring and protection plan for Navy activities did not exist. The Navy initiated the Marine Mammal Research program, managed by Dr. Frank Stone at Chief of Naval Operations Installations (OPNAV N4I; formerly OPNAV N45), to partner with other government agencies, universities and private industry to conduct scientific research required for monitoring and protecting marine mammals during Navy training and testing at sea.

Early on, Navy-funded research addressed broad study areas including marine mammal ecology and population dynamics, sound field characterization and monitoring methods. The research was targeted to provide a biological baseline that could be used when assessing the effects of Navy training activities on marine mammals.

Efforts were broadened in 2000 to include a new focus on the effects of mid-frequency sonar on beaked whales—the species thought to be most sensitive to that sonar. Between 2000 and 2007, the Navy began work to identify what information would be needed to obtain regulatory agency approvals for its major at-sea training ranges. In 2007, the research efforts were refocused to fulfill these information needs.

LMR program's fundamental mission is to support the Navy's ability to conduct uninterrupted at-sea training and testing, which preserves core Navy readiness capabilities.

With a significantly expanded knowledge base, the distinctions among basic research (6.1 and 6.2 programs), applied research and testing

(6.4 program) and the Marine Species Monitoring program became more well-defined. (For more on the distinctions among organizations responsible for marine mammal efforts, see our section, "Navy Programs That Enable Environmental Compliance" on page 11.) Thus in 2012, OPNAV N4I (formerly N45) transitioned the funding line and formally designated the LMR program as the 6.4 applied research, development, test and evaluation (RDT&E) program, and restructured it to address the Navy's at-sea environmental compliance needs. While OPNAV N4I remained the resource sponsor, controlling the budget and final approval authority, the program needed dedicated management. A program office and manager were established at the Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) in Port Hueneme, California. This location allowed the program to manage and focus the increasing number of research needs, solicit and evaluate proposals, award contracts and provide end users the results they need.

> The highest priority is to transition successful products to the Navy's at-sea environmental compliance process.

With Dr. Robert (Bob) Gisiner as its first program manager, the LMR program took important first steps to establish the program's new structure. This included setting up a program office, defining standard operating procedures, convening an advisory committee (the Living Marine Resources Advisory Committee (LMRAC)), issuing the first formal solicitation for research needs, and holding and documenting the first formal program review.

In June 2014, Anu Kumar was hired as program manager, following Bob Gisiner's retirement. Mandy Shoemaker was selected to fill the deputy program manager position. The new team brought complementary skills and experience as subject matter experts in the Navy's environmental compliance process and associated scientific needs to carry the program forward. They have continued to refine the research needs evaluation and contract management processes to ensure that funds are efficiently expended on those projects of highest priority to the Navy. They have emphasized a collaborative atmosphere among the principal investigators executing the research and have enhanced end user involvement in the research products to ensure that those products address the original need. They also have continually worked to strengthen interagency and international cooperation, leveraging resources across related programs, and optimizing limited funding resources (see the "Coordination/Collaboration with Other Programs, Agencies and Research Institutions" section on page 18 for examples). The highest priority is to transition successful products to the Navy's at-sea environmental compliance process in support of ensuring the uninterrupted training and testing needed for a combat-ready force.

NAVY READINESS DEPENDS ON ENVIRONMENTAL COMPLIANCE

For the Navy to be ready to fulfill its mission—to "maintain, train, and equip combat-ready naval forces capable of winning wars, deterring aggression, and maintaining freedom of the seas"—personnel must be able to train and test using realistic methods. To ensure uninterrupted training and testing, the Navy is responsible for compliance with a suite of federal environmental laws and regulations such as the National Environmental Policy Act (NEPA), the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA).

MCSN Christopher Jones

As part of the regulatory compliance process associated with these Acts, the Navy is responsible for assessing the potential impacts from military readiness activities. The Navy is required to apply for environmental permits to conduct activities that may result in impacts to protected species regulated under environmental statues such as ESA or MMPA.

Once permits are obtained, there are requirements set forth that the Navy must follow to maintain compliance. These requirements include

- Implementing mitigation measures to reduce potential impacts
- Implementing a monitoring program to collect data that will enable a better understanding of the animals and how Navy activities might impact them
- Reporting annually on applicable training and testing activity execution.

Without permits and associated environmental compliance, the Navy risks not being able to train or test. Without training and testing, the Navy cannot be ready to meet its mission. Environmental compliance is fundamental to continued uninterrupted training and testing, and ultimately, to Navy readiness.

NAVY PROGRAMS THAT ENABLE ENVIRONMENTAL COMPLIANCE

The U.S. Navy funds three main programs to support at-sea environmental compliance needs. These programs progress from basic research to applied research to monitoring implementation. The three programs are

1. The Office of Naval Research Marine Mammals and Biology program (ONR MMB)
2. The LMR program
3. The U.S. Navy Marine Species Monitoring (MSM) program.

To promote ongoing coordination among the three programs, the program manager from ONR MMB and representatives from the MSM program are members of the LMRAC (described on page 14).

The Office of Naval Research Marine Mammals and Biology Program

The ONR MMB program is the Navy's basic (6.1) and early applied (6.2) research program on marine mammals and biology. This program supports science-driven research related to understanding the effects of sound on marine mammals, including physiological, behavioral and ecological effects, as well as population-level effects. As a basic and early applied research program, this program focuses on new cutting-edge research topics and exploratory and developmental technological solutions, which help to advance the state of the science. These projects can often have high technical risk and long timelines.

Outcomes from this program are often transitioned to the LMR program to continue to develop, demonstrate and validate solutions, and then link products directly to an end user need. In some cases, outcomes can be transitioned directly to the Navy MSM program if ready for integration.

The Living Marine Resources Program

The LMR program is structured to focus on outcomes for Navy end users and to address the needs of the Navy's at-sea environmental compliance community. As a 6.4 late stage applied research program, LMR develops, demonstrates, validates and assesses the data, methods and technology solutions needed to study protected living marine resources that may be affected by training and testing activities.

The LMR program serves multiple unique functions that the other two programs cannot provide. These functions help to address priority, end user-focused needs at the applied research level:

- Collect and evaluate data on hearing abilities of marine speciess.
- Conduct research on species groups other than marine mammals (e.g., fish, sea turtles, birds).
- Anticipate and conduct research on potential impacts resulting from new Navy sources (e.g., continuous active sonar).
- Demonstrate and validate technologies, tools, models and methods.
- Develop standards and metrics for data collection or analysis.

> By providing a centralized program to address the Navy end users' stated needs, LMR provides a clear path for getting solutions and results to all who need them.

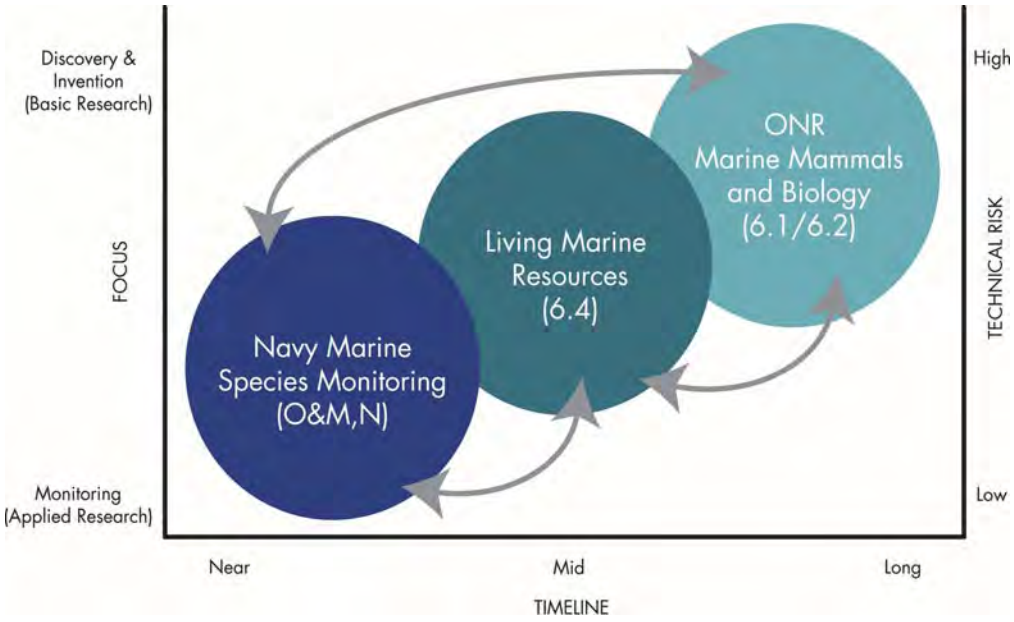
The LMR efforts are critical to ensuring an efficient process for obtaining the most effective tools and reliable data to support environmental compliance. By providing a centralized program to address the Navy end users' stated needs, LMR provides a clear path for getting solutions and results to those who need them.

U.S. Navy Marine Species Monitoring Program

The U.S. Navy's MSM program is a requirement of the Navy's permits for training and testing. The primary objectives are to

- Monitor and assess the effects of Navy activities on protected marine species
- Ensure that data collected at multiple locations are collected in a manner that allows comparison between and among different geographic locations
- Add to the overall knowledge base of protected marine species and the effects of Navy activities on these species.

Since this program is requirements-driven, the projects should have low technical risk and often have short timelines. This demands proven tools and methods that have already been developed under the ONR MMB program, and field tested/validated or developed by the LMR program.



As the chart above shows, there is significant interplay of projects and support among the three programs, yet each serves a distinct role in the compliance process. When an ONR MMB project is deemed ready to transition to the next stage of development, it might be selected for continued development, demonstration and validation within LMR. Following LMR-funded demonstrations and refinements, products can become reliable components of the monitoring program or results can be directly incorporated into environmental compliance documentation. In some cases, when a technology or method is ready for application, it will be transferred directly from ONR MMB development to the monitoring program. Case studies in previous annual reports (2018 and 2020) summarized examples of this process.

It is important to note that the main goal of all three programs is to support the Navy in collecting all data and information necessary to obtain or comply with environmental permits and ensure uninterrupted training and testing.


MC1 John Bellino

STRUCTURE

The LMR program structure was carefully defined to ensure robust communication among Navy commands, other program managers and the LMR resource sponsor—OPNAV N4I. The organization bolsters program communication, accountability and credibility.

Advisory Committees

The LMR program is supported by two defined committees—the LMR Advisory Committee and the Technical Review Committee—as described below.

LMR Advisory Committee

The LMR Advisory Committee (LMRAC) includes representatives from relevant Navy Fleet and SYSCOM activities affected by at-sea environmental compliance issues, as well as members of the Navy's research and monitoring community. The LMRAC includes representatives from

- OPNAV N4I
- Office of the Deputy Assistant Secretary of the Navy for Environmental and Mission Readiness (DASN E&MR)
- Commander, U.S. Pacific Fleet (PACFLT)
- U.S. Fleet Forces (USFF)
- Naval Information Warfare Systems Command (NAVWAR)
- Naval Sea Systems Command (NAVSEA)
- Naval Air Systems Command (NAVAIR)
- Naval Facilities Engineering Command (NAVFAC)
- ONR.

LMRAC members provide critical Navy end user perspectives on many program components including defining needs, evaluating and ranking project proposals, participating in the annual In-progress Review and identifying transition pathways.

Technical Review Committee

The purpose of the technical review committee (TRC) is to serve as an expert panel to review proposals and provide feedback to the Navy regarding technical sufficiency. Based on the need topics for which the Navy solicits proposals, the TRC membership may change to ensure the committee possesses the relevant technical expertise required. The TRC consists of subject matter experts from within the Navy and from other federal agencies, industry or academia, as appropriate.

Program Office

The LMR program is managed by NAVFAC EXWC in Port Hueneme, California. The LMR program manager and the deputy program manager have the primary responsibility for executing the program.

MC3 Eloise A. Johnson

Resource Sponsor

The LMR program is sponsored by OPNAV N4I through its RDT&E action officer. Among its many roles as program sponsor, OPNAV N4I provides the LMR program's annual funding, sets policy and guidance for the Navy's environmental research priorities, approves the list of needs and authorizes new starts.

PROGRAM INVESTMENTS AND PROCESS

The LMR program follows a formal process each year—from identifying Navy needs that fall within program investment areas to transitioning solutions into the Navy's at-sea environmental compliance process. The projects funded by the program are carefully selected to achieve the program's mission. Four key factors that guide project selection are

1. Program investment areas
2. Navy needs
3. Priority species and geographic regions
4. Coordination/collaboration with other programs, agencies and research institutions.

Program Investment Areas

The program investment areas establish the broader boundaries within which the program works to achieve its mission. The investment areas also help to guide the annual process to identify Navy needs. The LMR investment areas are:

1. **Data to support risk threshold criteria**

   Goal—to improve the Navy's acoustic and explosive impact assessments and validate mitigation requirements. This information is critical to the Navy's environmental compliance and permitting processes, and ultimately helps ensure uninterrupted training and testing.

   Approach—obtain and analyze data on how well animals can hear, how and when animals may be exposed to acoustic and explosive sources, and how animals respond or are affected when exposed. The data are used to develop risk threshold criteria, to inform the Navy's acoustic and explosive impact assessments and to determine appropriate mitigation measures to reduce impacts to protected marine species. Projects in this area can include hearing studies, sound exposure and behavioral response studies.

2. **Data processing and analysis tools**

   Goal—to make required monitoring program data processing and analysis more efficient and cost-effective. These tools provide more productive, technologically advanced and practical solutions that improve the Navy's capability to utilize data and information, which supports the Navy's competitive advantage in the undersea domain. The ability to collect, process, exploit and disseminate vast amounts of information is key to continually advancing the Navy's undersea capabilities.

   Approach—develop tools to automate the processing of large amounts of data to reduce costs, increase productivity and provide consistency. Develop tools to improve existing data analysis methods or foster development of new methods, both of which provide improved data products and results. Projects in this area can include new detection and classification algorithms, improvements to software programs or development of novel analytical methods.

3. **Monitoring technology demonstration**

   Goal—to further develop technology to improve field data collection methods. Specific emphasis is given to utilizing existing Navy technologies and sensors for advancing environmental research and data collection. These technology investments enable efficient and

Northern right whale.
Kelly Dilliard, NOAA

cost-effective implementation of the Navy's MSM program to support the Navy's environmental compliance and permitting processes.

Approach—demonstrate and validate system upgrades or advanced capabilities of new or existing monitoring technologies and platforms, including sensors, tags, moored devices, buoys and mobile autonomous devices. This investment area aligns with the goals of the Navy's Task Force Ocean to make every Navy platform a sensor for data collection.

4. **Standards and metrics**

   Goal—to establish interagency and scientific community standards and metrics for data collection, management and analysis. This facilitates information exchange, which is necessary to harness the capabilities of aggregated data to ensure the Navy maintains information dominance.

   Approach—promote data comparability and enable data aggregation from different data sets. Ensure consistent, agreed-upon standards and metrics in order to provide cost-effective improvements to data and results that can be utilized to establish policy and technical guidance. Projects in this area can include standards for data collection methods, standardized data management tools and new metrics for reporting performance of data analysis methods.

5. **Emergent topics**

   This investment area is reserved for other priority topics that are associated with emerging technologies or capabilities. This includes research needs that arise out of the Navy's environmental compliance process, or topics that do not squarely fall within the preceding categories.

Navy Needs

Within the defined investment areas, the LMR program refines its investment decisions based on Navy needs that meet one or more of the following conditions:

- Address research challenges faced by the Navy at-sea environmental compliance community to provide solutions that will reduce operational constraints.
- Identify an existing gap in knowledge, technology and/or capability in order to provide flexibility to the Navy to achieve the mission.
- Fulfill an environmental constraint or regulatory driver to ensure that Navy training and testing occurs in a legally compliant manner.

Anyone within the Navy may submit needs for consideration by the LMR program. For details on submitting needs, see the program website at exwc.navfac.navy.mil/lmr. Non-Navy personnel can discuss need ideas with a Navy employee

for consideration. The Navy employee can choose to sponsor and submit externally generated needs as appropriate. Submitted needs are validated and ranked by the LMRAC, and then recommendations are made to the OPNAV N4I resource sponsor.

LMR-sponsored projects are assigned within a need category. The need associated with a given project is identified in the project summaries presented in the Program Portfolio section of the report.

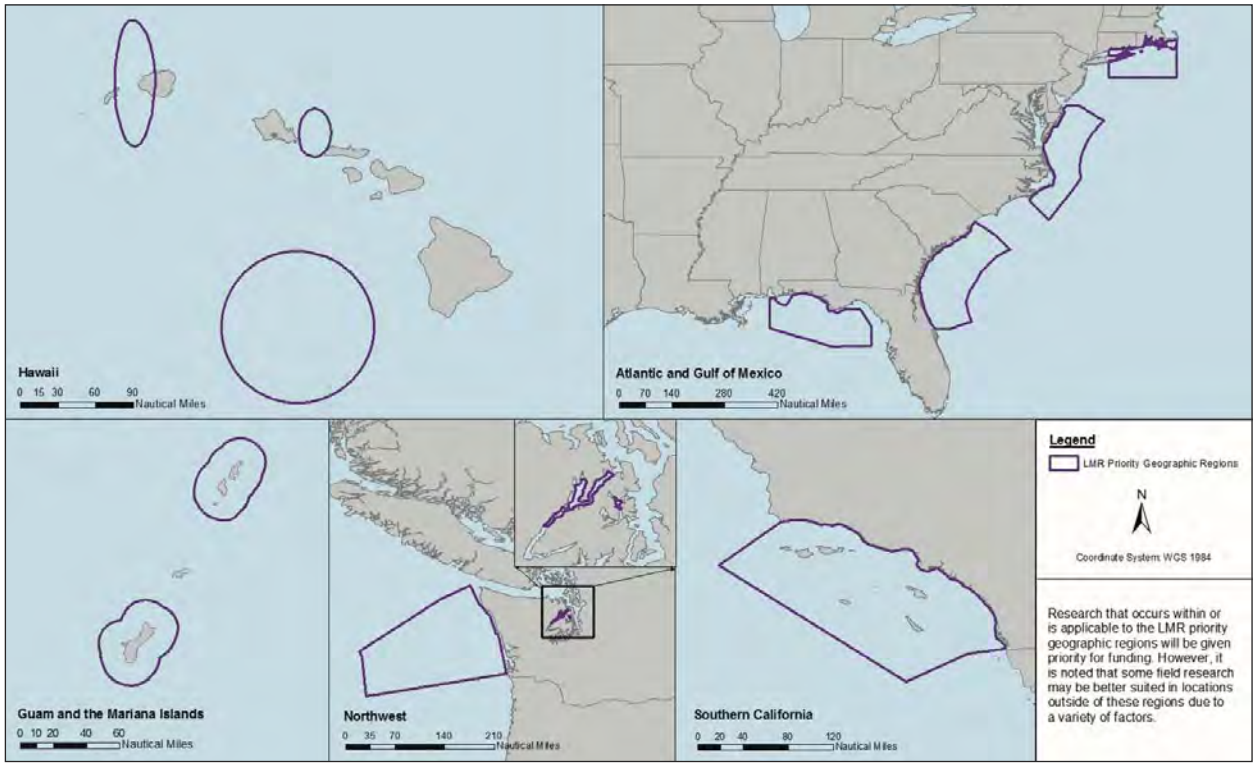
Priority Species and Geographic Regions

In addition to the program investment areas and the identified needs, the program also considers priority species and geographic regions when evaluating and ranking proposals for program funding. While the program is interested in increasing knowledge and understanding of all marine mammal species, projects must be considered within the program's budget. To provide some guidance on research priorities, the priority marine mammal species for the program include

- Deep-diving species (beaked whales, sperm whales and other deep-diving species)
- ESA-listed species.

In addition to marine mammal species, the LMR program has funded projects that are increasing knowledge and understanding of the potential impacts to sea turtles, diving sea birds and fish in response to specifically identified priority Navy needs.

The LMR program is primarily interested in funding research that is applicable to geographic regions that are important to the U.S. Navy. The map below shows the LMR program priority geographic regions. It is important to note that the LMR program acknowledges that a variety of factors could lead to some field research being conducted outside of these geographic regions, although results still apply to Navy needs within the regions.



LMR priority geographic regions.

Coordination/Collaboration with Other Programs, Agencies and Research Institutions

The program makes a concerted effort to continually expand and strengthen our network of partners, which is the fourth line of effort described in the Navy's Design for Maintaining Maritime Superiority (Version 2.0). The program does this by

- Maintaining close alignment across the U.S. government, including partnerships with agencies such as National Oceanographic and Atmospheric Administration (NOAA), Marine Mammal Commission (MMC) and Bureau of Ocean and Energy Management (BOEM)
- Advancing the Navy's partnership with industry through Broad Agency Announcements (BAAs) and Small Business Innovative Research (SBIR) efforts
- Enhancing cooperation with academic and research institutions, shown by the program's projects being conducted by roughly 15 different academic and research institutions.

An example of multi-agency coordination is LMR's active support to the Subcommittee on Ocean Science and Technology (SOST). The SOST's purpose is to advise the National Science and Technology Council's Committee on the Environment, Natural Resources, and Sustainability (CENRS) on national issues of ocean science and technology, and to serve as the lead interagency entity for federal coordination on those matters. One component of SOST is the Interagency Task Force on Ocean Noise and Marine Life (ITF-ONML), formed to increase coordination and communication across federal agencies in addressing issues related to the potential impacts of anthropogenic noise on marine life. The SOST ITF-ONML issued a call for pre-proposals via the LMR program in July 2018 pertaining to development of audiograms for mysticetes. The LMR program is currently managing two of the three projects chosen from the pre-proposals. These two projects, Collection of AEP Hearing Thresholds in Minke Whales, and Towards a Mysticete Audiogram Using Humpback Whales' Behavioral Response Thresholds, are summarized on pages 59 and 61, respectively.

The LMR program is also expanding partnerships with industry through the SBIR program, which

MC2 Claire DuBois

provides an opportunity for domestic small businesses to engage in federal research and development that has the potential for commercialization. The research topic submitted by LMR, Unmanned Underwater Vehicle (UUV) Technology to Enable Readiness of Navy Ranges, seeks technologies that can collect a broad spectrum of ocean acoustic data to support largescale spatial and temporal research on ambient and biological sources of sound. The following three companies participated in Phase I:

1. Triton Systems
2. OASIS
3. EOM Offshore.

After the completion of Phase I, Triton Systems was selected for a Phase II, which will go through Fall of 2022. At the end of Phase II, Triton will be eligible for an additional Phase II option.

Since 2014, LMR has managed ten projects that involve coordination with outside organizations. These projects have leveraged over $8.5 million in external funding. Of this leveraged funding, forty percent ($3.4 million) has come from other Navy programs (e.g., ONR and SBIR) and the other sixty percent ($5.1 million) has come from outside the Navy. In addition to funding benefits, these projects build a knowledge base and relationships with other agencies that increase mutual awareness of needs and potential changes in criteria, technologies and methods that could affect Navy activities.

Project Lifecycle

The program's annual project cycle begins with soliciting and defining Navy needs. (See previous section, "Navy Needs.") The needs are then the basis for issuing a pre-proposal solicitation. The pre-proposal solicitation includes a BAA for offerors that are outside the federal government. After the solicitation closing date, the proposal analysis process—conducted by the LMRAC, TRC and program staff—begins with a review to identify those pre-proposals of greatest interest for development into a full proposal, followed by a full proposal review and final recommendations to the program sponsor of projects to be funded.

Funded projects are initiated with a project kick-off communication between the principal investigator and program staff to discuss project and program expectations. Discussions cover details such as project milestones, spending plan and financial expectations, reporting requirements and ongoing communication with program staff. The goal is to establish a framework that promotes project success and keeps projects targeted on meeting Navy needs.

LMR projects have leveraged over $8.5 million in external funding.

When a project approaches its completion and its results demonstrate that an approach can successfully meet the Navy need, the program works to move the demonstrated solutions out of research and into the hands of the appropriate Navy end users. While this stage represents the final step in the formal project process, the LMR program does continue to track a project's success and solicit feedback about the integration. Some of the conditions that define successful integration:

- The project provides a feasible, desirable solution to the end user.
- Stakeholders or end users have accepted and integrated the solution.
- Funding has been planned for and is in place for transition, if necessary.

MANAGEMENT AND COMMUNICATION TOOLS

To promote efficient management and progress toward meeting goals and program mission, the program works to ensure clear communication among all participants and interested parties. The primary tools for these efforts are summarized below.

Quarterly Newsletters

The LMR program issues a quarterly newsletter, *LMR News*, to provide readers with the latest information about program operations, significant accomplishments, milestones and future investment areas for the LMR program. The digital newsletter can be viewed at the LMR website. Subscribers are notified by email when a new issue is available.

Research Publications Spreadsheet

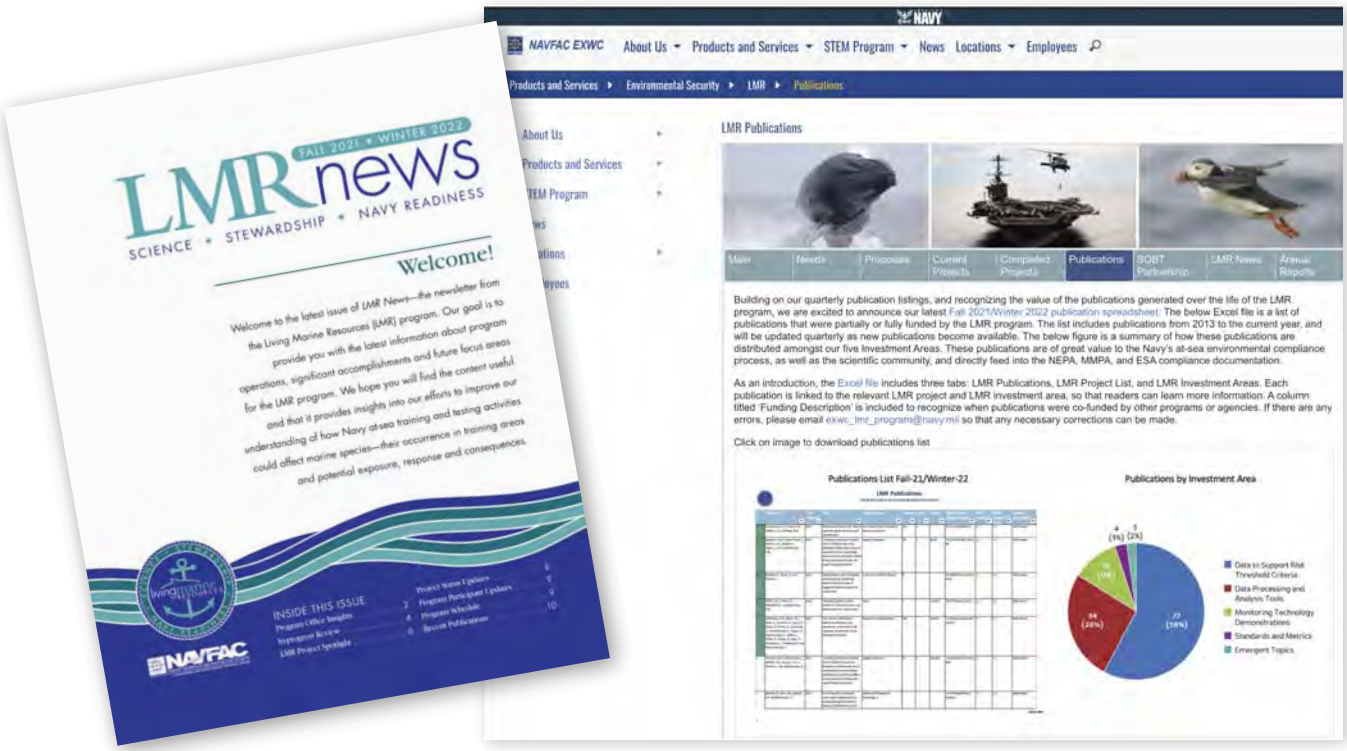
During 2020, the LMR program added a full listing of program research publications, in spreadsheet format, to the LMR website. At the close of 2021, the spreadsheet list included 131 publications, beginning in 2013 from the earlier Marine Mammal Research program, which preceded the LMR program's establishment in 2014. While the list focuses on publications resulting from Navy LMR funding, it also includes publications not specifically funded by the LMR program but that acknowledged use of data, methodology or technology developed with funding from LMR.

The spreadsheet provides full citations (authors, year, title, journal, issue, etc.) and, as appropriate, the LMR project number and investment area under which it was funded. In addition to journal publications, the spreadsheet includes entries for final and technical reports.

The spreadsheet is updated quarterly. To obtain the latest spreadsheet, go to exwc.navfac.navy.mil/lmr and click on the Publications tab.

Project Highlights Fact Sheets

Fact sheets highlighting key aspects of LMR-funded projects provide a quick view into



program investments. The fact sheets, available on the LMR website, provide a summary of the following topics for each project:

- The need it addresses29
- The solution
- The methodology
- The schedule
- Navy benefits
- Transition steps
- Information about the principal investigator(s).

In-progress Review

Fact sheets highlighting key aspects of LMR-funded projects provide a quick view into program investments. The fact sheets, available on the LMR website, provide a summary of the following topics for each project:

LMR's new website address is exwc.navfac.navy.mil/lmr.

LMR Website

The program website serves as a centralized repository for public information about the program. The site offers ready access to the newsletter, research publications list, project highlight fact sheets and annual reports. It also includes an announcement when a pre-proposal solicitation is issued, and provides information needed for pre-proposal submission.

Once again, the program website address has changed. The new URL (exwc.navfac.navy.mil/lmr) is now up and running. Please contact the program manager at exwc_lmr_program@navy.mil if you have any trouble accessing the website.

PORTFOLIO

Completed Projects

Six projects were completed during 2021 and are summarized in this section. Results from these projects are now available for use by the Marine Species Monitoring program and those involved in environmental compliance.

The completed LMR projects are

1. Project 21—Extended Duration Acoustic Tagging of Right Whales
2. Project 24—Frequency-dependent Growth and Recovery of TTS in Bottlenose Dolphins
3. Project 27—High Fidelity Acoustic and Fine-scale Movement Tags
4. Project 29—3S3: Behavioral Responses of Cetaceans to Naval Sonar
5. Project 36—Analytical Methods to Support Development of Noise Exposure Criteria for Behavioral Response
6. Project 39—Use of "Chirp" Stimuli for Non-invasive, Low-frequency Measurement of Marine Mammal Auditory Evoked Potentials.

LMR Projects

Extended Duration Acoustic Tagging of Right Whales

Principal Investigators:
Susan Parks, Doug Nowacek
Project Status: Completed, Project 21

NEED

N-0102-16: Behavioral Response Research to Study the Effects of Sound on Marine Mammals

The Navy needs more information on aspects of marine mammal behavior in response to Navy training and testing activities. Two related topics within this need are: 1) research on how different variables may impact the behavioral response of the animal, including range between the source and animal during exposure, frequency range of the source, and behavioral state of the animal during exposure, and 2) demonstration of tags that can collect high-fidelity animal movement and behavioral responses over a longer-term duration (preferably weeks to months). The Navy needs improved behavioral response data in order to update risk threshold criteria and reduce the uncertainty of the current impact assessments.

PROJECT

The digital acoustic recording tag (DTAG) is one type of tag that can be non-invasively attached to an animal to capture data on surrounding sound and an animal's movements in response to sound for a wide range of critical marine mammal species. As tag technology has improved, these tags offer longer recording times (up to 72 hours), which would provide better insights into the tagged animal's behavior. The non-invasive suction cup attachment mechanisms that are often used with DTAGs, however, generally do not stay attached for long periods, thus limiting data collection to less than one day.

This project tested new suction cup materials with micro-texture for non-invasive tags on baleen whales to provide the longer sampling times needed to improve animal movement and behavioral response data collection. Attachment mechanisms employing biocompatible glues also were evaluated. The testing within this study was the

first to apply tags with the newly developed micro-texture suction cups to a free-ranging baleen whale.

