Abstracts

Fourth International Conference on the Effects of Noise on Aquatic Life

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Ranging Baleen Whale Calls Using Towed Hydrophone Arrays During Seismic Reflection Surveys and Studying Effectiveness of a Mitigation Process

Shima H. Abadi  
School of STEM, University of Washington, Bothell, WA 98011, abadi@uw.edu

Maya Tolstoy  
Lamont–Doherty Earth Observatory, Columbia University, Palisades, NY 10964, tolstoy@ldeo.columbia.edu

William S. D. Wilcock  
School of Oceanography, University of Washington, Seattle, WA 98195, wilcock@uw.edu

Marine seismic surveys use low-frequency acoustic energy to image the structure of the seafloor. There are growing concerns that they may disturb marine mammals, particularly baleen whales that communicate in the same frequency range, and impede their communications. All seismic surveys utilizing airguns conduct visual marine mammal monitoring surveys concurrent with the experiment. Once a marine mammal is observed within the safety zone, the seismic source will be powered down to the mitigation gun (a small airgun) to avoid disturbance of the observed animal. To resume full-volume shooting, a ramp-up of the airgun array is mandatory. During this process, the number of firing airguns gradually increases to warn marine mammals in the vicinity and to provide enough time for them to leave the area and thus avoid any potential injury or impairment of their hearing abilities. In addition to the visual monitoring, passive acoustic monitoring (PAM) methods have been developed to acoustically locate vocally active marine mammals, but the use of PAM for detecting baleen whales remains a developing field due to the complexity of low-frequency signal propagation and the limited length of dedicated PAM arrays.

In this presentation, a low-frequency sound source ranging technique is introduced that utilizes the full capabilities of the long hydrophone streamer used for the seismic survey. This method is a grid search technique that uses beamforming outputs to estimate the range of baleen whale calls during a mitigation process and study the mitigation effectiveness in repelling animals. The experimental data utilized here are from the seismic experiment conducted with two 8-km seismic hydrophone arrays by the R/V Marcus G. Langseth near Alaska in Summer 2011. Results were obtained both for synthetic simulations to understand the quality of the locations as a function of a marine mammal’s position relative to the streamer and to compare with data from the experiment. Locations obtained for both fin and humpback whales during the experiment compare well with those obtained from marine mammal observers.
Effect of Noise on Aquatic Life: A Literature Review

Michael Adedotum Oke
Michael Adedotun Oke Foundation, Nigeria, maof2020@gmail.com
Olumuyiwa Oke
Michael Adedotun Oke Foundation, Nigeria, agricproject2020@gmail.com

Noise pollution has effects on aquatic life and has been a recognized problem for decades. Also, the sea is actually a very noisy place. Sound is a convenient mediator of information in water because it travels far, irrespective of daylight and visibility. This has been exploited by all sorts of animals living in the sea. However, the acoustical properties of water put special demands on sea animals trying to use sound. This paper gives the necessary information that will allow us to know what other people have said and the effect of noise on aquatic life in general. The finding shows that different noises cause a lot of problems to aquatic animals such as frogs and fishes, including changes in physiology, behavior, chronic stress, energy, reproduction, and long-term survival. The most common noises are made by humans, commercial oil exploration, the movement of ships, railways that are very close to the waterways, and the effect of airplanes when taking off and during military wars. This paper therefore suggests that humans should try all means to reduce the various noises from urban and rural areas and learn to protect and value the rights of other animals to live a peaceful and healthy life.
From Physiology to Policy: A Review of the Physiological Effects with Implications for Mitigation of Noise Effects on Marine Fauna

Natacha Aguilar de Soto
CREEM, University of St. Andrews, UK, naguilar@ull.es

Conservation law and guidelines for mitigating noise impacts require data about thresholds of injury and an assessment of the significance of effects at individual and population levels. Noise may impact animals by two main avenues, both with potential population-level effects: bottom-up responses, where genetic, cellular, and physiological-level responses affect the individual, and top-down effects, where these base responses are modulated by the life style of an animal. Effects can be recoverable in some cases. However, recorded alteration of DNA/gene expression and a variety of cell and tissue damages in different vital organs may not be reversible, especially if they occur at key developmental stages. Acute behavioral reactions to noise may also have lethal or sublethal effects, and these may occur at levels below those causing hearing injury. The significance of effects for a local stock will depend on the character and level of the effects and on the variability in the vulnerability of different individuals to similar stimuli. Bottom-up and top-down avenues of the noise impact on marine fauna are interrelated, but bottom-up base responses/mechanisms are expected to be shared between individuals and even between taxa because of the evolutionary basal origins of many hormonal, genetic, and biochemical mechanisms of the response to stress. In contrast, top-down responses, i.e., behavioral reactions driven by the life style of each species, which may be nonconsequential in some cases but can result in physiological damage and even death in other cases, will be modulated by the overall characteristics of the species/individual, including internal factors and how they relate to their environment. Most mitigation thresholds are currently based on a hearing injury to marine mammals, although there are initiatives and recent research that includes fish. This work reviews physiological effects of noise on marine fauna (invertebrates, fish, seabirds, marine turtles, and mammals) and relates the results with recent findings on behavior and population structure. The results have implications for mitigation guidelines to consider nonhearing physiological damage, disturbance, and effects on nonmammal species. The often transboundary character of underwater noise pollution underlies the need for intergovernmental and industry coordination of minimum guidelines both to monitor effects and for mitigation. These can be supported during seismic surveys by technology currently used by the industry.
Standardization of Underwater Acoustical Terminology: Why Bother?

Michael A. Ainslie, TNO, The Hague, michael.ainslie@tno.nl; Tomonari Akamatsu, National Research Institute of Fisheries Engineering, akamatsu@affrc.go.jp; Michel André, Technical University of Catalonia, michel.andre@upc.edu; Christian Audoly, DCNS, christian.audoly@dcns-group.com; M. A. Bahtiarian, Noise Control Engineering, mikeb@noise-control.com; Susan Blaeser, Acoustical Society of America, sblaeser@acousticalsociety.org; Maria Boethling, Federal Maritime and Hydrographic Agency maria.boethling@bsh.de; Yi Hangzhou Chen, Applied Acoustics Research Institute (HAARI) y.chen@163.com; Cuillerier, Pascal, Institut national de plongée professionnel cuillerier@inpp.org; Charlotte Cerema Curé, Dter Est, Laboratory of Strasbourg, Acoustics Group Charlotte.cure@cerema.fr; Peter H. Dahl, APL University of Washington, dahl@apl.washington.edu; John Dalen, Soundmare johndal@broadpark.no; Christ A. F. De Jong, TNO christ.dejong@tno.nl; René Dekeling, Ministry of Infrastructure and the Environment rene.dekeling@minienm.nl; Alec Duncan, Curtin University a.duncan@cmst.curtin.edu.au; Alexander Enyakov, VNIIFTRI, enyakov@vniiftri.ru; George Frisk, Florida Atlantic University gfrisk@fau.edu; Hervé Glotin, University of Toulon CNRS LSIS, h.glotin@gmail.com; Michele B. Halvorsen, CSA Ocean Sciences Inc., MHalvorsen@conshelf.com; Anthony D. Hawkins, Loughine Ltd. a.hawkins@btconnect.com; Andrew Holden, Defence Science and Technology Laboratory apholden@dstl.gov.uk; Dorian S. Houser, National Marine Mammal Foundation dorian.houser@nmmf.org; Alexander Isaev, VNIIFTRI isaev@vniiftri.ru; Darlene Ketten, Harvard Medical School and WHOI dketten@whoi.edu; Pavel Korotin, Institute of Applied Physics of Russian Academy of Sciences monitor@appl.sci-nnov.ru; Robert Laws, Schlumberger Gould Research rmlaws@slb.com; Chris Morley, University of Southampton (emeritus) morleys.4042@gmail.com; Andreas Müller, Müller-BBM andreas.mueller@mbbm.com; Stephen P. Robinson, National Physical Laboratory stephen.robinson@npl.co.uk; René Smidt Lützen, Lloyd’s Register rene.smidtluetzen@lr.org; Michael Stocker, Ocean Conservation Research mstocker@ocrc.org; Eric I. Thorsos, APL University of Washington eit@apl.washington.edu; Patrick Welton, patrickwelton@verizon.net

Applications of underwater sound include sonar, geophysical imaging, acoustical oceanography, communication, positioning, and bioacoustics. Scientists and engineers from distinct disciplines typically work with little interdisciplinary interaction, and the terminology employed in these disciplines has evolved separately within fields and across applications, to the point that transdisciplinary confusion and misunderstandings are common. Furthermore, increasing societal concern about possible detrimental effects of underwater noise on aquatic animals has led to national and international regulation requiring monitoring of underwater noise, with a consequent need for cross-disciplinary harmonization of terminology. We can facilitate the effective conveyance of concepts and information in underwater noise studies, as in all branches of underwater acoustics, whether for research, technology, or regulation, by adopting a common language. In the words of William H. Taft, “Don’t write so that you can be understood, write so that you can't be misunderstood.” A Dutch initiative (2009 to 2011) led to the publication of a report recommending acceptable underwater acoustical terminology as determined by an ad hoc group formed of primarily European scientists. In parallel, a US initiative led to the formation in 2011 of the Underwater Acoustics Subcommittee (ISO/TC 43/SC 3) of the International Organization for Standardization (ISO), the purpose of which is to provide international standards for underwater acoustics, including measurement and assessment of underwater sound and of its effects on aquatic life. At the inaugural meeting of SC3 (2012, Woods Hole Oceanographic Institution), the recognition of the need for a common terminology led to the creation of an ISO working group on standardization of underwater acoustical terminology. This working group has addressed the need for clear definitions of widely used terms such as those used for the characterization of sound fields (e.g., “soundscape” and “ambient noise”), sound sources (“source level” and “source waveform”), sound propagation (“transmission loss” and “propagation loss”), sound reception (“hearing threshold” and “detection threshold”), and the risks of exposure of aquatic animals to underwater noise (“sound exposure” and “hearing threshold shift”). In some disciplines, some of these terms tend to be used synonymously, whereas in others they have distinct meanings (we have in mind examples such as “hearing threshold” vs. “detection threshold” and “transmission loss” vs. “propagation loss”). Distinct definitions for these and many other acoustic terms are provided in the emerging standard (ISO 18405). This paper describes the present status of ISO 18405 and illustrates the benefits of its use.
The potential impact of seismic surveys on marine life has given regulators and scientists a shared interest in quantifying the sound field produced by an airgun or array of airguns. Predictions do not always agree well with measurements (Aerts and Streever, 2016), and the reasons for the disagreement are often not understood. It is necessary to build confidence in model accuracy by demonstrating that the different modeling techniques produce the same solution for a well-specified problem or, if they do not, to investigate the implications of different methods, assumptions, or approximations to understand how and why they differ. Propagation in shallow water and in deep water are both relevant, with different challenges arising from each. In shallow water, there are uncertainties caused by unknown seabed parameters, whereas in deep water, the difficulties are associated with propagation distances of thousands of kilometers. The near field is of interest because it includes distances that are relevant for physiological effects, whereas distances beyond the near field, up to tens of kilometers, are relevant to behavioral disturbance. At even greater distances, of hundreds of kilometers or more, the contribution from airguns to the ambient sound might become an issue, especially in deep water. To address this concern, we have invited experts in airgun signature modeling and propagation modeling to participate in an international workshop to take place on July 16 at the same venue as Aquatic Noise 2016. Our purpose is to meet the demand for increasingly precise assessments of environmental impacts, requiring accurate characterization of the airgun array sound field. We choose to start with a shallow-water case because, for a model comparison, we can eliminate uncertainties in model inputs by specifying these inputs carefully. The specified scenarios for shallow water will include propagation distances from the near field up to a few tens of kilometers from the array. The specific goals of the workshop are to provide well-specified biologically relevant scenarios for acoustic propagation, involving received sound pressure and particle motion at prespecified distances from an airgun array in shallow water; to obtain a set of solutions to these scenarios by combining airgun signature and sound propagation models; to provide a comparison of the various model results; to quantify the differences between them; to provide a description of the causes of these differences; and to correct errors where appropriate.

A Simple Calibration Method for Low-Frequency Underwater Sounds Using a Small Tank

Tomonari Akamatsu
National Research Institute of Fisheries Science, Fisheries Research Agency,
akamatsu@affrc.go.jp

Ryuzo Takahasi
National Research Institute of Fisheries Science, Fisheries Research Agency,
takahashiryuzo@affrc.go.jp

To observe the effect of noise on aquatic life, quantitative measurement of exposure level to an animal is required. Any type of hydrophone such as handheld, bottom-mounted, animal bone, or cable-connected ones should be calibrated in advance. However, the calibration of the hydrophone in low-frequency range has not been an easy task. Many aquatic species are sensitive at low-frequency sounds, which are often produced by anthropogenic sources. Wavelengths of such sounds are equivalent to or even larger than the size of an experimental tank that causes a serious distortion of the waveform. Here we propose a simple calibration method for a hydrophone using a small tank. Even in a small tank, the measurement of hydrophone sensitivity is possible at the fundamental resonant frequency of the tank. In this specific circumstance, sound pressure level in the tank was nearly constant within a proposed stable area, except for the area nearby the boundary such as the tank wall and the water surface. A commercially available polycarbonate tank with a diameter of 1.5 m and a height of 0.8 m was used for the calibration. The stable exposure level could be observed as a 30-cm sphere at the center of the tank within 3 dB, which is large enough compared with the size of an acoustic sensor element in a hydrophone. Because the tank wall is soft enough acoustically, it renders a sound pressure equivalent to the air pressure at the boundary. Only at the resonant frequency of the tank does a relatively constant sound field area appear, which can be used for the quantitative measurement of the sensitivity of a hydrophone. When a pure-tone sound, which frequency is higher than the fundamental resonant frequency, is projected in the tank, sound pressure changes location by location even within a few centimeters due to the constructive or destructive phase interference. Pure-tone sound having a lower frequency than the fundamental resonant frequency attenuated exponentially. Quick reduction of the received level was observed within 1 m. In either case, exposed sound pressure is location sensitive that makes the calibration of a hydrophone in a tank difficult. Note that the near-field effect is canceled at the center of the tank because of its symmetric sound field at the fundamental resonant frequency.
Underwater Hearing in the Great Cormorant, *Phalacrocorax carbo sinensis*

Kirstin Anderson Hansen  
University of Southern Denmark, kirstinhansen@biology.sdu.dk  
Magnus Wahlberg  
University of Southern Denmark, magnus@biology.sdu.dk  
Ole Næsby Larsen  
University of Southern Denmark, onl@biology.sdu.dk  
Ursula Siebert  
University of Veterinary Medicine Hannover, Ursula.Siebert@tiho-hannover.de

To be able to determine the effects of underwater noise on cormorants and other marine birds, there must be a better understanding of the hearing abilities of marine birds. Underwater hearing thresholds of a great cormorant, *Phalacrocorax carbo sinensis*, were measured using psychophysical methods. Using a go/no-go testing paradigm, 1 kHz, 2 kHz, and 4 kHz were tested. Previous testing in air and in water suggests that cormorants have rather poor hearing compared with other birds of similar size (Johansen, 2016), but these initial studies were made under poorer psychophysical conditions. Preliminary data, with the new underwater paradigm and in a larger pool, indicate that cormorants consistently respond to underwater sound and may therefore have special adaptations for underwater hearing.