The original project plan was to test the attachment of third generation tags (DTAG-3s) using micro-textured cups and biocompatible glues during monitoring studies of North Atlantic right whales off the Southeastern United States. The monitoring studies, supported by U.S. Fleet Forces, are focused on right whales due to their endangered status and proximity to the undersea warfare training range off Jacksonville, Florida. This training range is one of the identified priority regions for the LMR program and the Navy.

> The testing within this study was the first to apply tags with the newly developed micro-texture suction cups to a free-ranging baleen whale.

Lack of right whale sightings during the during the 2017 monitoring season prevented testing the new tag attachments on right whales. The team was able to conduct a few tests of suction cups of three stiffness levels (all with micro-texture) on humpback whales in the Northeast during summer 2017. Researchers analyzed the results of the humpback tagging to identify possible design modifications.

Testing over the course of the project evaluated three material stiffness types: Shore 30A (soft), Shore 40A (the standard DTAG-3 suction cup) and Shore 60A (firmer material). Tests also included adding micro-texture to the cup edges, combining the firmer 60A with a softer (30A) lip and, in limited number of tests, adding adhesive to cups.

The 2018 field trials used two suction cup versions—a Shore 40A cup with micro-texture and a slightly firmer Shore 60A cup. (A third version, the Shore 30A, that had been tested in 2017 was deemed too soft for general use.) These two suction cup versions were used for tagging during the June 2018 Stellwagen Bank National Marine Sanctuary humpback whale research program's field season. Analysis of tag data revealed that all tags ultimately detached due either to extended periods of whale breaching or to impacts with other whales and/or the bottom during foraging activities. The team also used the firmer Shore 60A cup while tagging Southern right whales as a part of a Marine Mammal Commission-funded field season in Brazil in August 2018.

Based on field results from both 2017 and 2018, the team modified suction cup configurations for 2019. While the Shore 60A material stiffness provided promising results for attachment times, there also was evidence of sliding prior to detachment. The team revisited potential benefits offered by the softer Shore 30A, including less sliding. A cup that combined the overall stiffness of the 60A with a softer lip of silicone material was developed.

A DTAG with combination material cups.
Susan Parks

Right whales.
NOAA

Over four deployments in June 2019, this combination provided attachment times ranging from 9.7 to 23.3 hours. While the average attachment durations between the stiffer Shore 60A and the combination cups were comparable, analyses suggest that each cup version appears to offer benefits related to an animal's speed and skin condition.

In addition to suction cup materials and textures, the project evaluated if biocompatible glues could safely offer additional attachment durations. Glue work in 2020 converged on a cyanoacrylate adhesive, then moved to design and testing the cup material/adhesive combinations under laboratory conditions. Testing focused on attachment, strength and release mechanisms.

While COVID-19 pandemic restrictions prevented the planned 2020 field testing of the final cup/adhesive design, the team was able to deploy tags during two field efforts in 2021. In the first field trials, on Stellwagen Bank National Marine Sanctuary, four tags were deployed onto humpback whales, two with adhesive and two without adhesive. Of the four tags, one was not recovered, two without adhesive stayed on the animals for approximately five and 14 hours, and the recovered tag with adhesive remained attached for just over 35 hours. Data from this tag indicates significant stability during the deployment and, although it slid on the whale at one point, it remained attached during at least two breaching events.

Final field testing occurred during a Northeast Fisheries Science Center Right Whale Survey cruise in October 2021. A total of eight tags were deployed and successfully recovered. Tags with the material combination of firmer cup material (Shore 60A), softer lip and micro-texture remained attached longer than the standard silicone suction cups.

The project did advance our understanding of new suction cup materials and configurations.

Northern right whale.
NOAA

The firmer cup material with micro-texture on the lip showed significantly increased attachment times. Attachment times do vary by species and the animal's skin condition and are affected by an animal's physical contact with other animals or the seafloor. Limited testing with adhesives showed promise for additional attachment times.

This type of progress on new suction cup materials is helping to prolong attachment times for the longer-term recording tags, extending behavioral response data collection.

This type of progress on new suction cup materials is helping to prolong attachment times for the longer-term recording tags, extending behavioral response data collection. Such tag and attachment systems could apply to a broad range of endangered species in multiple Navy areas of interest. Tag suction cups of firmer material with micro-textured edges are now available for use.

About the Principal Investigators

Susan Parks is an associate professor in the Department of Biology at Syracuse University in Syracuse, NY. She specializes in bioacoustics, focusing on the use of sound for communication and the impacts of noise on development, behavior, sound production and reception. Dr. Parks holds a Ph.D. in biological oceanography from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution.

Douglas Nowacek is a professor of conservation technology with joint appointments in the Nicholas School of the Environment and the Pratt School of Engineering at Duke University. His research topics include the behavioral and acoustic ecology of marine mammals, the effect(s) of anthropogenic noise on marine mammals and the development of technology for marine conservation research. Dr. Nowacek holds a Ph.D. from the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution.

Frequency-dependent Growth and Recovery of TTS in Bottlenose Dolphins

Principal Investigator: Jim Finneran
Project Status: Completed, Project 24

NEED

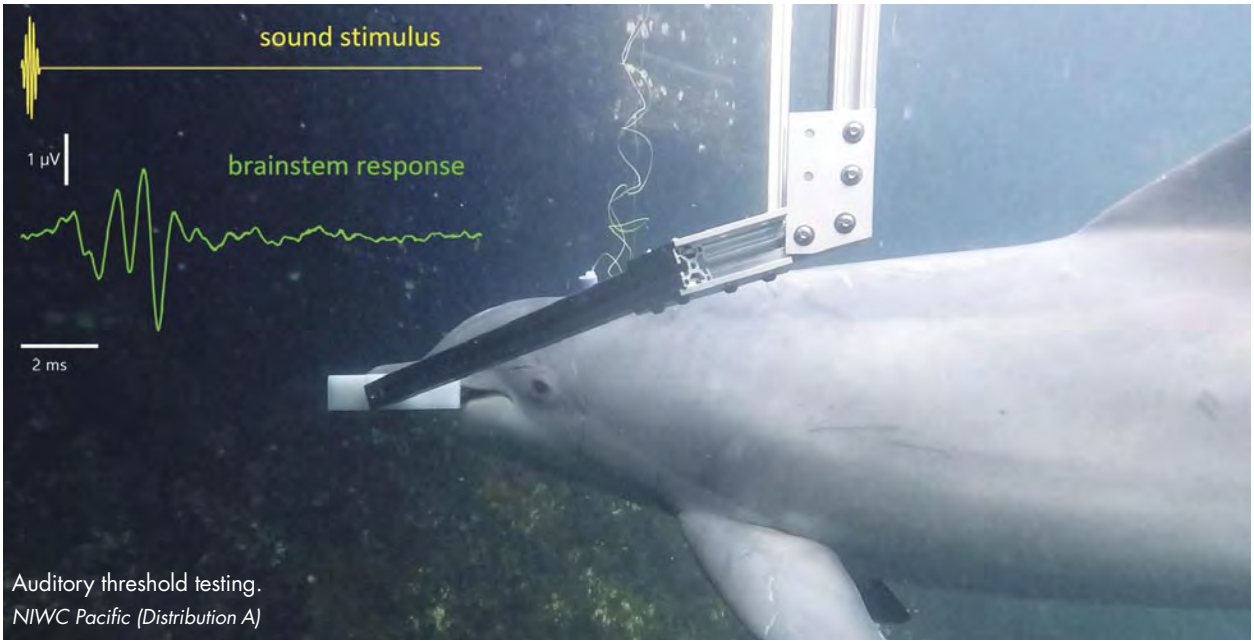
N-0103-16: Marine Species Hearing Research Related to the Acoustic Effects Criteria

The Navy needs new data to improve the Navy's acoustic and explosive impact assessments for marine species. Priority interest is in species for which no, or insufficient, data are available. Areas of focus include audiograms of hearing capability in marine species, data on temporary threshold shift (TTS) at multiple frequencies, and effects to fish from the detonation of explosive devices of various charge sizes, depths and distances to the subjects. The Navy needs improved hearing and TTS data in order to update risk threshold criteria, reduce the uncertainty of the current impact assessments and validate mitigation measures.

PROJECT

Navy acoustic impact assessments apply auditory weighting functions, similar to those used in assessing risk to human hearing, to predict the occurrence of TTS and permanent threshold shift (PTS) as functions of frequency. Threshold shift is one of the few direct measures of adverse effects of intense sound on hearing. The associated weighting functions are mathematical functions that emphasize, or "weight," noise at different frequencies according to the listener's susceptibility to noise at that frequency. Direct measurements of TTS in representative marine mammal species—across a broad spectrum of sound frequencies—are needed to support the TTS/PTS thresholds and weighting function derivations.

The existing thresholds for assessing TTS and PTS in bottlenose dolphins were based on measurements from only a few individuals. These measurements were taken at selected frequencies thought to represent the range of the animal's best hearing, or the frequencies at which a sound source would be most likely to affect the animal. However, because recent research done with harbor porpoises has demonstrated that TTS susceptibility varies by frequency, information is needed on the entire frequency range. Additionally, the largest effects to hearing often occurred



Auditory threshold testing.
NIWC Pacific (Distribution A)

Bottlenose dolphins.
Wayne Hoggard, NOAA/NMFS

a half octave above the center exposure frequency. Therefore, this project investigated this in bottlenose dolphins.

The objectives of this effort were to: 1) determine exposure levels corresponding to the onset of TTS across a broad range of frequencies in bottlenose dolphins (*Tursiops truncatus*) with full hearing bandwidth (up to frequencies of about 140 to 160 kilohertz (kHz)); 2) develop TTS recovery models for use in acoustic impact assessments; and 3) examine the relationship between TTS measured using behavioral methods and auditory evoked potential (AEP) methods.

The methodology included measuring the hearing thresholds in bottlenose dolphins using both behavioral audiometric methods and electrophysiological AEP methods. Researchers established baseline hearing thresholds, then measured hearing thresholds immediately before and after exposure to a fatiguing noise to determine any threshold shift occurrences. Subject health, welfare and behavior were continuously monitored and managed by attending veterinarians and animal care staff at the Naval Information Warfare Center Pacific.

Early project efforts focused on animal training, baseline hearing measurements and refining the TTS exposure protocols for this study. These were followed in 2018 by beginning high-frequency TTS data collection, including testing with 80-kHz fatiguing noise with a single dolphin. That testing included 54 control sessions and 21 one-hour exposure sessions at exposure levels of approximately 139 to 165 decibels (dB) sound pressure level, equivalent to approximately 175 to 201 dB sound exposure level. The project team also initiated TTS testing with 40-kHz fatiguing noise during 2018. Two publications were released by the close of 2018 (see Publications sidebar for citation).

During 2019, the project completed behavioral and AEP threshold testing at 20, 40 and 80 kHz. A manuscript discussing auditory brainstem response in these dolphins was published in *The Journal of the Acoustical Society of America* in 2019 (see Publications sidebar for citation).

The low- and mid-frequency TTS testing was completed in 2020. During these exposures the dolphins were equipped with digital acoustic recording tags (DTAGs) to support received level estimates. Post-testing hearing (recovery) was also characterized. The team then worked to reconcile sound field/video analysis results and DTAG recordings to correct received exposure level estimates.

The project data helped to improve methods for rapid AEP-based measures of hearing.

Data analyses were completed in 2021 and TTS growth curves at each frequency were incorporated into the Navy's criteria updating the weighting function and TTS/PTS values for the mid-frequency cetacean group. A final manuscript for peer-reviewed publication was in preparation by the close of 2021, with publication anticipated in 2022.

In addition to results contributing to updated weighting function and TTS/PTS values for the mid-frequency cetacean group, the project data helped to refine the extrapolation procedures used to derive weighting functions and TTS/PTS values for other species groups and to improve methods for rapid AEP-based measures of hearing. This information is directly applicable to all Navy environmental compliance documents analyzing potential impacts from acoustic sound sources.

About the Principal Investigator

James Finneran has worked as a research scientist at the Naval Information Warfare Center (NIWC) Pacific since 2002, investigating marine mammal echolocation and marine animal auditory capabilities and studying the physiological effects of sound on marine animals. He has a Ph.D. in mechanical engineering from The Ohio State University.

Publications

Schlundt, C.E., Mulsow, J. and Finneran, J.J. (2019). "Using behavioral and auditory brainstem response methods to test frequency-dependent growth and recovery of TTS in bottlenose dolphins," presented at the Fifth International Conference on the Effects of Noise on Aquatic Life (Den Haag, The Netherlands, 7-12 July 2019).

Finneran, J.J., Mulsow, J. and Burkard, R.F. (2019). Signal-to-noise ratio of auditory brainstem responses (ABRs) across click rate in the bottlenose dolphin (*Tursiops truncatus*). *The Journal of the Acoustical Society of America*, 145:1143-1151. DOI 10.1121/1.5091794.

Burkard, R., Finneran, J.J. and Mulsow, J. (2018). Comparison of maximum length sequence and randomized stimulation and averaging methods on the bottlenose dolphin auditory brainstem response. *The Journal of the Acoustical Society of America*, 144:308-318. DOI 10.1121/1.5046069.

Burkard, R.F., Finneran, J.J., Mulsow, J. and Houser, D.S. (2017). The effects of click rate on the auditory brainstem response (ABR) of the bottlenose dolphin. *The Journal of the Acoustical Society of America*, 141, 3396-3406. DOI 10.1121/1.4983447.

High-fidelity Acoustic and Fine-scale Movement Tags

Principal Investigator: Alex Shorter
Project Status: Completed, Project 27

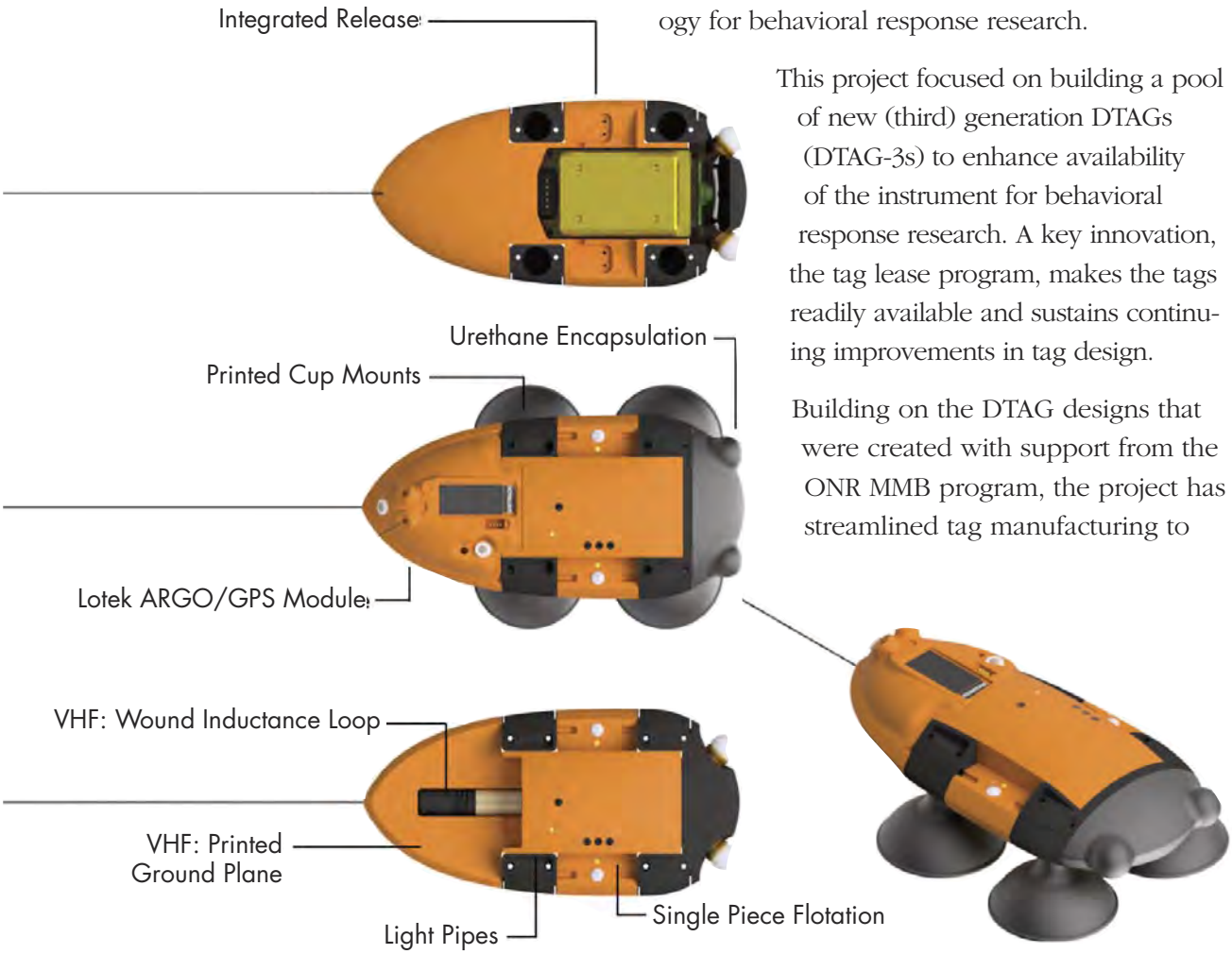
NEED

N-0102-16: Behavioral Response Research to Study the Effects of Sound on Marine Mammals

The Navy needs more information on aspects of marine mammal behavior in response to Navy training and testing activities. Two related topics within this need are: 1) research on how different variables may impact the behavioral response of the animal, including range between the source and animal during exposure, frequency range of the source, and behavioral state of the animal during exposure, and 2) demonstration of tags that can collect high-fidelity animal movement and behavioral responses over a longer-term duration (preferably weeks to months). The Navy needs improved behavioral response data in order to update risk threshold criteria and reduce the uncertainty of the current impact assessments.

PROJECT

The DTAG, a biologging tag, is often used for research and monitoring when both acoustics and movement of the animal are of interest. DTAGs are highly integrated, compact, low-power, high-fidelity acoustic biologging tags that are well suited for studying both deep-diving beaked whales and large baleen whales. The combination of high-resolution acoustic and movement sensors makes these tags key enabling technology for behavioral response research.



This project focused on building a pool of new (third) generation DTAGs (DTAG-3s) to enhance availability of the instrument for behavioral response research. A key innovation, the tag lease program, makes the tags readily available and sustains continuing improvements in tag design.

Building on the DTAG designs that were created with support from the ONR MMB program, the project has streamlined tag manufacturing to

An attached DTAG-3+.
Marc Lammers, permit 19655

produce field-ready tags. The tags are leased to researchers on a monthly basis, with support and technical advice for the field effort provided as needed.

> Importantly, the revenue generated by the leasing pool is applied to the costs of improving tag designs and manufacturing new field-ready tags.

When fieldwork is completed, tags are returned for inspection and testing. The researchers who used the tags under rigorous field conditions provide feedback, which is used to inform design improvements for field reliability and performance. Importantly, the revenue generated by the leasing pool is applied to the costs of improving tag designs and manufacturing new field-ready tags.

The project exceeded initial plans by successfully producing and fielding more than the 20 pool tags from the original proposal. The funds generated by the leasing program have supported additional tag improvements and production, enabling the lease pool to grow to meet the increasing needs of the researchers. The use of these tags by researchers in the field had been increasing every year since the project began in 2016, with 71 tag months supported in 2019. This is one-and-a-half times the usage from 2018 and seven times the usage amount from 2016. The 2020 and 2021 field seasons were exceptions due to COVID restrictions.

Improved design and manufacturability of the tags have been demonstrated over the project's life. The tags now have a modular design that enables incremental adjustments, rather than requiring overall tag redesign. For example, the connector used for data offload and recharge was upgraded during 2018, as was the integrated VHF transmitter. During 2019, tag antenna configurations were tested to evaluate tradeoffs in increasing VHF tracking distances with changes to the tag design. The most recent version of the tag now includes an improved antenna based on results from these experiments. Design improvements in 2020 included adding Fastloc® GPS and ARGOS capabilities while reducing mass and volume by 30 percent.

> This project has significantly expanded the availability of the DTAG-3 for more field efforts.

Design changes during 2021 included a modified frame for the electronics, modular electronics assembly, a new LED display (status, charging, communication), and a clip-in style suction cup mount to facilitate changing out suction cups. Manufacturing was streamlined by reducing the number of parts and creating new methods for production. Ten new tags were produced with the GPS and ARGOS capabilities and the improved antenna design. The number of tag lease months in 2021 were similar to 2020 with a total of 35. This continues to reflect fewer field efforts due to COVID-19 restrictions. As restrictions ease, the number of tag lease months is expected to rise

Algorithm development started in 2020 continued in 2021. The new algorithms are being developed to help users process the data provided by the multiple new sensors within the new DTAG-3+. The algorithms apply a statistical particle filter method that combines data on tag position on the animal, animal position and estimated animal speed with the periodic GPS data to improve detailed location estimation. A manuscript on this work is in preparation.

This project has significantly expanded the availability of the DTAG-3 for more field efforts. The iterative improvements in design and manufacturing, supported largely by the innovative leasing pool, are increasing the benefits from this tag technology.

It is a great example of a technology that has moved through the Navy's three marine resource programs—development initiated under the ONR MMB program, demonstration and validation supported under the LMR program, and implementation occurring through use by the Navy's MSM program. This reflects the way in which these three Navy programs are coordinated to meet Navy needs.

About the Principal Investigator

Alex Shorter is an assistant professor in the University of Michigan's mechanical engineering department. He specializes in biomechanics and persistent monitoring applications for both people and animals. Shorter was one of the original DTAG engineers and has extensive experience with the design and fabrication of marine biologging tags. Dr. Shorter earned his Ph.D. in mechanical engineering from the University of Illinois at Urbana-Champaign.

3S3: Behavioral Responses of Cetaceans to Naval Sonar

Principal Investigators: Frans-Peter Lam, Petter Kvadsheim, Patrick Miller
Project Status: Completed, Project 29

NEED

N-0135-17: Understanding the Range to Effect on the Behavioral Response of Marine Mammals from Sonar Exposure

Results from previous behavioral response studies indicate that the context in which marine mammals experience exposure to acoustic sources could affect their response. In particular, the Navy needs information on how the range (distance) of the sound source to the animal may affect behavioral response. Behavioral response data from a variety of operational Navy sources such as hull-mounted sonar, dipping sonar, and other types are needed. The Navy needs improved behavioral response data in order to update risk threshold criteria and reduce the uncertainty of the current impact assessments.

PROJECT

Several factors pertaining to a sound source can influence behavioral response to sonar including sonar source level, source frequency, duty cycle (the ratio of transmission time to repetition time) and the effect of distance between the source and animals. This project is evaluating the potential effects of a relatively new type of sonar—continuously active sonar (CAS)—as well as several of the other influencing factors, including the distance from a sound source to a whale.

This project was the third phase of the international 3S (Sea mammals, Sonar, Safety) research effort. The overall 3S project has been conducting behavioral response studies on six different cetacean species in North Atlantic waters since 2006. This phase, (3S3), evaluated whether exposure to CAS leads to different types or severity of behavioral responses than exposure to traditional intermittent pulsed active sonar (PAS) signals.

Royal Norwegian Navy frigate KNM *Otto Sverdrup* (Nansen class). The towed operational sonar is visible at the aft of the frigate.
CDR René Dekeling, RNLN

Sperm whale.
Jacqueline Bort Thornton

The project has been funded in partnership with the LMR program and the United Kingdom, French, Norwegian and Dutch naval authorities. Coordinating with this international effort provides results for both the U.S. Navy and allies in the North Atlantic Treaty Organization (NATO).

The data from this work will contribute to the U.S. Navy's behavioral response curve evaluations and will continue to improve the impact assessment of behavioral response.

This phase focused on addressing two separate questions in parallel using the same experimental design:

1. Does exposure to CAS lead to different types or severity of behavioral responses than exposure to traditional PAS signals, or does the CAS feature of high duty cycle lead to acoustic responses that indicate masking?
2. How does the distance to the source affect behavioral responses?

Field efforts were conducted in Norwegian waters along Norway's northern coast. Focus animals included sperm whales (*Physeter macrocephalus*) and long-finned pilot whales (*Globicephala melas*).

The project employed controlled (sonar) exposure experiments (CEE) using operational sonar sources from a research vessel and from a Norwegian frigate. The research team used visual observers and acoustic arrays to locate whales of interest and determined whether they met the requirements outlined within the experimental

protocol. When animals were located, a digital acoustic monitoring tag (DTAG)—in this case DTAG-3 or a mixed-DTAG—was attached by non-invasive suction cups to each animal that could be approached. The sensor package of the mixed-DTAG added a GPS logger and satellite transmitter to the DTAG-3 sensor package. The tags were programmed to release after 15–17 hours.

After establishing baseline behavior characteristics of each tagged whale, and ensuring all protection measures are in place, the team initiated the experimental phase, the CEE. Each tagged subject was exposed to both CAS and PAS as well as a no-sonar control experiment. Well-established analytical approaches to contrast the effects of range and CAS versus PAS were employed during data analysis.

The project collected data during three field seasons in 2016, 2017 and 2019. During the 2016 and 2017 field seasons, the team successfully deployed DTAG-3s or mixed-DTAGs on 16 sperm whales and four pilot whales to record vocal, movement and dive behavior. The tags captured 236 hours of sperm whale behavioral data. Twelve full series of sonar CEEs were conducted with sperm whales using a scaled sonar source (Socrates) from the research vessel. Data collection for pilot whales included baseline data and a single CAS exposure.

The 2019 field work, conducted from mid-August to mid-September, included CEEs using both the previously used scaled source (Socrates) from the research vessel HU *Sverdrup II* and an operational source (Captas) from the Norwegian Navy frigate KNM *Otto Sverdrup*. The team successfully tagged sperm whales with mixed-DTAGs (recording sound, movement, location and diving depth) and conducted CEEs using PAS at different levels and ranges using the operational source on the Norwegian Navy frigate. Using the scaled source, the team completed additional CEEs mimicking the operational source transmission scheme but at lower levels. Overall, the team deployed 24 tags and conducted 11 CEEs.

In total over the field seasons, the project tagged and conducted controlled exposure experiments with 36 sperm whales and one pilot whale. The tagging efforts also helped to test new DTAG configurations, including comparing a combined DTAG-3+ with GPS and ARGOS location information against a mixed-DTAG. This work has helped the team to further refine the design of the mixed DTAG for optimal use in the 3S studies.

> The direct data on actual behavioral responses in controlled conditions with free-ranging cetaceans will allow the Navy to better estimate the potential effects of sonar use on marine mammals.

During 2018, 2020 and 2021, the team focused on analyzing data collected during the respective field seasons. Multiple manuscripts and technical reports have been produced or are in final preparation. All publications available by the close of 2021 are listed in the publication sidebar and the full publication list at the end of this report.

Results show that sperm whale (species for which data were available) responses to CAS and PAS were statistically equivalent when the sound exposure level (SEL) was the same. For the effect of range (distance) between sound source and animal, received levels and range both influenced response of sperm whales; received levels at close range have a greater influence, and beyond 16 kilometers the probability of response is insignificant. This result on sperm whales from an area

where they are relatively frequently exposed to naval sonar is contrasted by the results from ONR-funded work on bottlenose whales (also part of 3S3) in a pristine environment near Jan Mayen. The naïve bottlenose whales responded at the same received level independent of range out to the 30km range tested.

The data from this work will contribute to the U.S. Navy's behavioral response curve evaluations and will continue to improve the impact assessment of behavioral response. The direct data on actual behavioral responses in controlled conditions with free-ranging cetaceans will allow the Navy to better estimate the potential effects of sonar use on marine mammals.

About the Principal Investigators

Frans-Peter Lam, lead principal investigator (PI), is a senior scientist at The Netherlands Organization for Applied Scientific Research. Dr. Lam earned his Ph.D. in physics and astronomy from Utrecht University in The Netherlands. His main research interests are the effects of sound on marine mammals and military oceanography.

Petter Kvadsheim, co-PI, is a principal scientist and program manager with FFI (Norwegian Defence Research Establishment). Dr. Kvadsheim earned his Ph.D. in zoophysiology from the University of Tromsø, Norway.

Patrick Miller, co-PI, is a senior research fellow at the Sea Mammal Research Unit and professor in the School of Biology, University of St Andrews, Scotland. Professor Miller earned his Ph.D. in biological oceanography from the Woods Hole Oceanographic Institution/Massachusetts Institute of Technology joint program.

Publications

Curé, C., Isojunno, S., Siemensma, M.L., Wensveen, P.J., Buisson, C., Sivle, L.D., Benti, B., Roland, R., Kvadsheim, P.H., Lam, F.P.A. and Miller, P.J.O. (2021) Severity scoring of behavioral responses of sperm whales (*Physeter macrocephalus*) to novel continuous *versus conventional pulsed active sonar. The Journal of Marine Science and Engineering*, 9(4):444. DOI 10.3390/jmse9040444.

Isojunno, S., von Benda-Beckmann, S., Wensveen, P., Kvadsheim, P., Lam, F-P., Gkikopoulou, K., Pöyhönen, V., Tyack, P., Benti, B., Foskolos, I., Bort, J., Neves, M., Biassoni, N. and Miller, P. (2021). Sperm whales exhibit variation in echolocation tactics with depth and sea state but not naval sonar exposures. *Marine Mammal Science*, 38(2):682-704 (print version, 2022). DOI 10.1111/mms.12890.

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Isojunno, S., Wensveen, P.J., Lam, F-P.A., Kvadsheim, P.H., von Benda-Beckmann, A.M., Martín López, L.M., Kleivane, L., Siegal, E.M. and Miller, P.J.O. (2020). When the noise goes on: received sound energy predicts sperm whale responses to both intermittent and *continuous navy sonar. Journal of Experimental Biology*, 223(7): jeb219741. DOI 10.1242/jeb.219741.

Analytical Methods to Support Development of Noise Exposure Criteria for Behavioral Response

Principal Investigators:
Len Thomas, Catriona Harris
Project Status: Completed, Project 36

NEED

N-0135-17: Understanding the Range to Effect to the Behavioral Response of Marine Mammals from Sonar Exposure

Results from previous behavioral response studies indicate that the context in which marine mammals experience exposure to acoustic sources could affect their response. In particular, the Navy needs information on how the range (distance) of the sound source to the animal may affect behavioral response. Behavioral response data from a variety of operational Navy sources such as hull-mounted sonar, dipping sonar, and other types are needed. The Navy needs improved behavioral response data in order to update risk threshold criteria and reduce the uncertainty of the current impact assessments.

PROJECT

Criteria for estimating the effects of anthropogenic sound on marine mammal species are currently established for species groups based on functional hearing characteristics. Results of various behavioral response studies (BRS) suggest that these groupings might not be sufficient for predicting responses to sonar. To expand the utility of data collected from the BRS and to improve the approach to grouping species for exposure criteria, the Navy needs additional, more efficient modeling methods for estimating responses of multiple species.

This project focused on developing a computationally efficient model selection method that supports and expands upon the existing and often used Bayesian hierarchical dose-response framework. Under the previous approach, modeling more than six species or adding contextual variables required excessive computation times. The project's goal was to develop a method that will enable many more species and contextual variables (e.g., signal type, whale-source range, received exposure level, animal behavior at time of exposure, etc.) to be included in the model. This included developing an objective, data-driven methodology for selecting species groupings, contextual variables and dose metrics, and appropriate functional forms for the dose-response function in support of noise exposure criteria.