Particle Motion Observed During a Large-Scale Piling Operation

Mathias H. Andersson  
FOI, Swedish Defence Research Agency, mathias.andersson@foi.se  
Markus Linné  
FOI, Swedish Defence Research Agency, markus.linne@foi.se  
Andreas Nöjd  
FOI, Swedish Defence Research Agency, andreas.nojd@foi.se  
Leif K. G. Persson  
FOI, Swedish Defence Research Agency, leifp@foi.se  
Peter Sigray  
FOI, Swedish Defence Research Agency, peter.sigray@foi.se  
Andrew B. Gill  
Cranfield University, a.b.gill@cranfield.ac.uk  
Frank Thomsen  
DHI Denmark frth@dhiigroup.com

Pile driving of foundations into the seabed for offshore wind turbines or to stabilize a harbor is known to generate high-energy impulsive sounds. The particle motion component of the radiated noise from activities of this kind have rarely been measured. It is well-known that most fish, sharks, and rays as well as some invertebrates sense the particle motion of an acoustic pulse and not the pressure per se because their sensory organs are only sensitive to particle motion. Thus, it is vital to determine this component of sound as well and not only the sound pressure estimate the impact on these species from pile driving. One of the aims of the MaRVEN (Marine Renewables, Vibrations, Electromagnetic Fields and Noise) project, funded by the European Commission Directorate for Research and Innovation, was to demonstrate that it is possible to measure particle motion from a large-scale offshore piling operation and to estimate the received levels. This study successfully measured pile-driving sounds in terms of particle motion from two steel monopile foundations (7.5 m diameter) driven into the seabed by a hydraulic hammer. A custom-built autonomous particle motion sensor was used in the measurement campaign, which took place at an offshore location in the North Sea. The sensor part of the measurement device is a nearly neutral buoyant sphere, which houses a 3-axis piezoelectric accelerometer attached to a platform holding the data amplifier, acquisition system, and batteries. The system was deployed 750 m from the piling operations. The measurement gave information on the zero-to-peak particle acceleration and the acceleration exposure (defined similar to sound exposure level for pressure), from an unmitigated pile-driving operation as well as information of the effectiveness of various mitigation measures on the reduction of particle acceleration. The measured levels of particle acceleration at 750 m were well above ambient levels but varied to a large extent depending on the mitigation measure used. Without any mitigation active or in place, the received levels in terms of broadband zero-to-peak particle acceleration were well above literature values of both hearing and reaction thresholds for fish and, to some extent, sharks, rays, and invertebrates.
New Comprehensive Understanding of the Role of Individual Structures Within the Head of Echolocating Dolphins in the Formation of Biosonar Signal and Beam

Whitlow W. L. Au  
Hawai’i Institute of Marine Biology, University of Hawai’i, wau@hawaii.edu  
Chong Wei  
Hawai’i Institute of Marine Biology, University of Hawai’i and College of Ocean and Earth Sciences, Xiamen University, Xiamen 361005, China

Recent research has resulted in a significant increase in our understanding of sound propagation within the head of dolphins. Results of Au et al. (2016) reinforce the notion that source intensity is the primary factor controlling the peak and center frequencies of biosonar clicks which in turn affects the duration of each click along with the bandwidth and other parameters associated with clicks. Finite element simulation of broadband acoustic signals propagation in the head of the Baiji (Wei et al., 2016), and ongoing simulation with Phocoena phocoena and Tursiops truncatus coupled with acoustic measurements on the head of Tursiops truncatus have shown that the air sacs and skull are the major contributor on the shape of the beam and that the melon has a minimum role in the focusing the signals but does affect the axis of the beam. The acoustic impedance structure of the melon with its small amount of gradient does not allow sufficient ray bending to take place even if the melon is deformed slightly. The wave front of a broadband signal propagating through the melon show almost no changes in the shape of the wave front as the signal moves through the melon. Au et al. (2016) just completed a comparison between field measurement of free swimming dolphin holding a special device that extended a hydrophone in front of the animal while performing a biosonar detection task with in- pen measurements involving a target discrimination tasks show a similar tendency of dolphins like bats to emit longer duration signals with greater variability while free swimming. The wide off-angle measurements of the biosonar beam of Tursiops truncatus by Au et al. (2012) and measurement of the biosonar signal on the surface of a dolphin’s head by Au el al. (2010) has revealed the complexity of sound propagation that occurs within the head of dolphins. An internal reflection component has been mistaken for the simultaneous operation of the two phonic lips. The relationship with head size and directionality of the biosonar beam will be addressed based on the finite difference simulation of sound propagation in the head of baiji, Phocoena phocoena and Tursiops truncatus, along with recent measurements of beam pattern. Combining together the results of the below references along with a few other studies provide us with the most comprehensive and new understanding of what is occurring within head of an echolocating dolphin and clearing some important misconceptions.

Ground-Truthed Probabilistic Shipping Noise Modeling and Mapping: Application to Blue Whale Habitats in the Gulf of St. Lawrence

Florian Aulanier  
ISMER-UQAR, Florian.Aulanier@uqar.ca

Yvan Simard  
Fisheries and Oceans Canada and ISMER-UQAR, Yvan.Simard@dfo-mpo.gc.ca

Nathalie Roy  
Fisheries and Oceans Canada, Nathalie.Roy@dfo-mpo.gc.ca

Cédric Gervaise  
Chaire Chorus, University of Grenoble-Alpes, cedric.gervaise@gipsa-lab.grenoble-inp.fr

Marion Bandet  
ISMER-UQAR, Marion_Bandet@uqar.ca

To assess the effects of shipping noise on the quality of blue whale habitats in the Estuary and Gulf of St. Lawrence, Eastern Canada, shipping noise was simulated over the whole northwest Atlantic marginal sea for representative summer and winter months. Shipping traffic was monitored with a dense AIS network covering the whole area. The actual source levels of the merchant fleet ships was obtained from an acoustic observatory following the ANSI/ASA S12.64 protocol that was set up in the 350-m × 40-m deep channel of the main seaway. Water mass characteristics were taken from the outputs of an operational regional hydrodynamic circulation model. This information was combined with seafloor bathymetry and estimated geoacoustic properties to feed a parabolic equation (PE) acoustic propagation model to simulate shipping noise in the 15- to 100-Hz call bands at 30-min intervals throughout the months, with a resolution of 1 km² for 10 depth layers. Model outputs at 16, 20, 40, and 63 Hz one-third octave bands successfully reproduced the probability density functions (PDFs) of the noise observed over the month at the three measuring depths of the seaway acoustic observatory. The roles of the seaways and of modulations by the three-dimensional basin shape are illustrated. Modal shipping noise excess compared with natural ambient noise varied with depth and frequency from 10 to 30 dB. Levels in the infrasonic band were 5 to 10 dB weaker near the surface compared with deeper depths. The shipping noise in the D-call frequency band tended to be 20-30 dB higher than that of the A-call infrasonic band. Effects of summer/winter changes were weak. The modeled shipping noise PDFs were then used to map the risk to exceed given noise thresholds or the chance to remain under given noise levels in an effort to circumscribe at-risk and quiet areas. Shipping noise blue whale A- and D-calls masking probabilities were estimated at representative locations in the in the study area. Both calls were masked in proportion with traffic density in the vicinity of shipping lanes, which can fragment the communication space into several pieces. D-calls were much more masked than A-calls by present shipping noise compared with ancient ambient-noise conditions.
Analysis of Submarine Environmental Noise in Laguna de Términos, Campeche

Pamela Alejandra Azamar Reyes  
Facultad de Estudios Superiores Iztacala, UNAM, azamar.pamela@gmail.com

Whitlow W. L. Au  
University of Hawai’i, wau@hawaii.edu

María del Carmen Bazúa Durán  
Facultad de Ciencias, UNAM, bazua@unam.mx

Sound is energy that spreads more efficiently in the marine environment, produced by both natural and anthropogenic sources and called submarine noise or background noise in the ocean. In Laguna de Términos, Campeche, the submarine environmental noise is a problem for marine life and one of its main threats. Therefore, the objective of this work was to analyze the submarine environmental noise in Laguna de Términos using digital submarine recordings made over 5 years (2004-2008) in 17 sampling periods with 57 stations in *.wav format at a sampling rate of 48 kHz with 16 bits and a duration of 1 minute for each of the stations. Recordings were high passed with a filter to remove all sound below 1.5 kHz and recording gain settings were considered to compute the total intensity of the environmental noise in the recordings with a semiautomatic MATLAB routine designed for this purpose. Preliminary results indicate that submarine environmental noise in the lagoon changed from one sampling to another; thus we are investigating the reasons for these changes and their relationship with the presence of bottlenose dolphins (*Tursiops truncatus*) in the lagoon. Analyzing submarine environmental noise is of great importance because it is relevant to understand the contribution of anthropogenic sources and their effect on the ecology of marine wildlife such as dolphins.
The Science and Policy Drivers Leading to a Mitigation Zone for Beaked Whales Along the Irish Shelf Edge

**Simon Berrow**  
Galway-Mayo Institute of Technology, simon.berrow@gmit.ie

**Joanne O’Brien**  
Galway-Mayo Institute of Technology, joanne.obrien@gmit.ie

**Dave Wall**  
Irish Whale and Dolphin Group, dave.wall@iwdg.ie

In 2013, a mitigation zone along the continental shelf margin was declared by the Irish government because of concerns about the potential effects of seismic activity on deep-diving whale species. All seismic survey activity was excluded from this zone until a proper assessment of the importance of this habitat could be made following the recommendations of three consecutive strategic environmental assessments of offshore exploration (www.dcner.gov.ie). The mitigation zone extends for some 300 km and covers a strip up to 60 km wide, 180,000 km² in total area. In this paper, we describe the evolution of this mitigation zone, including the scientific evidence and conservation concerns regarding the sensitivity of these habitats for beaked whales and the policy drivers that lead to this important precautionary measure. An offshore cetacean atlas involving 1,078 days at sea over a 7-year period identified the northwest shelf edge as a potential hot spot for beaked whales (Wall et al., 2013). A pilot scheme to assess the feasibility of using static acoustic monitoring to monitor beaked and other deep-diving whales in these shelf habitats was carried out, with 4 sites monitored over a 12-month period with 2 independent SAM experiments (Wall et al., 2012). A dedicated passive acoustic survey targeting beaked whales was carried out in 2010 and 2011, with over 2,800 km of track line surveyed (MCR, 2011). The results from these studies were used to inform the licensing authority. The oil and gas industry still wish to acquire seismic data along the shelf edge and the Irish government has recently commissioned two research projects, including passive and static acoustic monitoring and aerial surveys, to further inform them on the importance of these habitats for all cetacean species. This is an excellent example of best practice in marine spatial planning and the management of offshore habitats for whales and dolphins.


Silence is Golden, at Least for a Common Goby Male Who Wants to Mate

Eva-Lotta Blom
University of Gothenburg, eva-lotta.blom@bionev.gu.se

Sofie Schöld
University of Gothenburg, sofie.schold@gmail.com

Lotta Kvarnemo
University of Gothenburg, lotta.kvarnemo@bioenv.gu.se

Ola Svensson
University of Gothenburg, ola.svensson@bioenv.gu.se

Clara Amorim
ISPA Instituto Universitário, Lisbon, amorim@ispa.pt

Anthropogenic underwater noise is a global pollutant of increasing concern and its effect on marine organisms is largely unknown. Importantly, direct assessments of fitness consequences are lacking and especially in fish. The effect of noise pattern with continuous or intermittent noise is also poorly understood and the few existing studies investigating the effect highlight contradictory responses in fish. We set up an experiment to evaluate the impact of ambient, intermittent and continuous noise on the common goby’s (*Pomatoschistus microps*) behavior and reproductive success, assessed by the number of obtained eggs. The results revealed a strong effect on behavior. Males exposed the continuous noisy treatment showed lower courtship levels and experienced significantly longer time until spawning than fish in the ambient and intermittent noise tanks. Males exposed to continuous noise got significantly fewer egg clutches (4 compared to 11 and 15 in the intermittent noise and silence treatments). Clutch area did not differ among treatments but clutches in the intermittent and continuous noise treatment had significantly more eggs per cm$^2$ (80.2 compared to 91.5 and 92.5 in the intermittent noise and continuous noise). In addition, the eggs in the control tanks hatched earlier than in the intermittent and noisy treatments. These results strongly indicates that a continuous, but also intermittent noisy environment have the potential to negatively affect reproductive success in the common goby and are therefore highly likely to affect other species of fish.
Acoustic Behavior of Blue Whales (*Balaenoptera musculus*) in the Gulf of Corcovado, Chile, Recorded on DTAGs

**Alessandro Bocconcelli**  
Woods Hole Oceanographic Institution, Woods Hole, MA 02543, abocconcelli@whoi.edu

**Leigh Hickmott**  
Open Ocean Consulting 2 Borough House, 72 Borough Road, Petersfield, Hants GU32 3LF, UK, leighhickmott@theopenocean.co.uk

**Gustavo Chiang**  
Melimoyu Ecosystem Research Institute, MERI Foundation, Santiago, Chile, gchiang@fundacionmeri.cl

**Francesco Caruso**  
Institute for Coastal Marine Environment, National Research Council, Torretta Granitola (TP), Italy, fcaruso@unime.it

**Paulina Bahamonde**  
Melimoyu Ecosystem Research Institute, MERI Foundation, Santiago, Chile, pbahamonde@fundacionmeri.cl