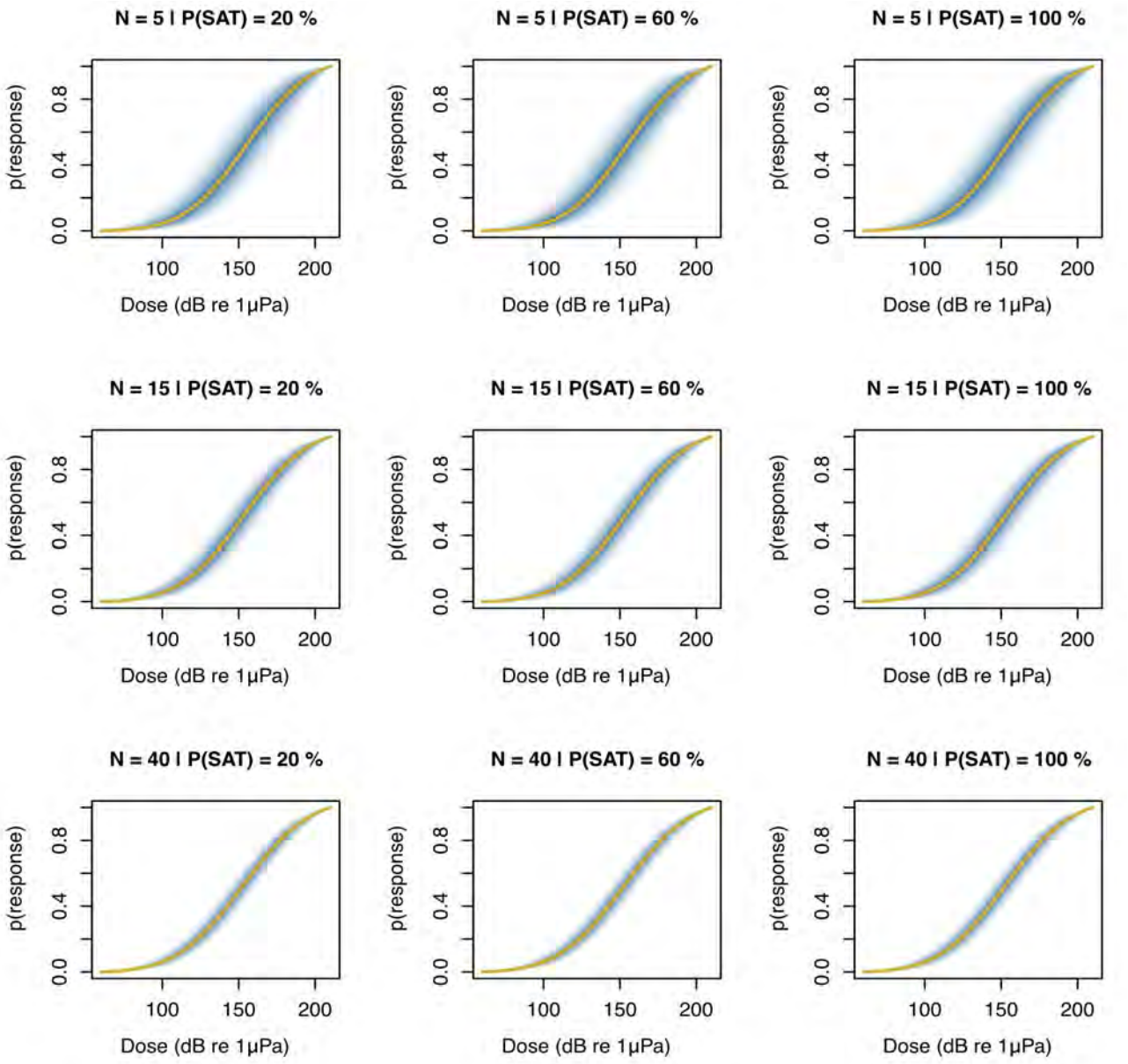
The project team began with results of the ONR MMB-funded MOCHA (Multi-study Ocean Acoustics Human Effects Analysis) project to develop a new model selection method. They investigated species groupings and contextual variables, evaluating the support for each using model selection methods. They also developed methods for fitting alternative dose-response functional forms (e.g., biphasic functions). The methods were tested using simulated data and multi-species data compiled during the MOCHA project, as well as data collated from more recent BRSs.

During 2019, team members met with behavioral response study researchers to identify available data and formats. The team collated the data from controlled exposure experiments (CEEs) for a wide range of variables including exposure history, signal type, animal behavior (foraging/non-foraging) in pre-exposure period, distance between source and animal and others. Working with Navy environmental compliance experts, data were carefully reviewed to ensure data quality. Team members also began developing methods for model selection, reviewing algorithms to be used and improving existing code.

Based on hypothetical CEE scenarios that included high-resolution data from digital acoustic tags (DTAGs) and low-resolution data from satellite tags, the project team conducted a simulation

study to investigate the balance between the data types and the effect of uncertainty in received levels from both data types on the resulting dose-response functions. The team presented the results to the environmental compliance team. The results are available through a technical report available at http://hdl.handle.net/10023/19909 and in a 2021 publication in *Frontiers in Marine Science* (see Publication sidebar for citation).

In 2020, the project team focused on testing and completing the model selection methods and applying methods to the full data set. Bayesian hierarchical dose-response models with a reversible-jump Markov chain Monte Carlo (RJMCMC) model selection algorithm have been implemented in the R programming language. The R functions have been generalized to apply to any number of species, and to allow the selection of



Example dose-response curves estimated for a range of sample sizes (N) and proportions of animals fitted with satellite tags (P(SAT)). The solid line represents the average posterior median across Ns=500 simulations, followed by the average 5%, 10%, 15%....and 95% credible intervals in darker to lighter shades of blue.

both contextual covariates (both continuous and categorical) and functional forms for the dose-response relationship (mono vs. biphasic). In addition, the code has been adapted to allow species groupings and functional forms to be specified *a priori*, in recognition that parameter estimation for pre-determined species groupings (e.g., based on hearing sensitivity) may be of interest to the Navy. The code was tested on simulated data and benchmarked against other model selection methods.

During 2021, the team extensively tested and refined model selection methods, and analyzed the complete set of available data. One publication describing the methods is planned for 2022.

Two key outcomes from this work include the R software package "espresso" and a simulation tool. The R package (https://pjbouchet.github.io/espresso) allows for dose-response modeling across functional forms, species and covariates, and model selection across species and covariates. This is a new capability that would have been infeasible with previous methods. The package is designed to be flexible for use by the research community and the Navy Environmental Compliance Team. It includes a step-by-step vignette for multi-species Bayesian dose-reponse model selection using RJMCMC and options for switching different elements of the model selection on and off depending on needs and questions. Some package capabilities specifically address Navy needs, including left-censoring required for CEE data from captive studies, and incorporating risk-function data. The simulation tool explored the role of satellite tag data in future dose-response functions. This tool and publication have expanded the conversation about including satellite tag data in Navy models when data are available.

The results offer the Navy a package to use during development of the Navy's behavioral risk functions. While the groupings may not be appropriate for use in the behavioral risk functions at this time, they will, at a minimum, help the Navy to understand the relationship between responsiveness and dose metrics other than those related to received sound level. This model selection method and simulation tool will offer guidance on data requirements, data formats, priority covariates and dose metrics to ensure data collected in the future can be utilized in this framework.

About the Principal Investigators

Len Thomas, Professor of Statistics at University of St Andrews and a member of the Centre for Research into Ecological and Environmental Modelling (CREEM), specializes in developing statistical methods to apply to ecological problems. Professor Thomas has a Ph.D. in forestry from the University of British Columbia.

Catriona Harris is a senior research fellow at, and Deputy Director of, the University of St Andrews Centre for Research into Ecological and Environmental Modelling (CREEM). Her research focuses on the impact of anthropogenic noise on marine mammals, specifically behavioral responses of marine mammals to noise, for over seven years. Dr. Harris holds a Ph.D. from the University of St Andrews.

Publication

Bouchet, P., Harris, C. and Thomas, L. (2021). Assessing the role of sampling uncertainty for predicting behavioural responses of tagged cetaceans exposed to naval sonar. *Frontiers in Marine Science*. 8:674554. DOI 10.3389/fmars.2021.674554.

Use of "Chirp" Stimuli for Non-invasive, Low-frequency Measurement of Marine Mammal Auditory Evoked Potentials

Principal Investigator: James Finneran
Project Status: Completed, Project 39

NEED

N-0202-19: Development of Audiograms for Mysticetes

There is a need to improve understanding and measurement of auditory capabilities and sensitivities of low-frequency cetaceans (mysticetes) to anthropogenic sound. Research necessary to generate a mysticete audiogram includes developing and validating finite element modeling (FEM) methods, developing and testing *in situ* auditory evoked potential (AEP) measurement methods for mid- and high-frequency hearing sensitivities of mysticetes, developing tools for AEP measurements below 1 kHz, evaluating behavioral response methods and identifying other appropriate approaches or methods.

> The chirp stimuli were specially designed so that the rate at which the frequency sweeps upward optimally matches the properties of the inner ear.

PROJECT

This project focused on examining potential tools to inform AEP measurements below 1 kHz in mysticetes. AEP methods involve measuring small voltages that the brain and auditory nervous system generate in response to sound and

Bottlenose dolphin.

California sea lion.
Cordelia Shea

are measured and used to evaluate auditory capabilities. Often, AEPs measure the auditory brainstem response (ABR). The goal of this project was to determine the extent to which an upward "chirp" stimulus—a sound whose frequency increases with time—can increase ABR amplitudes at lower frequencies in marine mammals. The chirp stimuli were specially designed so that the rate at which the frequency sweeps upward optimally matches the (species-specific) properties of the inner ear. Experimentally determined properties of the "optimal" chirp could then be compared with anatomical properties of the inner ear. This approach was designed to support predicting optimal chirp for other species, such as mysticetes, for which only anatomical data exist.

The project's three broad objectives were to

1. Determine the extent to which *broadband* upward chirps increase ABR amplitudes and how the effectiveness of a broadband chirp varies with chirp sweep rate, duration, frequency range and level
2. Determine the extent to which *narrowband* upward chirps increase ABR amplitudes compared to tone burst stimuli and if narrowband chirps provide advantages (compared to tone bursts) for marine mammal auditory threshold testing
3. Determine if optimal chirp properties can be predicted from cochlear traveling wave speed (TWS) estimates and/or anatomical measurements of the cochlea.

Data were collected with bottlenose dolphins (*Tursiops truncatus*) and California sea lions (*Zalophus californianus*). These species are available at the U.S. Navy Marine Mammal Program, and they represent echolocating cetaceans with good high-frequency (10–100 kHz) hearing and marine carnivores with good mid-frequency (1–10 kHz) hearing. Sea lions provided a means of approximating the frequency range of hearing expected for some mysticetes.

During 2020 the project team was able to measure ABRs to broadband (1–152 kHz) noise bursts and

high-pass noise (HPN) in several dolphins. The data were used to estimate cochlear TWS and to examine the relationship between noise burst duration and ABR amplitude. The team analyzed data examining relationships between stimulus offset and "offset ABR" in dolphins.

Measurements in both dolphins and sea lions were completed during 2021. These included measuring ABRs to broadband (1–152 kHz) noise bursts and HPN in sea lions. Measurements of ABRs to narrowband chirps and tone bursts and HPN were completed for both species.

Four manuscripts were completed and submitted to *The Journal of the Acoustical Society of America* on these topics (see Publications sidebar for citations). An additional manuscript is in preparation, with publication expected in 2022.

The project's results help to establish conditions for which chirp stimuli can enhance ABR measurements in marine mammals.

In general, it appears that the improvement in ABR amplitude due to chirps will be task- and species-specific. For some species (e.g., dolphins and porpoises) and for narrowband stimuli, chirps are not likely to significantly increase ABR amplitude. However, for animals with best hearing at lower frequencies and when ABRs are difficult to measure, chirps will provide more benefit.

The project's results help to establish conditions for which chirp stimuli can enhance ABR measurements in marine mammals. This will help to improve efficiency of future ABR testing with novel and difficult-to-measure species, such as mysticetes, and could help to advance ABR measurements below 1 kHz in some species.

About the Principal Investigator

James Finneran has worked as a research scientist at the Naval Information Warfare Center (NIWC) Pacific since 2002, investigating marine mammal echolocation and marine animal auditory capabilities and studying the physiological effects of sound on marine animals. Dr. Finneran earned his Ph.D. in mechanical engineering from The Ohio State University.

Key contributors: Dr. Jason Mulsow (National Marine Mammal Foundation), Dr. Robert F. Burkard (University at Buffalo).

Publications

Mulsow, J., Finneran, J.J., Houser, D.S., Burkard, R.F., Strahan, M.G. and Jones, R. (2021). The offset auditory brainstem response in bottlenose dolphins (*Tursiops truncatus*): Evidence for multiple underlying processes. *The Journal of the Acoustical Society of America*, 149(5):3163-3173. DOI 10.1121/10.0004830.

Burkard, R., Finneran, J.J., Mulsow, J. and Jones, R. (2020). Offset auditory brainstem response (ABR) amplitude in bottlenose dolphins. *The Journal of the Acoustical Society of America*, 148(3):1445-1455. DOI 10.1121/10.0001900.

Finneran, J.J., Mulsow, J., Strahan, M.G., Houser, D.S. and Burkard, R.F. (2020). Role of the temporal window in dolphin auditory brainstem response onset. *The Journal of the Acoustical Society of America*, 148(5):3360-3371. DOI 10.1121/10.0002703.

Ongoing and New Start Projects by Investment Area

INVESTMENT AREA 1
DATA TO SUPPORT RISK THRESHOLD CRITERIA

LMR Investment Area 1 improves the Navy's acoustic and explosive impact assessments and validates mitigation requirements. This information is critical to the Navy's environmental compliance and permitting process, and ultimately helps ensure uninterrupted training and testing.

Projects in this area can include hearing studies and sound exposure and behavioral response studies. Researchers collect and analyze data pertaining to animal hearing, potential exposure of animals to acoustic and explosive sources and how the animals respond or are affected. These data support risk threshold criteria and inform the Navy's acoustic and explosive impact assessments. Risk threshold criteria are values that estimate the likelihood that certain types of specified effects will occur. These criteria are also used to estimate the distance from sound source to animal response to help determine appropriate measures to reduce impacts to protected marine species. Improving the accuracy of such estimates will reduce overly burdensome mitigation requirements that can reduce training and testing realism.

The following section includes summaries of 14 projects—nine ongoing projects and five new projects started in 2021.

The ongoing projects are

1. Project 22—Hearing and Estimated Acoustic Impacts in Three Species of Auk: Implications for the Marbled Murrelet
2. Project 23—Cuvier's Beaked Whale and Fin Whale Behavior During Military Sonar Operations: Using Medium-term Tag Technology to Develop Empirical Risk Functions
3. Project 26—The Effects of Underwater Explosions on Fish
4. Project 30—Measuring the Effect of Range on the Behavioral Response of Marine Mammals Through the Use of Navy Sonar
5. Project 32—Behavioral Assessment of Auditory Sensitivity in Hawaiian Monk Seals
6. Project 37—Collection of AEP Hearing Thresholds in Minke Whales (SOST)
7. Project 38—Towards a Mysticete Audiogram Using Humpback Whales' Behavioral Response Thresholds (SOST)
8. Project 40—Temporary Threshold Shifts in Underwater Hearing Sensitivity in Freshwater and Marine Turtles
9. Project 45—Frequency-dependent Underwater TTS in California Sea Lions.

The new start projects are

1. Project 47—Standardizing Auditory Evoked Potential Hearing Thresholds with Behavioral Hearing Thresholds
2. Project 50—Loudness Perception in Killer Whales (*Orcinus orca*); Effects of Temporal and Frequency Summation
3. Project 51—Dependence of TTS on Exposure Duration During Simulated Continuously Active Sonar: Examining the Equal-energy Hypothesis for Long-duration Exposures
4. Projects 52, 53, 54—Studying Marine Mammal Behavioral Response to SURTASS LFA Sonar
5. Project 55—Dolphin Conditioned Hearing Attenuation.

Ongoing Projects

Hearing and Estimated Acoustic Impacts in Three Species of Auk: Implications for the Marbled Murrelet

Principal Investigator: Aran Mooney
Project Status: Ongoing, Project 22

NEED

N-0103-16: Marine Species Hearing Research Related to the Acoustic Effects Criteria

The Navy needs new data to improve the Navy's acoustic and explosive impact assessments for marine species. Priority interest is in species for which no, or insufficient, data are available. Areas of focus include audiograms of hearing capability in marine species, data on temporary threshold shift (TTS) at multiple frequencies, and effects to fish from the detonation of explosive devices of various charge sizes, depths and distances to the subjects. The Navy needs improved hearing data in order to update risk threshold criteria, reduce the uncertainty of the current impact assessments and validate mitigation measures.

PROJECT

Some Navy readiness activities occur in areas that overlap with the natural habitat of the marbled murrelet (*Brachyramphus marmoratus*), a member of the Auk (or Alcidae) family that is listed as threatened under the ESA in Washington, Oregon and California, and state-listed as endangered in California. Potential effects from sound-producing activities might include auditory impacts such as temporary and permanent hearing threshold shifts as well as behavioral effects. Yet there currently are no basic data on the hearing of marbled murrelets or any other Auk species. Current impact assessments and mitigation measures for birds are based on fish or marine mammal data, which may be resulting in unrealistic mitigation zones and assessments of effect. Therefore, the Navy needs data to improve impact assessments and validate associated mitigation zones related to birds.

This project is defining the hearing of up to three Auk species—including the marbled murrelet—to provide data needed to predict the marbled murrelet's hearing. Over the course of the project, researchers are conducting both auditory evoked potential (AEP) methods and behavioral audiometric methods. Data collection efforts include in-air AEP tests, in-air behavioral audiometry tests and underwater behavioral audiometry tests. These tests will allow researchers to compare AEP and behavioral audiometric methods and to compare in-air and underwater measurements. In addition to AEP and behavioral audiometry testing, the team also is conducting computed tomography (CT) scans to define anatomical differences and similarities among the species.

Following an initial 2017 field effort focused on collection of in-air AEP data with a puffin and

Atlantic puffins.

Marbled murrelet.

common murre, the team collected full in-air AEP audiograms on 10 puffins in 2018. In 2019, the project was expanded to add field-collected in-air AEPs on common murres in northwestern Iceland and marbled murrelets in Alaska in 2020. During 2018 and 2019, the team also continued in-air behavioral hearing training with a common murre in a controlled test setting. Preliminary measurements and thresholds were initiated and the team worked to improve false detection rates.

> This project is defining the hearing of up to three Auk species to provide data needed to predict the marbled murrelet's hearing.

The team trained birds for sound-sensitivity tests and collected underwater behavioral hearing data during 2018 and 2019. The first set of underwater trials revealed that these birds do hear underwater, which previously was unknown. In 2019, training of one of the common murres was initiated for a more controlled test: to swim through an underwater hoop, which would trigger a sound, then to swim to the appropriate target based on whether it detected the sound. The test includes sounds across a range of frequencies. This work is building a behavioral audiogram of an Auk species.

Other work during 2019 included data analyses, manuscript preparation and publication, and anatomical scans. Two publications from 2019 included one detailing methods for collecting AEPs in the field and another on potential noise impacts on puffins. Twenty-four anatomical scans in 2019 brought the total number of scans to near 39. The highest quality samples were from Atlantic puffins (*Fratercula arctica*), for which the team conducted sound exposure modeling on the reconstructed hearing structures. By modeling a simulated sound source, the team can estimate pressure distribution across the ear canal at different frequencies to predict the most sensitive frequency. These results may ultimately be applied to marbled murrelet anatomical scans.

Plans for 2020 were affected by COVID-19 travel and work restrictions. Field-based in-air AEP measurements in Iceland and Alaska were postponed until 2021. Underwater behavioral audiogram training and testing work was slower than expected because of variable work schedules, as well as seasonal behavioral changes among the birds. The project team did push ahead with training and testing within the limitations. They also continued data analyses and had two manuscripts published during 2020 (see Publications sidebar for citations).

> The project will provide key hearing data needed to support refining acoustic criteria for the marbled murrelet.

The team was able to resume field efforts in 2021. Their field-based AEPs included measurements from ten individual non-endangered marbled murrelets in Alaska and from 12 common murres in Iceland. Analyses are underway. Additional in-air and underwater behavioral audiogram testing of trained common murres was conducted, with 240 sessions per media completed. These were conducted in the same controlled test setting used in the 2018 and 2019 efforts. Through these research sessions the team has worked to resolve the behavioral responses and evaluate their sound-sensitivity and perception. Anatomical modeling efforts, with initial measures of the auditory structures and comparative analyses, were completed during 2021. The team is refining these analyses for a report and publication.

Work in 2022 will focus on completing data analyses and preparing manuscripts on the behavioral and field audiograms, as well as the anatomical modeling. All manuscripts will be submitted for peer review and publication.

The project is providing key hearing data needed to support refining acoustic criteria for the marbled murrelet. This will allow the Navy to improve the assessment of potential impacts on birds from training and testing activities and will result in more realistic mitigation zones.

About the Principal Investigator

Aran Mooney is an associate scientist in the biology department at the Woods Hole Oceanographic Institution, where he leads the Sensory Ecology and Bioacoustics Laboratory. His research addresses how marine animals detect and use sound and how animals may be affected by anthropogenic noise. Dr. Mooney holds a Ph.D. in zoology (marine biology emphasis) from the University of Hawaii.

Key collaborators: Marianne Rasmussen, University of Iceland; Magnus Wahlberg, University of Southern Denmark.

Publications

Hansen, K.A., Hernandez, A., Mooney, T.A., Rasmussen, M.H., Sørensen, K. and Wahlberg, M. (2020). The common murre (*Uria aalge*), an auk seabird, reacts to underwater sound. *The Journal of the Acoustical Society of America*, 147(6):4069. DOI 10.1121/10.0001400.

Mooney, T.A., Smith, A.B., Larsen, O.N., Hansen, K.A. and Rasmussen, M. (2020). A field study of auditory sensitivity in the Atlantic puffin, *Fratercula arctica*. *Journal of Experimental Biology*, 223(15):jeb228270. DOI 10.1242/jeb.228270.

Cuvier's Beaked Whale and Fin Whale Behavior During Military Sonar Operations: Using Medium-term Tag Technology to Develop Empirical Risk Functions

Principal Investigators:
Greg Schorr, Erin Falcone
Project status: Ongoing, Project 23

NEED

N-0102-16: Behavioral Response Research to Study the Effects of Sound on Marine Mammals

The Navy needs more information on aspects of marine mammal behavior in response to Navy training and testing activities. Two related topics within this need are: 1) research on how different variables may impact the behavioral response of the animal, including range between the source and animal during exposure, frequency range of the source, and behavioral state of the animal during exposure and 2) demonstration of tags that can collect high-fidelity animal movement and behavioral responses over a longer-term duration (preferably weeks to months). The Navy needs improved behavioral response data in order to update risk threshold criteria and reduce the uncertainty of the current impact assessments.

PROJECT

This project has been collecting fine-scale animal behavior data during Navy activities involving the use of mid-frequency active sonar (MFAS) from multiple platforms across a range of distances. The project team deploys longer-duration, high-resolution behavior recording tags within an opportunistic exposure (OE) approach to document the behavior of two species—Cuvier's beaked whales (*Ziphius cavirostris*) and ESA-listed fin whales (*Balaenoptera physalus*)—before, during and after actual Navy exercises.

The OE approach involves tagging animals in areas where Navy activities occur; the tags then collect data on how the animals behave when exposed to activities that happen to take place near the animal. Animal behavioral data are collected without needing to schedule with the Navy platforms (e.g., ships, helicopters), which enables recording a larger sample of real-world exposures. The team uses data archives from the Marine Mammal Monitoring on Navy Ranges (M3R) system, automated sonar detector outputs and a ship tracking database to confirm acoustic inputs from Navy activities.

This project is closely related with another LMR-funded project, Measuring the Effect of Range

The tagging boat Phoenix approaches a group of Cuvier's beaked whales.
Adam U, MarEcoTel permit 20465

A biopsy arrow is seen in the water after collecting a sample from an adult male Cuvier's beaked whale.
Adam U, MarEcoTel permit 14097

on the Behavioral Response of Marine Mammals Through the Use of Navy Sonar (Project 30, page 53). That project augments response data collection by using coordinated sonar exposure experiments.

Field efforts in Southern California began in 2017, where the team deployed the first Lander2 tag on a fin whale that was then subsequently exposed to helicopter dipping sonar. The Lander2 tag captures high-resolution diving, movement and location data, but does not record acoustics. During 2018, the project team completed five productive field efforts, including successfully collecting opportunistic exposure data from three Lander2 tags deployed on Cuvier's beaked whales. The team also began developing the processes required to combine animal movements and diving behavior from tags, tracks from ships and helicopters participating in exercises, and archived acoustic data from the range hydrophones and/or acoustic recording tags within a unified framework.

Field tagging efforts and data analyses continued during 2019. Two more Lander2 tags were deployed (one on a Cuvier's beaked whale and one on a fin whale) along with five next-generation Sound and Motion Recording and Telemetry (SMRT) tags (all on Cuvier's beaked whales). The SMRT tags record acoustics in addition to depth, movement and GPS locations. All seven of the whales tagged in 2019 were exposed to operational Navy sonar, including both ship and helicopter sonar at a range of distances and while in a variety of behavioral states.

The team also worked with both the Naval Postgraduate School and NAEMO (Navy Acoustic Effect Model) analysts to model sonar received level estimates from the 2018 tag data, which did not include direct acoustic measurements. An added data analysis effort during 2019 focused on using the fine-scale movement and accelerometry data from the Landers tags deployed in 2017 and 2018 to evaluate the potential to identify foraging activity when acoustic data are not available.

After the first field effort of 2020, during which one SMRT tag was successfully deployed on a Cuvier's beaked whale, all subsequent field efforts planned for 2020 were canceled due to COVID-19 travel and work restrictions. The project team then productively redirected efforts to more detailed data analyses. While the original plan included a basic acoustic audit of SMRT tag data to capture animal sounds (e.g., click start/end times) and sonar pings, a more detailed audit was conducted that included differentiation of tagged animal versus conspecific animal clicks, buzz (prey capture attempt) identification, impulsive events and other anthropogenic sounds. The results of these detailed audits advance cue rate assessments and address some basic biology questions for Cuvier's beaked whales that are relevant to this and other Navy research. The team also progressed on accurately identifying foraging dives without acoustic data through the use of SMRT tags, which provide both acoustic and accelerometer data. The 2020 analysis period also provided time to identify suitable cetacean response models for processing extensive, multi-stream data sets earlier than planned.

During 2021, the project team resumed tagging efforts, continued data analyses and pursued statistical model refinements. An additional eight tags were deployed during the year (five on Cuvier's beaked whales and three on fin whales). Project tag deployments by the close of 2021 totaled 20, including both Lander2 and SMRT tags. The resulting data are being used to model behavior (e.g., dive cycles, foraging effort, displacement) as a function of received levels of, and distance to, MFAS.

> The final project report and publications will provide results that are directly applicable to risk function development for Navy compliance efforts.

While most project field work was completed by the close of 2021, one additional field effort was planned for January 2022. Acoustic audits of tags from late 2021 are near completion, sonar data are being compiled and all data will be integrated into the analytical framework as the project nears completion. A manuscript summarizing the detection of foraging dives without acoustics has been accepted for publication, and several others using data from this project are in preparation or will be started in 2022.

This project is contributing valuable high-resolution behavioral data, including accurate movements surrounding real MFAS exposure, for beaked and fin whales. This includes responses to

An SMRT tag attached to an adult male Cuvier's beaked whale.
Shannon N. Coates, NMFS/MarEcoTel permit 21163

novel sonar signal types, such as Continuous Active Sonar (CAS), and responses to explosives or other impulsive sounds. This project also provides collateral data, such as photographs, to related studies. Multiple publications reporting on data collected by this project thus far are available (see Publications sidebar).

The final project report and publications will provide results that are directly applicable to risk function development for Navy compliance efforts. Data analysis methods developed for use with these tags will ultimately be contributed to an existing online repository (http://animaltags.org/doku.php), along with documentation and instructional vignettes. These tools will be readily transferrable to other species and geographic regions where the Navy needs similar data to estimate the effects of its activities.

About the Principal Investigators

Greg Schorr, a research biologist at the Foundation for Marine Ecology & Telemetry Research, has been studying marine mammals for more than 20 years. His most recent focus has been using remotely deployed satellite tags to study beaked whale ecology and behavioral responses to anthropogenic sources of sound.

Erin Falcone, a research biologist at the Foundation for Marine Ecology & Telemetry Research, is a cetacean photo-ID specialist. Erin has been co-principal investigator on marine mammal studies at the Southern California Offshore Range since 2006.

Key collaborators: Stephanie Watwood, Karin Dolan, and the entire M3R team from the Naval Undersea Warfare Center; Stacy DeRuiter, Calvin University; Brenda Rone, Russ Andrews, David Sweeney, Shannon Coates and Alex Zerbini, Foundation for Marine Ecology & Telemetry Research.

Publications

Curtis, K.A., Falcone, E.A., Schorr, G.S., Moore, J.E., Moretti, D.J., Barlow, J. and Keene, E. (2020). Abundance, survival, and annual rate of change of Cuvier's beaked whales (*Ziphius cavirostris*) on a Navy sonar range. *Marine Mammal Science*, 37(2):399-419. DOI 10.1111/mms.12747.

Barlow, J., Schorr, G.S., Falcone, E.A. and Moretti, D. (2020). Variation in dive behavior of Cuvier's beaked whales with seafloor depth, time-of-day, and lunar illumination. *Marine Ecology Progress Series*, 644:199-214. DOI 10.3354/meps13350.

Publications acknowledging data

Barlow, J., Fregosi, S., Thomas, L., Harris, D. and Griffiths, E.T. (2021). Acoustic detection range and population density of Cuvier's beaked whales estimated from near-surface hydrophones. *The Journal of the Acoustical Society of America*, 149(1):111. DOI 10.1121/10.0002881.

Keen, E.M., Scales, K.L., Rone, B.K., Hazen, E.L., Falcone, E.A. and Schorr, G.S. (2019). Night and day: Diel differences in ship strike risk for fin whales (*Balaenoptera physalus*) in the California Current system. *Frontiers in Marine Science*, 6:730. DOI 10.3389/fmars.2019.00730.

The Effects of Underwater Explosions on Fish

Principal Investigators:
Peter H. Dahl, Keith Jenkins
Project Status: Ongoing, Project 26

NEED

N-0103-16: Marine Species Hearing Research Related to the Acoustic Effects Criteria

The Navy needs new data to improve the Navy's acoustic and explosive impact assessments for marine species. Priority interest is in species for which no, or insufficient, data are available. Areas of focus include audiograms of hearing capability in marine species, data on temporary threshold shift (TTS) at multiple frequencies, and effects to fish from the detonation of explosive devices of various charge sizes, depths and distances to the subjects. The Navy needs data on the effects of explosives on fish in order to update risk threshold criteria, reduce the uncertainty of the current impact assessments and validate mitigation measures.

PROJECT

U.S. Navy training and testing activities can include underwater explosive charges, and additional data are needed regarding the effects of such explosives on fish. A multidisciplinary team of researchers has designed field-based experiments for collecting data needed to develop guidelines and threshold criteria for effects on fish resulting from exposure to underwater explosives.

The project team is studying explosive effects on fish species with differing characteristics (e.g., swim bladder morphology) and size, at varied water depths and distances from the source. Tissues from exposed fish (as well as from an extensive set of control samples) are examined using well-established necropsy techniques. Careful attention has been focused on ensuring a statistically valid experimental design. This approach will provide a broader and more comprehensive understanding of potential effects and dose-response relationships.

The Phase I trials completed in 2018 used Pacific sardines (*Sardinops sagax*), held in cages deployed at 10 meters depth at multiple distances from the explosive source. Results from those trials were presented at the 2019 Effects of Noise on Aquatic Life Conference.

Phase II trials were conducted during September 2019 following protocols and experimental design informed by the 2018 study. The target fish for these trials were Pacific mackerel (*Scomber japonicas*), representing a slightly

Explosive gases breach the surface moments after detonation of 10-pound charge.
FISHEX

larger species and different morphology. Drawing upon Phase I results, necropsy and ear tissue preservation techniques were modified to help to refine Phase II results.

Work during 2020 focused on analyzing 2019 mackerel data. Initial analyses suggest different outcomes between the sardines from 2018 and the mackerel, despite similar test conditions. Factors contributing to these differences could include different acoustic propagation conditions between trial years and morphological differences between the two species. The first project manuscript was published in 2020 (see Publication sidebar for citation).