**Laela Sayigh**  
Woods Hole Oceanographic Institution, Woods Hole, MA 02543, lsayigh@whoi.edu

The blue whale (*Balaenoptera musculus*) is listed as “endangered” on the IUCN Red List of Threatened Species. In the Southern Hemisphere, the species was once abundant, but commercial whaling has reduced it to near extinction during the twentieth century. A joint effort between WHOI and the Melimoyu Ecosystem Research Institute (MERI) is focusing on a population of Chilean blue whales in the Gulf of Corcovado, Chile, which is an important feeding ground for these animals. This investigation set out to obtain data on the ecology, foraging, and acoustic behavior of individual blue whales through the deployment of suction cup-attached sound and orientation recording tags (DTAGs). Tagging efforts took place in March 2014, 2015, and 2016, with 17 tags deployed for a total duration of 124 h 12 min. Dives were generally shallow, predominantly between 10 and 50 m in depth. Occasional deeper dives were recorded, with a maximum depth of 139 m. Acoustic data on the 2014 tags revealed numerous calls previously identified as “SEP” calls from distant blue whales, and an apparent call exchange was recorded between a tagged juvenile whale and a distant animal. The call was also detected on the juvenile whale’s accelerometers, confirming caller identification. Analysis of 2015 and 2016 acoustic data is ongoing but reveals a great variety of sound types, including short pulsed sounds and downsweeps. Tag data will prove useful for interpretation of data collected in this area from passive acoustic monitors (PAMs) for both species identification and possibly density estimation. Thus this work has the potential to contribute to efforts to protect this important population of endangered blue whales.
ETAW: Exploring the Thermal and Technological Limits of Automatic Whale Detection

Olaf Boebel
AWI, olaf.boebel@awi.de

Daniel P. Zitterbart
AWI, Daniel.Zitterbart@awi.de

Louise Bennett
The University of Queensland, louisebennettmail@gmail.com

Elke Burkhardt
AWI, Elke.Burkhardt@awi.de

Alejandro Cammareri
MaryBio, alecammareri@hotmail.com

Michael Flau
AWI, michael.flau@awi.de

Hendrik Kniest
UON, eric.kniest@newcastle.edu.au

Catherina Lanfredi
Politecnico di Milano, caterina.lanfredi@polimi.it

Kylie Owen
The University of Queensland, kylie.mackenzie3@gmail.com

Hanna Michel
AWI, hanna.michel.mb@gmail.com

Michael Noad
The University of Queensland, mnoad@uq.edu.au

Aude Pacini
Hawaii institute of Marine Biology, University of Hawaii at Manoa, aude@hawaii.edu

Thermographic imaging has been shown to reliably detect marine mammals, both day and night, for operational mitigation in polar and subpolar waters (Zitterbart et al., 2013), with encouraging findings having recently been reported for temperate waters (NOAA Southwest Fisheries Science Center, 2015). Because thermographic imaging is based on thermal contrast between whale body or blow and the sea surface, thermographic discriminability is expected to wane with increasing sea surface temperatures. EТАW explored the upper sea surface temperature limit of this approach by deploying high-end thermal cameras on North Stradbroke Island, Queensland, Australia (subtropical conditions) and on both the north and south shore of Kauai, HI, (tropical conditions). The study design included both acquisition of thermographic video as well as concurrent visual sightings, including double-blind setups. Our findings show that cues of humpback whales are thermally discriminable even under the highest sea surface temperatures encountered (26°C/79°F). Thermal discriminability and the performance of computer-based automatic detection of cues appear, based on the (subjective) experience gained in the field, to be more dependent on covariates such as camera height, sea state, and glare than on sea surface temperature. Although increasing sea surface temperatures appear to reduce the operational radius of thermographic images (yet not below typical mitigation radii of 1-3 km), they did not render cues entirely indistinguishable from the background image, whereas glare and increased sea states caused increased numbers of false alerts. Comparisons of different IR technologies (scanning LWIR 8–12 µm, focal plane array LWIR 8.0–9.4 µm, focal plane array MWIR 3.7–5.5 µm) suggest that the broadband LWIR sensor produced the clearest image least affected by glare. Tests of polarization filters in different orientations revealed that glare is somewhat, but not significantly, reduced for horizontal polarization orientation but that the benefits are outweighed by image degeneration because of the additional optics, at least for the high-temperature resolution required in this application.


An Investigation of Irish and British Inland Water Soundscapes: Which Sound Sources Influence Acoustic Levels?

Marta Bolgan  
Marine and Freshwater Research Centre, Department of Natural Sciences, Galway-Mayo Institute of Technology, Dublin Road, Galway, Ireland, marta.bolgan@gmail.com

Joanne O’Brien  
Marine and Freshwater Research Centre, Department of Natural Sciences, Galway-Mayo Institute of Technology, Dublin Road, Galway, Ireland, joanne.obrien@gmit.ie

Ian J. Winfield  
Lake Ecosystems Group, Centre for Ecology and Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK, ijw@ceh.ac.uk

Martin Gammell  
Marine and Freshwater Research Centre, Department of Natural Sciences, Galway-Mayo Institute of Technology, Dublin Road, Galway, Ireland, martin.gammell@gmit.ie

The acoustic ecology of freshwater habitats is less understood than that of marine environments. Our current knowledge of underwater spectral contents and levels mainly pertain to the marine environment, whereas very few studies have investigated the spectral profiles of freshwater soundscapes. Although it is well recognized that the biological communities inhabiting inland aquatic habitats currently face unprecedented threats from human activities and that anthropogenic pressures often act in a multimodal fashion, the potential occurrence of noise pollution in inland waters has been largely overlooked to date. As a result, no legislative effort has been made toward the conservation of good quality freshwater acoustic environments. The aims of this paper were (1) to investigate the environmental characteristics that influence noise levels in a glacial lake in which anthropogenic noise was absent and (2) to investigate the contribution of anthropogenic noise to the overall noise levels of a large multiuse lake. Acoustic recordings were carried out in two different glacial lakes (i.e., Lough Na Fooey, Ireland, and Windermere, England) using different passive acoustic monitoring approaches. At Lough Na Fooey, a vessel-based survey over preestablished sampling stations covering the entire lake surface (together with a bottom survey) was carried out while a moored sampling was carried out around the clock at selected sites in the shallow, gravel littoral shores of Windermere. Acoustic data were collected at different depths and over different bottom types at Lough Na Fooey during daytime hours. In Windermere, acoustic data were collected at the same depth and over the same bottom type during nighttime and daytime hours. Acoustic recordings from Lough Na Fooey lacked both the biophonical and anthropogenic component of the soundscape. Nighttime acoustic recordings from Windermere were characterized by biophonical sources such as invertebrate (family Corixidae) and fish air passage sounds. Daytime acoustic recordings from Windermere were characterized by consistent boat traffic noise. Classification models were used to investigate which sonic sources (i.e., environmental parameters, biophonical or anthropogenic sources) contributed to the detected noise levels. This preliminary application of classification models to freshwater soundscapes seems to indicate that when anthropogenic noise is present, this can represent an important factor ruling the acoustic environments of the biological communities inhabiting these already delicate environments. Based on the results obtained, it is recommended that further studies focus on a wider geographical and temporal range to start filling the knowledge and legislative gaps regarding anthropogenic noise monitoring in freshwater environments.
Using Interim Population Consequences of Disturbance to Explore Potential Cumulative Effects of Pile-Driving Disturbance on the North Sea Harbor Porpoise Population

Cormac Booth
SMRU Consulting, cgb@smruconsulting.com
John Harwood
University of St. Andrews, jh17@st-andrews.ac.uk
Rebecca Walker
Natural England, Rebecca.Walker2@naturalengland.org.uk
Sonia Mendes
Joint Nature Conservation Committee, Sonia.Mendes@jncc.gov.uk

The interim population consequences of disturbance (iPCoD) framework was developed to evaluate the potential effects of offshore marine renewable energy construction and operation on UK marine mammal populations (King et al., 2015). iPCoD has now been used to assess the aggregate effects of 10 years of English wind farm construction on the North Sea harbor porpoise population. iPCoD simulations are run thousands of times and the differences between (otherwise identical) pairs of disturbed and undisturbed populations are compared. Information was collated from 10 wind farms on construction schedules, sound impact ranges, and the predicted number of porpoises impacted. Initially, the information presented in the licensing documents (e.g., environmental statements [ESs]) was used for each site and simulations run exploring how the disturbance associated with construction of these sites impacted the porpoise population. However, because licensing documents are prepared years in advance of construction and because of uncertainties in final wind farm design, they tend to represent the worst case (i.e., longest construction period and largest estimates of disturbance). Therefore, a second set of up-to-date scenarios was built by liaising directly with the relevant offshore wind farm developers. In addition, the estimates of porpoises disturbed were refined by applying the adapted dose-response relationship from Thompson et al. (2013) to more realistically represent the gradient of effect with distance away from the pile-driving location. The recovery times (i.e., how long it takes for porpoises to return to the area) were also graded according to the distance from the pile-driving location by using the data presented in Brandt et al. (2011). Using the worst case from the ESs resulted in predictions of the risk of a decline of greater than 1% per year of the North Sea population, occurred in between approximately 1 in 5 and 1 in 8 scenarios 12 years after the start of construction. The updated, more realistic simulations resulted in a lowering of this risk, with between approximately 1 in 20 and 1 in 250 scenarios. More research on the response of individual harbor porpoises to pile-driving noise in the open sea is required to reduce the uncertainty around these estimates. In addition, the iPCoD framework relies on the opinions of experts, and although the process used to collect this information was designed to minimize potential biases and provide a realistic measure of uncertainty, these forecasts should be interpreted with caution until more empirical data are available.

Measurements of Underwater Sound Irradiated from a Plant for the Regasification of Liquid Natural Gas

Junio Fabrizio Borsani  
ISPRA, jf.borsani@gmail.com
S. Curcuruto  
ISPRA, salvatore.curcuruto@isprambiente.it
F. Pace  
Baker Consultants Marine Ltd., f.pace@bakerconsultants.co.uk

In Summer 2015, underwater sound irradiated into the Northern Adriatic Sea from an offshore plant for the regasification of liquid natural gas (LNG) was measured. LNG has recently become popular as a cost-effective alternative to crude oil and coal for generation of industrial electricity as well as for the heating network of buildings. Large gas tankers approach the docking terminal and unload their gas by means of pumps; LNG is then regasified by passing a pipe system that is heated via the seawater temperature gradient. Once LNG has regained its gas form, it is introduced into a pipeline system that distributes it on land. Various sound sources are present in the area that is associated with LNG operations; these include noise from pumps and generators located on the terminal itself, from the gas tanker as well as from the tugs that support the tanker while docking and unloading. Sound was recorded via sensors placed both above and below the seasonal thermocline. Measurements were taken at distances that ranged from ~500 m to ~2,000 m from the source. At all distances, peak SPL values between 62.99 Hz and 999.1 Hz ranged between ~100 dB re 1 µPa and 150 dB re 1 µPa. Because of the bathymetry and sediment characteristics, modeling showed that at a distance of 100 m, all peak SPL values were below values described in the literature as relevant for eliciting behavioral reactions in cetaceans. Reference measurements of ambient noise were taken at ~16,000 m from the source. Ambient noise was generically 50-60 dB re 1 µPa higher than the Wenz values because of a major contribution from shipping traffic noise present in the area. Whether the increase on low-frequency noise within the measured radius impacts marine life in the area remains to be determined.
Marine Mammal Monitoring During Navy Explosives Training Events Off the Coast of Virginia Beach, Virginia

Jacqueline Bort Thornton  
Naval Facilities Engineering Command Atlantic, 6506 Hampton Boulevard, Norfolk, VA 23508, jacqueline.bort@navy.mil

Cara Hotchkin  
Naval Facilities Engineering Command Atlantic, 6506 Hampton Boulevard, Norfolk, VA 23508, cara.hotchkin@navy.mil

Jaime Gormley  
Naval Facilities Engineering Command Atlantic, 6506 Hampton Boulevard, Norfolk, VA 23508, jaime.gormley@navy.mil

Mandy Shoemaker  
Naval Facilities Engineering Command Engineering and Expeditionary Warfare Center, 1000 23rd Avenue, Port Hueneme, CA 93043

Anurag Kumar  
Naval Facilities Engineering Command Engineering and Expeditionary Warfare Center, 1000 23rd Avenue, Port Hueneme, CA 93043

Jene Nissen  
United States Fleet Forces Command, 1562 Mitscher Avenue, Suite 250, Norfolk, VA 23551

Ron Filipowicz  
Commander, U.S. Naval Forces Europe and Commander, Sixth Fleet, Naples, Italy

Navy training events involving the use of explosives pose a potential impact to marine mammals. This study used passive acoustic and visual monitoring data to evaluate marine mammals’ behavioral responses to noise from explosive events. Monitoring was conducted during six explosive ordnance disposal (EOD) training events in the Virginia Capes (VACAPES) Range Complex during August 2009 through October 2015. During the EOD training event, inert mine shapes were placed either at the surface or at depth. A Navy EOD team located and subsequently neutralized the mine shapes using an explosive charge. Navy biologists performed monitoring for one day before the explosive events, on the day of the explosive events, and one day after the explosive events. Although the goals of this study remained the same every year, monitoring methods (both visual and acoustic) were modified throughout the study period to improve the usefulness and accuracy of the data. Passive acoustic monitoring methods ranged from a single hydrophone to an array of sonobuoys positioned around the EOD event location and monitored in real time. During sonobuoy-monitored events, 53F or 53F-GPS DIFAR sonobuoys were placed a safe distance from the planned explosive event location. Sonobuoy data were transmitted to a portable receiver for real-time detection and analysis of marine mammal vocalizations. During all events, data were also recorded on archival acoustic recorders for additional post hoc analysis. Visual monitoring effort over the 6 events totaled ~48 hours (day before events: 12.26 hours; days of events: 22.15 hours; day after events: 12.95 hours), yielding a total of 55 marine mammal sightings. Survey methods evolved over time, with more recent events utilizing formalized line transect surveys. Approximately 171 hours of acoustic data were collected before, during, and after the six events. Potential behavioral changes were evaluated based on analysis of vocalizations detected before, during, and after explosions and concurrent data from visual sightings. When possible, the total number of individual vocalizations of marine mammals was also evaluated. For time periods with both visual and acoustic-monitoring data, detection methods were compared to evaluate effectiveness and confirm species identifications. The primary species detected both visually and acoustically was the bottlenose dolphin (*Tursiops truncatus*). Continuing use and evaluation of both visual and passive acoustic methods for monitoring of explosive training events will improve our knowledge of potential impacts resulting from explosive events and help improve the management and conservation of marine mammals.
Noise from Recreational and Commercial Vessel Sonars in the 50-Hz to 100-kHz Range: Preliminary Measurements from San Diego Bay

Ann E. Bowles
Hubbs-SeaWorld Research Institute, abowles@hswri.org
Kenneth M. Toy
Axium Technology Solutions, ktoy@axiumtech.com
Michael A. Shane
Hubbs-SeaWorld Research Institute, mshane@hswri.org

The literature on marine mammal responses to navigational sonars is small, but these sonars can produce pings within the hearing range of odontocetes or pings with audible sidebands (Deng et al., 2014). We collected noise measurements at three sites in water 10–18 m deep on the slope of the boat channel in outer San Diego Bay on one weekday and one weekend day in early October 2015. A total of 14 h of data were collected in 30-min blocks during the afternoon (higher vessel activity) and evening (lower vessel activity). Data were collected with two RESON TC4032-1 hydrophones deployed at 2 m and 8 m depth connected to a PC laptop with a Data Translation DT9847-3-1 A/D converter sampling at 216 kHz. Vessel activity was sufficiently common at all three study sites that vessel passes were difficult to distinguish. Pings from navigational sonars in the range from 30 to 100 kHz were detected frequently as well. Most were short pings at 50 kHz or 80–85 kHz. However, forward-looking sonar from a large cruise ship produced 30–40 kHz sweeps with received levels up to 163.0 dB re 1 μPa at an estimated range of 200 m from the oncoming vessel. Noise from sonars was detectable 25% of recorded time, exceeding levels from vessel transits and snapping shrimp at sonar frequencies. From the perspective of human observers, the pings were a useful source of information about the proximity and orientation of vessels. This suggests that they could serve as cues to vessel activity and as a result alter, whether positively or negatively, marine mammal behavioral responses to vessel.

The United Kingdom’s Marine Impulsive-Noise Registry

Tetrienne Box  
JNCC, tetrienne.box@jncc.gov.uk  
Paul Gilbertson  
JNCC, paul.gilbertson@jncc.gov.uk  
Sónia Mendes  
JNCC, sonia.mendes@jncc.gov.uk  
Mark Tasker  
JNCC, mark.tasker@jncc.gov.uk

The EU Marine Strategy Framework Directive was adopted in 2008 and transposed to UK legislation in 2010. The directive sets out 11 high-level descriptors of good environmental status (GES) that must be achieved in EU marine waters by 2020. The Marine Noise Registry (MNR) is the UK’s option to address Descriptor 11 for impulsive noise sources. The introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment. The MNR is a database with an online interface that collects and stores data for activities within UK seas generating low- to midfrequency (10-Hz to 10-kHz) impulsive noise, including impact pile driving, explosions, and seismic surveys. Many of these activities may only be carried out under licenses granted by a regulatory authority. Other activities, such as those undertaken by the Ministry of Defence, are not licensed. In both cases, the location and date information is submitted to the MNR by developers, by regulators, or via the JNCC. The MNR also collects source property data, for example, maximum airgun volume, sound pressure level, and sound exposure level when this is known. Development of the MNR database and processes for data input have been managed by the JNCC over the last 5 years in collaboration with UK government departments and the devolved administrations, regulators, and industry representatives. The MNR was built using Agile methodology and the source code has been open sourced under the Open Government Licence. The MNR will initially be used to quantify the pressure on UK seas by making available an overview of relevant impulsive low- and midfrequency sound sources throughout the year. This will aid in the definition of a baseline level for impulsive noise in UK seas and inform the definition and assessment of GES. In particular, maps will be produced presenting impulsive noise events in pulse-block-days. Pulse-block-days represent the number of days over a set time period when impulsive noise has been generated (via activities mentioned above) within each UK oil and gas licensing block. The MNR also has the potential to be used as a management, planning, or advisory tool, for example, to help assess and manage cumulative impacts on marine species.
HAMMER: A Tool to Predict Impacts of Anthropogenic Noise on Fishes

Rick Bruintjes  
University of Exeter and HR Wallingford, r.bruintjes@exeter.ac.uk  

Thomas Benson  
HR Wallingford  

Kate Rossington  
HR Wallingford  

Stephen D. Simpson  
University of Exeter

Anthropogenic noise is a pollutant of growing global concern. Pile-driving operations during the construction of marine structures such as offshore windfarms, oil platforms, and harbors typically create impulsive sounds and seabed vibrations that have been shown to affect marine organisms, including various fish species. Predicting the effects of noise generated by such activity on both mammals and fish is now becoming common practice in the planning consent process of offshore structures. Here we present results from the Hydro-Acoustic Model for Mitigation and Ecological Response (HAMMER). This model incorporates two modules, the first of which is designed to predict underwater noise propagation from a sound source using information concerning water depth and the inherent physical properties of the water and seabed sediments. An integrated behavioral module then predicts the response of individual fish or mammals to the noise. To achieve meaningful results, parameterization of the likely behavioral response for the species of interest is paramount. To test this, we obtained measurements of fish behavior from trials conducted with experimental pile driving in an industrial-sized former shipbuilding dock. Using commercially important Atlantic cod (Gadus morhua), we observed immediate increases in swim speed and active avoidance of the pile-driving noise source after a lag of several minutes. Incorporating such information, the HAMMER tool can be used to explore simulated responses of individuals over large regions, including the influence of 2-D or 3-D hydrodynamic flows from a coupled numerical model (TELEMAC). Other forms of fish behavior can be also be included in the model, such as schooling behavior or the tendency to remain at preferred feeding sites such as spawning areas. The capabilities of the model are demonstrated in the form of a case study based on a windfarm construction project in which cod are parameterized using the noise-response attributes obtained from the dock experiment. The results highlight the value of exploring the implications of noise numerically using more realistic representations of behavioral response and the natural living environment. Moreover, the results demonstrate how predictive models can assist in forecasting potential anthropogenic impacts that might be difficult or too costly to determine through field measurements.
Procedures and Standards Relating to the Calibration of Acoustic Transients: Challenges for Marine Species

Robert Burkard  
University at Buffalo, rfb@buffalo.edu

James Finneran  
US Navy Marine Mammal Program, james.finneran@navy.mil

Dorian Houser  
National Marine Mammal Foundation, dorian.houser@nmmpfoundation.org

Jason Mulsow  
National Marine Mammal Foundation, jason.mulsow@nmmpfoundation.org

There are numerous standards related to the specification and calibration of sound in air, primarily as a result of extensive auditory research with humans. A review of these standards highlights the challenges associated with developing analogous standards for marine species with diverse auditory capabilities. Most acoustic standards are developed to specify quantification of long-duration sound where measures such as fast and slow exponentially time-weighted functions are appropriate. Couplers have been developed to simulate the “average” transfer function of the human outer ear, and transducers have been developed that have a reasonably flat spectrum throughout the frequency range where humans hear best. There are international standards specifying the quantification of brief acoustic transients, e.g., clicks, in terms of how one specifies the maximum level of a transient whose duration is far less than the time constant of the fast exponentially time-weighted function. Conversely, there is very little in the way of current standards specifying the quantification of underwater sound. Marine mammals have good hearing in frequency ranges well above that heard by humans, and transducers are generally not flat throughout the frequency range of hearing for marine mammals. Although there are couplers, artificial ears, and artificial mastoids intended to simulate the transfer function of the human ear or temporal bone, there are no similar couplers, artificial ears, or bone-conduction simulators for marine mammals. In this presentation, we discuss the different challenges and potential ways forward regarding standardization of the presentation and calibration of airborne versus underwater sound for marine mammal research. We present an overview of the methods for quantifying stimulus level of acoustic transients (both peak SPL and peak-equivalent SPL) and the consequences of decreasing stimulus duration on the spectra of these signals. A relatively straightforward approach to digitally manipulating the spectrum of acoustic transients is presented. We discuss why upward-sweeping chirps have become popular acoustic stimuli in human auditory brain stem response testing and the type of cochlear transmission delay (i.e., traveling-wave delay) information needed to optimize this approach in marine mammals. We also describe signal-processing approaches that allow obtaining auditory evoked responses using interstimulus intervals that are much less than the duration of the auditory brain stem responses of marine mammals.
An Integrated Approach to Understanding the Potential Impact of Marine Seismic Surveys on Fish and Invertebrates

Andrew Carroll  
Geoscience Australia, andrew.carroll@ga.gov.au  

Rachel Przeslawski  
Geoscience Australia, rachel.przeslawski@ga.gov.au  

Barry Bruce  
Commonwealth Scientific and Industrial Research Organisation, Barry.Bruce@csiro.au

The extent to which low-frequency sound from marine seismic surveys impacts marine fauna is a subject of growing concern. The predominant frequency range of seismic airgun emissions is within the hearing range of cetaceans, reptiles, and fishes, and it can also elicit a neurological response in some invertebrates. Offshore seismic surveys have long been considered to be disruptive to fisheries, but comparatively few studies target commercially important species in realistic exposure scenarios. One of the main challenges in underwater sound impact studies is the meaningful translation of laboratory results to the field. Underwater sound properties are affected by the sound source as well as by characteristics of the water column, substrate, and biological communities. The experimental setup is also critical in determining accurate response measurements, and the design features of holding tanks can lead to misinterpretation of results, particularly those related to behavior. This project was developed in response to concerns raised by the fishing industry during stakeholder consultation in the lead-up to a seismic survey conducted in the Gippsland Basin (Victoria, Australia) in 2015 in addition to a broader need to add field-based analyses to improve science-based decision-making processes. The project involves seven experimental components conducted before, during, and after the seismic survey in both control and experimental areas of the Gippsland Basin: (1) theoretical noise modeling, (2) field-based noise monitoring and modeling, (3) image acquisition by autonomous underwater vehicle (AUV), (4) bivalve sampling by dredging, (5) fish movement analysis by tagging, (6) catch rate analysis, and (7) environmental modeling during the 2010 mortality event. In this presentation, we describe these components and summarize the key findings from a critical review of our current understanding of low-frequency sound impact on marine fish and invertebrates.
Detection and Tracking of Fin Whales During Seismic Exploration in the Gulf of California

Francesco Caruso
Institute for Coastal Marine Environment, National Research Council, Torretta Granitola, Italy, fcaruso@unime.it

John Collins
Department of Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, jcollins@whoi.edu

Jimmy Elsenbeck
Department of Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, jelsenbeck@whoi.edu

Dan Lizarralde
Department of Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, danl@whoi.edu

Laela Sayigh
Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, MA, lsayigh@whoi.edu

Walter M. X. Zimmer
Centre for Maritime Research and Experimentation, NATO, La Spezia, Italy, wzimmer@whoi.edu

The endangered fin whale (Balaenoptera physalus) commonly produces low-frequency and high-intensity sounds that extend across 20 Hz, named “20-Hz pulses.” The calls emitted by this species can occur in a variety of patterns that change in different seasons and geographic areas. The frequency bandwidth associated with seismic exploration (using airgun instruments) overlaps with these signals. The data analyzed in this work came from a geophysics project conducted in the Gulf of California in October 2002. In several locations across the Gulf, a series of ocean bottom seismometers (OBS) were deployed on the seafloor. This study focused on 60 OBSs deployed in Guaymas Basin. The instruments had two data channels, a hydrophone, and a vertical geophone, recording at 125 samples/second. The array continuously recorded data over a period of ~11 days, during which airgun surveys were conducted over 6 days during daylight hours only. A substantial acoustic data set was produced and abundant vocalizations of numerous fin whales were recorded. The OBSs were spaced ~12 km apart from each other, allowing the individual localization and tracking of whales. Specific algorithms were developed to automatically detect whale calls and to use these calls to track the direction of movement of the whales. For each whale, the intercall interval (ICI) was highly stable and this facilitated the identification of specific individuals. Individual whale calls were identifiable on multiple instruments, enabling tracking by means of arrival time differences. In this preliminary study, several whales were tracked during the survey before and after airgun shooting. Further application of this analysis could provide insights into the responses of individual fin whales to airgun signals of known amplitude and has the potential to provide insights into how seismic surveys may affect marine mammals.
The main objective of the European LIFE+ project named ARION is the improvement of the conservation status of the bottlenose dolphin (*Tursiops truncatus*) that is listed in the Annex II of Habitat Directive (European Directive, 2007) as the coastal species among Mediterranean cetaceans most exposed to threats due to human activity and resource exploitation. In the framework of this project, concrete conservation actions take place in the Portofino Marine Protected Area (MPA), Italy. We show the implementation of an interference avoidance system capable of detecting and tracking the dolphins to identify the threats and to prevent collisions with ships and other risks by diffusing presence warning messages in real time to all categories involved (tourists, fishermen, MPA management). On reception of the warning messages, the ships and boats present in the area are invited to follow the protocol of conduct and the Coast Guard supervises its application. This approach will ensure the species protection improvement, the sustainable coexistence of dolphins, and anthropic activities and will promote responsible usage of the sea, especially in one of the most touristic MPAs in the Mediterranean Sea.

The core of the project consists of the creation of a virtual corridor for monitoring and surveillance. A controlled area has been set up by implementing and operating a passive acoustic monitoring (PAM) system (Brunoldi et al., 2016) capable of detecting and tracking a mobile acoustic source in underwater marine environment in real time, 24 hours year-round. The acoustic sources of interest are the bottlenose dolphin, detected through their whistles (Zimmer, 2011), and boats, detected by their engine noise (Fillinger et al., 2011). Two acoustic stations were deployed next to the boundaries of the Portofino MPA. Each unit was a particular type of marine buoy equipped with four hydrophones, autonomous, solar powered, and bottom moored, and performed real-time onboard underwater sound acquisition, digitization, and data elaboration to detect the presence of dolphins and anthropic activities. Raw acoustic data collected by the hydrophones were sent to a ground station and stored for off-line analysis.

During two years of data collection, frequent passages of bottlenose dolphins and the contemporary maritime traffic were detected by the ARION system. Several analyses on the different detected acoustic signals emitted by dolphins were performed. The presence of bottlenose dolphins was studied according to seasonal, day/night, and monthly frequency. Future analysis will check the environmental noise influence on the presence of bottlenose dolphins within the study area.