The third set of trials, originally planned for 2020 and delayed due to COVID-19 restrictions, was conducted in October 2021. The 2021 event again used Pacific mackerel. An opportunistic set of samples of wild sardines was also collected near the site when the sardines were discovered at the surface. This final round of testing benefitted from refined fish handling protocols, which were improved after each of the preceding field efforts. The team was able to investigate short-term survival after the explosion, onset of injury at a finer scale than the previous two trials and how fish depth affects susceptibility to injury. Data analyses were ongoing through 2021.

Two additional manuscripts were underway in 2021, one reporting results from the 2019 Pacific mackerel tests and the other focused on analyses of ear tissues. Publication is anticipated in 2022.

Work in 2022 will focus on completing data analyses from the 2021 field effort and preparing two additional manuscripts for publication, one on the 2021 results and the other providing an overall project review and recommended thresholds. Final results will support the Navy's fish criteria.

The results of this applied research and accompanying criteria will be immediately useful within the Navy environmental compliance process when quantifying potential explosive impacts to fish.

About the Principal Investigators

Peter H. Dahl is a senior principal engineer in the acoustics department at the University of Washington Applied Physics Laboratory, and professor in the University of Washington's Department of Mechanical Engineering. Dahl's research is in areas of acoustics with a primary focus on underwater sound. Dr. Dahl earned his Ph.D. from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution in 1989.

Keith Jenkins is a senior marine resource specialist at Naval Information Warfare Center Pacific. He has been conducting acoustic analyses for the Navy for almost 20 years and participates in developing Navy-wide acoustic effects criteria and thresholds. Mr. Jenkins has a B.S. and M.S. in biology from Old Dominion University, Virginia.

Key collaborator: Art Popper, University of Maryland.

Publications

Dahl, P.H., Jenkins, A.K., Casper, B., Kotecki, S.E., Bowman, V., Boerger, C., Dall'Osto, D.R., Babina, M.A. and Popper, A.N. (2020). Physical effects of sound exposure from underwater explosions on Pacific sardines (*Sardinops sagax*). *The Journal of the Acoustical Society of America*, 147(4):2383. DOI: 10.1121/10.0001064.

Measuring the Effect of Range on the Behavioral Response of Marine Mammals Through the Use of Navy Sonar

Principal Investigator: Stephanie Watwood
Project Status: Ongoing, Project 30

NEED

N-0135-17: Understanding the Range to Effect on the Behavioral Response of Marine Mammals from Sonar Exposure

Results from previous behavioral response studies indicate that the context in which marine mammals experience exposure to acoustic sources could affect their response. In particular, the Navy needs information on how the range (distance) of the sound source to the animal may affect behavioral response. Behavioral response data from a variety of operational Navy sources such as hull-mounted sonar, dipping sonar, and other types are needed. The Navy needs improved behavioral response data in order to update risk threshold criteria and reduce the uncertainty of the current impact assessments.

PROJECT

While data from several Navy-funded projects have documented cetacean responses, particularly by Cuvier's and Blainville's beaked whales, to mid-frequency active sonar (MFAS) from ships, data from some field efforts have raised questions about whether those responses were based on received levels alone or other factors. Some data indicate that a given animal can react differently to similar exposures (i.e., within the same range of received sound levels) depending on the sonar source itself and the distance the animal is from the source.

This project is conducting coordinated sonar exposure experiments (CSEE) using a lower source level sonar than hull-mounted ship sonar, deployed at multiple, pre-defined distances from tagged animals. The effort is closely coordinated with another LMR-funded project that is using high-resolution, medium-duration monitoring tags to record behavioral responses of Cuvier's beaked whales and fin whales during Navy training and testing activities. That project (Project 23, page 47)

The moment before a tag is deployed on a Cuvier's beaked whale.
Brenda Rone, NMFS/MarEcoTel permit 21163

Fin whale.
Marjorie Foster, NOAA

has employed an opportunistic exposure (OE) approach, in which animals are tagged prior to Navy training activities in order to document the behavior of animals before, during and after the actual Navy exercises. The data from the CSEEs will augment the OE data.

The CSEE project includes both exposure and control scenarios for helicopter-deployed dipping sonar, which is frequently used during training on the Southern California Antisubmarine Warfare Range (SOAR). Standard mitigation measures are conducted prior to all CSEEs, as outlined in the Navy's Letter of Authorization under the Marine Mammal Protection Act.

The tagging team from Project 23 has been deploying the high-resolution, behavior recording tags on whales on SOAR to collect animal response data. The two species of particular interest are Cuvier's beaked whales (*Ziphius cavirostris*) and ESA-listed fin whales (*Balaenoptera physalus*). After successfully tagging, the team would coordinate with the helicopter crews that work with dipping sonar. Using tag location data, the team would calculate a proposed dipping location for the helicopter crew.

During 2018, data were collected in coordination with three helicopter dips. These were for two tagged Cuvier's beaked whales and included two exposure dips and one silent dip. This type of coordination enables more finely detailed data on the sonar sources regarding time, distance and the source characteristics.

In 2019, the teams completed three CSEEs with helicopter dipping sonar on Cuvier's beaked whales, filling in missing exposure distances collected from the opportunistic approach taken in Project 23. Additionally, one control CSEE was conducted on a tagged fin whale. Data analysis efforts included reviewing Marine Mammal Monitoring on Ranges (M3R) archive files for the presence of sonar during the tagging periods of 2017-2019. The team also began comparing received levels, using multiple models, to assess variance between modeling approaches and compare that with received levels from the acoustic tags. The coordination with the dipping helicopters in these cases provides a precise source location and depth, which combined with the Fastloc® GPS locations from the tagged whale makes this data set ideal for conducting this type of test.

Additional CSEEs planned during 2020 were canceled due to COVID-19 travel and work restrictions. The team productively pivoted its focus to detailed data analyses and evaluation of received level modeling options. The received level

models from the Naval Postgraduate School (NPS) and from the Navy Acoustics Effects Model (NAEMO) were compared. Based on the analysis conducted, the team has decided to move forward with the NAEMO for estimating received levels for the non-acoustic tags. During 2021, the team made significant progress refining analysis methods and continued to process data collected thus far. A comparison of modeled and recorded received levels from sonar exposures was presented at a scientific conference in March 2021 for feedback from the scientific community on the methodology.

> The results will allow the Navy to better estimate the potential effects of sonar use on Cuvier's beaked whales and fin whales within the Southern California ranges.

A report on the methods, data analyses and model outcomes is projected for completion in mid-2022. Manuscripts for publication will also be prepared during 2022 and beyond.

As with the OE project, data from this project will be analyzed within a unified framework that combines whale movements and diving behavior from tags, tracks from platforms participating in the experiments and archived acoustic data from the range hydrophones and/or acoustic recording tags. Data will be assessed on both the long-term (foraging interruption) and short-term (order of seconds to minutes) to assess the full spectrum of responses. Combining these pieces will help to predict the likelihood of a behavioral change as a function of sonar use, including variables such as sonar type, received level (recorded on animal or estimated), distance of the transmitting platform, and the sonar exposure characteristics. The team continued to make progress on developing a hierarchical hidden Markov model framework and plans to present the methods at multiple meetings in 2022.

Adding this CSEE effort to the ongoing OE project is generating larger samples of high-resolution behavioral data, including both transmission and non-transmission control experiments in predictable patterns at multiple, predetermined distances. This approach enhances assessment of range to effect on behavioral response and continues development of the CSEE methodology.

The results will allow the Navy to improve impact assessments and better estimate the potential effects of sonar use on Cuvier's beaked whales and fin whales within the Southern California ranges.

About the Principal Investigator

Stephanie Watwood manages the Marine Mammal Monitoring on Navy Ranges (M3R) Program in the Ranges, Engineering and Analysis Department at the Naval Undersea Warfare Center (NUWC). She has extensive experience in collecting and analyzing cetacean acoustic data, particularly related to cetacean behavior. Dr. Watwood holds a Ph.D. in biological oceanography from the Massachusetts Institute of Technology-Woods Hole Oceanographic Institution Joint Program in Oceanography/Applied Ocean Science.

Key collaborators: Karin Dolan, Joseph Fayton, NUWC; Greg Schorr, Erin Falcone, Brenda Rone, Russ Andrews, David Sweeney and Shannon Coates, Foundation for Marine Ecology & Telemetry Research (MarEcoTel); Stacy DeRuiter, Calvin University.

Behavioral Assessment of Auditory Sensitivity in Hawaiian Monk Seals

Principal Investigators:
Colleen Reichmuth, Jillian Sills
Project Status: Ongoing, Project 32

NEED

N-0103-16: Marine Species Hearing Research Related to the Acoustic Effects Criteria

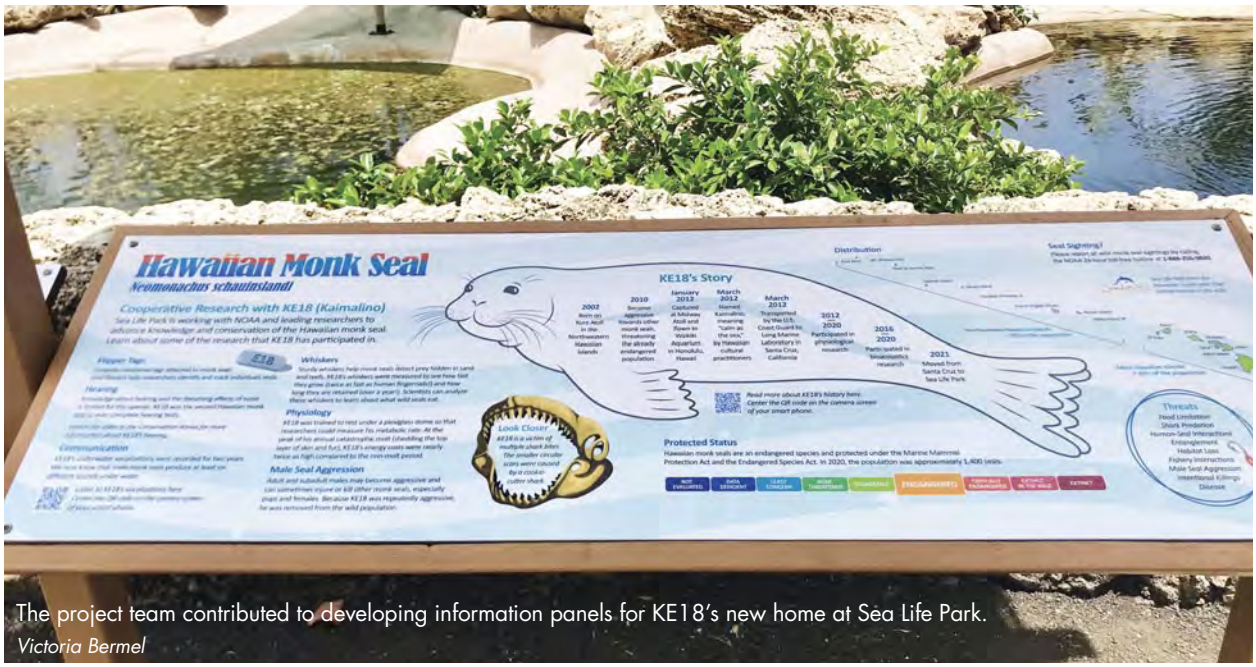
The Navy needs new data to improve the Navy's acoustic and explosive impact assessments for marine species. Priority interest is in species for which no, or insufficient, data are available. Areas of focus include audiograms of hearing capability in marine species, data on temporary threshold shift (TTS) at multiple frequencies, and effects to fish from the detonation of explosive devices of various charge sizes, depths and distances to the subjects. The Navy needs improved hearing data in order to update risk threshold criteria, reduce the uncertainty of the current impact assessments and validate mitigation measures.

PROJECT

Navy training and testing activities occur in waters surrounding the Hawaiian Islands, including areas overlapping habitat for the ESA-listed Hawaiian monk seal (*Neomonachus schauinslandi*). However, there are few bio-acoustic data available for the monk seal, including information about hearing abilities and the production of underwater sounds. The lack of substantive information currently available for the species makes it difficult to make science-based decisions relative to the possible effects of naval and other anthropogenic activities on these marine mammals.

This project has succeeded in obtaining reliable measures of auditory sensitivity—across the full frequency range of hearing—for a specially trained adult male Hawaiian monk seal, KE18. The resulting data has been used to generate both underwater and in-air audiograms that will help to support impact assessments of the Hawaiian monk seal's

Monk seal KP2 at Long Marine Laboratory.
Colleen Reichmuth, NMFS permit 19590



The project team contributed to developing information panels for KE18's new home at Sea Life Park.
Victoria Bermel

hearing range and sensitivity to sound. This project has also included evaluation of audio and video recordings of the KE18's underwater sound production to provide previously unavailable descriptions of underwater calls emitted by male monk seals. The project now has been extended to enable similar underwater measurements with a second Hawaiian monk seal.

The work on this project began in 2018 with behavioral testing of KE18's underwater hearing capability and provided an initial description of underwater sound production for the species. During 2019, project efforts were directed to in-air hearing measurements, as well as continuing sound production recordings in water. Work during 2020 focused on measuring masked hearing thresholds in air and completing analysis of the underwater call repertoire. Two comprehensive manuscripts reporting on the work were prepared in 2020 and published in 2021 (see Publication sidebar for citations).

The underwater hearing test results from KE18 revealed that Hawaiian monk seals hear better at lower frequencies than previously believed, although with poorer sensitivity than that of related species. Similarly, the in-air hearing test results suggested that monk seals (in the Monachinae subfamily) have low sensitivity to airborne sounds, in contrast to northern seals in the Phocinae subfamily that have exceptional in-air hearing. The audio and video recordings of KE18's underwater sound production enabled the project team to characterize previously unknown call types. Replicating the underwater studies with a second trained seal will be a valuable addition to those results.

KE18 was successfully transported back to Hawaii and Sea Life Park in 2021. The project team contributed to developing information panels that were installed at KE18's new home at the park.

Shortly after KE18's return, a new male monk seal, KP2, was transported from the University of Hawaii's Waikiki Aquarium to the University of California Santa Cruz's Long Marine Laboratory. Both male seals in this project have been deemed non-releasable by the National Marine Fisheries Service and are housed in human care for zoological display, public education and conservation research.

Following KP2's arrival at Long Marine Laboratory, the team helped him adjust to his new surroundings. The planned hearing and sound studies will be conducted during 2022. The key tasks in this stage of the project will be measuring an underwater audiogram and recording and analyzing underwater sound production.

> The results of this effort allow the Navy to improve impact assessments and better estimate the potential acoustic effects of Navy training and testing activities on Hawaiian monk seals.

The results of this effort will provide a comprehensive understanding of hearing in endangered Hawaiian monk seals and will allow the Navy to improve impact assessments and better estimate the potential acoustic effects of Navy training and testing activities on Hawaiian monk seals.

About the Principal Investigators

Colleen Reichmuth is an animal behaviorist at the Institute of Marine Sciences, University of California at Santa Cruz. She has extensive experience conducting auditory research with marine mammals with a focus on behavioral psychoacoustic methods. Her expertise includes training marine mammals for voluntary participation in research, conducting field studies of animal acoustic communication and promoting best practices for the care and welfare of research animals. Dr. Reichmuth earned her Ph.D. in ocean sciences at the University of California at Santa Cruz.

Jillian Sills is a project scientist at the University of California at Santa Cruz. She is a skilled bioacoustican who has conducted auditory research with walruses, harbor seals, spotted seals, ringed seals, bearded seals, monk seals, sea lions and sea otters. She also studies sound production patterns in captive and free-ranging pinnipeds and conducts research on the effects of noise on marine mammals. Dr. Sills earned her Ph.D. in biological oceanography at the University of California at Santa Cruz.

Key collaborators: Graduate students Kirby Parnell, University of California, Santa Cruz and University of Hawai'i; Brandi Rusher, University of California, Santa Cruz, and monk seal specialists Traci Kendall and Beau Richter, University of California, Santa Cruz. The National Marine Fisheries Service and Sea Life Park Hawaii helped to facilitate this research program.Maryland.

Publications

Sills, J.M., Parnell, K., Ruscher, B., Lew, C., Kendall, T.L. and Reichmuth, C. (2021). Underwater hearing and communication in the endangered Hawaiian monk seal *Neomonachus schauinslandi*. *Endangered Species Research*, 44:61-78. DOI 10.3354/esr01092.

Ruscher, B., Sills, J.M., Richter, B.P. and Reichmuth, C. (2021). In–air hearing in Hawaiian monk seals: implications for understanding the auditory biology of Monachinae seals. *Journal of Comparative Physiology A*, 207(4):561-573. DOI 10.1007/s00359-021-01498-y.

Collection of Auditory Evoked Potential Hearing Thresholds in Minke Whales

Principal Investigator: Dorian Houser
Project Status: Ongoing, Project 37

NEED

SOST Need: Development of Audiograms for Mysticetes

There is a need to improve understanding and measurement of auditory capabilities and sensitivities of low-frequency cetaceans (mysticetes) to anthropogenic sound. Research necessary to generate a mysticete audiogram includes developing and validating finite element modeling (FEM) methods, developing and testing *in situ* auditory evoked potential (AEP) measurement methods for mid- and high-frequency hearing sensitivities of mysticetes, developing tools for AEP measurements below 1 kHz, evaluating behavioral response methods and identifying other appropriate approaches or methods.

PROJECT

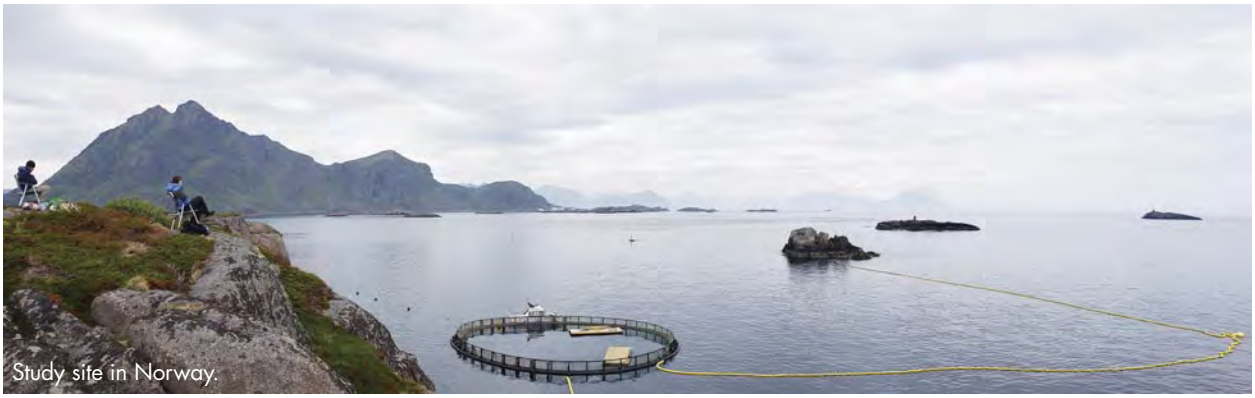
This project, funded in cooperation with the Subcommittee on Ocean Science and Technology Interagency Task Force on Ocean Noise and Marine Life (SOST ITF-ONML) (see the Partnerships section, page 116, for more information), is focused on obtaining *in situ* auditory evoked potential (AEP) measurements of the hearing sensitivity of mysticetes. AEP methods involve measuring small voltages that the brain and auditory system generate in response to hearing a sound. Using AEPs to determine hearing sensitivity has been common practice in human and terrestrial animal research for decades. Over the last two decades, the technology also has been used routinely to test hearing in odontocetes (toothed whales), both small (e.g., dolphins and porpoises) and large (e.g., beluga, pilot and killer whales). The project team plans to obtain AEP hearing thresholds for minke whales (*Balaenoptera acutorostrata*), which will provide the first direct measurement of hearing in a mysticete (baleen whales).

The project team will attempt to measure the hearing of minke whales temporarily confined in a fjord off the Norwegian coast. They will use AEP methods specifically modified for these animals. The research focuses on small (3–5 meters long) juvenile minke whales because they are more suitable for handling, should have good hearing capabilities and the chance of success with the AEP methods increase (because of their smaller size). Juvenile minke whales are similar in size to wild beluga whales that have been previously captured for AEP testing.

Modifications to AEP methods will largely consist of adapting approaches previously worked out on smaller cetaceans with a special focus on sound delivery and AEP recording at lower frequencies. Researchers will use both broadband and narrowband acoustic stimuli to optimize procedures and determine the frequency-specific information needed for a minke audiogram. Upon conclusion of testing, each whale will be fitted with a satellite tag to monitor its behavior after release.

Following a one-year delay due to COVID-19 pandemic restrictions, the project conducted a feasibility field effort in 2021. This work, which included securing and deploying necessary

Minke whale.
Wayne Hoggard, NOAA/NMFS


Study site in Norway.

equipment, provided valuable information for refining the field plan. Establishing the capture site, which requires positioning and repositioning large, weighted nets, proved to be more time-consuming than estimated. The combined length and weight of all the nets exceeds two kilometers and 20 tons, respectively. The team worked throughout the remainder of 2021 identifying solutions to logistical issues and shared recommendations with funding agencies, including a coordinated public outreach strategy, ahead of the next field effort. Based on the 2021 results and recommendations, the funding agencies approved a second field effort, which is planned for 2022.

> The results of this study will be invaluable to regulators, scientists, the U.S. Navy and others concerned with the potential impact of sound on mysticetes.

This study's results will be invaluable to regulators, scientists, the U.S. Navy and others concerned with the potential impact of sound on mysticetes. Determining frequency-specific information, particularly the upper-frequency limit of hearing and the region of best sensitivity, will provide data needed for validating models of hearing in mysticete whales.

Additionally, determining low-frequency thresholds will provide information needed to establish auditory weighting functions for mysticetes, which currently lack empirical data on which to base the functions. Techniques developed during the minke whale hearing tests also will facilitate future audiometric measurements on other mysticete species. Audiometric data and methods developed for testing of mysticete hearing will be described in peer-reviewed publications.

About the Principal Investigator

Dorian Houser is the Director of Biologic and Bioacoustic Research at the National Marine Mammal Foundation (NMMF). Dr. Houser has spent nearly two decades in the study of how anthropogenic sound affects marine mammals and has been involved in the development of numerous environmental impact statements for the U.S. government. He earned his Ph.D. in biology from the University of California, Santa Cruz.

Co-PIs are Jason Mulsow, Ph.D. (NMMF), Petter Kvadsheim, Ph.D. (Norwegian Defence Research Establishment), Lars Kleivane, MSc (LKARTS Norway), James Finneran, Ph.D. (U.S. Navy Marine Mammal Program) and Rolf Arne Ølberg, DVSc (Kristiansand Dyrepark).

Towards a Mysticete Audiogram Using Humpback Whales' Behavioral Response Thresholds

Principal Investigators:
Rebecca Dunlop, Michael Noad
Project Status: Ongoing, Project 38

NEED

SOST Need: Development of Audiograms for Mysticetes

There is a need to improve understanding and measurement of auditory capabilities and sensitivities of low-frequency cetaceans (mysticetes) to anthropogenic sound. Research necessary to generate a mysticete audiogram includes developing and validating finite element modeling (FEM) methods, developing and testing *in situ* auditory evoked potential (AEP) measurement methods for mid- and high-frequency hearing sensitivities of mysticetes, developing tools for AEP measurements below 1 kHz, evaluating behavioral response methods and identifying other appropriate approaches or methods.

PROJECT

This project, funded in cooperation with the SOST ITF-ONML (see the Partnerships section, page 116, for more information), is addressing the portion of the need related to evaluating behavioral response methods for generating an audiogram. The project team will measure the behavioral response of migrating humpback whales (*Megaptera novaeangliae*) to tones of various frequencies to infer their hearing sensitivity at each frequency. These behavioral response experiments will be a proxy for audiometric measurements to estimate hearing sensitivity.

The project team is conducting a series of field experiments in a unique site near Queensland, Australia. The team's field plan includes a team of land-based visual observers who record the movement and dive behaviors of focal groups of whales during the experiments. Some of the whales will also be tagged from a small research vessel to record fine-scale changes in movement and dive behavior as well as their acoustic environment.

Breaching humpback whale during a field experiment.
Hearing in Humpbacks Acoustic Research Collaboration 2021, permit WA0009021

Successful deployment of a DTAG onto a female humpback whale.
Hearing in Humpbacks Acoustic Research Collaboration 2021, permit WA0009021

The team will deploy a sound source from a vessel, playing upsweep tones at various frequencies to approaching whales. The source level of the tone will remain constant throughout the experiment. The playback will begin when the whales are too far from the source to hear it (based on assumptions about their hearing in noise conditions). As the whales approach the sound source, the received level of the tones at the focal group will increase until, at some point, the tones become audible to the whales. At this point, it is expected that the focal group will change behavior by avoiding the source vessel. This will be repeated multiple times for each frequency, using different groups of whales. Experiments will also be carried out in which the vessel will be present, but no tones are transmitted, to provide a control sample. This will help quantify the behavioral response, as well as make sure the response is to the tone stimulus and not the presence of the vessel.

A four-phase experimental routine will be followed:

1. Tagging phase—Attempt to tag an adult whale in the experimental group.
2. Before phase—Follow the group without interference to observe normal behavior and move the source vessel into position close to the projected path of the group.
3. During phase—Operate the sound source as the group approaches until the signal is detected and the whale responds by avoiding the acoustic source/vessel.
4. After phase—Conduct additional *in situ* acoustic measurements and recover tag.

The study site provides several benefits: lower noise levels than many ocean sites, an extensively measured and characterized acoustic environment, and 11 previous field seasons on humpback whale behavior and acoustics which provide a wealth of background data on whale

movements, normal behaviors and abundance. These benefits support tagging efforts and facilitate detecting responses to the sound source.

The original project schedule included a full field season in 2020. However, the field effort required skilled observers who would need to travel to, and be lodged in, the area. When the COVID-19 pandemic restrictions prevented travel into Australia and Queensland, as well as severely limiting lodging options, the core project team needed to revise their 2020 plan. Rather than lose an entire year, the two principal investigators conducted a pilot effort without assistants. Working at the planned site, they tested equipment and evaluated signal transmission and measurement under real field conditions.

> The resulting information on humpback whale hearing will help regulators, industry and the U.S. Navy to model the potential effects of noise-producing activities on humpback whales.

The 2021 field season was also affected by pandemic travel restrictions, which reduced volunteer staffing for the land-based observers by approximately one-third. The results of the test runs in 2020, however, significantly improved on-water efficiency in the 2021 field efforts. The team completed 15 experiments: one control (no signal), five 1 kHz, six 4 kHz and three 16 kHz. Although tag deployment was successful (three out of three attempts resulted in a tagged whale), the tags did not release and the data were not recovered.

With the experimental concept demonstrated, the team plans to return to the field in 2022. With some travel restrictions easing, the team plans to increase the land-based effort, which will increase visual data. Tag issues also are being addressed for the next season.

The resulting information on humpback whale hearing, including data on how well humpback whales can hear under ambient conditions, will help regulators, industry and the U.S. Navy to model the potential effects of noise-producing activities on humpback whales. Results also will inform hearing models already developed for mysticetes, will help to validate and integrate the modeling approach with real data, and will provide a robust measure of humpback whale responses to tones under realistic conditions. Hearing data can also be incorporated into models used to assess the effects of various sound sources on mysticete behavior and physiology.

About the Principal Investigators

Rebecca Dunlop is an associate professor in physiology and animal behavior at the School of Biological Sciences, University of Queensland, Australia. Dr. Dunlop earned her Ph.D. in neuroethology from The Queen's University of Belfast, Ireland. Her current research focuses on humpback whale behavior, social communication, physiology and the effects of anthropogenic noise.

Michael Noad is a professor at the School of Veterinary Science, University of Queensland, Australia. Dr. Noad earned his Ph.D. from the University of Sydney, Australia. His current work focuses on the evolution and function of humpback whale song, population ecology and effects of noise.

Temporary Threshold Shifts in Underwater Hearing Sensitivity in Freshwater and Marine Turtles

Principal Investigators:
Aran Mooney, Wendy Piniak
Project Status: Ongoing, Project 40

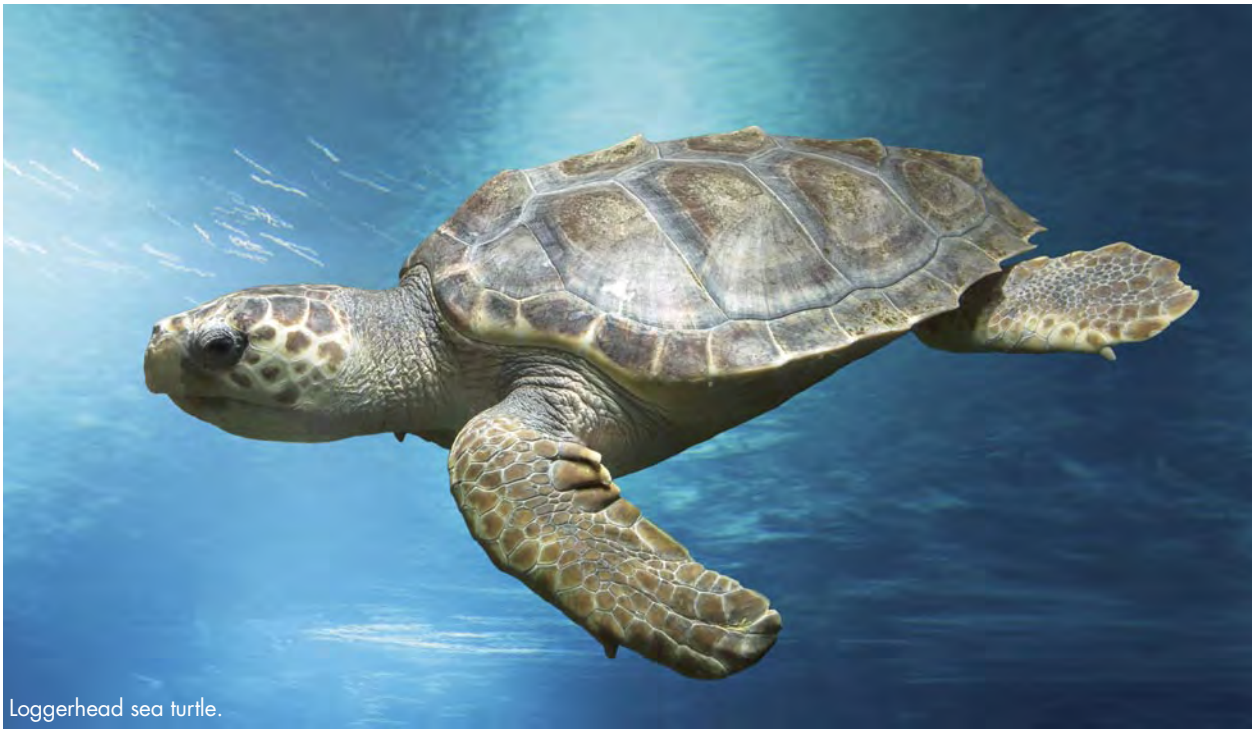
NEED

N-0208-19: Turtle TTS Feasibility Study

The Navy, National Marine Fisheries Service (NMFS) and other federal agencies require quantitative thresholds to examine the potential impacts of underwater sound on protected species. Basic audiometric information is available for some sea turtle species, however, data on the susceptibility of sea turtles to noise induced hearing loss (threshold shifts) is lacking. There is a need to obtain auditory temporary threshold shift (TTS) information for sea turtles. Due to their protected status under the Endangered Species Act, it is necessary to first determine the feasibility of generating TTS in a closely related surrogate—a non-ESA listed turtle species (e.g., red-eared slider, eastern painted turtle, pond slider, etc.). If feasible, steps to obtain TTS information for an ESA-listed sea turtle may be undertaken in follow-on research efforts.

PROJECT

This project is examining auditory TTS in two species of freshwater aquatic turtles and will potentially provide the cumulative sound exposure levels and durations that induce TTS in these species. The work also will include examining the turtles' ear anatomy to support physiological comparisons between freshwater and marine turtle hearing apparatus. This will help to identify potential TTS susceptibility of sea turtles based on freshwater turtle data. Results will provide researchers, managers and stakeholders critical data to improve estimates of acoustic effects to both freshwater and sea turtles, and to inform the development of appropriate mitigation measures to reduce potential effects to sea turtles from low-frequency anthropogenic sound. This project is co-funded by the LMR program and NOAA.



Loggerhead sea turtle.

Red-eared slider.
Andria Salas

Initial underwater hearing measurements and TTS assessments are being conducted with two freshwater turtle species—the eastern painted turtle (*Chrysemys picta picta*) and red-eared slider (*Trachemys scripta elegans*). Physiological auditory evoked potential (AEP) methodology is being applied. Testing two species increases sample sizes, which supports both developing robust TTS measurement methods and identifying if there are methodological challenges/differences between the species. Additionally, comparing TTS onset in the two surrogate taxa contributes to understanding potential TTS variability between turtle species. The AEP measurements are being followed by sound exposure trials and anatomical imaging as summarized below.

- **AEP testing**

  Baseline hearing sensitivity is measured by recording AEPs, a rapid, non-invasive technique that can be used to measure hearing in a diverse array of taxa including fishes, squid, seabirds, odontocetes, manatees, pinnipeds, sharks and sea turtles.

  Initial hearing thresholds to determine a baseline audiogram are measured at a variety of frequencies between 50 and 5,000 Hz (with additional frequencies added as needed). This method is well-established and encompasses the full anticipated range of turtle hearing. At each frequency, sound levels are decreased until AEP responses can no longer be detected (threshold).

> This work will help to identify potential TTS susceptibility of sea turtles based on freshwater turtle data.

- **Sound exposure trials**

  Sound exposure trials explore the durations and sound pressure levels required to induce TTS onset and develop an empirically based predictive curve of TTS onset. The trials expose turtles to broadband white noise that spans

Eastern painted turtle.
Andria Salas

their auditory frequency range and is likely to cause TTS. Fatiguing noise sound pressure levels (SPLs) start at lower levels and increase or decrease as needed to induce TTS (up to certain SPLs), after which durations are increased or decreased to achieve targeted overall sound exposure levels (SELs). These data are being used to define the hearing sensitivity curve of both species.

- **Anatomy**

  The project is also examining the similarities and potential differences of the auditory anatomy of control animals and those exposed to sound to identify potential short- and long-term anatomical effects of TTS. Auditory hair-cell damage and loss in some marine taxa have served as indicators of sound exposure and these indicators could apply to turtles. Defining methods by which to assess damage would support examining other turtle species in the future. Three methods are being explored. The first involves using x-ray computed microtomography (μCT) to examine morphology on the micro-scale. Although μCT on turtle ears has not been previously conducted and using these methods to gauge hair cell health and status may be challenging, it offers a good, non-invasive first step. Second, researchers may seek to image auditory hair cells using fluorescent immunohistochemical procedures (which provide high-resolution imaging at a cellular level) and other readily available methods used in an array of animals, from fish to invertebrates and mammals. The third imaging option is scanning electron microscopy.

Based on the results of these efforts, the team will explore dose-dependent effects to begin to create a noise-based, dose-dependent model of TTS. This will allow regulators and data users to predict the sound levels and durations that may produce

TTS onset in turtle species. Project products also will outline the methods likely needed to induce and measure TTS in sea turtles, if feasible.

Although work in 2020 was delayed due to permit delays resulting from COVID-19 restrictions, the team secured permits and acquired both turtle species. Initial work focused on refining testing methods, identifying variables to be addressed in testing and evaluating baseline threshold for the red-eared sliders. These tests were followed by AEP recordings and initial TTS onset evaluation.

> The project will provide protocols that will contribute to future investigations of noise-induced hearing loss in other turtle species, including sea turtles.

During 2021 the project team completed AEP and TTS evaluations in red-eared sliders and eastern painted turtles. Results were collected into a TTS SEL (SPL vs duration) matrix by species. The matrix provides a visual presentation of the test frequency and exposure time by sound pressure level for each animal tested. The team began preparing manuscripts for TTS results by species. Methods for evaluating auditory anatomical effects, such as hair-cell changes, were being addressed, with evaluations expected to continue in 2022.

Work in 2022 will also focus on additional tasks, including increasing the sample sizes, evaluating a few more frequencies, and further investigating TTS onset, growth and recovery with narrowband sounds. The result will be a composite audiogram and TTS curve for freshwater turtles, and a recommended interim TTS threshold offset when applying the curve to sea turtles. Manuscripts discussing results will be completed and submitted for peer-reviewed publication. This will provide guidance on how to revise the sea turtle criteria for the Navy's acoustic effects analysis.

Because no TTS data currently exist for turtles, the audiograms and TTS data produced by this research will inform analyses of the effects of sound-producing activities on sea turtles and provide appropriate data when developing the next phase of TTS criteria. The project will also provide protocols that will contribute to future investigations of noise-induced hearing loss in other turtle species, including sea turtles.

About the Principal Investigators

Aran Mooney is an associate scientist in the biology department at the Woods Hole Oceanographic Institution, where he leads the Sensory Ecology and Bioacoustics Laboratory. His research addresses how marine animals detect and use sound and how animals may be affected by anthropogenic noise. Dr. Mooney holds a Ph.D. in zoology (marine biology emphasis) from the University of Hawaii.

Wendy Dow Piniak is a biologist at NOAA's NMFS. Dr. Piniak's research focuses on sea turtle acoustic ecology. She has experience measuring turtle hearing and conducting field studies examining sea turtle behavioral responses to sound. Dr. Piniak holds a Ph.D. in marine science and conservation from Duke University.

Frequency-dependent Underwater TTS in California Sea Lions

Principal Investigator: Ron Kastelein
Project Status: Ongoing, Project 45

NEED

N-0224-20: Frequency-dependent, Underwater, Temporary Threshold Shift in California Sea Lions

California sea lions commonly occur all along the western coast of the continental United States of America, including in Navy training and testing areas. Because there has been limited research on the susceptibility of California sea lion hearing to underwater sound, measuring temporary threshold shift (TTS), the Navy needs additional data to determine appropriate criteria for impact modeling. Data that characterize frequency-dependent underwater TTS across the frequency hearing range of California sea lions are particularly needed.

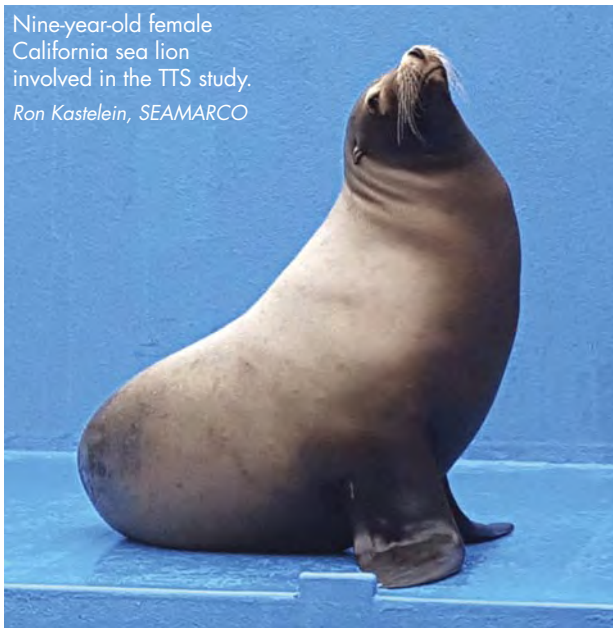
PROJECT

Navy acoustic impact assessments apply auditory weighting functions, similar to those used in assessing risk to human hearing, to predict the occurrence of TTS and permanent threshold shift (PTS) as functions of frequency. Threshold shift is one of the few direct measures of adverse effects of intense sound on hearing. The associated weighting functions are mathematical functions that emphasize, or "weight," noise at different frequencies according to the listener's susceptibility to noise at that frequency. Direct measurements of TTS in representative marine mammal species—across a broad spectrum of sound frequencies—are needed to support the TTS/PTS thresholds and weighting function derivations.

This project is testing how sounds of different frequencies may affect the underwater hearing of California sea lions (*Zalophus californianus*).

The goals of the project are to

1. Establish underwater behavioral audiograms (hearing thresholds over the entire hearing frequency range of a species) for two more California sea lions. Currently behavioral audiograms exist for only four animals
2. Determine the TTS susceptibility of California sea lions over their entire hearing range
3. Determine TTS onset sound exposure levels (SEL), a unit that incorporates both the sound level and the exposure duration, and TTS growth after exposure to sounds of various frequencies and SELs
4. Based on the information derived in items 1–3, construct equal TTS curves (one of which is the TTS onset curve), which can be used to produce an auditory weighting function for California sea lions
5. Determine which hearing frequency is most affected by each fatiguing sound frequency that sea lions are exposed to
6. Determine the recovery rate of hearing after the fatiguing sounds stop



Nine-year-old female California sea lion involved in the TTS study.
Ron Kastelein, SEAMARCO

Two-year-old male California sea lion involved in the TTS study.
Ron Kastelein, SEAMARCO

7. Test the equal-energy assumption, which will investigate whether exposure to the same SEL, but composed of different sound pressure level (SPL) and exposure duration combinations, elicits the same TTS
8. Test the effect of duty cycle (percent of total time sound is being produced) on TTS.

> This approach is similar to the methods used in studies of harbor seals and harbor porpoises, so results can be compared directly among the three species.

Two California sea lions, an adult female and a young male, with excellent hearing are being tested within a pool complex designed for acoustic studies. The animals are exposed to the fatiguing sounds and their hearing is tested pre- and post-exposure. The fatiguing sounds are continuous 1/6th-octave noise bands. Fatiguing sounds with the center frequencies 0.6, 1, 2, 4, 8, 16, 32 and 40 kHz are being tested, with a one-hour exposure duration. This approach is similar to the methods this team used in previous LMR-funded studies of harbor seals (*Phoca vitulina*) and harbor porpoises (*Phocoena phocoen*a), so results can be compared directly among the three species.

The equal-energy assumption study is collecting data to address potential effects of naval sonar that often operates for shorter durations and at higher sound levels. This study is evaluating two frequencies (4 kHz and 8 kHz) with five exposure durations (10, 20, 40, 64 and 80 minutes) with five different SPLs: all duration and SPL combinations leading to the same SEL.

Six duty cycles have been tested: 2.5 (representative duty cycle of 53C sonar), 60, 70, 80, 90 and 100 percent. Assessing duty cycle effect for the 4 and 8 kHz exposures will provide data on both the closest frequency to the actual signal of interest (4 kHz) and the scalability of the TTS as a function of duty cycle at 8 kHz.

During 2020, data collection from fatiguing sound at three frequencies—2, 4 and 8 kHz—was completed. The 4 and 8 kHz tests also provided data for the equal energy assumption study and the duty cycle study.

> The project will provide two behavioral audiograms for California sea lions with threshold for very low frequencies, which have not been measured before in this species.

During 2021, data collection at three additional frequencies—0.6, 1 and 16 kHz—was completed, and 32 kHz testing was initiated. Animal training for a new task, to measure sound exposures with sound recording DTAGs on the animal, was also initiated. This task requires training the animal to work with a harness to which the DTAGs will be attached. A task to determine the behavioral audiograms of the two California sea lions (CSL) was also initiated during 2021.

One manuscript reporting work from 2020 was published in 2021 (see Publication sidebar for citation). An additional manuscript on the 8 and 16 kHz work was submitted, with publication anticipated in early 2022.

Work planned for 2022 includes completing 32 and 40 kHz fatiguing sound exposures and data collection at very low frequencies for the audiograms. Additional data to be collected will compare the SPL measurements made with static hydrophones versus a DTAG mounted on the back of a swimming sea lion. Two manuscripts for results of TTS due to 0.6 and 1 kHz exposures and for the CSL audiogram will be submitted for publication. The manuscript for the 32 and 40 kHz exposures will be initiated.

This project will produce data (a 6 dB TTS onset curve) that can be used to improve the weighting function of otariids (eared seals) in the Navy's acoustic effects analysis criteria. Results will inform the validity of the equal energy rule and provide new insights regarding the effect of duty cycle on TTS. The project will also provide two behavioral audiograms for California sea lions with threshold for very low frequencies which have not been measured before in this species. These products will be directly applicable to all Navy environmental documents analyzing acoustic effects of tonal sounds (e.g., sonars) and broadband sounds (e.g., explosions).

About the Principal Investigator

Since 2002, Ron Kastelein, Ph.D. (University of Wageningen, The Netherlands) has been director and owner of SEAMARCO (Sea Mammal Research Company, Inc.) in The Netherlands. SEAMARCO specializes in applied acoustic research and energetic studies with marine fauna (mammals, fish, turtles and invertebrates).

Publications

Kastelein, R.A., Helder-Hoek, L., Defillet, L.N., Huijser, L.A.E., Terhune, J.M. and Gransier, R. (2021) Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 2 and 4 kHz: effect of duty cycle and testing the equal-energy hypothesis. *Aquatic Mammals*, 47(4):394-418. DOI 10.1578/AM.47.4.2021.394

New Start Projects

Standardizing Auditory Evoked Potential Hearing Thresholds with Behavioral Hearing Thresholds

Principal Investigator: Dorian Houser
Project Status: New Start, Project 47

NEED

N-0237-21: Standardizing Auditory Evoked Potential Hearing Thresholds with Behavioral Hearing Thresholds

Auditory Evoked Potential (AEP) methods are often used to study hearing capability in marine mammals and have expanded the available audiogram data for both captive and stranded animals. AEPs will continue to be the primary means by which sample sizes of audiograms increase because they are easier to implement than behavioral hearing threshold methods, and they can be used in untrained or stranded animals. However, due to the frequency–dependent elevation of AEP thresholds over behavioral hearing thresholds, AEPs are currently only used for defining species' upper–frequency limit of hearing. Thus, the Navy currently uses only behavioral hearing thresholds for assessing absolute hearing sensitivity. The ability to study and account for the differences in the two methods might enable AEP audiograms to be adjusted and made comparable to audiograms obtained from behavioral audiogram approaches. The Navy would benefit from a standardized approach by which AEP hearing thresholds could be adjusted and compared to behavioral thresholds. This would make a greater number of AEP audiograms available for use in weighting function development and other Navy environmental compliance efforts, broadening the application of AEP results in future criteria development.

Bottlenose dolphin.
Wayne Hoggard, NOAA/NMFS

Bottlenose dolphins.
Wayne Hoggard, NOAA/NMFS

PROJECT

This project is working to empirically determine relationships between behavioral hearing and AEP thresholds in small odontocetes to make behaviorally "equivalent" AEP audiograms. Although frequency-specific differences between behavioral and AEP audiograms have been previously explored in the bottlenose dolphin, a systematic evaluation of the differences between approaches has not been completed. By measuring behavioral and AEP hearing thresholds in the same individuals across the range of hearing, the team will determine the frequency-dependent relationship between behavioral and AEP thresholds. Results will be applied to existing AEP audiograms to increase the data available for the development of auditory weighting functions, which will allow AEP audiograms of untested small odontocetes to be converted to a form usable by the U.S. Navy in environmental compliance.

The project team is working with a subset of the bottlenose dolphins of the United States Navy Marine Mammal Program (MMP) that are trained for behavioral hearing tests and for participation in AEP studies.

The team's initial focus is on determining AEP threshold "equivalence" corrections for behavioral threshold prediction. At least four bottlenose dolphins will be tested to determine the frequency-specific offsets between behavioral and AEP hearing thresholds. After the behavioral threshold is established, AEP thresholds will be obtained in three different conditions: fully underwater, partially submerged and out of water ("beached").

After the behavioral threshold is established, AEP thresholds will be obtained in three different conditions: fully underwater, partially submerged and out of water.

The latter two test scenarios replicate the approaches commonly used with stranded and rehabilitating odontocetes. In-air testing will be limited to a subset of the dolphins that are tested

underwater because fewer animals will be available for daily, voluntary beaching. In each condition the thresholds will be obtained with two sets of stimuli—repetitive tone-pips and sinusoidal amplitude modulated tones.

> The behaviorally equivalent AEP audiograms will substantially increase the currently limited amount of data available for the development of auditory weighting functions.

The approaches planned will enable measuring variability for each test procedure to be characterized. Behavioral and AEP thresholds will subsequently be compared to determine frequency-specific corrections for AEP thresholds to bring the AEP audiograms in line with the behavioral audiogram.

Based on the results, "equivalence" corrections will be applied to previously acquired AEP audiograms to produce behaviorally equivalent audiograms. Many audiograms, collected by varying methods and reflected in this project's testing, are available in the Cetacean Evoked Potential Audiometry Database (CEPAD). The team will apply the correction factors to audiograms of small odontocetes within the CEPAD database, as well as to audiograms available from the open literature and others available but unpublished.

Behavioral and AEP testing began in mid-2021 and by the end of 2021 data collection was complete for three dolphins. Two of the dolphins had full bandwidth of hearing and the third had some high-frequency hearing loss (upper limit of hearing below 90 kHz). Data collection for an additional two dolphins is expected to be completed by mid-2022. The remainder of 2022 will focus on data analysis. Early in the project's third year the team expects to complete a manuscript for peer-review that discusses results of the behavioral and AEP comparisons. The behaviorally equivalent AEP audiograms will be published as a U.S. Navy Technical Report and provided to Navy personnel.

The equivalent audiograms should bolster weighting function design and add defensibility to the U.S. Navy's audiogram-based approach to predicting marine mammal auditory weighting functions. The behaviorally equivalent AEP audiograms will substantially increase the currently limited amount of data available for the development of auditory weighting functions and will allow AEP audiograms of untested small odontocetes to be corrected to a form the Navy will be able to use in its environmental compliance analysis.

About the Principal Investigator

Dorian Houser is the Director of Biologic and Bioacoustic Research at the National Marine Mammal Foundation (NMMF). He has spent nearly two decades in the study of how anthropogenic sound affects marine mammals and serves as the chair of an American National Standards Institute/ Acoustical Society of America (ANSI/ASA) committee on animal bioacoustics. Dr. Houser chaired the working group that led the development of the standard ANSI/ASA S3/SC1.6 2018, *Procedure for Determining Audiograms in Toothed Whales through Evoked Potential* Methods. He earned his Ph.D. in biology from the University of California, Santa Cruz.

Co-PIs are Dr. Jason Mulsow (NMMF) and Dr. James Finneran (U.S. Navy Marine Mammal Program).

Loudness Perception in Killer Whales (*Orcinus orca*); Effects of Temporal and Frequency Summation

Principal Investigator: Brian Branstetter
Project Status: New Start, Project 50

NEED

N-0239-21: Relationship Between Perceived Loudness of a Signal and Signal Length

To understand the potential effects of sounds created by Navy training activities on marine mammals, the Navy needs information not only on physiological effects (i.e., temporary threshold shift, permanent threshold shift), but also how sounds can influence marine mammals' behavioral response. Both context and perceived components of the sound, rather than the physical characteristics alone, may contribute to response. One perceptual component of sound is perceived loudness and one factor that may lower perceived loudness, and therefore reduce the potential for a behavioral response, is the duration of the sound or signal.

PROJECT

This project is investigating perceived loudness in killer whales using a multi-pronged approach:

1. Determine the effect of signal duration on response latency.
2. Determine the effect of signal duration on detection thresholds.
3. Determine the subjective loudness of short-duration signals compared to long-duration signals.

In addition, the relative loudness of multicomponent signals will be compared to pure tone (i.e., single frequency) signals to determine if summation across the frequency spectrum occurs. Because current auditory weighting functions are based on pure tone, long-duration signals, and may not generalize to pulsed tones or broadband sounds, the data from this effort may provide modifications for the weighting functions.

The project team is working with three trained killer whales (*Orcinus orca*) with good species-representative hearing. Due to their large size and increased sensitivity to lower-frequency sounds, killer whales are currently the best "hearing surrogates" for other large odontocetes such as beaked whales and sperm whales, where high-quality behavioral audiograms do not exist. Testing is being done at Sea World in a quiet and isolated pool that supports an exceptional amount of experimental control over the testing environment and acoustic stimuli. The effort is organized around the following three experiments.

1. **Detection thresholds and response latency as a function of signal duration and frequency**

   The goal is to measure audiograms (i.e., detection thresholds as a function of frequency) for short duration signals (i.e., less than the temporal integration time) and estimate weighting functions for different signal durations. Duration-specific audiograms will be developed and used to estimate auditory weighting functions with an additional parameter for signal duration.

2. **Subjective loudness comparison for different duration signals**

   This experiment will be a direct test (validation) of the duration-specific weighting functions from Experiment 1. Two tones will be presented, and the whale will indicate which sound (the first or second) is perceived louder by pressing a corresponding paddle (i.e., paddle one if the first sound is louder or paddle two if the second sound is louder). Within each session, the frequency of the two tones will be the same and held constant.

3. **Loudness of multicomponent signals**

   This experiment will test how well auditory weighting functions predict perceived loudness


Killer whale.

of broadband sounds and will provide data to modify weighting functions based on signal bandwidth. Testing harmonics and bandwidth is important to defining the detection threshold and indicating how the harmonic components in Navy sonar signals may be perceived as louder than simple model predictions from auditory weighting functions.

This study will provide the necessary data to modify current auditory weighting functions to include both pulsed tones and broadband sounds.

Initial training and data collection efforts were started with two whales in 2021. Efforts in 2022 will focus on completing Experiment 1 and initiating data collection for the remaining two experiments. The overall project is slated for completion in 2023.

This study will provide the necessary data to modify current auditory weighting functions to include both pulsed tones and broadband sounds. Results will be provided in project reports and in manuscripts to be submitted for peer-reviewed publication.

The data will support the Navy at-sea environmental compliance community in environmental criteria development by improving auditory weighting functions used in the criteria. Because the current auditory weighting functions are derived from long-duration pure tones and may not generalize to other types of sounds, developing duration-dependent, and bandwidth-dependent, auditory weighting functions will support perceived loudness estimations for a broad range of signals. Defining the relationship between perceived loudness and signal duration for killer whales will also provide data for other large odontocetes such as beaked whales and sperm whales, because killer whales are currently the best hearing surrogate for this group.

About the Principal Investigator

Brian Branstetter is a research scientist at the National Marine Mammal Foundation. Dr. Branstetter's research interests focus on marine mammal psychoacoustics and cognition, echolocation, auditory masking, whistle production and perception, and vigilance in dolphins. He also works on characterizing anthropogenic noise in marine environments. He earned his Ph.D. from the University of Hawaii, Manoa.

Dependence of TTS on Exposure Duration During Simulated Continuously Active Sonar: Examining the Equal-energy Hypothesis for Long-duration Exposures

Principal Investigator: Jason Mulsow
Project Status: New Start, Project 51

NEED

N-0238-21: Understanding Marine Mammal Hearing and Behavioral Response to Continuously Active Sonar

Results from previous behavioral response studies have indicated that both the type and the duration of Navy sonar signals may play a role in observed responses in marine mammals. As sonar technologies change, the Navy needs new information on the effects of new types of sonar on marine mammal hearing and behavior. Continuously active sonar is a type that can operate at lower energy levels than traditional pulsed signals, but operates at higher duty cycles (i.e., transmits for a longer time). In 2017, LMR began investing in studying and collecting data on behavioral response to continuously active sonar as part of the third phase of the Sea Mammals and Sonar Safety (3S3) project (LMR Project 29). The Navy needs more information to further understand the effects of continuously active sonar on marine mammals, particularly with additional marine mammal species.

PROJECT

This project is measuring temporary threshold shift (TTS) in the bottlenose dolphin using auditory evoked potential (AEP) and behavioral threshold measurements for longer duration signal exposure with signal qualities simulating continuously active sonar (CAS). The focus is to determine if equal energy exposures result in equal TTS, independent of exposure duration. In current Navy noise effects analyses, estimates of TTS onset are based on the equal energy hypothesis, which states that exposures of equal sound exposure levels (SEL) result in equal TTS. Therefore, the short, high sound pressure levels (SPLs) of pulsed sonar are considered equivalent¬—in terms of TTS—to lower SPL continuous exposures that have the same cumulative SEL. However, while source and received SPLs of CAS may be lower than those of pulsed sonars, accumulated SEL may be high due to the high duty cycles of CAS, as fewer quiet periods will be present during which SEL does not accumulate.

Bottlenose dolphin on the biteplate station for noise exposures. The noise levels received by the dolphin are continuously monitored using hydrophones placed on the lower jaw.

Jason Mulsow

The project goals are to

1. Determine the extent to which the equal energy hypothesis can be used to predict TTS for exposures up to 60 minutes
2. Determine if linear frequency modulation (LFM) common to CAS reduces TTS effects relative to continuous wave (CW) tones with equal SEL.

The research team will collect hearing data from two bottlenose dolphins at both a frequency representative of CAS (3 kHz) and a frequency closer to the region of best hearing sensitivity (28 kHz). The researchers will develop procedures for determining hearing thresholds in approximately 2-3 minutes for both behavioral and AEP methods so that thresholds can be measured on a short time scale relative to recovery.

> The data from this project will test how conservative the equal energy assumption may be for moderate-level CW and LFM exposures.

The fatiguing stimuli used to induce TTS will be both CW tones and LFM tones with bandwidths characteristic of CAS. Energy in the LFM signals will be modulated over approximately one-half octave; thus it is expected that TTS effects will be smaller than those observed for CW tones, which have noise energy distributed over a larger area in the frequency map in the inner ear.

Intermittent hearing tests will be conducted throughout the noise exposures to ensure that excessively large TTS are not induced during long duration exposures to minimize the chance of inducing a permanent threshold shift. The health and welfare of the dolphins will be monitored by the attending veterinarians and animal care staff at the Naval Information Warfare Center, Pacific over the course of the study.

Initial animal training, baseline hearing and 28 kHz TTS measurements will be initiated during 2022. During 2023, work will shift to 3 kHz TTS measurements. Data and reports will be provided to the LMR program to be available for Navy acoustic effects analyses. Results will also be shared through annual conference presentations and a manuscript for peer review, to be drafted following the completion of the study.

The data from this project will test how conservative the equal energy assumption may be for moderate-level CW and LFM exposures at durations of up to an hour. A potential goal is to determine a duration-based correction factor for TTS onset criteria to include in Navy criteria. Additionally, comparing CW and LFM TTS data will inform if the LFM is less likely to induce TTS. These results will support the Navy's acoustic effects criteria development.

About the Principal Investigator

Jason Mulsow is Deputy Director of the Biologic and Bioacoustic Research program at the National Marine Mammal Foundation (NMMF). His research uses behavioral and electrophysiological methods to examine sound reception and production in cetaceans and pinnipeds. He has worked on examining the effects of noise on marine mammals and in the development of criteria for estimating and mitigating such effects. Dr. Mulsow earned his Ph.D. in ocean sciences at the University of California, Santa Cruz.

Co-investigators are Dr. Alyssa Accomando (NMMF) and Dr. James J. Finneran (Naval Information Warfare Center, Pacific).

Studying Marine Mammal Behavioral Response to SURTASS LFA Sonar

Principal Investigators: Multiple (see text)
Project Status: New Start, Projects 52, 53, 54

NEED

N-0240-21: Studying Marine Mammal Behavioral Response to SURTASS LFA Sonar

The Navy plans to continue to train and test with the Surveillance Towed Array Sensor System (SURTASS) Low Frequency Active (LFA) sonar systems in the western and central North Pacific and eastern Indian oceans. Because acoustic stimuli from SURTASS LFA sonar use during training and testing has the potential to cause harassment of marine mammals, additional study and new data on these potential effects are needed. Understanding behavioral response to the LFA source is a priority.

The goal of this effort is to update previous studies done with LFA sources during the 1990s.

PROJECT

The goal of this effort is to update previous studies done with LFA sources during the 1990s, based on lessons learned and best practices from

The ocean surveillance ship USNS *Able* (T-AGOS 20).
MC2 Brian G. Reynolds

controlled and observational behavioral response studies using other sonar sources conducted over the last 10 years. The Navy will evaluate the feasibility and appropriate methods to collect new data to supplement the data available on behavioral responses of marine mammals to SURTASS LFA sonar using newer methods and technologies.

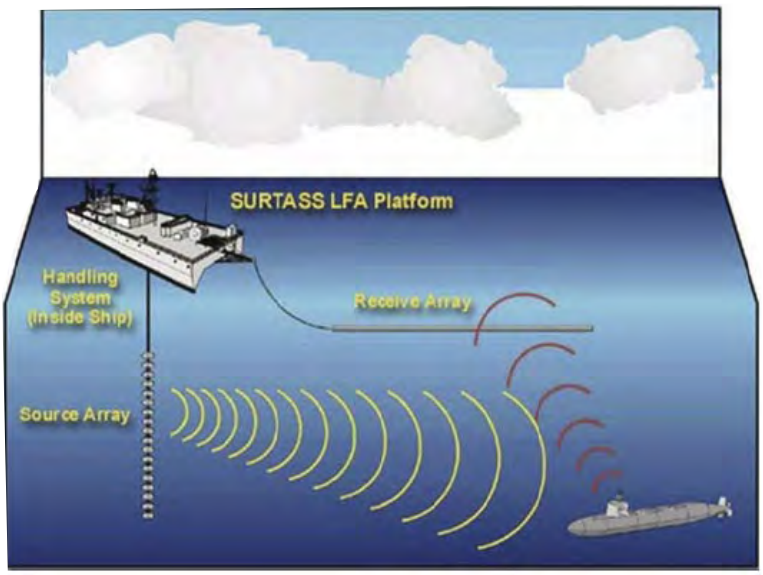


Diagram showing operation of a Navy SURTASS LFA platform at sea.

This is following a two-phase approach. Phase I, initiated in 2021, is a feasibility study to investigate the best approach to designing a scientific study to assess behavioral response to LFA sonar. This will involve discussions with the program managers regarding Navy participation, appropriate LFA sound sources and a final plan to conduct a study to collect data to best characterize behavioral responses to LFA sonar. Phase II will be based on results of Phase I.

The following three projects were awarded under Phase I:

- Project 52—Low Frequency Active Sonar Scientific Research Project 4 Feasibility Study (Adam Frankel, Marine Acoustics, Inc.).
- Project 53—Approaches for examining behavioral responses of whales to SURTASS Low Frequency Active sonar (John Calambokidis, Cascadia Research Collective/Brandon Southall, Southall Environmental Assoc.).
- Project 54—Simple and Understated: Risk Team Assessment of Low-Frequency Active Sonar (SURTASS LFA) (Stephanie Watwood, Naval Undersea Warfare Center/Greg Schorr, Marine Ecology and Telemetry Research).

Phase I, started in November 2021, will be completed by the end of 2022. Products of Phase I will be a final brief to the LMR program and the Phase II proposal submission. Phase II will be a separately funded effort. Phase I awardees will need to compete for a Phase II award. The anticipated Phase II period of performance to be based on proposed study design requirements, not to exceed five years.

> The data will be provided to the Navy and will support the at-sea environmental compliance community in environmental criteria development.

The results of the Phase II effort will provide the Navy with important and current data needed to meet environmental compliance for using SURTASS LFA during training and testing activities. The data will be provided to the Navy and will support the at-sea environmental compliance community in environmental criteria development.

Dolphin Conditioned Hearing Attenuation

Principal Investigator: Jim Finneran
Project Status: New Start, Project 55

NEED

N-0225-20: Marine Mammal Conditioned Attenuation of Hearing Sensitivity

Multiple studies with several marine mammal species have demonstrated conditioned reductions in hearing sensitivity. These results raise more questions about the mechanisms marine mammals use to reduce their hearing sensitivity and implications for marine mammal hearing. The Navy needs better understanding of the extent of control marine mammals may have over reducing their hearing sensitivity, what anatomical and physiological mechanisms they may be using, and the impact on temporary threshold shift (TTS) response. An investigation into any additional species available in captivity is needed.

PROJECT

This project is focused on three primary objectives:

1. Measure how quickly dolphins can learn to suppress (i.e., attenuate) their hearing in anticipation of an impending intense sound.
2. Determine how long they can maintain the attenuation.
3. Assess the role of outer hair cells in the conditioned hearing change.