Acoustic signaling plays an important role in marine mammal communication because sound transmission characteristics of the underwater environment allow signalers and receivers to remain in contact over relatively large distances. Determining the range over which a signal can be detected can clarify the relationship between a signal's structure and its function. This is especially true when considering the spatial and social dynamics of breeding populations. Source levels can be used to estimate the communicate range of a signal in a given noise background. Despite the importance of this metric, estimates of source levels for free-ranging marine mammals are often difficult to obtain because the location and distance of vocalizing individuals may be challenging to accurately determine. Furthermore, signal detectability is limited by the auditory sensitivity of the receiver, but quantitative hearing data are lacking for many species. This study provides the first source levels for the underwater roars produced by male harbor seals (*Phoca vitulina*) during the breeding season. Calls with high signal-to-noise ratios were obtained over multiple years from one captive adult male harbor seal of known age. Spontaneous roars were opportunistically recorded at distances ranging from 1 to 5 m, with caller orientation of 0° to 90°, using calibrated receivers. The calls were low-frequency, guttural vocalizations that lasted 5-10 s, with most energy between 200 and 500 Hz. These calls had similar features to the vocalizations produced by wild seals during the breeding season. Taking transmission loss into consideration, we determined the sound pressure level at 1 m over the entire call duration. The RMS level of these roars was ~145 dB re 1 μPa at 1 m. To predict the range of these calls in typical coastal ambient-noise conditions, we paired these source level data with low-frequency absolute detection thresholds published for the same individual. The findings from this captive study inform our understanding of how wild seals and other marine mammals communicate in natural noise and enable predictions of the effects of anthropogenic sound on communication space. (This study was supported in part by the Office of Naval Research.)
Onset of Barotrauma Injuries Related to the Number of Pile-Driving Strike Exposures in the Hybrid Striped Bass

Brandon M. Casper  
Naval Undersea Warfare Center, Newport, RI, and University of Maryland, College Park, MD, bcasper@umd.edu  
Michele B. Halvorsen  
CSA Ocean Sciences, Stuart, FL  
Thomas J. Carlson  
ProBioSound LLC, Holmes Beach, FL  
Arthur N. Popper  
University of Maryland, College Park, MD

Previous studies exploring the injury response to pile driving in fishes presented exposure paradigms (>900 strikes) that created a worst-case scenario in which the fishes cannot leave an area being ensonified. This is not likely to reflect the behavior of fishes in the wild where they can swim away from the source. Indeed, it is more likely that wild fishes are exposed to fewer potentially injurious strikes because they move to an area where the sound levels are lower. Because of the use of worst-case studies, it is unclear as to the number of exposures required to cause injuries. To answer this question, hybrid striped bass (white bass Morone chrysops × striped bass Morone saxatilis) were exposed to between 8 and 384 strikes in 3 different treatments. At the highest sound exposure level (SEL) treatment, swim bladder-related injuries began to appear with as few as eight pile strikes. In addition, injury patterns in fish exposed to similar cumulative SEL paradigms but different numbers of pile strikes were not consistent, suggesting that single-strike SEL is a more likely indicator for predicting injury. These results have important implications for pile-driving operations where SEL single-strike sound levels meet or exceed the levels of single-strike exposures tested in this study.
Using Fishes to Characterize Underwater Blast Injury Models

Brandon M. Casper  
Naval Undersea Warfare Center, Newport, RI, and Naval Submarine Medical Research Laboratory, Groton, CT, bcasper@umd.edu  
Stewart M. Simpson  
Naval Submarine Medical Research Laboratory, Groton, CT  
Matthew A. Babina  
Naval Submarine Medical Research Laboratory, Groton, CT  
Derek W. Schwaller  
Naval Submarine Medical Research Laboratory, Groton, CT  
Aric D. McCosh  
Naval Submarine Medical Research Laboratory, Groton, CT  
Michael K. Qin  
Naval Submarine Medical Research Laboratory, Groton, CT

The Naval Submarine Medical Research Laboratory is characterizing and evaluating the abilities of underwater blast models to predict injury to divers in response to impulsive sources. To assess the accuracy of the biophysical models, the fish swim bladder and surrounding organs were chosen as the test focus. The models were tasked with successfully predicting injury to these “simple” air-filled structures. Based on their success, their reliability on predicting more complex injury systems (i.e., lungs) will be further investigated. To this end, an assessment of the injury response to a four-airgun array exposure was made in two different sizes of brown trout, *Salmo trutta*, and one size of largemouth bass, *Micropterus salmoides*. High-resolution acoustic metrics were also measured. The caged fishes were exposed to a paradigm of three airgun pulses ranging from levels just below the expected threshold of injury to levels that were expected to result in injuries. Several different injuries were observed, primarily in the swim bladder and/or surrounding organs. No injuries were observed in control fishes. We then used these injuries and acoustics to characterize the predictability of the biophysical injury models. The value to the Navy is an improved understanding of underwater blast injury models. The value to regulatory committees is the more accurate information on impulse levels that can injure fishes as well as new injury models for regulatory guidance.
It is highly likely that for Cook Inlet belugas (CIB) sound plays a crucial role in navigation, feeding, and communication because of the high turbidity of their habitat. Because sound is so important to them, changes in ambient-noise levels may have a significant impact on their ability to thrive. An understanding of the extent of masking and potential stress response by anthropogenic noise is crucial for the writing of regulations for industrial underwater noise emission as well as for the correct management of these activities. Because mammalian hearing is highly nonlinear and depends on both frequency and temporal structure of signal and noise, masking studies clearly need to incorporate natural and complex structured noise maskers. Commercial shipping and pile driving are two of the most persistent man-made sources of noise in the CIB critical habitat. This study collected auditory evoked potentials (AEPs) in a trained beluga to document baseline hearing and masked hearing thresholds when exposed to both commercial shipping and pile-driving noise recorded in the CIB critical habitat, projected on-axis, 90° and 180°. Pile driving was projected at two rates. Exhaled breath condensate (blow) samples were collected “pre” and “post” sound exposures to measure cortisol. Baseline and masked hearing AEP data were collected at 4, 5.6, 8, 11.2, 16, and 32 kHz for all angles and each masker trial. Received levels of masking signals ranged from ~133 to 152 RMS dB re 1 µPa. For the pile-driving masker, the strike rate was tested at 0.2 s and 1 s. Results suggest masked thresholds as high as 23 dB over baseline hearing levels for some frequencies. Pile driving, which was a relatively broadband sound, yielded highest masked-threshold shifts at a 0.2-s strike rate, followed by same masker at a 1-s strike rate, followed by ship noise. Highest masked thresholds occurred at 8 kHz for both maskers. Masking was not observed at frequencies above 11.2 kHz. Preliminary data show no significant change in cortisol during sound exposures; however, increasing trends were observed after exposure to ship noise, with the largest increases observed after concurrent exposure to both maskers. These results suggest that both sources of noise generate very significant masked hearing thresholds when received at moderate levels (below regulatory thresholds for impulsive sources) at multiple frequencies within the beluga communication band.
Relationships of Sound Pressure, Particle Velocity, and Acceleration in a Confined Space

Maria Ceraulo
Department of Basic Sciences and Foundations, University of Urbino, Urbino, Italy, and Istituto per l'Ambiente Marino Costiero, U.O. di Capo Granitola, Consiglio Nazionale delle Ricerche, Via del Mare no. 3, 91021 Granitola, TP, Italy, maria.ceraulo@iamc.cnr.it

Rick Bruintjes
College of Life and Environmental Sciences, University of Exeter, Exeter EX4 4QD, UK, and HR Wallingford, Howbery Park, Wallingford OX10 8BA, UK, r.bruintjes@exeter.ac.uk

Thomas Benson
HR Wallingford, Howbery Park, Wallingford OX10 8BA, UK, T.Benson@hrwallingford.com

Kate Rossington
HR Wallingford, Howbery Park, Wallingford OX10 8BA, UK, K.Rossington@hrwallingford.com

Almo Farina
Department of Basic Sciences and Foundations, University of Urbino, Urbino, Italy, almo.farina@uniurb.it

Giuseppa Buscaino
Istituto per l'Ambiente Marino Costiero U.O. di Capo Granitola, Consiglio Nazionale delle Ricerche, Via del Mare no. 3, 91021 Granitola, TP, Italy, giuseppa.buscaino@cnr.it

Underwater sound is characterized by two different components, directional particle motion and scalar pressure waves. Accumulating evidence suggests that many marine animals have specially developed organs that permit them to detect either one or both of these two sound components with different sensitivities. Theoretically, the two components are linearly related, but the exact relationship between them is still poorly understood. Here, we studied sound pressure and particle motion during experimental pile driving in a confined industrial-sized former shipbuilding dock (dimensions: 92 × 18 × 3 m). The pile-driving noise was generated by a 200-kg hammer striking a 7.5-m steel pile (16.5 cm diameter, 0.65 cm thickness) that rested on a 3.5-m layer of simulated seabed. Noise data were collected using a hydrophone and a 3-axis accelerometer along 9 equally spaced transects within the dock, providing a total grid of 27 (9 × 3) measurement points, which was repeated at 1 m and 1.8 m depths. Our results show that during pile driving the sound pressure measured at 2 m from the source was 68 dB re 1 µPa (average single-strike sound pressure level [SPL_{ss}]) above ambient control conditions and reduced to about 51 dB re 1 µPa SPL_{ss} above ambient conditions at 30 m from the noise source. Particle velocity during pile driving was circa 51 dB re 1 nm/s SPL_{ss} higher than ambient conditions at 2 m from the source and approximately 31 dB re 1 nm/s SPL_{ss} higher than ambient conditions at 30 m from the pile. The spatial pattern of the measured sound levels within the dock appear to be consistent with phase interference caused by reflections from the dock sidewalls, both for sound pressure and particle motion. Nevertheless, sound pressure and particle motion showed a different frequency distribution. For sound pressure, a shallow water cut-off frequency below approximately 400 Hz was observed in the power spectrum which was independent of the distance from the source. This pattern was not observed for particle velocity. These results highlight a complex relationship between pressure and particle motion in confined spaces. This emphasizes the need for further study of sound propagation in large, but confined spaces, to better understand the relationship between the two components and their consequences in terms of potential responses of marine organisms during noise exposure.
Environmental Impact Study Concerning Underwater Noise in Taiwan

Chi-Fang Chen  
Ocean Technology Research Center, National Taiwan University, chifang@ntu.edu.tw

Wei-Chun Hu  
Ocean Technology Research Center, National Taiwan University, william_hu@outlook.com

Wei-Shien Hwang  
Ocean Technology Research Center, National Taiwan University, wshwang@ntu.edu.tw

Jeff Chih-Hao Wu  
Ocean Technology Research Center, National Taiwan University, d98525001@ntu.edu.tw

Lien-Siang Chou  
Institute of Ecology and Evolutionary Biology, National Taiwan University, chouls@ntu.edu.tw

Sheng Fong Lin  
Industrial Technology Research Institute/GEL, linsf@itri.org.tw

Nai-Chang Chen  
Ocean Technology Research Center National Taiwan University

In recent years, because of the development of offshore wind farms in Taiwan, an environmental impact assessment of this development is underway. Of all the impact factors, underwater noise becomes a major concern for the offshore wind farm sites that are very close to the habitats of *Sousa chinensis* (Chinese humpback dolphin). To assess the noise impact, underwater ambient-noise measurements were made in the regions. These measurements enhance the understanding of the underwater soundscape in western Taiwan. The noise impact zones were also simulated with pile-driving source levels obtained from the literature and ocean environment inputs from the historical database and ocean modeling (TCONF). This work was supported by the Ministry of Science and Technology of Taiwan, Taiwan Generations Corporation, and Swancor Ind. Co., Ltd. Project No. MOST 104-3113-E-002-002 - CC2.
Accurate noise propagation models and visualizations of the interactions between anthropogenic sound and the environment are imperative for the development of marine planning policy. Underwater noise modeling is a vital component of environmental impact assessments and must be provided to achieve good environmental status as set out by a number of regional standards such as the European Marine Strategy Framework Directive (MSFD) or the New Zealand Department of Conservation (DOC) code of conduct. Although underwater noise propagation models are becoming more widespread, there is currently a deficiency of visualization tools that can help the general public, regulators, and stakeholders to better understand the effect of offshore anthropogenic noise in the ocean environment. To fulfill this requirement, Gardline Environmental Ltd. has developed 360M, a comprehensive sound propagation and noise map model. 360M creates a visualization of an acoustic wave front, providing valuable information about the source sound transmission within a specific ocean environment. This two-dimensional predictive acoustic model is capable of modeling and mapping propagation loss in 360 radial transects from an underwater noise source. The acoustic map of underwater noise uses inputs such as bathymetry, sediment, and the sound speed profile of a particular area to create long-range propagation predictions. The model outputs include transmission loss at various ranges and estimated received levels across ranges described as a function of distance and bathymetry. The 360M model can be used as a geographical noise distribution of anthropogenic noise and may be used to reveal the complex propagation over oceans with varying topography. This model has been utilized in predictive noise-modeling reports, including a marine mammal impact assessment, and is being continually developed and expanded to include other acoustic effects such as near-field particle motion and cumulative acoustic exposure.
Blue whales (*Balaenoptera musculus* spp.) were once abundant in the southern hemisphere, but commercial whaling hunted them to near extinction in the previous century. The species is currently listed as endangered on the IUCN Red List of Threatened Species. The Chiloé-Corcovado region in Chile is one of the most important areas in the southern hemisphere for blue whales because it functions as a feeding and nursing ground. In recent years, ship traffic has increased considerably in the area and noise pollution is a major concern.

To examine the potential effects of ship noise on blue whale calling behavior, six marine autonomous recording units (MARUs) were deployed at four different locations (Northwest Chiloé, Guafo North, Tic Toc Bay, and Locos Islet) between January 2012 and April 2013. Audio files were analyzed in MATLAB by decimating and filtering into third-octave bands and then calculating the root-mean-square (RMS) amplitude of each band. Two types of blue whale calls (SEP1 and SEP2) were detected using a signal-to-noise ratio (SNR) threshold value in a particular third-octave band that was found to best represent the call energy. To avoid false detections, the script output was corrected manually by comparing it with spectrograms. The presence of ship noise was also systematically noted and confirmed by comparing RMS amplitudes during periods with and without ship noise.