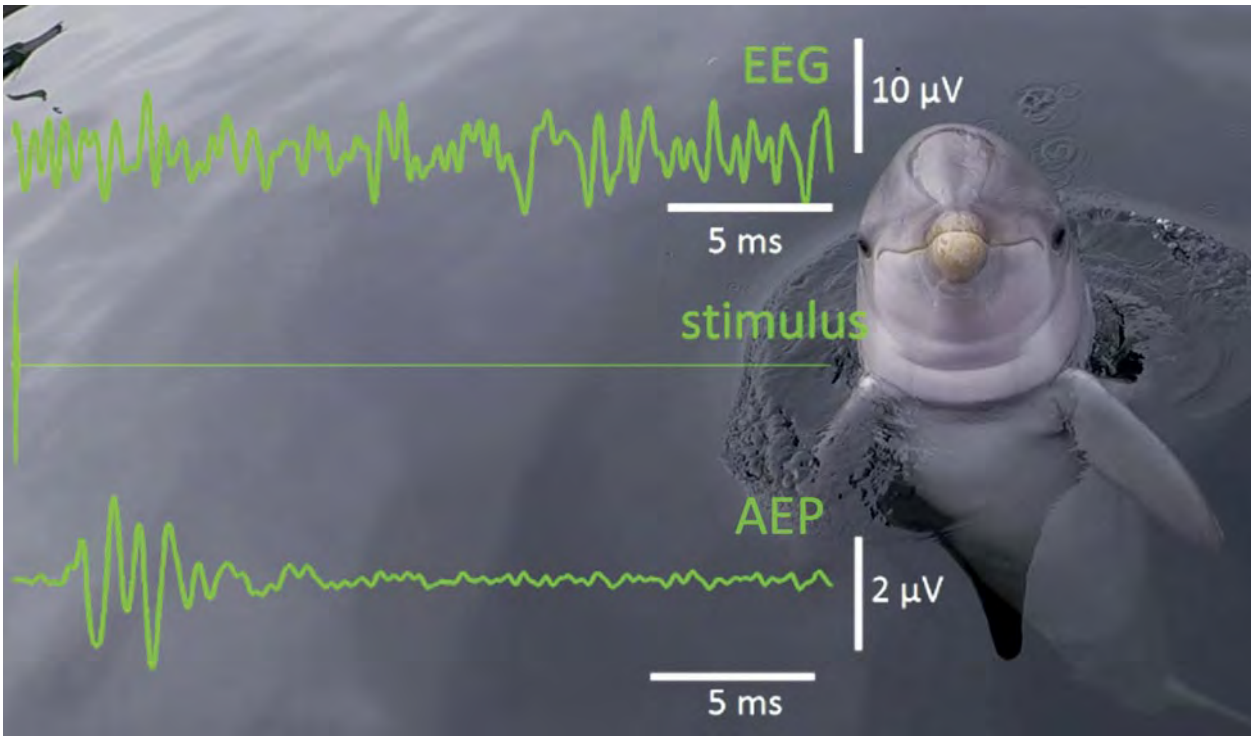
Understanding the extent to which dolphins can voluntarily manipulate their hearing sensitivity and the underlying mechanisms is required to properly evaluate laboratory data relating hearing loss to noise exposures.

This work is co-funded by the LMR program and the Naval Innovative Science and Engineering (NISE) program. The project team is assessing conditioned hearing attenuation in bottlenose dolphins by measuring changes in auditory evoked potentials (AEPs)—small voltages generated by the brain and auditory nervous system in response to sound—when dolphins are warned of an impending intense sound. The team will work with bottlenose dolphins from the United States Navy Marine Mammal Program (MMP) that are trained for behavioral hearing tests and for participation in AEP studies.

> The results will improve understanding of the potential impacts of conditioned hearing attenuation on marine mammal hearing and on current acoustic criteria.

During each experimental trial, AEPs generated by a continuous sequence of tone bursts will be tracked first before a warning sound, then after the warning sound but before an intense sound and, finally, after the intense sound. Conditioned hearing changes are expected to be revealed by decreases in AEP amplitude and increases in AEP latency occurring after the warning sound, but before the intense sound. This temporal separation will eliminate the possibility that AEP attenuation is a result of auditory masking or noise-induced hearing loss (i.e., caused directly by the intense sound). Across experimental sessions, features of the hearing test—


Bottlenose dolphins.



Examples of a dolphin instantaneous electroencephalogram (EEG) and an auditory evoked potential (AEP) measured in response to a tone burst sound stimulus.

the AEP stimulus, the warning sound and the intense sound—will be manipulated to reveal temporal and spectral characteristics of the conditioned hearing attenuation phenomenon. Measurements of AEPs in the presence of on- and off-frequency masking noise will be used to determine if outer hair cell function is affected during conditioned hearing attenuation. These data will reveal if the conditioned hearing attenuation is mediated by changes to outer hair cells/cochlear amplifier gain.

The project began in late 2021 and is expected to be completed by late 2023. Work started in 2021 included refining testing procedures and conducting baseline testing followed by measuring whether the dolphins learn conditioned attenuation. During 2022 the team will move onto tasks that will help to determine role of outer hair cells in conditioned attenuation. The team will provide quarterly reports to LMR throughout the project and expects to complete applicable manuscripts by the end of the project's second year.

The results will improve understanding of the potential impacts of conditioned hearing attenuation on marine mammal hearing and on current acoustic criteria. The data will support developing accurate acoustic criteria and ensure compliance with environmental laws.

About the Principal Investigator

James Finneran has worked as a research scientist at the Naval Information Warfare Center (NIWC) Pacific since 2002, investigating marine mammal echolocation and marine animal auditory capabilities and studying the physiological effects of sound on marine animals. Dr. Finneran earned his Ph.D. in mechanical engineering from The Ohio State University.

Key contributors: Dr. Jason Mulsow and Dr. Dorian Houser (National Marine Mammal Foundation).

INVESTMENT AREA 2
DATA PROCESSING AND ANALYSIS TOOLS

LMR Investment Area 2 projects develop tools to enable more efficient data processing and improve analysis methods. These tools provide more technologically advanced and cost-effective solutions to improve the Navy's capability to utilize data and information to maintain the Navy's competitive advantage in the undersea domain. The ability to collect, process, exploit and disseminate vast amounts of information is key to continually advancing the Navy's undersea capabilities.

The ability to collect, process, exploit and disseminate vast amounts of information is key to continually advancing the Navy's undersea capabilities.

This investment area also aligns with the Navy's strategy to increase the use of machine computing tools to optimize data and analytics. Developing tools to automate the processing of large amounts of data can reduce costs, increase productivity and provide consistency. Research on data analysis tools can improve existing methods or foster development of new methods, both of which provide improved data products and results. Projects in this area can include new detection and classification algorithms, improvements to software programs or development of novel analytical methods.

The following section includes summaries of four ongoing projects and one new start project.

The ongoing projects are

1. Project 31—DenMod: Working Group for the Advancement of Marine Species Density Surface Modeling
2. Project 42—ACCURATE: ACoustic CUe RATEs for Passive Acoustics Density Estimation
3. Project 43—MSM4PCoD: Marine Species Monitoring for the Population Consequences of Disturbance
4. Project 44—Demonstration and Validation of Passive Acoustic Density Estimation for Right Whales.

The new start project is

1. Project 49—Combining Global OBS and CTBTO Recordings to Estimate Abundance and Density of Fin and Blue Whales.

MC1 John Bellino

Ongoing Projects

DenMod: Working Group for the Advancement of Marine Species Density Surface Modeling

Principal Investigator: Len Thomas
Project Status: Ongoing, Project 31

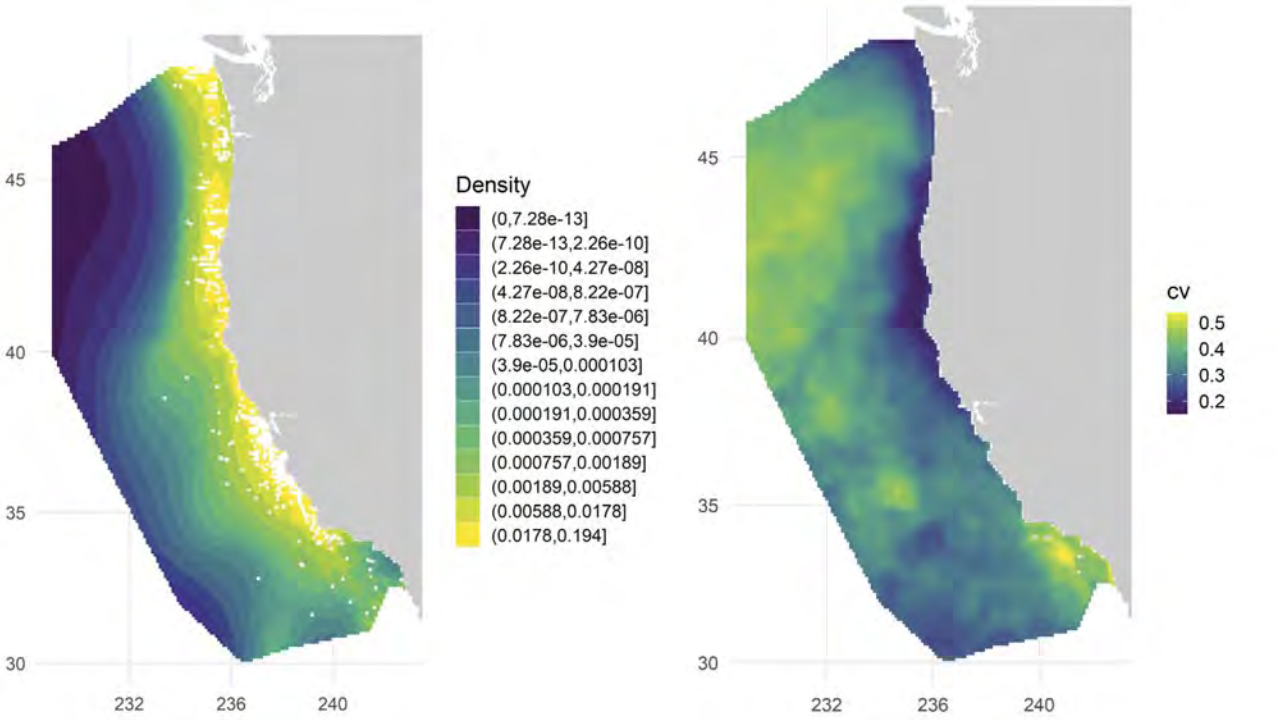
NEED

N-0136-17: Coordination for the Advancement of Density Spatial Modeling Methods Using Visual and Acoustic Survey Data

There is a need to identify and address priority issues in density surface modeling that are common to academia, NMFS Science Centers, Navy and other agencies. This need requires coordination of a working group, with involvement from stakeholders that can identify priority research issues and advance density surface modeling methods. The Navy needs advancements in density surface modeling methods to ensure that the best available science is used to determine take estimates.

PROJECT

To estimate species density, statistical modeling can be applied to data collected from surveys of biological populations. One method, called a density surface model (sometimes called a spatial or habitat model), estimates animal population density as a function of spatially and, in some cases, temporally referenced oceanographic biotic and abiotic variables. These variables can include bathymetry, distance to ocean fronts, sea surface temperature and chlorophyll. Improvements to estimation procedures, including an increasing understanding of the uncertainties associated with density estimates, are needed to improve the Navy's quantitative impact assessments.



Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for humpback whales. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996–2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996–2018 summer/fall ship surveys for the respective species.

Jason Roberts, Duke University

Pilot whale.

In this project, a working group is focused on developing and implementing innovative approaches to improve spatial modeling methods used to characterize seasonal abundance and distribution of marine species. The participating organizations—the University of St Andrews, Duke University and four regional NOAA Fisheries labs (Northeast, Southeast, Southwest and Alaska Fisheries Science Centers)—lead the development and application of the survey and analysis methods used and include the parties largely responsible for collection and analysis of transect data used in Navy impact assessments. Goals include producing software tools that implement new approaches and providing statistical support to those tasked with undertaking density surface modeling for the Navy. The project team is developing concrete guidance on best practices in this type of modeling.

The working group has met annually to review progress and priorities. The group's fifth and final meeting was held virtually in 2021, as was its fourth meeting in 2020, due to COVID-related travel limitations. The three prior meetings (in 2017, 2018 and 2019) were all held prior to the Marine Mammal Conferences. The MMC setting also offered a venue for two of three planned public workshops, during which the DenMod working group presented the current state of project efforts and solicited input from workshop attendees. The final public workshop will take place as an online webinar in June 2022. Reports from these public workshops can be found at the DenMod website (https://denmod.wp.st-andrews.ac.uk).

Several technical sub-groups have been organized to focus on key issues. There are now six topics that have been assigned to subgroups. Each is discussed briefly below.

1. **Uncertainty estimation**

   There are numerous sources of uncertainty when modeling the spatial distribution of animals that are hard to see (and sometimes submerged) in a dynamic environment. This subgroup focuses on correctly quantifying the effects of these uncertainties on the final uncertainty in maps and abundance estimates. A tool for variance propagation has been developed in the R programming language and the subgroup has been testing and implementing the variance propagation method within Southwest Fisheries Science Center density surface models.

   During 2020, the group continued to investigate sources of uncertainty and developed a simulation-based approach that includes multiple sources of uncertainty. The model simulates

possible model predictions under different conditions. An example application can be found in *NOAA Technical Memo NMFS-SWFSC-638* (see Publications sidebar for citation).

In 2021, a manuscript describing the variance propagation tool for estimating variance in density surface models was published in the *Journal of Agricultural, Biological and Environmental Statistics* (see Publications sidebar for citation). Methods have been integrated into the Southwest Fisheries Science Center's modelling process. The methods are being integrated into Duke University's Arctic/East Coast modeling. During 2022, it is anticipated that the methods will also be integrated into the Northeast Fisheries Science Center models. Publication of an additional manuscript, currently in preparation, is expected in 2022.

> The Navy has benefited from this collaborative approach to advancing the density surface modeling methods.

2. **Extrapolation**

   The Navy requires density estimates in areas beyond the bounds of the survey data. Such extrapolation makes assumptions on the correctness of the model used. During 2019 this subgroup drafted a guidance document along with a software toolkit (dsmextra), available at densitymodelling.github.io/dsmextra.

   The subgroup in 2020 continued to work on extrapolation issues and developed methods for addressing this when setting up a model. The peer-reviewed manuscript, dsmextra: Extrapolation Assessment Tools for Density Surface Models, was published in 2020 in *Methods in Ecology and Evolution* (see Publications sidebar for citation).

   In 2021, methods developed in 2020 were refined, including specifying when the model should be more conservative about its predictions and which model component should be used to control the model outside sample areas. With methods completed, the group is preparing a manuscript targeted for publication in 2022.

3. **Model unification**

   There are various modeling techniques that can be used to obtain spatially explicit estimates of density, but many of these lead to similar results. This subgroup has been looking at the similarities between existing methods to ensure that practitioners are using the best possible methods and not investing time and resources in new methods that provide little benefit. They completed a mathematical comparison of different spatial modeling approaches. Two peer-reviewed articles have been published—one in 2019 and a second in 2020 in the *Journal of Agricultural, Biological, and Environmental Statistics* (see Publications sidebar for citations).

   Subgroup efforts included addressing new approaches to factor-smooth interactions, which could include spatial smooths by group size. The group also evaluated better approaches to quantifying uncertainty within model unification. One manuscript was published in the *Journal of Agricultural, Biological, and Environmental Statistics* in 2021 (see Publications sidebar for citation).

4. **Workflow**

   Many data preparation and modeling workflows have evolved over time within the different organizations that provide density estimates to the Navy. The workflow subgroup led an effort to encapsulate this information. During 2019, the subgroup compiled a wiki of frequently asked questions that gives information on best practices and software/literature resources and includes a forum for discussion among those engaged in modeling. The wiki was reviewed

by the broader DenMod group and is now publicly available online at osf.io/5eza8/wiki. This site is being continually updated through the period of the DenMod project.

5. **Pinnipeds (seals and sea lions)**

   This subgroup was formed based on input from the project's first public meeting (2017). Pinnipeds raise unique issues when it comes to abundance estimation, as at-sea data are scarce, but counts from haul-outs and movement data from tags are common. Operating under separate funding, this subgroup is focused on working out how best to use and combine these disparate data.

   A paper led by the team at the Alaska Fisheries Science Center, describing the advancements that have been made, was published in *Methods in Ecology and Evolution* in 2021 (see Publications sidebar for citation).

6. **Acoustic and visual data integration**

   This subgroup was formed following the second DenMod working group meeting in October 2018. It is investigating methods for integrating density surfaces estimates derived from visual surveys and from separate, but spatially and temporally overlapping, acoustic surveys. Work during 2019 focused on identifying possible data sets and establishing priorities for a case study.

   In 2020 the group determined that the best possibility for conducting a comparative study would involve modeling deep diving odontocete (toothed whale) species using data from selected shipboard surveys.

   During 2021, the group initiated a case study to evaluate integrating data from visual and acoustic surveys to produce density surface estimates. The case study used data from surveys of deep-diving odontocetes from NOAA's Northeast and Southeast fisheries science center, under the Atlantic Marine Assessment Program for Protected Species. The case study focused on sperm whales. An example analysis is in preparation for dissemination during 2022.

Two additional efforts started in 2020 saw progress in 2021. One was to address requests from NOAA Fisheries Science Centers for software

Sperm whale.

tools for modeling, validation and other analysis needs. Work on this in 2021 included improvements to the R programming language package 'dsm' and associated tools to support survey data modeling. One example, a tutorial on segmenting survey transects in R, is available at https://examples.distancesampling.org.

In the second, a subgroup was formed to address incorporating visual data from unmanned aerial vehicles (UAV). The group held a virtual meeting during 2021 and agreed to pursue a case study on dugongs in Shark Bay, Western Australia. The case study, started in 2021, is evaluating methods for integrating UAV data and a product is expected in 2022.

This project's outcomes will lead to a substantial improvement in the reliability of the Navy's impact assessments in training and testing areas. The Navy has benefited from this collaborative approach to advancing the density surface modeling methods that are applied in developing population estimates for the Navy impact assessments.

About the Principal Investigator

Len Thomas is Professor of Statistics and member of the Centre for Research into Ecological and Environmental Modelling (CREEM) at the University of St Andrews. He specializes in developing statistical methods to apply to ecological problems. Dr. Thomas has a Ph.D. in forestry from the University of British Columbia.

Key collaborators: David L. Miller and Catriona M. Harris, University of St Andrews; Pat Halpin, Jason Roberts, Ana Canadas, Tina Yack and Rob Schick, Duke University.

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ACCURATE: ACoustic CUe RATEs for Passive Acoustics Density Estimation

Principal Investigator: Tiago Marques
Project Status: Ongoing, Project 42

NEED

N-0205-19: Investigation of the Effects of Cue Rate and Cue Stability on Passive Acoustic Monitoring (PAM)-Based Density Estimation Methods

Marine mammal density estimates are a critical input for the Navy's acoustic effects modeling. While visual aerial or shipboard surveys are standard methodologies for estimating marine mammal density, they can be very expensive to conduct, are limited both in their spatial and temporal coverage, and are not effective at documenting cryptic species (species that are difficult to see). Estimating density using fixed passive acoustic monitoring (PAM) has the potential to increase the amount of density data that can be used in the Navy's acoustic effects modeling. In some PAM-based density estimation (PAM-DE) methods, the "cue rate" or the marine mammal sound production rate is an important multiplier to get to a final density estimate. Cue rates can vary in marine mammals as a function of multiple factors, including time of day, year, group size, age, sex, behavioral state, season, bottom depth and location. Also cue rates often are determined from limited data sets and assumed to be representative for the species. The Navy needs recommendations of the most appropriate species for which to collect cue rate data and the appropriate cue rates to use in density estimates.

PROJECT

The ACCURATE project is designed to deliver a comprehensive, quantitative synthesis of the current state of knowledge on acoustic cue rates and cue rate stability for marine mammal density estimation from passive acoustics. Cue rate is a fundamental multiplier required to convert the number of detected sounds into an estimate of animal abundance or density. The ultimate project goal is to determine the most appropriate cue rates to use in different contextual settings. The project will produce a comprehensive set of recommendations of the most appropriate means by which to advance this field to meet Navy needs. This information will be made publicly available to the wider scientific community involved in estimating density from passive acoustics.

The project tasks include

- Identifying, reviewing, compiling and providing open access to all data available on cue rates (and their variability) across deep-diving and baleen whale species

Male Cuvier's beaked whale with teeth.
Jenny Trickey, SEMARNAT permit SGPA/DVGS/00451/18

- Developing methods to estimate cue rates from different data types (e.g., time-depth data) and for different taxa
- Exploring the factors that determine cue rate variability over time and space
- Investigating inter–click interval (ICI) patterns for deep divers (e.g., Cuvier's and Blainville's beaked whales)
- Evaluating impacts of cue rate variability on density estimates from cue–based methods
- Applying these methods to species of interest for the Navy.

During its start-up in 2020, the project initiated several tasks. First was an extensive bibliographic search for peer-reviewed papers and grey literature reports as well as contacting researchers involved in PAM work to understand existing, but unpublished, data sources. Project participants established multiple online options for other researchers to provide references and recommendations for PAM data sources. These include

- A dedicated email at papers4accuratereview@gmail.com
- An information and contact page at Research Gate www.researchgate.net/project/ACCURATE-ACoustic-CUe-RATEs-for-passive-acoustics-density-estimation, which is also supported by requests sent to MARMAM email list
- A new dedicated webpage hosted at https://accurate.st-andrews.ac.uk
- A Twitter account (@ACCURATEProject) where project news is released.

The ACCURATE team hopes to be able to collaborate with any other teams that might have relevant data and information on the topic, with a natural focus on, but not exclusive to, other LMR-funded projects.

Team members also began working with researchers who deploy animal tags (e.g., DTAG, Acousonde) on marine mammals to secure digital acoustic tag data and extract whale vocalizations (e.g., click data). Tagged species include Blainville's beaked whales (*Mesoplodon cavirostris*), Cuvier's beaked whales (*Ziphius cavirostris*), pilot whales (*Globicephala melas*), sperm whales (*Physeter macrocephalus*) and narwhals (*Monodon monoceros*). Cues and cue types from each processed tag are being counted to obtain a cue rate per tag. The estimated cue rate per tag then will be combined into a simple cue rate per species. Where possible, factors affecting cue rate will be identified.

> This project will advance the practical application of PAM–DE for Navy purposes.

Work in 2021 focused on furthering the bibliographic review and tag data processing and analyses. A draft document summarizing the bibliographic review results, including the synthesis of identified data sets, is in review by co-authors, with completion expected in 2022. Nearly 800 tags have been identified for processing. For sperm whales alone, approximately 135 tags have been processed producing almost seven million echolocation clicks to be analyzed. Data from the tags are informing subsequent tasks, including identifying factors that influence cue rate and caller identification for individual whales.

Team members also continued cue rate estimations for baleen whales, analyzing acoustic and auxiliar sensor data from right whales, blue whales and fin whales. Work on evaluating data from the different types of tags (i.e., time-depth recorders vs acoustic tags) is helping to refine

Cuvier's beaked whale .
Jenny Trickey, SEMARNAT permit SGPA/DVGS/00451/18

methods and determine how proxy data could be used to estimate cue rates.

Analyses of deep diver cue rate variability, using sperm whale data from three years of line-transect surveys, were initiated in 2021. The work has included, thus far, analyzing 42 hours of data and annotating 119,000 clicks in the data.

Work on evaluating how signal detector/classifiers might affect cue rate estimations was just beginning in late 2021 and will continue in subsequent years. The team is testing a simulation-based approach to evaluate how the detector/classifiers could affect the actual definition of what a cue rate is (e.g., single clicks, multiple clicks in close succession).

The bibliographic review, tag processing and assessment of factors influencing cue rates will be largely completed in 2022, followed by refining methods to identify cue rates from proxy data, evaluating deep diver cue rate variability and defining detector/classifier implications for cue rates.

Marine mammal density estimates are a critical element of the Navy's acoustic effects modeling, which supports environmental compliance. Passive acoustic monitoring potentially offers a cost-effective method to generate density estimates for a wide range of species across Navy priority areas.

By addressing a fundamental aspect of PAM-DE—understanding cue rates and cue rate stability—this project will advance the practical application of PAM-DE for Navy purposes. The resulting repository of synthesized data will support future density estimation from passive acoustic monitoring.

About the Principal Investigator

Tiago A. Marques is a senior research fellow at the Centre for Research into Ecological and Environmental Modelling (CREEM), University of St Andrews, UK. Dr. Marques has been involved in several projects related to different aspects of statistical ecology, mostly with an emphasis on estimating animal abundance considering a large variety of methods and taxa and with passive acoustic data. He earned his Ph.D. in statistics from the University of St Andrews, UK.

Key contributors: Len Thomas, Danielle Harris, Doug Gillespie and Peter Tyack (University of St Andrews, UK), Cormac Booth and Chloe Malinka (SMRU Consulting, University of St Andrews, UK), Ana Širović (Texas A&M University, Galveston, USA), Susan Parks (Syracuse University, USA), Erin Oleson and Karlina Merkens (NOAA NMFS Pacific Islands Fisheries Science Center, USA), Simone Bauman-Pickering (UC San Diego, Scripps Institution of Oceanography, USA).

MSM4PCoD: Marine Species Monitoring for the Population Consequences of Disturbance

Principal Investigator: Cormac Booth
Project Status: Ongoing, Project 43

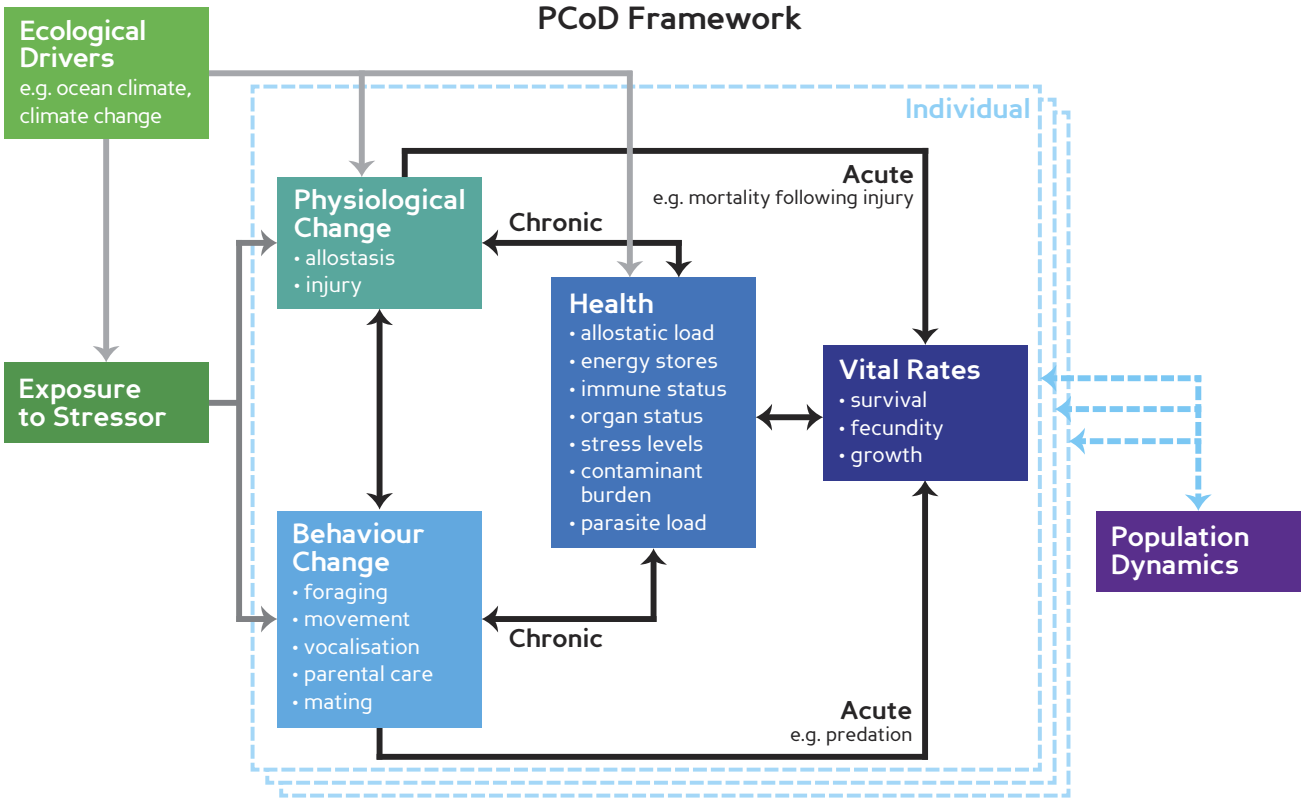
NEED

N-0207-19: Identification of Monitoring Priorities for Studying the Population Consequences of Disturbance on Marine Mammals

The population consequences of disturbance (PCoD) framework provides a conceptual framework which can be used to forecast a plausible range of outcomes for the possible effects of Navy activities on marine mammals. However, significant data gaps exist and it may take decades to fill these gaps. There is interest in identifying current methods for monitoring populations subject to disturbance that may also provide insights into the processes through which disturbance may affect these populations. The Navy is interested in a study that will inform the Navy Marine Species Monitoring program in terms of the methods and approaches that will enable the future ability to conduct PCoD analyses.

PROJECT

The overall objective of the MSM4PCoD project is to review the U.S. Navy Marine Species Monitoring (MSM) program to date and identify how current monitoring efforts could be adapted to supply appropriate data for future analyses of the consequences on marine mammals from possible disturbance by Navy activities. A working group supported by ONR MMB previously developed a mathematical framework for assessing PCoD. However, the PCoD framework requires a specific set of input data. It is critical to identify the data gaps that need to be filled to improve such models. This project will assess how well current Navy MSM program efforts can support PCoD analyses and recommend what could be improved.



Short-finned pilot whale.
Suzanne E. Yin, NMFS permit 14451

There are three core steps in the project's plan:

1. Review applicable current and historical MSM projects and methodologies for priority areas and species and compile information into a reference database. This will include assessing the monitoring that has been conducted over the past 20 years of the MSM effort. For each monitoring study, the team will document the methods employed, the species sampled and the sample sizes obtained for different species/method combinations. The elements of monitoring determined to be relevant for PCoD will be compiled into a database.

2. Select suitable metrics for monitoring populations of deep-diving odontocetes and large baleen whales using PCoD models that already exist or are currently in development. The results of the first step will be used to identify appropriate metrics or population characteristics that may be suitable for monitoring, and that could support PCoD analyses. The modeling outputs developed (and conclusions drawn) from previous PCoD-related projects will help to define the most appropriate metrics for the power analyses planned in the third step.

3. Conduct power analyses to assess the power of these metrics to inform PCoD analyses when collected within existing MSM projects, and determine the effort required to increase this power. Power analyses ensure sample sizes are sufficiently large to allow detection of an effect, such as changes in population size and demographics. Conducting power analyses on information from the monitoring program will indicate whether MSM efforts to date can support PCoD analyses and will help to identify what efforts would be required for different species/method/metric combinations. A series of power analyses for a minimum of two priority case study species (likely one deep-diving odontocete and one large whale species), as determined by the most suitable species from the MSM review, are expected.

   Power depends on effect size (in this case magnitude of the long-term decline or sudden decrease) and so an important early task is to develop a range of scenarios for what determines a biologically meaningful change. After the initial power analyses, a set of simulation scenarios will be developed to determine the amount and type of sampling effort that would be required for different approaches to inform PCoD in the future.

The results of these efforts will be synthesized in a report that also provides recommendations for how the MSM program could inform PCoD analyses.

In 2020, the project team began by holding meetings with Navy stakeholders to review monitoring objectives and efforts to date and to discuss and potentially refine the scope of the project. During review meetings and a scoping workshop, participants worked to focus the scope of the project and agree on next steps to ensure the project would support Navy needs. Parameters discussed included geographic regions for Navy monitoring and species within regions that were priorities.