In an analysis of 888 hours of data collection from January and February 2012 from Northwest Chiloé, 20,511 blue whale calls were detected. The SEP1 call rate was significantly lower in the presence of ship noise (1.4 vs. 2.1; Mann-Whitney *U* test [MWU], *P* < 0.01), whereas the rate of loud SEP2 calls (SNR > 2) was higher (4.1 vs. 3.6; MWU, *P* = 0.03). A higher percentage of incomplete SEP2 calls with low RMS values were detected when ship noise was absent, suggesting that ship noise has the potential to mask long-range communication by blue whales in the area. Further research is needed to understand the implications of missing information, reduced communication range, and changing vocal behavior.
Modeling the Potential Exposure of Blue and Humpback Whales to Acoustic Disturbance: Toward an Understanding of the Population Consequences of Disturbance

Daniel P. Costa  
University of California, Santa Cruz, costa@ucsc.edu

Luis Huckstadt  
University of California, Santa Cruz, lahuckst@ucsc.edu

Bruce Mate  
Oregon State University, bruce.mate@oregonstate.edu

Ari Friedlander  
Oregon State University, Ari.Friedlaender@oregonstate.edu

Alexandre N. Zerbini  
NOAA Fisheries, alex.zerbini@noaa.gov

Nick Gales  
Australian Antarctic Division, Nick.Gales@aad.gov.au

Lisa M Schwarz

Although many studies have examined the sensitivity of marine animals to underwater noise, an essential component of any risk assessment is the likelihood that individuals of a given population will be exposed to that acoustic disturbance in the first place. In other words, assessing any population-level effects requires information on the proportion of the population that will be exposed, for how long, and during what activity (i.e., feeding, migrating, and breeding). Using satellite telemetry data for humpback and blue whales in a variety of habitats, including feeding and migratory regions in Antarctica, Australia, California, and Alaska, we modeled the potential exposure of individuals to an acoustic disturbance by estimating how many individuals would be exposed and for how long. We used switching-state space models to identify foraging and transit regions along the tracks and calculated the time spent in each foraging region and the time spent in transiting between foraging sites. A series of 100 mobile sound sources were modeled within the foraging habitat of each of these species. We then used the tracking data to estimate the amount of time the animals would be exposed to a sound, assuming exposure is sufficient to cause a change in behavior. As in earlier models, this will be the worst-case scenario and would overestimate the potential impact of a sound source. After the previous work (Costa et al., 2016; New et al., 2014) on population consequences of disturbance, these analyses are a necessary first step to estimate the population impact of a disturbance because they provide an estimate of the proportion of the population that would be exposed. These results can then be used to estimate the energetic costs of that disturbance on a female’s energetic budget in terms of energy expended but not acquired, followed by an estimate of the additional time a female would have to spend foraging to offset this lost foraging time, and finally estimating the subsequent effects on offspring growth and survival.


Introduction of Accredited Standards for Passive Acoustic Monitoring Equipment and Operators Is Overdue

Randal Counihan
Gardline Environmental Ltd., randal.counihan@gardline.co.uk

There are currently no accredited standards in the world to which passive acoustic monitoring (PAM) systems must conform. Various groups around the world, including the International Association of Geophysical Contractors (IAGC) and the National Oceanic and Atmospheric Administration (NOAA), have made available recommendations and memos, although none of them are binding and the level of technical detail included in these documents is very low. When it comes to existing guidelines and regulations, the focus has always been on how PAM should be applied and not what is required to be considered suitable equipment. Although PAM manufacturers strive to produce quality equipment, there is no guide available to the industry that indicates a baseline-level quality that must be achieved.

In 2013, the New Zealand Department of Conservation was the first body to implement and enforce an accredited standard of training for PAM operators. This remains the only standard for training and experience in the world. Elsewhere, training courses are run mostly by manufacturers of PAM equipment or suppliers of PAM operators. However, these courses focus almost exclusively on the PAMGuard software and teach little of the background to the technology and its use in the field. Even with the limited number of courses available, there is no necessity to take part in one of these courses before someone can call themselves a PAM operator.

Anyone with experience who has worked with acoustic systems in the field, for industrial monitoring and mitigation or for research applications, will attest to the huge differences in ability between relatively similar systems. This difference is mirrored in the abilities and experience of operators and their training levels. A combined international standard to cover both aspects of PAM needs to be created to achieve consistent and comparable implementation of guidelines and data collection.

In this presentation, I discuss some of the suggestions that have been made for inclusion in such a combined standard, how these suggestions would benefit both the operators themselves and the industries that use their services, and what the future holds for PAMs based on the current market opportunities.
Hearing mechanisms in baleen whales (Mysticeti) are essentially unknown, but their vocalization frequencies overlap with low-frequency anthropogenic sound sources. Synthetic audiograms were generated for a fin whale by applying finite-element modeling (FEM) tools to X-ray CT scans. We scanned the head of a small fin whale (*Balaenoptera physalus*) in a CT scanner designed for solid-fuel rocket motors. Our custom FEM toolkit allowed us to visualize the interactions between sound and the anatomic geometry of the whale's head. Simulations reveal two mechanisms that excite each of the bony ear complexes (TPCs): (1) the skull vibration-enabled bone conduction mechanism and (2) a pressure mechanism transmitted through soft tissues. Bone conduction is the predominant mechanism that contributes to low-frequency sound sensitivity (Cranford and Krysl, 2015). Recent preliminary simulations also suggest that directional cues for received sounds may be gained by phase differences between waves that arrive at the TPCs through skull deformation. We have also succeeded in reconstructing an entire minke whale specimen (*Balaenoptera acutorostrata*) from CT scan data. These results have important implications for assessing mysticete exposure to levels of anthropogenic noise and for understanding various aspects of ecological morphology associated with baleen whale sound reception.

Sound Levels from a 3-D Seismic Survey in the Porcupine Basin: Validation of a Sound Propagation Model Using Observed Data

Sinéad Crawford  
Earth and Ocean Sciences, School of Natural Sciences, Ryan Institute, NUI Galway, Ireland, s.crawford1@nuigalway.ie  
Colin Brown  
Earth and Ocean Sciences, School of Natural Sciences, Ryan Institute, NUI Galway, Ireland  
Eugene McKeown  
RPS Group, Galway, Ireland  
Fiona Stapleton  
RPS Group, Galway, Ireland  
Alec Duncan  
Centre for Marine Science and Technology, Curtin University, Perth, Australia  
Robert McCauley  
Centre for Marine Science and Technology, Curtin University, Perth, Australia  
Martin White  
Earth and Ocean Sciences, School of Natural Sciences, Ryan Institute, NUI Galway, Ireland

After Ireland’s 2015 Atlantic Margin Oil and Gas Exploration Licensing Round, the Porcupine Basin continues to be a significant site for seismic exploration activities to investigate subbottom structure. Recent literature has reported on the environmental implications of marine seismic surveys, highlighting alarmed and avoidance behavior in several marine mammal species as a common response to airgun signals. The European Habitats Directive (92/43/EEC) orders the protection of all cetacean species in European waters, 23 of which inhabit Irish waters for at least part of the year. As such, underwater acoustic monitoring and mapping has been targeted as a research priority under the EU’s Marine Strategy Framework Directive. The findings will be essential for designing and implementing appropriate regulation regarding underwater noise. In this study, a modeling method that employs the parabolic equation technique (RAMGeo) was used to model the transmission loss (TL) of low-frequency noise across real, range-dependent 2-D source-to-receiver sections from the Porcupine Basin. RAMGeo, run in a MATLAB environment, is freely available through the Acoustic Toolbox User Interface and Post-Processor (AcTUP) developed by Curtin University. The TL values computed in the model were measured against their corresponding observed values, which were recorded during a research cruise in July 2014, to coincide with 3-D seismic operations in the area at locations across the Basin. RAMGeo will be validated and then evaluated for predictive power, usability, and transparency. The aim of this research is to produce an efficient working model of sound propagation for the Porcupine Basin that will enable the prediction of sound levels generated by seismic operations in the area.
Flexible Criteria for Pile-Driving Sound on Dutch Offshore Wind Farm Development Based on a Model-Based Assessment of the Impact on the Harbor Porpoise Population

Christ de Jong  
TNO, christ.dejong@tno.nl

Floor Heinis  
HWE, fheinis@hwe.nl

Bas Binnerts  
TNO, bas.binnerts@tno.nl

Sander von Benda-Beckmann  
TNO, sander.vonbendabeckmann@tno.nl

Aylin Erkman  
RWS-ZD, aylin.erkman@rws.nl

The new Offshore Wind Energy Act in The Netherlands states that the government is responsible for the so-called “wind farm site decision,” which concerns spatial planning arrangements and an assessment of the environmental and ecological effects of the proposed wind projects. In preparation for the wind farm site decisions, a Dutch expert group, commissioned by the government, developed an approach for the assessment of the cumulative impact of the long-term plans for offshore wind farm development in the North Sea on the harbor porpoise population. Of the species that are discussed in the Dutch environmental impact studies for the plot decisions, the harbor porpoise is considered to be the most sensitive to acoustic disturbance. Therefore, mitigation of the disturbance of harbor porpoises is considered to be beneficial for marine life in general. The approach combines modeling of the underwater sound distribution during the construction of offshore wind farms with seasonal porpoise abundance data to estimate the number of porpoises that are potentially disturbed during piling days. The interim population consequences of disturbance (PCoD) model, developed by scientists at the University of St. Andrews and made publicly available in the fall of 2014, was applied to translate the number of porpoises that are potentially disturbed to an effect on the size of the porpoise population. Calculations for a realistic worst-case scenario of North Sea wind farm development in the years 2016 to 2022 indicate a 5% probability for a 40% reduction of the North Sea porpoise population because of the cumulative effect of all piling activities after these six years. The number of disturbed porpoises during piling depends on the underwater sound exposure level (SEL), the number of animals in the area where this SEL exceeds a threshold value for disturbance, and the number of days during which the exposure lasts. Based on these findings, the wind farm site decisions for future Dutch wind farms include a requirement for underwater noise mitigation during construction. To allow for flexibility and control of the costs for the industry, the requirements are flexible. Criteria for underwater noise (SEL at 750 m from the pile) depend on the number of turbines (piling days) per farm and also on the season in which the construction takes place (porpoise presence).
Two Species of Marine Gobies Similarly Change Acoustic Courtship in Response to Noise

Karen de Jong  
Ecological Research Station Grietherbusch, University of Cologne, karende@alumni.ntnu.no

Clara Maria Amorim  
ISPA, amorim@ispa.pt

Paulo Fonseca  
University of Lisbon, pjfonseca@fc.ul.pt

Adrian Klein  
University of Bonn, adrian@uni-bonn.de

Katja U. Heubel  
University of Tübingen, katja.heubel@uni-tuebingen.de

Increasing levels of background noise in our oceans are a major cause of concern and are likely to hamper acoustic communication underwater. When signals used during reproduction are affected, this could lead to a decrease in reproductive success. However, because behavior is often flexible, animals may be able to adapt their behavior to overcome reduced signal efficacy. The ability to adapt communication to the acoustic environment has been found in mammals, birds, and frogs, but evidence in fish is still very scarce. We studied two closely related marine species that use two call types during courtship: the two-spotted goby (Gobiusculus flavescens) and the painted goby (Pomatoschistus pictus). In both species, males defend a nest, attract females to spawn, and take care of the eggs until they hatch. The two-spotted goby is semipelagic and lives in kelp forests, whereas the painted goby is benthic and lives on sandy bottoms. We compared male courtship behavior and female spawning behavior in a noisy versus a quiet environment. For the two-spotted goby, we used a repeated-measures design; males were allowed to court constrained females in both treatments in alternating order. For the painted gobies, we allowed males to freely interact with the females and to receive eggs after courtship, which precluded the use of a repeated-measures design. Even though the experiments thus differed, we found that males of both species reacted similarly to increased noise levels. In the noisy treatment, males used less of the call type that was most masked by the experimental noise but not of the other call type. Our data thus suggest that males may be able to assess the acoustic environment and respond accordingly. We found no significant effect of treatment on the number of spawnings or the area of eggs spawned in the painted goby. Therefore, we conclude that reproduction in this species may be robust to noise, possibly due to its flexibility in courtship behavior. We discuss our findings in relation to the results from a field experiment on the two-spotted goby that was conducted before the meeting.
The European Marine Strategy Directive (2008) defines human-induced marine underwater noise as a pollutant and requires EU member states to ensure that deleterious effects of that pollutant on the ecosystem be prevented. The Directive further requires member states to address the effects at an ecosystem level and to ensure coordination in regional sea conventions, leading to programs of measures that achieve or maintain good environmental status (GES) in all European seas.

By now, EU member states have developed marine strategies, which must be reviewed periodically (the first time was in 2018). The requirement to address the ecosystem level will require member states to broaden the scale at which the effects of noise are considered; in future assessments, member states should aim to determine whether the scale of sound-generating activities and anthropogenic underwater noise levels requires further action at a larger scale or in a wider region than the current mostly national approach. We see this trend toward larger scale assessment not only in the European Union but also with the US NOAA Ocean Noise Strategy.

Member states working together in regional sea conventions like HELCOM or the Barcelona Convention are now developing monitoring programs. An international register for impulsive noise-generating activities is now operational within OSPAR, and this will help to make a better assessment of the cumulative impacts of noise from different sectors, over longer periods, and across borders. Joint monitoring programs that would provide insight into the levels and trends of ambient sound in European waters are under development.

Although we still struggle to understand and quantify the impact of ambient noise, the knowledge about the effects of loud impulsive noise sources has increased significantly over the last years. Although research driven by environmental concerns focused initially on the physiological effects in marine organisms, the behavioral disturbance leading to habitat loss, which may happen at low levels of exposure and thus on a large scale, may be more significant for ecosystems. Multidisciplinary scientific expertise is needed to further quantify the scale of habitat loss and understand the effect of this (often temporary) habitat loss on the ecosystem to identify the zones where action is needed to protect marine values. Transatlantic harmonization as encouraged by the Galway Statement will also be needed for future monitoring programs developed for the EU Marine Strategy and the US Ocean Noise Strategy.
Impacts of Anthropogenic Sounds on Fish Behavior

Mathias Deleau
International Centre for Ecohydraulics Research, School of Civil Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK, deleau.mathias@hotmail.fr

Paul Kemp
International Centre for Ecohydraulics Research, School of Civil Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK, P.Kemp@soton.ac.uk

Paul White
Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, UK, prw@isvr.soton.ac.uk

Tim Leighton
Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, UK, T.G.Leighton@soton.ac.uk

The use of sound as a fisheries management tool is a growing area of research. A large amount of interest has been directed toward the use of ultrasound as a means of deterring clupeid and salmonid fish from hazardous areas and guiding them toward safer alternative routes. Infrasound has also been used in an attempt to deter other species, such as the European eel (*Anguilla anguilla*). The aim of this study was to investigate the potential use of sound to manipulate fish behavior to mitigate the impacts of man-made structures. Attempts were made to deter, attract, or elicit other behavioral responses in two migrating species, the European eel and the river lamprey (*Lampetra fluviatilis*). Various sound intensities and frequencies were investigated under different experimental settings. Individuals were exposed to tones of incrementally changing frequency at various sound levels in single tanks while their behaviors were recorded. This allowed us to study the response of the two species to sounds of different frequencies at different levels. To test the applicability of these findings in a wider context, a second set of experiments were conducted in an outdoor recirculatory flume. The first experiment consisted of an “acoustic maze” that presented each fish, one at a time, with a multiple choice of corridors to go through, with some corridors containing far more intense sound fields than others. The aim of this experiment was to observe any bias in favor of either the corridors with sound or the corridors without sound illustrating an attraction or repulsion for the stimulus. A continuous broadband noise, including frequencies between 60 and 1,000 Hz, was used as the stimulus. The second experiment consisted of a setup with a standard vertical bar screen and a bypass channel. In this experiment, a series of three underwater speakers were set up to create an area of sound anterior to the screen. The effectiveness of using combined physical and acoustic screens to deflect fish to more benign bypass routes was tested. The same type of stimulus as in the previous experiment was used, and another run of trials was done with 100-Hz pulsed tones. Preliminary results have suggested that sound was having an effect on both species behaviors, although the response varies intra- and interspecifically. In addition, fish have shown a significant number of repulsions to sound exposure in both experiments held in the recirculatory flume.
Does Underwater Noise Affect the Gill Microbiome of *Mytilus edulis*?

Karen Diele  
School of Life, Sport and Social Sciences, Edinburgh Napier University, Edinburgh, UK, and St. Abbs Marine Station, St. Abbs, UK, k.diele@napier.ac.uk  
Matthew A. Wale  
School of Life, Sport and Social Sciences, Edinburgh Napier University, Edinburgh, UK, m.wale@napier.ac.uk  
Marco Fusi  
Biological and Environmental Science and Engineering Division (BESE), King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia, marco.fusi@kaust.edu.sa

Underwater noise is a now widely recognized pollutant in the marine realm. It adversely affects the biochemistry, physiology, morphology, behavior, or survival in a number of marine species and life stages, from large mammals to invertebrate larvae. Bacteria have received only little attention in this context, although they play important functional roles in the environment and can significantly influence the biota with which they are associated, e.g., by mediating metabolic pathways (e.g., Moran and Sloan, 2015). Ultrasound was recently shown to cause cell death in two bacterial species by affecting their cell integrity and obstructing metabolic performance (Li et al., 2016). To the best of our knowledge, the effect of low-frequency noise on marine bacteria has not yet been investigated. We are testing the hypothesis that ship noise playbacks affect the viability and alter the relative abundance of bacterial taxa that compose the gill microbiome of the mussel *Mytilus edulis*. Gills from noise-exposed and control animals were dissected immediately after 6 h of low-frequency noise exposure ($t_0$) as well as 4, 8, and 24 h later to investigate potential recovery of the gill microbiome. Samples for testing bacterial viability (taken at $t_0$) and for 16S rRNA gene sequencing (taken at all time points) are currently being analyzed. This study will yield novel insights as to whether underwater noise affects the viability and composition of bacteria associated with *M. edulis* gills. The expected outcomes have the potential to guide future research that takes a more holistic approach to, and understanding of, noise-induced effects in benthic marine invertebrates.

Acoustic Dose-Behavioral Response Relationship in a Bivalve Mollusk, the Common Cockle (*Cerastoderma Edule*)

**Dominic Dijkstra**  
SEAMARCO, Julianalaan 46, 3843 CC Harderwijk, The Netherlands, researchteam@zonnet.nl, dominicdijkstra@hotmail.com  
**Ron Kastelein**  
SEAMARCO, researchteam@zonnet.nl

Many marine organisms rely heavily on bioacoustics to survive. They may, for instance, engage with their surroundings through sound by using species-specific acoustic adaptations for hunting, territorial behavior, mate attraction, spatial orientation, and predator avoidance. Ecologically important behaviors in which acoustics play a role can be negatively influenced by anthropogenic noise. Little is known about the effects of anthropogenic noise on organisms such as crustaceans and mollusks, but acoustic disturbance of such lower trophic level organisms may have important repercussions for aquatic fauna at higher trophic levels. Bivalve mollusks live buried in the substrate and extend two siphons above the surface of the substrate to extract food from the water by filter feeding. The common cockle occurs in large numbers in the North Sea. The responses of cockles to sound were examined. Groups of 10 cockles that had buried themselves in sand were exposed for 2 min to pure tones between 50 and 1,000 Hz. Behavioral responses were filmed during and for 12 min after sound exposure by means of an underwater camera. The sounds/vibrations were measured with a hydrophone near the sand surface, accelerometers on the sand box, and a geophone in the sand. Control sessions without sound were also conducted to study the normal behavior of the cockles in the sand. The cockles responded to the sounds by retracting their siphons and moving deeper into the sand; this response resembled antipredator behavior. Clear acoustic dose-behavioral response relationships were established for a number of sound frequencies. The cockles reacted most strongly to sounds in the 400- to 800-Hz range and generally responded within 10 s of the onset of each sound. The cockles continued to respond to sounds in the postexposure period after the sound had stopped (possibly recovery behavior). When cockles retract their siphons, they stop feeding, which may reduce their fitness and thus may increase mortality or decrease reproduction. Therefore, some anthropogenic sounds in the marine environment are likely to have severe negative effects on these bivalve mollusks. As far as we are aware, this is the first study showing the effects of sound on the feeding behavior of a bivalve mollusk.
Seismic airguns are among the most widespread and long-range sources of underwater sound pollution. To understand how such sound affects marine life, it is essential to investigate what parts of the sound signal trigger a disturbance. Mackerel is an important pelagic fish species both ecologically and commercially in the North Atlantic and is subject to claims from fishermen of abandonment of fishing grounds close to seismic operation. To date, few studies have examined the behavioral response toward sound exposure, and the mackerel audiogram is not mapped. In this study, we investigated the hearing ability of mackerel by measuring inner ear microphonic responses to vibration of anesthetized mackerel in air, thus mapping its ability to detect particle motion at different frequencies. Because they lack a swim bladder, mackerel are sensitive to the particle motion and not the pressure component of sound. Results indicate sensitivity up to ~300 Hz and well into the infrasound range. Furthermore, we investigated the avoidance behavior responses in captive mackerel by subjecting schools to 5 sound signals; 2 pure-tone signals of 14 and 112 Hz and playbacks of 3 authentic seismic signals that lacked frequencies below 50 Hz, modified with different sound exposure levels (SELS) and peak pressures, in a randomized block design. The strongest reactions were induced by the 14-Hz tone; the signal of greatest particle acceleration (0.01 ms$^{-2}$), with responses entailing startle, increased swim speeds and changes in the schooling dynamic. The remaining sound exposures included no startle responses, but there were minor changes in behavior at particle accelerations levels of 0.001-0.004 ms$^{-2}$. The seismic signal with the highest SEL induced a stronger response than that of the similar particle acceleration and peak pressure but had a lower SEL, indicating that this component was also important. This study has produced the first mackerel audiogram, demonstrating the ability of mackerel to sense acoustic accelerations well into the infrasound range and that infrasound can induce strong avoidance behavior at accelerations of ~0.01 m/s$^2$. Moderate behavioral responses to the seismic signals at merely one-tenth of the accelerations for the infrasound signal indicate that stronger reactions might occur at greater acceleration levels. Hence, we cannot conclude whether the frequency or the level is the most important component to trigger the observed reaction. Such abrupt changes in behavior during a fishing operation may affect catch success. Seismic signals comprise much energy in the lower frequency band, which can propagate over great distances, thus having the potential to affect fishing operations.
Some Lessons from the Effects of Highway Noise on Birds

Robert J. Dooling  
University of Maryland, rdooling@umd.edu

Arthur N. Popper  
University of Maryland, apopper@umd.edu

Recent literature on the effects of anthropogenic noise on fishes and marine mammals shows that the underwater world is becoming a noisier place and that the effects of single and chronic noise exposure on these animals can be both significant and complex. Compared with studies on terrestrial species, behavioral studies on fish and marine mammals are notoriously challenging and the specification of underwater sound is much more complex. Among terrestrial vertebrates, birds present an interesting animal model to examine the effects of noise because their auditory behavior and their acoustic communication behavior are easy to study in both the laboratory and the field, resulting in a large database from which to extrapolate. A recent review for CALTRANS by the authors focused on estimating the effects of traffic noise on birds and nicely illustrates the remaining complexities of the problem, even with traffic noise where the relevant variables are relatively well-studied and well-specified. There are as yet no studies definitively and reliably identifying traffic noise as the critical variable affecting bird behavior near roadways and highways. There are well-documented adverse effects of sustained traffic noise on humans and both field and laboratory studies on birds suggest that similar effects may be true in birds. Auditory system damage and hearing loss from acoustic overexposure from intense construction noise represent another potential problem, but a wealth of laboratory data from acoustic overexposure in birds over the years strongly suggests that this is not a major concern. Our review shows that masking from traffic noise remains a significant problem, especially when considered as additive to the noise already present from increasing urbanization. Because traffic noise can be so well-characterized in natural environments and so much is known about bird hearing, we can estimate the effect of anthropogenic noise on communication distances. Most important, a considerable number of well-controlled experimental field studies over the past 10 years have had a significant impact on our understanding. They reveal that there are wide species differences in the effects of noise on birds and on the strategies that birds use to maximize acoustic communication in a noisy world. Birds have been found to use many of the strategies that humans to maximize communication in a noisy environment, including changes in the behavior of the sender and the receiver and changes in the behavior of the receiver that in turn affect the behavior of the sender.
Does wind cause a natural bubble curtain minimizing porpoise avoidance effects during pile driving operations?

Anne-Cécile Dragon  
Bioconsult-SH, ac.dragon@bioconsult-sh.de

Miriam Brandt  
Bioconsult-SH, m.brandt@bioconsult-sh.de

Ansgar Diederichs  
Bioconsult-SH, a.diederichs@bioconsult-sh.de

Georg Nehls  
Bioconsult-SH, g.nehls@bioconsult-sh.de

During offshore wind farms construction, abundance in harbour porpoise (*Phocoena phocoena*) is known to be negatively affected by pile driving. From 2011 to 2013, extensive passive acoustic monitoring was conducted during research projects accompanying the construction of two offshore wind farms in the German North Sea (Global Tech 1 and Trianel Windkraftwerk Borkum, phase 1). We studied effect ranges of pile driving disturbance on acoustic porpoise detections (using C-PODs) to test how these may change with different wind speeds. Porpoise detections were available for wind speeds ranging from 0 to 12 m/s with pile driving mainly occurring under good weather conditions. We found that disturbance radii highly depended on the prevailing wind speed during construction, with further reaching disturbance effects at lower wind speed. Disturbance effects reached to about 16 km at wind speed of 2 m/s and to about 10 km during wind speed of 5 m/s. For wind speed greater than 3 m/s, wave breaking entrains air bubbles into the upper water column assumed to thus form a “natural bubble curtain”. Our results suggest that greater noise mitigation occurs at higher wind speed thanks to this transient layer of bubbles in the upper water column. This effect could also be related to porpoises perceiving piling noise as less disturbing as the signal to noise ratio decrease with higher background noise caused by waves breaking and sediment movement at high wind speed. Our results indicate that wind speed and possibly background noise are important factors when assessing disturbance effects of anthropogenic noise on marine mammals.
Use of Passive Acoustics to Measure Potential Effects of Noise on Aquatic Life

Gerald D'Spain  
Scripps Institution of Oceanography, gdspain@ucsd.edu  
Scott Jenkins  
Scripps Institution of Oceanography, sjenkins@ucsd.edu  
Tyler Helble  
SPAWAR Systems Center Pacific, tyler.helble@gmail.com

Passive underwater acoustic recordings have been increasingly used to investigate the effects of man-made noise on aquatic life. This approach is fraught with potential pitfalls given that the response under study (change in animal sound production) represents the same physical phenomenon as the stimulus (human-generated sound). As one example, the ability to detect animal sounds is affected by changes in the level and character of man-made sound that occurs in the same frequency band, independent of any changes in the character (amplitude, repetition rate, frequency content) of the animal calls. The purpose of this presentation is to discuss ways of designing receiving systems and signal-/array-processing algorithms to avoid these pitfalls, to account for the effects of the ocean environment, and to improve overall passive acoustic monitoring performance. The benefits, and drawbacks, of using directional receiving systems and mobile receiving systems will be discussed, along with a summary of some of the mobile and directional receiving systems designed and built by the Scripps Institution of Oceanography. An emphasis will be placed on the use of quantitative measures of performance from the statistical signal- and array-processing literature to evaluate acoustic monitoring performance.