The priority regions and species (in alphabetical order) defined for the project were

- Atlantic Fleet Testing and Training (AFTT)
  1. Cuvier's beaked whale
  2. Short-finned pilot whale
  3. Sperm whale
  4. Humpback whale
  5. Fin whale
  6. North Atlantic right whale
- Pacific (Hawaii & SOCAL-HSTT)
  1. Cuvier's beaked whale
  2. Blainville's beaked whale
  3. Short-finned pilot whale
  4. False killer whale
  5. Humpback whale
  6. Minke whale (lower priority)
  7. Bryde's whale (lower priority).

Databases of Atlantic and Pacific monitoring studies were largely completed in 2021. Each data spreadsheet contains a tab for each data type and includes data columns specific to data collection method. For example, acoustic data collection details include type of PAM device, number of detections and recording hours. For tasks 2 and 3, the project team also began selecting metrics, using bioenergetic models for relevant species and developing an analytical framework for determining how best to combine multiple data streams into improved power analyses.

Work in 2022 will focus on collecting and verifying data, selecting and conducting case studies, identifying suitable metrics, and performing associated modeling and retrospective power analyses (analyzing how data from past monitoring efforts will inform PCoD). Two manuscripts resulting from this project are planned to be written in 2022–2023.

Overall project results will also include a set of practical recommendations of how PCoD elements could be incorporated into existing MSM efforts. This offers the opportunity for Navy monitoring of consequences to target those species and populations best studied for identifying PCoD. This will help to enhance the information collected and the analyses produced by marine species monitoring, which will increase monitoring benefits.

About the Principal Investigator

Cormac Booth is Principal Scientist at SMRU Consulting, University of St Andrews, UK. Dr. Booth has served as lead scientist and project manager for multiple projects involving investigating the potential impacts of marine activities on marine mammal species, including a number of PCoD projects. He has extensive experience in marine mammal biology, statistics and acoustics. Dr. Booth earned his Ph.D. at the University of St Andrews, UK.

Key contributors: John Harwood, Megan Ryder, Ursula Verfuss and Rachael Sinclair (SMRU Consulting, University of St Andrews, UK), Len Thomas and Eiren Jacobson (CREEM, University of St Andrews, UK).

Demonstration and Validation of Passive Acoustic Density Estimation for Right Whales

Principal Investigators:
Susan Parks, Len Thomas
Project Status: Ongoing, Project 44

NEED

N-0204-19: Demonstration and Validation of Passive Acoustic Monitoring (PAM)-based Density Estimation Methods Using Visually-verified Survey Data

Marine mammal density estimates are a critical input for the Navy's acoustic effects modeling. While traditional ship and aerial visual survey estimates of marine mammal density are standard methodologies for obtaining density estimates, they are very expensive to conduct, are limited in their spatial and temporal coverage and are not effective at documenting cryptic species (species that are difficult to see). The use of fixed PAM for density estimation has the potential to increase the amount of density data in all U.S. waters and Navy ranges that can be used in the Navy's acoustic effects modeling. The Navy is interested in demonstrating and validating fixed PAM-based density estimation methods using vessel or shore–based visual surveys on species that have a high confidence level in being sighted.

PROJECT

This project is coupling shore-based observations with a continuous acoustic recording array to obtain acoustic cues (i.e., vocalizations) for density estimation in a Brazilian population of southern right whales (*Eubalaena australis*). This population offers a useful study opportunity because the population travels close to shore in areas with elevated hillsides suitable for concurrent fixed passive acoustic monitoring and visual observation of individuals. Previous studies with southern right whales from multiple habitats have demonstrated that the acoustic repertoires of all right whale species are similar, with the same call types described for each species. The southern right whale can thus serve as a proxy for the highly endangered North Atlantic right whale (*Eubalaena glacialis*).

The visually verified acoustic data set will be used to assess and validate a range of PAM density estimation methods for right whales. This approach could also improve the understanding of the sensitivity to variation in biological (age, sex, behavior), environmental (time of day, weather) and anthropogenic (ship noise) parameters.

The project's approach is to collect visual survey data concurrently with acoustic recordings of vocally active right whales using a time-synchronized

North Atlantic right whale.
NOAA

Southern right whales.
Israel Maciel, Instituto Australis, permit SISBIO 60324-2

fixed PAM array. Results will be used to validate range-specific detection probability, false positive rates and cue (or call) rates for estimating acoustic density. Visual data will be recorded from a land-based survey platform using a theodolite and a visual observation team. Whale presence can reliably be detected out to 8 kilometers (km), but the survey will be focused within a 3km radius area from the survey platform. The visual observation team will detect, localize and track all right whale groups within that observation area.

Acoustic data will be collected using six underwater sound recorder units (Soundtrap 300 STD) arrayed over the 3km radius observation area. Three additional units, added to the north, south and east of the visual observation area, will help to determine if sounds come from outside or inside the visual detection area. For example, whales calling offshore will be detected first on the offshore unit, before detection on any of the recordings within the central array.

Additional field efforts to obtain estimates of cue rates to apply to the PAM density estimation approach will include acoustic animal-borne tag (DTAG-3) attachments on suitable weather days and focal follows and acoustic tracking of whales within the acoustic array. Density estimation will focus on two cue types (all calls and contact calls).

The effective detection area estimates will be explored through three approaches:

1. **Spatial Capture Recapture (SCR)**

   This will be the primary approach for estimating the effective detection area. It relies on detecting at least some calls on multiple underwater sound recorders.

2. **Extended SCR**

   In addition to hydrophone location, additional information such as received level and time of arrival will be used to make more accurate inferences.

3. **Acoustic model-based assessment of effective detection area (EDA)**

   This will be based on published values for right whale call source levels and acoustic propagation modeling. The EDA estimates will be validated using visually tracked animals.

Finally, the visually obtained density estimation of right whales in the bay will be compared to the output of PAM density estimates to validate the approaches applied for estimation of right whale density using passive acoustic methods.

Field efforts planned for 2020 were delayed due to COVID-19 pandemic restrictions. This also prevented the planned acoustic density estimations,

which were to be based upon the data from the field efforts.

With continued travel restrictions in 2021, the project implemented a modified field effort. A local field team in Brazil worked with local fishermen on two deployments of a five-element acoustic array for passive acoustic data. A shore-based team collected visual data along with the acoustic data. The deployments provided approximately 1,500 hours of total acoustic data. The shore teams completed nine full days and five half days of visual data collection with shore-based theodolite, totaling almost 92 hours of visual data. Data analyses, including synchronizing acoustic data and acoustic signal detection and hourly density counts from the visual survey, are underway.

> This validation work will allow scientists to better assess the application of different PAM density estimation approaches for right whales.

Field work planned for 2022 will collect more visual counts and passive acoustic array data. Boat-based focal follows and animal tags will collect additional data on the animal's movement patterns and calling rate. Statistical analyses for calling/cue rate and acoustic density estimation will follow the data collection in 2022.

This study is focused on developing and validating a PAM survey design for acoustic density estimation of a right whale species with concurrent visual and acoustic localization of all right whales. The results of this validation work will allow scientists to better assess the application of different PAM density estimation approaches for right whales. These data will inform density estimation approaches for other right whale species, including the endangered North Atlantic right whale, by providing a better understanding of the variability in cue rates and the most appropriate methods to estimate density from PAM.

The project will result in peer-reviewed scientific publications and oral presentations at scientific meetings. At the completion of this study, visual survey data collected under the project will be contributed to the OBIS-SEAMAP online database, and tag data to the Movebank data repository. Results from this study will be shared with the ACCURATE project.

About the Principal Investigators

Susan Parks is an associate professor in the Department of Biology at Syracuse University in Syracuse, NY. She specializes in bioacoustics, focusing on the use of sound for communication and the impacts of noise on development, behavior, sound production and reception. Dr. Parks holds a Ph.D. in biological oceanography from the Massachusetts Institute of Technology-Woods Hole Oceanographic Institution Joint Program in Oceanography/Applied Ocean Science.

Len Thomas is Professor of Statistics and member of the Centre for Research into Ecological and Environmental Modelling (CREEM) at the University of St Andrews. He specializes in developing statistical methods to apply to ecological problems. Dr. Thomas has a Ph.D. in forestry from the University of British Columbia.

Key contributor: Graduate student Julia Dombroski (Syracuse University).

New Start Project

Combining Global OBS and CTBTO Recordings to Estimate Abundance and Density of Fin and Blue Whales

Principal Investigator: Danielle Harris
Project Status: Start, Project 49

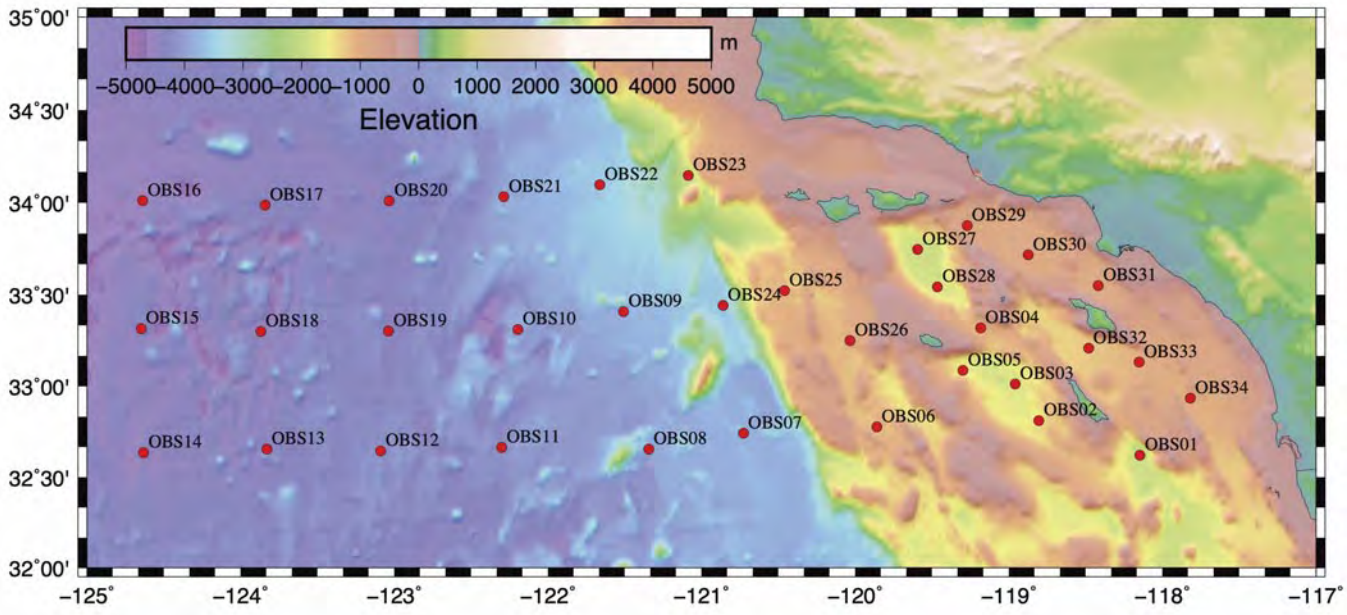
NEED

N-0206-19: Demonstration and Validation of Passive Acoustic Monitoring Sparse Arrays to Estimate the Density of Low-frequency Whales Over Large Spatial Areas

Marine mammal density estimates are a critical input for the Navy's acoustic effects modeling using the Navy acoustic effect model (NAEMO). Although the ship and aerial visual surveys traditionally used to estimate marine mammal density are viable for the Navy, such surveys are limited in spatial and temporal coverage. The Office of Naval Research Marine Mammals and Biology (ONR MMB) program has developed passive acoustic monitoring (PAM) approaches using sparse arrays in which sensors may be distributed evenly but widely over a large area of interest. These are often referred to as 'platforms of opportunity' when their primary monitoring purpose is not for marine mammals. Examples include Ocean Bottom Seismometers (OBS) and Comprehensive Nuclear Test Ban Treaty Organization International Monitoring System (CTBTO IMS) recorders. Density estimation methods have been applied to a few case studies using both OBS and CTBTO IMS data containing fin and blue whale calls. While these studies have demonstrated the utility of OBS and CTBTO IMS data, the techniques to estimate range to calling animals and to estimate density still need to be compared and validated under different conditions to be able to fully utilize the worldwide data sets.

PROJECT

This project is working to demonstrate and refine a suite of methods previously developed to obtain density estimates across a variety of OBS and CTBTO IMS deployments. The data used will reflect a variety of instrument configurations and acoustic propagation conditions. The suite of density estimation methods demonstrated for both



Map showing an example of an Ocean Bottom Seismometer array deployed for the Albacore seismic experiment off the coast of Southern California, August 2010–September 2011.

OBS and CTBTO IMS data will provide the framework for a set of software tools and training materials to enable a wide range of stakeholders to estimate blue and fin whale density from OBS and CTBTO IMS data and other similar instrumentation.

> The data used will reflect a variety of instrument configurations and acoustic propagation conditions.

This work is co-funded by LMR and ONR MMB and will build on information compiled under previous ONR MMB funding. The early tasks, funded by ONR MMB, include reviewing existing OBS and CTBTO IMS data sets around the world, selecting a set of case study data sets containing blue whale and/or fin whale calls, comparing ranging methods, evaluating results and developing methods for density estimation. Varying conditions such as spatial configuration, hardware specifications and oceanographic settings of different arrays will dictate which signal processing methods, and therefore density estimation methods, can be applied to a given data set.

The first part of the LMR-funded portion of the project will focus on signal processing of the OBS and CTBTO IMS case study data sets and implementing the density estimation methods developed under ONR funding. An additional task under this phase will include analyzing the case study data sets to explore various ecological and behavioral questions at a range of scales, from analyzing fine scale tracks of calling whales to assessing large-scale spatial and temporal patterns of animal vocal activity. The project team will then focus on documenting the research software and case study data sets and developing training materials. The team will configure the software developed during the project so that the different code modules and data formats work together. This includes ensuring that the code for each ranging method produces outputs that are formatted for use with the density estimation algorithms (typically written in R, a free statistical software package).

Training materials will combine the various algorithms and will include developing a flow chart to help users in different geographic areas

Blue whale.
Robert Schwemmer, NOAA/CINMS


Fin whale.

produce density estimates from their OBS or CTBTO-IMS instruments. These training materials will contain extensive documentation and examples. This will provide the basis for future work to incorporate these techniques into a single user-friendly package.

The techniques being demonstrated will potentially make available extensive data sets reflecting large geographic areas at relatively low cost.

The project is beginning with the ONR MMB-funded task of comparing ranging methods with subtasks continuing into 2024. LMR tasks to estimate density for case study data sets will be initiated in early 2022 and continue into 2025. Documentation and training materials will be completed by the project's conclusion in mid-2025. Project results will also be shared through peer-reviewed publications and conference presentations.

The techniques being demonstrated through this project will potentially make available extensive data sets reflecting large geographic areas at relatively low cost. This work will facilitate the use of both OBS and CTBTO-IMS data by (a) synthesizing and refining existing ranging and density estimation methods for these platforms and (b) creating guidance documents and tools for the Navy and other stakeholders to use.

About the Principal Investigator

Danielle Harris is a senior research fellow at the Centre for Research into Ecological and Environmental Modelling at the University of St Andrews, where she earned her Ph.D. in biology and statistics. Dr. Harris' research focuses on using acoustic data to monitor wildlife populations, in particular developing methods to estimate the density and abundance of marine mammal species.

Co-PIs are Len Thomas, Tiago Marques and Peter Tyack (University of St Andrews, UK), Kevin Heaney and Kerri D. Seger (Applied Ocean Sciences, LLC, VA, USA), Luis Matias (University of Lisbon, Portugal) and David K. Mellinger (Oregon State University, OR, USA).

INVESTMENT AREA 3
MONITORING TECHNOLOGY DEMONSTRATIONS

LMR Investment Area 3 focuses on further development of technology to improve field data collection methods. Specific emphasis is given to utilizing existing Navy technologies and sensors for advancing environmental research and data collection. These technology investments enable efficient and cost-effective implementation of the Navy's MSM program in support of the Navy's environmental compliance and permitting processes.

> These technology investments enable efficient and cost-effective implementation of the Navy's MSM program.

This investment area aligns with the goals of the Navy's Task Force Ocean to make every Navy platform a sensor for data collection. Advances in sensor technologies and platforms are increasing rapidly so it is important to continually integrate these new capabilities to reduce financial or operational constraints that impact the mission. In addition, investments by the LMR program in existing Navy technologies can have a return benefit to the operational community by demonstrating new system upgrades or advanced capabilities.

Projects in this area can include demonstrating and validating new monitoring technologies and platforms (such as sensors, tags, buoys, gliders and other autonomous unmanned vehicles).

The ongoing project in this section is

1. Project 41—Improved Tag Attachment System for Remotely-deployed Medium-term Cetacean Tags.

MC3 Thaddeus Berry

Ongoing Project

Improved Tag Attachment System for Remotely-deployed Medium-term Cetacean Tags

Principal Investigator: Russ Andrews
Project Status: Ongoing, Project 41

NEED

N-0203-19: Improvement of Medium-term Telemetry Tag Attachment Duration

The Navy requires data to support behavioral response criteria in its acoustic effects modeling. Animal telemetry (i.e., tagging) provides much of the needed marine mammal baseline behavioral data (diving, movement) and behavioral and physiological response to exposure from Navy sources. Longer tag attachment durations could offer improved data to better understand the duration and severity of behavioral responses to anthropogenic noise. The Navy is interested in research towards the re design and/or improvement of medium term tag attachment methods for dart style tag attachments for marine mammals. Improved dart design is needed to increase tag deployment durations to an average of one to several months.

PROJECT

This demonstration project is building on previous Office of Naval Research-funded efforts to assess the feasibility of producing an alternative tag attachment element for remote tag deployment. The current attachment for the Low Impact Minimally Percutaneous External-electronics Transmitter (LIMPET) tag system employs darts—small diameter metal shafts with externally facing barbs, or petals. A significant concern is how these rigid anchors interact with the surrounding tissue when the external part of the tag is subjected to large dynamic forces (including physical contact with other animals and the seafloor or breaking the water surface), which are common occurrences for many tagged cetaceans. The project team is exploring attachment mechanisms that are

- More compatible with the animal's tissue
- Less susceptible to breakage
- Well balanced with the external tag electronics package
- Easily attached
- Able to remain attached for longer periods
- Designed to work with the current suite of LIMPET tags and Sound and Motion Recording and Transmitting (SMRT) tags.

The project is organized into four separate phases, with each subsequent phase determined by the outcome of the preceding one.

- **Phase 1**

  Refine two existing designs—1) an elastic connection between a more tissue-friendly implanted anchor and existing LIMPET external package and 2) a single-point attachment, loosely tethered tag.

- **Phase 2**

  Conduct field deployments of the most promising designs identified in Phase 1.

- **Phase 3**

  Implement the lessons learned from field trials to improve the attachment element design(s). Demonstrate the final design in field trials with the same two species chosen for Phase 2. Prepare a final report on the field trials.

- **Phase 4**

  Conduct dedicated detailed follow-up studies to assess the condition of the previously tagged whales and demonstrate that the improved anchor design has not increased the negative effects of tagging. This will include quantifying wound healing and the effects of tagging on whale survival, reproduction and behavior.

Short-finned pilot whales.
Suzanne Yin, NMFS permit 16239

The team will use high-resolution digital photos, histological examination of biopsy samples and imaging from forward-looking infrared (FLIR) cameras to examine how well tag attachment sites are healing and to evaluate thermoregulatory function in the dorsal fin. The diving and movement behavior of tagged animals will also be evaluated.

> The prototype designs met all defined testing criteria, qualifying both for field demonstration.

Phase 1 of the project, originally slated for completion in 2020, saw some COVID-19-related changes and delays. When personnel and access to real whale tissue became limited, the work plan had to be modified. Computer modeling of tissue and prototype anchor interactions ceased and work focused more on physical prototype design and testing. This included developing appropriate simulated tissue for more repeatable testing of attachment designs. Once a material was developed, various prototypes of the two attachment designs were tested, including comparisons of insertion force and retention strength. Additionally, because the new attachments may be heavier than existing darts, the project team reviewed available projectors for remote tag delivery to determine whether new off-the-shelf options can be used successfully with heavier, more robust tag attachments.

The project was able to proceed with Phase 1 design and testing in 2021, completing two new designs and lab and simulated field tests of both designs. The key elements for redesign are the terminal anchor and attachment materials. Design 1 uses an elastic connection between a more tissue-friendly anchor and an off-the-shelf LIMPET satellite tag external package. Design 2

uses a single-point attachment with a loosely tethered tag. Lab tests of the designs evaluated multiple criteria, including measures of insertion impact and retention strength. The prototype designs met all defined testing criteria, qualifying both for field demonstration.

> Improved attachment mechanisms will improve the Navy's ability to monitor cetaceans before, during and after exposure to Navy sources.

Phase 2 field demonstrations are planned for late 2022. The prototypes will be tested in Southern California (beaked and fin whales) and Hawaii (pilot whales). The primary goal in these field tests will be to significantly reduce variation in attachment times compared with the existing attachment technology. Results will identify any needed modifications to the designs.

Baird's beaked whale.
Brenda K. Rone, MarEcoTel permit 20465

Improved attachment mechanisms that support recording the movements and behavior of cetaceans over longer periods of time, and more consistently, than is currently possible will improve the Navy's ability to monitor cetaceans before, during and after exposure to Navy sources. This will enable the Navy to develop behavioral response functions that are more closely aligned to the statutory definition of take for military readiness activities.

Project results will be presented at scientific conferences and submitted for publication in scientific journals. If successful, the improved tag anchor systems will be transitioned to the commercial market after completion of all functionality tests.

About the Principal Investigators

Russel Andrews, lead PI, is a senior scientist with the Foundation for Marine Ecology & Telemetry Research. His expertise includes marine mammals, diving behavior and physiology, and remote monitoring equipment and instrumentation. Dr. Andrews earned his Ph.D. in zoology at the University of British Columbia.

Greg Schorr, co-PI, is a research biologist at the Foundation for Marine Ecology & Telemetry Research. He has been studying marine mammals more than 20 years with much of his research focused on telemetry studies and deploying a wide variety of tags. His most recent focus has been using remotely deployed satellite tags to study beaked whale ecology and behavioral responses to anthropogenic sources of sound. Greg earned his geology degree from Colorado College.

INVESTMENT AREA 4
STANDARDS AND METRICS

LMR Investment Area 4 projects establish interagency and scientific community standards and metrics for data collection, management and analysis. This facilitates the information exchange needed to harness the capabilities of aggregated data, which supports Navy information dominance. Data that have been collected, managed or analyzed using varied techniques and methodologies can make it difficult to incorporate and use the information in the environmental compliance process. For example, data pertaining to a particular species are often quantity-limited, making it necessary to aggregate data for multiple species that are often collected from a variety of sources. However, in order to aggregate data, the data need to be comparable, raising the need for agreement on standards and metrics.

Establishing interagency and scientific community standards and metrics for how data are collected, managed and analyzed promotes data comparability and enables data aggregation from different data sets. Ensuring consistent, agreed-upon standards and metrics provides multiple benefits, including cost-effective improvements to data, and results that can be utilized to establish policy and technical guidance. Projects in this area can include standards for data collection methods, standardized data management tools, as well as establishing metrics for reporting performance of data analysis methods.

> Ensuring consistent, agreed-upon standards and metrics provides multiple benefits.

The two ongoing projects in this section are

1. Project 34—Standardizing Methods and Nomenclature for Automated Detection of Navy Sonar
2. Project 46—Tethys Capability Enhancements

MC3 Nicholas A. Russell

Ongoing Projects

Standardizing Methods and Nomenclature for Automated Detection of Navy Sonar

Principal Investigators: Elizabeth Henderson, Susan Jarvis, Tyler Helble
Project Status: Ongoing, Project 34

NEED

N-0158-18: Evaluations and Standardization of Sonar Signal Processing Tools for Marine Mammal Research

The Navy needs standard automated detectors for identifying U.S. Navy sonar sources within data sets used for passive acoustic monitoring (PAM) of marine mammals. The multiple automated sonar detectors currently in use by different researchers each produce varying results that are difficult to compare. To evaluate detection performance, the outputs from existing automated sonar signal detectors need to be statistically compared. Comparing the algorithms' performance using passive acoustic data sets with known occurrence of sonar signals (i.e., ground truthing) would provide a benchmark for assessing the probability of missed and false detections. In addition, there is a need to uniformly characterize sonar signal types into standardized groupings and terminology. This work will enable more comparable data analysis of behavioral responses observable within passive acoustic data. These results can then be used for criteria development and impact assessments.

PROJECT

This project is taking a collaborative approach to develop a set of standardized detectors and classifiers, along with a set of standardized nomenclature for Navy sonar signals. The project team includes Navy investigators who are assessing the efficacy and broad applicability of existing sonar detectors, which are provided with support by non-Navy researchers. The group is working to ensure that the greater research and signal detection communities are involved in developing a standardized and generalizable sonar detector.

The project is pursuing the following six overall tasks, with project team member responsibilities carefully defined to protect classified information while working toward standardized non-classified methods.

1. Review literature for existing detectors/sonar signals descriptions
2. Compile classified sonar data sets from Navy ranges
3. Gather sonar detectors and non-classified sonar data from collaborators
4. Run detectors on data sets
5. Develop sonar detector/classifier (or suite of detectors if needed) based on results of comparison test
6. Develop standardized nomenclature describing different signal types to be used by bioacoustics community.

The project team includes Navy investigators who are assessing the efficacy and broad applicability of existing sonar detectors.

Work during 2019 focused on the literature review, initiating work with collaborators, obtaining, testing and adjusting existing detectors and obtaining non-Navy sonar data.

The literature review examined papers and reports with descriptions of sonar, including AN/SQS-53 hull-mounted, DICASS (directional command

USS Decatur (DDG 73).
MC3 Justin McTaggart

activated sonobuoy system) sonobuoys and AN/AQS-22 dipping sonar. The effort highlighted characteristics such as frequencies, source levels, sonar components, duty cycle, bandwidth and others. It also included identifying descriptors used in the Navy's Acoustics Effects Model (NAEMO). This helped to identify issues regarding the detection and classification of sonar signals. The Navy sonar classification guidelines are informing how to select descriptive nomenclature. The review also identified sonar descriptions that are already in the public domain (e.g., within environmental impact statements or published papers).

Work to compile classified sonar data sets from Navy ranges revealed tasks needed to select and prepare data sets for use. Tasks included digitizing data, defining recording length and identifying data issues such as clipping, harmonics and noise.

Other work during 2019 included running available test data sets using Cornell's Raven-X detector, Bio-Waves SonarFinder, a generalized power-law (GPL) detection algorithm and the Silbido detector from San Diego State University and the University of California San Diego. Initial results helped to identify potential pitfalls in detector comparisons, data preparation steps that might be required prior to analyses and core characteristics that might be appropriate for a standardized detector.

Work in 2020 focused on more in-depth analyses of detector capability comparisons and applying detectors to more data sets. The team focused on using Raven-X as the analysis platform and worked to incorporate the existing detectors mentioned above. Using the Raven-X platform, the team was able to run all the detectors in parallel on the same data set, over a variety of detector settings. This capability was instrumental for properly comparing the detectors in a timely manner. Raven-X was also used to train a machine learning "net" for the GPL and Cornell detectors.

The team used both unclassified data and real Navy training data from the Pacific Missile Range Facility (PMRF). The testing work encompassed: 1) comparing results across detectors against manually validated detections; 2) generating multiple performance metrics (e.g., precision/recall curves, ROC curves, DET curves) and 3) using Detection, Classification, Localization (DCL) committee standards to score and assess each detector's relative performance. The tests revealed that the existing detectors had been optimized to perform best on their original data sets and were less reliable for use on other data sets.

During 2021, the team then redirected its efforts from adapting an existing detector to developing a new detector. Continuing work in Raven-X, team members employed a subset of data from Scripps Institute of Oceanography, Cornell University and PMRF to train, test and evaluate a new detector. The data included 770 sonar and 19,300 non-sonar examples.

To broaden testing of the new detector, the team collaborated with the Sanctuary Soundscape Monitoring Project (SanctSound). SanctSound is a four-year project managed by NOAA and the U.S. Navy to better understand underwater sound within national marine sanctuaries. Passive acoustic monitoring devices were placed at 30 recording locations in seven sanctuaries and one marine national monument within the Sanctuary system. The project team used 17 data sets from eight of the SanctSound recording locations, including five in the Hawaiian Islands Humpback Whale National Marine Sanctuary and three in the Papahānaumokuākea Marine National Monument. Many of these data sets contained sonar and humpback whale calls. SanctSound data analysts provided manual detection logs from two locations to validate the sonar detector output in the presence of humpback singing. Initial runs indicated that the sonar detector works well, with fewer than three false

Humpback whales.
NOAA

detections per hour. For comparison, 20 false detections per hour is the cutoff for determining if a detector is useful.

Other work during 2021 included continuing to organize a standardized and unclassified nomenclature for describing sonar signal detections in passive acoustic data sets. The team began by identifying sonar descriptors used in NAEMO. They shared the initial set with U.S. Fleet Forces sonar operators both to ensure accuracy and to avoid classified information. Drawing on feedback, the team has developed a technical report of recommended nomenclature.

This will promote comparable results from independent research on the effects of Navy training and testing activities, including Navy sonar, on marine life.

Work planned for 2022 includes analyzing the remaining Hawaiian Island SanctSound data sets for the presence of sonar and finalizing work on the sonar detector. This will include some general bandwidth-based classification and testing on additional Navy range data. The team also will finalize the nomenclature report, which will be made available later in the year. The project team plans to present project results at the 2022 Detection, Classification, Localization and Density Estimation (DCLDE) meeting and to begin training Navy-funded researchers on the detector and nomenclature applications.

This effort will provide validated automated detectors/classifiers for detecting the presence of sonar in marine mammal PAM data sets. It will also provide recommendations on tuning the characteristics of these detectors for optimal use. In addition, standardized unclassified sonar nomenclature will be made available to researchers. This will promote comparable results from independent research on the effects of Navy training and testing activities, including Navy sonar, on marine life.

About the Principal Investigators

Elizabeth Henderson is a bioacoustic scientist at the Naval Information Warfare Systems Center. Dr. Henderson earned her Ph.D. in biological oceanography and bioacoustics at the University of California San Diego. She focuses on marine mammal acoustic behavior and noise impact analyses for environmental compliance.

Susan Jarvis is an electronics engineer at the Naval Undersea Warfare Center, Newport and an assistant teaching professor at Worcester Polytechnic Institute, Worcester, Massachusetts. Dr. Jarvis earned her Ph.D. in computer engineering at the University of Massachusetts, Dartmouth. Her work focuses on real-time acoustic signal processing for real-time detection, classification and localization of marine mammals.

Tyler Helble is a bioacoustics scientist and electrical engineer at the Naval Information Warfare Systems Center, Pacific. Dr. Helble earned his Ph.D. in applied ocean sciences at the University of California San Diego. His main area of focus is developing tools for detection, classification, localization and density estimation of cetaceans using passive acoustics.

Tethys Capability Enhancements

Principal Investigator: Marie Roch
Project Status: Ongoing, Project 46

NEED

N-0228-20: Marine Mammal Acoustic Software Application Enhancements

The Navy's need for efficient methods to analyze passive acoustic data continues to grow with the increasing amount of data collected by the Navy's Marine Species Monitoring Program. While publicly available acoustic analysis software applications have improved over the years, additional improvements are needed to enhance overall processing efficiency when identifying, characterizing and cataloging acoustic signals of interest.

PROJECT

This project is enhancing Tethys, a workbench and standardization scheme for archiving and using acoustic metadata. Tethys offers researchers and mitigation specialists a method to record these data in a manner that can be preserved over long time periods and accessed from a variety of platforms such as web browsers, MATLAB®, Java, Python and R.

The prior version of Tethys was developed under a previous LMR project (Project 18), which was co-funded by the Bureau of Ocean Energy Management (BOEM). That project built upon early work funded by the ONR MMB program. As the Tethys user group expanded and became increasingly diverse, the need for additional enhancements to make the workbench more accessible became apparent.

This project is working to address following five key enhancements. Each is summarized below with its purpose and status at the close of 2021.

1. **Technology updates to ensure security and prevent obsolescence**

   This task was largely completed during 2021. There were two primary components targeted for upgrade. The server code was migrated to the most recent version of Python (Python 3). The team identified existing library packages that are no longer supported under the new version and made minor code changes to the core code base and reengineered functionality to support the packages.

   The second major direction of the code update was replacing the underlying data storage technology to upgrade the database engine to the most recent version of Oracle's Berkeley extended markup language database (Berkeley DBXML). Recent changes to the system provide high-performance indices which provide additional scalability. The team used a software interface generator to created interfaces to the Berkeley database.

Gray whale.
Steven Swartz, NOAA/NMFS

2. **A drag-and-drop data import interface**

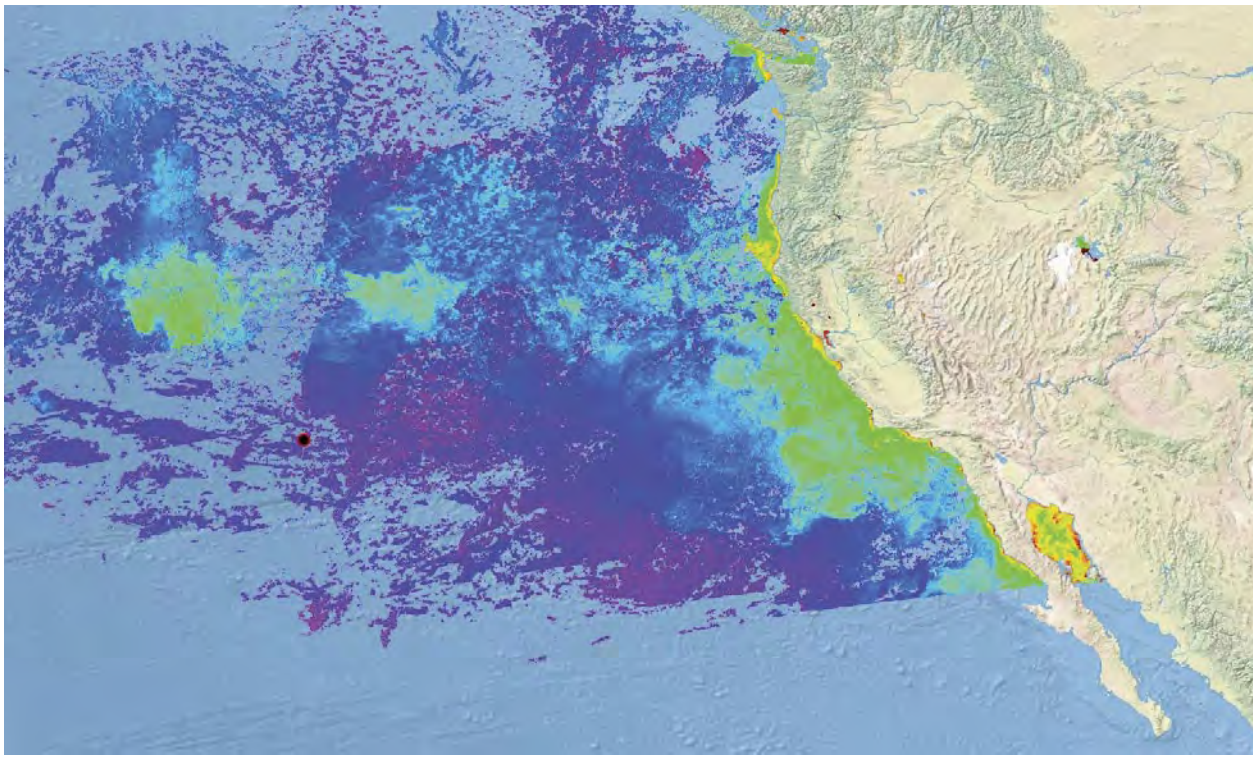
   While the previous data import methods are both usable and teachable, user feedback indicates that the text file specification requirement could be confusing for new users. The project team has made significant progress building an alternative method that provides a drag-and-drop type interface. The goal is to combine a simpler interface with a software agent that offers advice, such as suggestions on potential matches for common non-standard data field names and help on fields that are required but not yet matched. During 2021, the team structured data exploration modules for Tethys and user data, designed new user interfaces and developed algorithms to implement user data with Tethys mappings and data queries.

3. **An advanced mapping interface**

   The project will migrate from the current proprietary Google Maps application programming interface to the open-source OpenLayers map library. During 2021, the team began designing a new OpenLayers interface and will be leveraging current environmental data retrieval capabilities to generate mapping layers. This will provide the capability to add layers on existing web client maps to provide improved functionality over what can be implemented with the current Google Maps interface. It will support overlaying oceanographic and atmospheric data (sea surface temperature, wind, etc.) onto animal detections, and when applicable, the ability to show the evolution of these data over time.

4. **A beta-user program**

   The Tethys team will engage with a set of bioacoustics "power users" identified by the LMR program. The team will provide a set of educational resources and direct training and responses to issues identified by these users. Training could include a combination of short



An open-source OpenLayers map showing chlorophyll concentrations in the Eastern Pacific. This is an example of environmental data the new mapping interface library would provide for overlaying with monitoring data, such as marine mammal tracks or detections.

online sessions and one multiple-day in-person training. Feedback from this set of users will influence whether and how to proceed with optional tasks. This workshop, originally planned for 2021, will be deferred until summer of 2022.

5. **Responsive help and enhancements to address user needs**

   Experience has shown that each user group can have specific data organization needs that are not currently addressed within the Tethys schema. The project team will continue, within reasonable levels of effort, to provide necessary enhancements and training. The team also will remain alert to potential overlaps of needs among user groups to avoid duplication.

> Retaining data from large-scale spatial and temporal studies provides clear benefits for enhancing the Navy's capabilities for preparing detailed environmental impact assessments.

Three optional tasks have been identified that might be considered as the project proceeds.

1. **PAMGuard/Tethys integration**

   The team would develop interfaces between Tethys and PAMGuard to enable a seamless transfer of PAMGuard detection and localization data to Tethys.

2. **Database consultant review**

   A database technology company, identified by the LMR program, would review the technologies used in the Tethys project, with the goal of identifying areas that could be improved and lead to desired outcomes such as a central repository. The Tethys team would provide time to support the review.

3. **Standards development**

   Previous Tethys work included moving the Tethys schemata towards an American National Standards Institute (ANSI) standard. The existing standards committee has addressed many of the issues related to deployments, detection and classification. However, the beta user group noted above may identify additional needs to be incorporated into the ongoing standards work.

Work in 2022 will focus on completing all tasks and testing to ensure smooth technical transitions.

This project will help the Navy to retain long-term information about marine mammal species that is needed for Navy monitoring and mitigation plans. As previous research has demonstrated, Tethys's data preservation and the ability to reuse data have expanded the scope of science and policy-based questions that can be asked. Retaining data from large-scale spatial and temporal studies provides clear benefits for advancing science, enhancing the Navy's capabilities for monitoring cetaceans and preparing detailed environmental impact assessments.

About the Principal Investigator

Marie Roch is an interdisciplinary computer scientist whose work on the bioacoustics of marine mammals is internationally recognized. She is a professor of computer science at San Diego State University and is affiliated with Scripps Institution of Oceanography's Marine Acoustics Laboratories. Dr. Roch holds a Ph.D. in computer science from the University of Iowa.

INVESTMENT AREA 5 EMERGENT TOPICS

Investment area 5 is reserved for other priority topics that are associated with emerging technologies or capabilities. This includes research needs that arise out of the Navy's environmental compliance and permitting processes, or topics that do not squarely fall within the preceding categories.

There are two projects in this section—one ongoing and one new start.

The ongoing project is

1. Project 35—Multi-spaced Measurement of Underwater Sound Fields from Explosive Sources.

The new start project is

1. Project 48—Collection of *in situ* Acoustic Data for Validation of Navy Propagation Models of Ship Shock Trial Sound Sources.

Ongoing Project

Multi-spaced Measurement of Underwater Sound Fields from Explosive Sources

Principal Investigator: Peter H. Dahl
Project Status: Ongoing, Project 35

NEED

N-0159-18: *In situ* Explosive Sound Characterization and Propagation Data Collection and Analysis

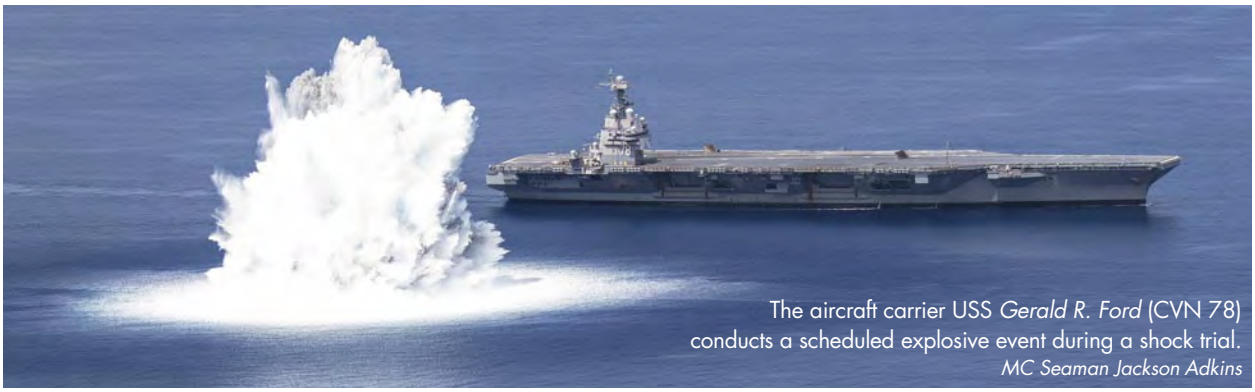
The Navy models the effects of explosive detonations to determine the potential impacts to marine species (mammals, sea turtles, fish and birds). The current models are validated using *in situ* data recorded for a small subset of the types of munitions—largely data from small explosive charges in shallow water depths—that the Navy could use in training and testing activities. These data may not fully represent the sound source characteristics and propagation conditions that could be generated by larger size charges in more variable training and testing environments. Therefore, the Navy seeks to collect additional data on a broader range of charge sizes and at a variety of distances/depths to improve the validation of the Navy's Acoustic Effect Model (NAEMO) explosive propagation, and to ensure that predictions of effects to marine species are as accurate as possible.

PROJECT

This project has been established to conduct a set of well-documented and calibrated underwater acoustic field measurements associated with explosive detonations. It will include measurements at both very close range and longer ranges that are influenced by multiple reflections from the sea surface and seabed, changing bathymetry and sound speed conditions. Results will be used to update NAEMO, which simulates potential impacts on marine species.

For the close-range measurements, the team will deploy acoustic measurement instrumentation at two sites, arranged to measure both a direct waterborne path between the explosive source and the receiver and a path reflected from the seabed. A vertical line array (VLA) will be used to measure the bottom reflection, and tourmaline sensors deployed from a surface buoy will be used to measure the direct waterborne path.

The far-range measurements will be configured to provide data on effects of varying depths and distances from the explosive source. Measurement sites will be equipped with VLAs to collect site-specific data, which will encompass varying depths (up to 1000 meters), thermocline influences and overall acoustic field. The equipment also will collect essential environmental data, such as water sound speed and surface wave spectra,



The aircraft carrier USS *Gerald R. Ford* (CVN 78) conducts a scheduled explosive event during a shock trial. *MC Seaman Jackson Adkins*

needed for the modeling and interpretation of the observations of acoustic propagation.

Due to COVID-19 pandemic restrictions and associated difficulties coordinating opportunities with Navy range testing, all planned field tests for both 2020 and 2021 were canceled, preventing any progress on this project. The project team will try again in 2022 to conduct field tests.

The data collected directly apply to improving the accuracy and verification of NAEMO-based predictions of underwater sound fields from explosives.

During 2021, however, a task was added to this project in support of the Navy's full ship shock trial (FSST). Project team members from the Applied Physics Laboratory (APL) were tasked with providing one of the environmental teams on the FSST with a portable device for measuring the explosive signal. Specifically, the APL team assembled an easy-to-use portable sound recording package capable of recording high-intensity acoustic fields from explosive sources and trained personnel on an environmental support vessel to deploy and retrieve it. The project team is analyzing data collected from the successful deployment. The results will complement recordings taken in the broader effort under Project 48, Collection of *in situ* Acoustic Data for Validation of U.S. Navy Propagation Models of Ship Shock Trial Sound Sources. Results of the device performance will also inform any potential changes to equipment used in the originally planned explosives testing.

The data collected directly apply to improving the accuracy and verification of NAEMO-based predictions of underwater sound fields from explosives at both close and long ranges. This is critical to improving the Navy's analysis of the effects of explosive sources on marine species.

About the Principal Investigator

Peter H. Dahl is a senior principal engineer in the Acoustics Department at the University of Washington Applied Physics Laboratory and professor in the University of Washington's Department of Mechanical Engineering. Dahl's research is in areas of acoustics with a primary focus on underwater sound. Dr. Dahl earned his Ph.D. from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution in 1989.

Key collaborators: David Dall'Osto, University of Washington Applied Physics Laboratory; Altan Turgot, Naval Research Laboratory.

New Start Project

Collection of *in situ* Acoustic Data for Validation of U.S. Navy Propagation Models of Ship Shock Trial Sound Sources

Principal Investigators:
Kerri Seger, Shyam Madhusudhana
Project Status: New Start, Project 48

NEED

N-0226-21: Ship Shock Trial Acoustic Measurement

Each new class (or major upgrade) of surface ships constructed for the Navy undergoes an at sea shock trial. A shock trial is a series of underwater detonations at various distances from the ship, each of which sends a shock wave through the ship's hull to simulate near misses during combat. The Navy collects data on the acoustic shock waves effects on the ship and equipment and estimates the impact to the environment though acoustic models. However, few *in situ* measurements of the extent of the acoustic propagation within the marine environment have been taken. The Navy needs *in situ* data on acoustic shock wave propagation from the trials through the surrounding marine environment to enhance the Navy's predictive acoustic modeling methods.

PROJECT

The goal of this project is to collect relevant *in situ* data on the acoustic shock wave propagation from a full ship shock trial (FSST). This project began in April 2021 to support the FSST of the new Navy aircraft carrier, USS *Gerald R. Ford* (CVN-78).

> The data will ensure that the Navy's estimates of acoustic impacts from explosive sources are as accurate as possible.

To capture *in situ* data, underwater acoustic recording devices were deployed at near- and far-field locations around the ship shock trial zone. To determine optimal locations for the recording devices, the team analyzed physical environmental

The aircraft carrier USS *Gerald R. Ford* (CVN 78) completes the first scheduled explosive event of a ship shock trial.
MC3 Riley B. McDowell

Rockhopper acoustic recording devices ready for a research deployment.
Shyam Madhusudhana

data—including water column structure, depth, wave height and wind speed, bathymetry, bottom sediment type—as well as anticipated (modeled) received level maps. All recorders were largely configured the same way at all sites to ensure that measurements could be easily standardized across devices. The deployed device settings did differ in the hydrophone sensitivities and gain control settings based on proximity to the ship shock trial location (i.e., near-field or far-field).

Recorders, including 15 moored autonomous devices (Rockhoppers) and six SoundTrap underwater acoustic recorders, were deployed in June 2021 and recovered in September 2021. During the course of the FSST, three detonations occurred (June 18, July 19, and August 8). After retrieving the devices in late August 2021, the team made copies and delivered the data to the Navy for security screening. Data screening is expected to be completed by January 2022. Once the project team receives the screened data, they will begin analyses of the acoustic shock wave propagation and estimated received levels at each of the recorders. In addition, the team will also document any observations of acoustical behavior changes by surrounding marine mammals.

These *in situ* data will provide measurements of received levels and estimated source levels and spectra to support the Navy's efforts to validate the NAEMO acoustic propagation model with ship shock trial explosive sources. The data will ensure that the Navy's estimates of acoustic impacts from explosive sources are as accurate as possible.

About the Principal Investigators

Kerri Seger is a senior scientist at Applied Ocean Sciences. She is also an affiliate research professor with the Center for Acoustics Research and Education at the University of New Hampshire. Her areas of expertise include soundscape parameterization, propagation modeling, bioacoustics and field design. Dr. Seger holds a Ph.D. in oceanography (specialty in bioacoustics) from Scripps Institution of Oceanography.

Shyam Madhusudhana is a postdoctoral research associate at the K. Lisa Yang Center for Conservation Bioacoustics, Cornell Lab of Ornithology, Cornell University, under the supervision of Dr. Holger Klinck. His areas of expertise include passive acoustics, automatic pattern recognition and signal processing. Dr. Madhusudhana earned his Ph.D. in applied physics at Curtin University, Australia.

Key contributors: Holger Klinck (Cornell University), Kevin Heaney and Christopher Verlinden (Applied Ocean Sciences).

Partnerships

The LMR program often works with other organizations on projects that offer benefits to Navy needs. Such partnerships help to leverage funding, expand demonstration and validation options, and draw on additional expertise.

The two ongoing partnerships are

1. The Sonobuoy Liaison Working Group
2. The Subcommittee on Ocean Science and Technology Interagency Task Force on Ocean Noise and Marine Life.

Ongoing Partnerships

Sonobuoy Liaison Working Group

LMR continues to participate in and keep members of the Sonobuoy Liaison Working Group informed on the sonobuoy allocation for marine mammal research. LMR is responsible for determining which priority research projects receive available sonobuoys. Unfortunately, in 2021 the allocation of sonobuoys available for research was cut and the LMR program was unable to provide projects with sonobuoys. We have been assured that our allocation is expected to be restored in 2022.

These sonobuoys play a significant role in expanding our data sets, and thus knowledge, related to where animals occur and when they are present.

Sailors load sonobuoys onto an MH-60R Sea Hawk helicopter.
MC3 Bryan Mai

The Subcommittee on Ocean Science and Technology Interagency Task Force on Ocean Noise and Marine Life

The Subcommittee on Ocean Science and Technology (SOST) Interagency Task Force on Ocean Noise and Marine Life (ITF-ONML) partnership moved to a new level during 2019 when three projects were jointly selected and funded by five participating agencies.

Operating under the auspices of the National Science and Technology Council's Committee on the Environment, Natural Resources, and Sustainability (CENRS), the SOST advises CENRS on national issues of ocean science and technology and serves as the lead interagency entity for federal coordination on those matters. The SOST ITF-ONML was organized to increase coordination and communication across federal agencies in addressing issues related to the potential impacts of anthropogenic noise on marine life.

Humpback whale.

Five of the SOST ITF-ONML participants—the Chief of Naval Operations Installations, Office of Naval Research, the Bureau of Ocean Energy Management, the National Oceanic and Atmospheric Administration, and the Marine Mammal Commission—partnered to jointly fund research on the auditory capabilities of mysticete whales. The group issued a call for proposals, via the LMR program, in July 2018 pertaining to development of audiograms for mysticetes. Following careful review and discussion by members of the review committee, three projects that covered a variety of methods were funded to increase the chance of success in obtaining data to address the need topic. The three projects are

1. Collection of AEP Hearing Thresholds in Minke Whales
2. Towards a Mysticete Audiogram Using Humpback Whales' Behavioral Response Thresholds
3. Investigating Bone-conduction as a Pathway for Mysticete Hearing.

Fact sheets for each of these projects are available on the LMR website under the SOST Partnership tab.

Two of the three projects—Collection of Auditory Evoked Potential Hearing Thresholds in Minke Whales, and Towards a Mysticete Audiogram Using Humpback Whales' Behavioral Response Thresholds—are being managed by the LMR program. Summaries of these two are presented in this report on page 59 and 61, respectively. The third project—Investigating Bone-conduction as a Pathway for Mysticete Hearing—is being managed by ONR MMB. Fact sheets for each of these three projects are available on the LMR website under the SOST Partnership tab.

FORECAST

We are looking forward to even more accomplishments in 2022 and beyond. Several LMR projects will be completed in 2022 and the project results, methods and technologies will become available for transition into application within the Navy's environmental compliance process and the Navy Marine Species Monitoring program.

In 2022, LMR will continue to meet the Navy's need for the tools and technologies to sustain at-sea training and testing within environmental permit requirements. LMR anticipates funding several projects, from our Fiscal Year 2022 (FY22) Broad Agency Announcement, that will demonstrate new and refined tools and technologies. The demonstration projects could address existing sparse acoustic arrays, improving existing marine mammal tags and enhancing the ability to identify calling individuals from acoustic tags. These tools can help the Navy's Marine Species Monitoring program meet monitoring requirements in a cost-effective manner. The tools also enable us to continue to collect important marine species data needed to study critical questions within a challenging oceanic environment that does not readily reveal its secrets.

Looking beyond 2022, we plan to select at least one of the SURTASS LFA Phase I projects to advance to a Phase II in 2023. In addition, we are strengthening our collaboration with NOAA and BOEM by co-investing in the expansion and continued development of a federal archive for passive acoustic monitoring data. Lastly, we will be discussing among Navy end users which priority research need topics LMR should consider investing in 2023 and beyond.

To that end, we value the sustained collaboration and partnerships with other programs within the U.S. Navy—LMR, ONR and the Navy's Marine Species Monitoring program—as well as with other programs, agencies and countries. Building on shared interests helps us all to effectively leverage investments and achieve common goals.

During each of our eight years managing the LMR program, we have been reminded of how critical it is to be ready to adapt and address new challenges. That includes those posed by a continuing worldwide pandemic. Thanks to the support of some of the greatest scientists and engineers in the field, who continued during 2021 to demonstrate their ability to address challenges, we are optimistic about LMR's future. We will continue, in the same spirit, to adapt and ensure that we are fulfilling our mission to support the Navy with priority research needs during these difficult times.

As always, this work ultimately is about our Sailors and our ability to maintain an effective and resilient Navy while being good stewards of the environment. LMR research will continue to directly support the Navy's ability to train and test at-sea and preserve core Navy readiness capabilities.

NAC2 Thomas Dougherty

LMR Publications

Included here is a list of publications that became available in 2021 and that were partially or fully funded by the LMR program. These publications are of great value to the Navy's at-sea environmental compliance process and directly feed into the NEPA, MMPA and ESA compliance documentation.

A spreadsheet with all LMR publications since 2013 is now available for download at the publications tab of our website. The spreadsheet is updated quarterly.

Bouchet, P., Harris, C. and Thomas, L. (2021). Assessing the role of sampling uncertainty for predicting behavioural responses of tagged cetaceans exposed to naval sonar. *Frontiers in Marine Science*. DOI 10.3389/fmars.2021.674554.

Bravington, M.V., Miller, D.L. and Hedley, S.L. (2021). Variance Propagation for Density Surface Models. *Journal of Agricultural, Biological and Environmental Statistics*. (Online). DOI 10.1007/s13253-021-00438-2.

Curé, C., Isojunno, S., Siemensma, M.L., Wensveen, P.J., Buisson, C., Sivle, L.D., Benti, B., Roland, R., Kvadsheim, P.H., Lam, F.P.A. and Miller, P.J.O. (2021). Severity Scoring of Behavioral Responses of Sperm Whales (*Physeter macrocephalus*) to Novel Continuous versus Conventional Pulsed Active Sonar. *The Journal of Marine Science and Engineering*, 9(4):444. DOI 10.3390/jmse9040444.

Isojunno, S., von Benda-Beckmann, S., Wensveen, P., Kvadsheim, P., Lam, F-P., Gkikopoulou, K., Pöyhönen, V., Tyack, P., Benti, B., Foskolos, I., Bort, J., Neves, M., Biassoni, N. and Miller, P. (2021). Sperm whales exhibit variation in echolocation tactics with depth and sea state but not naval sonar exposures. *Marine Mammal Science*. DOI 10.1111/mms.12890.

Kastelein, R.A., Helder-Hoek, L., Cornelisse, S.A., Defillet, L.N., Huijser, L.A.E. and Gransier, R. (2021). Temporary hearing threshold shift in a harbor porpoise (*Phocoena phocoena*) due to exposure to a continuous one-sixth-octave noise band centered at 0.5 kHz. *Aquatic Mammals*, 47(2):135-145. DOI 10.1578/AM.47.2.2021.135.

Kastelein, R.A., Helder-Hoek, L., Defillet, L.N., Huijser, L.A.E., Terhune, J. M. and Gransier, R. (2021). Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 2 and 4 kHz: effect of duty cycle and testing the equal-energy hypothesis. *Aquatic Mammals*, 47(4):394-418. DOI 10.1578/AM.47.4.2021.394.

Miller, D.L., Fifield, D., Wakefield, E. and Sigourney, D.B. (2021). Extending density surface models to include multiple and double-observer survey data. *PeerJ*, 9:12113. DOI 10.7717/peerj.12113.

Mulsow, J., Finneran, J.J., Houser, D.S., Burkard, R.F., Strahan, M.G. and Jones, R. (2021). The offset auditory brainstem response in bottlenose dolphins (*Tursiops truncatus*): Evidence for multiple underlying processes. *The Journal of the Acoustical Society of America*, 149(5):3163-3173. DOI 10.1121/10.0004830.

Ruscher, B., Sills, J.M., Richter, B.P. and Reichmuth, C. (2021). In air hearing in Hawaiian monk seals: implications for understanding the auditory biology of Monachinae seals. *Journal of Comparative Physiology A*. DOI: 10.1007/s00359-021-01498-y.

Sills, J.M., Parnell, K., Ruscher, B., Lew, C., Kendall, T.L. and Reichmuth, C. (2021). Underwater hearing and communication in the endangered Hawaiian monk seal *Neomonachus schauinslandi*. *Endangered Species Research*, 44:61-78. DOI 10.3354/esr01092.

von Benda-Beckmann, A. M., Isojunno, S., Zandvliet, M., Ainslie, M. A., Wensveen, P.J., Tyack, P.L., Kvadsheim, P. H., Lam, F.P.A. and Miller, P.J.O. (2021). Modeling potential masking of echolocating sperm whales exposed to continuous 1-2kHz naval sonar. *The Journal of the Acoustical Society of America*, 149(4):2908. DOI 10.1121/10.0004769.

Wakefield, E.D., Miller, D.L., Bond, S., Carvalho, P., Catry, P., Dilley, B., Fifield, D., Gjerdrum, C., González-Solís, J., Hogan, H., Laptikhovsky, V., Miller, J., Miller, P., Pinder, S., Pipa, T., Thompson, L., Thompson, P. and Matthiopoulos, J. (2021). The summer distribution, habitat associations and abundance of seabirds in the sub-polar frontal zone of the Northwest Atlantic. *Progress in Oceanography*. DOI 10.1016/j.pocean.2021.102657.

*Barlow, J., Fregosi, S., Thomas, L., Harris, D. and Griffiths, E.T. (2021). Acoustic detection range and population density of Cuvier's beaked whales estimated from near-surface hydrophones. *The Journal of the Acoustical Society of America*, 149(1). DOI 10.1121/10.0002881.

*Ver Hoef, J.M., Johnson, D., Angliss, R. and Higham, M. (2021). Species density models from opportunistic citizen science data. *Methods in Ecology and Evolution*, 12:1911-1925. DOI 10.1111/2041-210X.13679.

**Publication included data from or work in cooperation with LMR-funded projects.*

Staff Sgt. Jesus Sepulveda Torres

Acronyms and Abbreviations

3S3 .....Sea mammals, Sonar, Safety project phase 3
ABR.....Auditory brainstem response
AEP.....Auditory evoked potentials
ANSI.....American National Standards Institute
AN/SQS-53C.....Computer-controlled surface-ship sonar
ASA .....Acoustical Society of America
BAA .....Broad Agency Announcement
BOEM .....Bureau of Ocean Energy Management
BRS .....Behavioral Response Study
CAD .....Computer-aided design
CAS .....Continuously active sonar
CEE .....Controlled exposure experiment
CENRS .....Committee on the Environment, Natural Resources, and Sustainability
CEPAD.....Cetacean Evoked Potential Audiometry Database
CREEM.....Centre for Research into Ecological and Environmental Modelling
CSEE.....Coordinated sonar exposure experiments
CT .....Computerized tomography
CTBTO IMS.....Comprehensive Nuclear Test Ban Treaty Organization International Monitoring System
CW .....Continuous wave
DCLT .....Detection, classification, localization and tracking
dB.....Decibels
DET.....Detection error tradeoff
DICASS .....Directional command activated sonobuoy system
DenMod .....Density Surface Modeling (project)
DTAG.....Digital acoustic recording tag
EDA.....Effective detection area
EIS.....Environmental Impact Statement
ESA .....Endangered Species Act
FSST.....Full ship shock trial
GPL .....Generalized Power Law
GPS .....Global positioning system
HMM.....Hidden Markov model
HPN .....High-pass noise
HSTT.....Hawaii-Southern California Testing and Training Ranges
ICI.....Inter-click interval
ICMP .....Integrated Comprehensive Monitoring Plan
ITF-ONML .....Interagency Task Force on Ocean Noise and Marine Life
IPR .....In-progress Review
ISO .....International Organization for Standardization
kHz.....kilohertz
LFA .....Low Frequency Active sonar
LFM .....Linear frequency modulation
LIMPET.....Low Impact Minimally Percutaneous External-electronics Transmitter
LMR.....Living Marine Resources
LMRAC .....Living Marine Resources Advisory Committee
M3R .....Marine Mammal Monitoring on Navy Ranges
MARMAM.....Marine Mammals Research and Conservation Discussion
MFAS .....Mid-frequency active sonar
MMC.....Marine Mammal Commission
MMPA.....Marine Mammal Protection Act
MOCHA.....Multi-study Ocean Acoustics Human Effects Analysis
MSM.....U.S. Navy Marine Species Monitoring Program
NAEMO.....Navy Acoustic Effect Model
NEPA.....National Environmental Policy Act
NAVAIR .....Naval Air Systems Command
NAVFAC EXWC.....Naval Facilities Engineering and Expeditionary Warfare Center
NAVO/NAVOCEANO.....Naval Oceanographic Office
NCEI.....National Centers for Environmental Information
NEFSC .....Northeast Fisheries Science Center (NOAA)
NIWC.....Naval Information Warfare Center
NMFS.....National Marine Fisheries Service
NMMF.....National Marine Mammal Foundation
NOAA.....National Oceanic and Atmospheric Administration
OBS .....Ocean Bottom Seismometers
OE.....Opportunistic exposure
ONR.....Office of Naval Research
ONR MMB .....Office of Naval Research Marine Mammal Biology
OPNAV N4I .....Chief of Naval Operations Installations
OPNAV N45 .....Chief of Naval Operations Energy and Environmental Readiness Division
PAM .....Passive acoustic monitoring
PAM-DE .....PAM-based density estimation
PAS .....Pulsed active sonar
PCoD .....Population consequences of disturbance
PMRF .....Pacific Missile Range Facility
PTS .....Permanent threshold shift
RDT&E.....Research, development, test and evaluation
RJMCMC.....Reversible-jump Markov chain Monte Carlo
ROC.....Receiver-operator curves
SBIR .....Small Business Innovative Research
SCORE.....Southern California Offshore Range
SCR .....Spatial Capture Recapture
SEL.....Sound exposure levels
SMRT.....Sound and motion recording and telemetry
SOCAL.....Southern California
SOST ITF-ONML .....Subcommittee on Ocean Science and Technology Interagency Task Force on Ocean Noise and Marine Life
SPL.....Sound pressure levels
SURTASS LFA .....Surveillance Towed Array Sensor System Low Frequency Active sonar systems
TRC.....Technical Review Committee
TTS .....Temporary threshold shift
TWS .....Traveling wave speed
UAV .....Unmanned aerial vehicle
UUV.....Unmanned underwater vehicle
VHF.....Very high frequency
VLA .....Vertical line array
WHOI .....Woods Hole Oceanographic Institution
µCT.....Computed microtomography

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