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Ifremer Code of Conduct to Limit the Acoustic Impact of Seismic Surveys on Marine Mammals

Cécile Ducatel
Ifremer, Cecile.Ducatel@ifremer.fr

Yves Le Gall
Ifremer, Yves.Le.Gall@ifremer.fr

Xavier Lurton
Ifremer, Xavier.Lurton@ifremer.fr

Increasing man-made noise in the oceans has the potential to impact marine mammals at various levels. Possible impact levels range from behavior disruption to temporary and permanent threshold shifts. In the absence of regulations applicable nationally or at the European level and to address local requirements, an internal Ifremer group has been set up to respond to inquiries in the field of environmental acoustics. Since 2005, Ifremer has committed itself in a systematic risk prevention evaluation policy with regard to marine mammals and the use of acoustic sources. Modeling and measurements conducted over the past few years has led Ifremer to define a first Code of Conduct (2011) aimed solely at seismic sources (airguns). This code is widely inspired from existing regulations; however, these depend on local policy and may differ greatly between countries. Some measures found in the current guidelines are difficult to define mainly because of a lack in feedback from results relative to monitoring procedures applied during seismic surveys, i.e., arbitrary-sized safety zones, prewatch and soft-start definition, inadequate observer training, and lack of standardized data collection. Relevant mitigation measures with consistent biological and acoustic meanings could be defined by using this feedback as well as adding to the acoustic and biological current knowledge. In this context, we reviewed and analyzed comparatively the measures proposed by various guidelines and recommendations and the current state of scientific knowledge to update our Code of Conduct. This new protocol (2016) now contains the most relevant and appropriate mitigation plan (covering both planning and operations) that can be applied to cruises using Ifremer seismic sources. First, we present a brief review of guidelines around the world to date, with their strengths and weaknesses. From this analysis, we detail the new Ifremer Code of Conduct to limit the acoustic impact of seismic surveys to marine mammals. Finally, we present what the current data lacks as well as the research axes to develop.
Issues Associated with Sound Exposure Experiments in Small Tanks

Alec J. Duncan
Centre for Marine Science and Technology, Curtin University, a.j.duncan@curtin.edu.au

Robert D. McCauley
Centre for Marine Science and Technology, Curtin University, r.mccauley@cmst.curtin.edu.au

Christine Erbe
Centre for Marine Science and Technology, Curtin University, c.erbe@cmst.curtin.edu.au

For many practical reasons, it is often convenient, or even necessary, to carry out sound exposure experiments on marine animals in small tanks that may have dimensions ranging from less than a meter to a few tens of meters. The floor and walls of such tanks are almost invariably highly reflective to underwater sound, as is the water surface. This results in a sound field that can vary spatially in unexpected ways and in which the relationship between pressure and particle velocity can be quite different from that in an animal’s natural environment. This paper introduces the physical basis for these effects and considers the implications for experiments investigating the hearing of aquatic animals or the impacts of underwater sound on marine animals. Sounds generated using a simple simulation of the acoustic field in a tank will be used to help audience members to gain some appreciation of how these effects change what an animal might perceive. Additionally, some insight into the value of using spatially separated hydrophones to quantify low-frequency particle acceleration and issues in the calibration of low-frequency acoustic receivers will be briefly discussed.
A Spatially Explicit Model of Movement of Humpback Whales Relative to a Source Vessel in Response to Airgun Signals

Rebecca Dunlop  
University of Queensland, r.dunlop@uq.edu.au  
Michael Noad  
University of Queensland, mnoad@uq.edu.au  
Robert McCauley  
Curtin University, R.MCCAuley@cmst.curtin.edu.au  
Douglas Cato  
University of Sydney, doug.cato@sydney.edu.au

Usually, when measuring the behavioral response of large whales, multiple measures of behavior can be used (e.g., horizontal movement, dive profile, and surface behavior). Although this helps to determine fine-scale changes in behavior, using multiple measures means that an adjustment of significance level must be made to account for multiple comparisons on the same data set. In addition, many of these behavioral measures do not account for the position of the source vessel relative to the animal or group. This is a measure of displacement behavior, which takes into account the position of the group relative to the source vessel. Previous work measuring the behavioral change in humpback whales in response to seismic air guns found a change in group horizontal movement (Dunlop et al., 2015, 2016). To put this in the context of the source vessel, the “MDD” was developed as a new metric, which compared the distance of the group to the source vessel, had they not have changed movement behavior (expected), with their actual distance to the source vessel (observed). An increase in MDD meant that their observed distance from the source vessel was greater than their expected distance, implying an avoidance response. Here we expand on this previous work by using a modified version this variable (and measures of movement behavior) to compare the baseline responses of humpback whales with a set of controls (where the vessel was moving in the exposure phase but the airguns were not operating): a 20-in.³ air gun, a 140-in.³ array of airguns, and to a ramp-up sequence from 20 to 440-in.³ (with 30 minutes of exposure for each treatment). Within the 30 min, groups significantly changed their horizontal movement in response to all treatments, including the controls. However, the groups deviated more from the source vessel in response to the 140-in.³ array and ramp-up sequence compared to the controls and the 20-in.³ airgun. The results also suggested a more sustained avoidance response to the larger airgun arrays during the exposure time, although there was no evidence of a simple dose-response-type relationship. This measure is a complementary technique that takes into account the alteration in group horizontal movement relative to the source vessel. It is a spatially explicit model that can be applied to other marine mammal behavioral-response studies and therefore provides a more comparable response measure.


Use of Underwater Soundscapes to Characterize Nocturnal Fish Behavior and Habitat Use Within a Complex Mosaic of Estuarine Habitats

David B. Eggleston
Department of Marine, Earth, and Atmospheric Sciences, NC State University, eggleston@ncsu.edu
Shannon W. Ricci
Department of Marine, Earth, and Atmospheric Sciences, NC State University
Del R. Bohnenstiehl
Department of Marine, Earth, and Atmospheric Sciences, NC State University

Structurally complex estuarine habitats such as seagrass beds, salt marshes, and oyster reefs are used by fish for foraging, avoiding predators, and spawning. These shallow-water habitats often occur as a complex mosaic, where sampling fish, particularly at night, is difficult with traditional methods such as trawls and throw traps. This study used passive acoustics to characterize the spatiotemporal dynamics of the fish chorusing to investigate habitat use within an estuarine reserve system (Middle Marsh, Back Sound, North Carolina). Over a 3-month period, 2-minute-duration underwater sound recordings were made every 20 minutes at 8 sites within the reserve. Fish chorusing was spatially variable between sites, and the sounds associated with spawning occurred primarily during nighttime flood tides. Spotted sea trout produced sounds after sunset, and their sounds ended with the onset of silver perch chorusing. Silver perch chorusing, like sea trout, occurred only at night during slack high and ebbing tides. Chorusing by other sciaenids was present throughout most of the tidal cycle and occurred during night and day. Soundscape characterization can provide a high temporal resolution record of habitat use and soniferous fish activity in estuarine environments. The method is noninvasive and operates effectively even under conditions of low visibility and high sea state when traditional sampling approaches can be difficult to implement.
Anthropogenic sound in the oceans is known to have a range of detrimental effects on a number of taxa. Cetaceans are particularly sensitive to excessive man-made noise, which can cause temporary and permanent hearing damage. More subtle responses to increased noise include both changes in vocal production and animal distribution patterns. In the last decade, there has been a sixfold increase in studies using active acoustic tags to study marine animals (mostly teleosts and elasmobranchs), with over 40,000 tags deployed worldwide from a single major manufacturer. Acoustic tags typically produce narrowband time-coded pulses emitted approximately every 2 min in the 69- or 180-kHz frequency range (amplitude 136-162 dB re 1 μPa for 69-kHz tags). Because cetaceans are highly acoustically oriented, acoustic tags (notably those at 69-kHz that overlap significantly with dolphin hearing) may act to advertise the presence of the tagged fish or actively deter animals from the acoustic tag location in a similar manner to acoustic deterrent devices. We investigated the response of bottlenose dolphins (*Tursiops truncatus*) to a single 69-kHz acoustic tag in a paired control-impact study. Two C-PODS (automated cetacean click detectors) were placed on moorings 2 km apart in a high dolphin use area near to shore. An acoustic tag was positioned next to the C-POD to investigate the differences in dolphin click detection in the vicinity of the tags. The tags were alternated between moorings over a 5-month period. Responses investigated were dolphin click detection rates (detection positive hours per day), dolphin encounter duration, and potential foraging/investigatory buzzes during tagON and tagOFF periods, both within and between locations. During TagON periods, the overall dolphin presence was significantly lower both within and between moorings while encounter durations were longer, possible suggesting group-level differences. However, the proportion of feeding (investigatory) buzzes detected did not differ significantly with tag presence. Our results show that even in the absence of additional prey- or predator-associated cues, the sound alone from acoustic tags may cause significant changes in dolphin acoustic behavior (click rate), distribution, or both. Visual confirmation of behaviors is needed to determine which effect is taking place. Further investigation on other species and investigation in areas where tags may be associated with either prey or predator species would be beneficial to better understand the potential impacts of these types of tag.
Underwater noise, whether of natural or anthropogenic origin, may interfere with the abilities of marine mammals to receive and process relevant sounds and could potentially impact individual fitness. Of all the ways in which noise can affect the lives of marine mammals, auditory masking is perhaps the most pervasive. Masking occurs when the ability to detect or recognize a sound of interest is degraded by the presence of another sound (the masker). Quantitatively, masking refers to the amount in decibels by which an auditory detection threshold is raised in the presence of a masker. Although masking is a common, if not universal, feature of natural communication systems, masking levels are difficult to predict for any particular combination of sender, environment, and receiver characteristics. At present, there is no species for which a complete masking model exists; however, certain models have proven to be effective for some species in many listening situations. Here, we present our understanding of masking in marine mammals, review the parameters that affect hearing in noise (audiograms, critical ratios, critical bands, auditory integration times), explain the power spectrum model of masking, and discuss the masking release processes of receivers (including comodulation masking release and spatial release from masking) and the antimasking strategies of signalers (e.g., Lombard effect). Considering the available information, we highlight information gaps and suggest a research strategy to address these gaps. Our review indicates that more research is needed to understand the process of masking, the risk of masking by various anthropogenic activities, and the biological significance of masking and antimasking strategies before masking can be incorporated into regulation strategies or approaches for mitigation for marine mammals.
The national “energy agreement for sustainable growth” in the Netherlands will result in an increase in the offshore wind capacity of the country from the current 1,000 MW to 4,500 MW in 2023. The uncertainty around the potential impact of the construction of 10 wind farms with a total capacity of 3,500 MW motivated the Dutch government to develop a “framework for assessing ecological and cumulative effects of offshore wind farms.” The central question to the framework was “How can the sustainable energy targets be met and several wind farms be built without significant damage to the marine environment?” One of the topics the framework deals with is the effects of impulsive underwater sound produced during the construction of wind farms on the harbor porpoise (*Phocoena phocoena*). In the future, the framework can be expanded to include more activities and more species of concern. The framework, based on the DPSIR (EEA, 1999), is an approach that is open to accommodate specific models and studies and continues development and improvement of the results. The framework also identifies the gaps in knowledge that need to be addressed in the future. The quantification of effects on the harbor porpoise showed that although there is large uncertainty in the results, the cumulative effects of unmitigated piling of wind farms might be substantial. A maximum acceptable limit was needed to determine if the effects were significant in terms of the Habitats Directive. The ASCOBANS interim objective of restoring/maintaining populations at 80% carrying capacity was the most suitable reference. Because the carrying capacity could not be quantified, the Netherlands defined the maximum acceptable limit at 5% reduction of the current population of the Dutch continental shelf for the wind farms built until 2023. Based on this limit and the effects, a system of variable sound thresholds was devised. The threshold takes into account the location of the project, the season of construction, and the number of piles that will be driven into the seabed. The work on the framework made clear that international cooperation is essential for defining a common maximum acceptable limit of effects because populations are not limited to national borders. International cooperation, also required by the Marine Strategy Framework Directive, is essential to develop a common framework, and a joint research effort is needed that aims to improve the methods for quantifying the effects and decrease uncertainty.

Multidecadal Variability in the Spatial Dynamics of Southern Bluefin Tuna

Karen Evans
CSIRO Oceans and Atmosphere, karen.evans@csiro.au

Toby Patterson
CSIRO Oceans and Atmosphere, toby.patterson@csiro.au

Paige Eveson
CSIRO Oceans and Atmosphere, paige.eveson@csiro.au

Campbell Davies
CSIRO Oceans and Atmosphere, campbell.davies@csiro.au

Juvenile (1-4 yr) southern bluefin tuna (SBT) undertake extensive migrations between winter foraging grounds in the Indian and Pacific Oceans and summer foraging grounds in the Great Australian Bight (GAB). Valuable commercial and recreational fisheries target SBT throughout their range, and commercial catches are internationally managed by the Commission for the Conservation of Southern Bluefin Tuna. The GAB is currently the focus of exploration activities associated with large-scale oil and gas development. This has generated concern for the potential impacts on the migration and behavior of SBT, with associated consequences for annual abundance indices collected as part of management strategies associated with the recovery and future sustainable harvest of the species. As part of a large ecosystem study of the GAB, historical archival tag data collected from 1990 to 2010, in combination with new deployments of tags, will characterize multidecadal variability in the horizontal and vertical movements and foraging behavior of SBT. Novel statistical approaches to geolocation used in combination movement and behavioral models will characterize foraging behavior from horizontal and vertical movement behavior. Results from this project will provide baseline information from which future assessments of the impacts of exploration and extraction activities in the GAB can be undertaken.
Maps of underwater noise levels can be used in the marine spatial planning process to assess the risk of impact to marine fauna. Sound maps are based on modeled source levels and the acoustic propagation characteristics of the environment. However, modeling the sound field generated by large numbers of sources using numerical propagation models is computationally intensive, and present sound mapping approaches have not been rigorously validated with experimental data. Here, we present a computationally efficient modeling approach for producing instantaneous shipping noise maps of large spatial areas and long time periods and assess the predictions against measured noise levels. Automated identification system (AIS) ship-tracking data are used to produce source-level estimates for each tracked vessel at intervals of one hour or less, based on ship length and ship speed. The propagation losses are precomputed on a 5-km resolution grid using a numerical model based on the RAM parabolic equation method, taking into account bathymetry, water column, and seabed properties. Seasonal environmental variations are accounted for by precomputing a propagation-loss matrix for each typical calendar month. The source level estimates are combined with the propagation loss matrices to produce noise maps having the temporal resolution of source-level data and the spatial resolution of the propagation-loss grid. Optionally, the contribution of wind-driven ambient noise can be added into the noise maps. The methodology is employed to produce shipping noise maps of the UK North Sea shelf covering the year 2013 at one-hour intervals. Higher resolution (20-minute interval) results are validated against measurements taken at 10 monitoring stations along the east coast of Scotland during Summer 2013 as part of the Marine Scotland East Coast Marine Mammal Acoustic Study (ECOMMAS). We assess the model and measurement agreement and discuss challenges to producing fully validated sound maps for marine spatial planning applications.
Preliminary Characterization of the Acoustic Signals Emitted by the Crab *Neohelice granulata* (Brachyura, Varunidae) in Different Social Layouts

**Francesco Filiciotto**  
National Research Council, francesco.filiciotto@cnr.it  
**María Paz Sal Moyano**  
Universidad Nacional Mar del Plata, Argentina  
**Valentina Corrias**  
National Research Council  
**Martín Lorusso**  
Universidad Nacional Mar del Plata, Argentina  
**Fernando Hidalgo**  
Universidad Nacional Mar del Plata, Argentina  
**María Cielo Bazterrica**  
Universidad Nacional Mar del Plata, Argentina  
**Salvatore Mazzola**  
National Research Council  
**Giuseppa Buscaino**  
National Research Council  
**María Andrea Gavio**  
Universidad Nacional Mar del Plata, Argentina

Beginning in late 1989, an explosion of work involved the ecology, physiology, toxicology, and behavior of the burrowing crab *Neohelice granulata*, considered as a model species in a variety of biological fields even if, until now, there are no studies about its acoustic emissions. The aim of this study was to characterize preliminarily the acoustic signals emitted by the crab *N. granulata*, evaluating them in different social layouts. The study was conducted in the Estación Costera J. J. Nágera of the Universidad Nacional Mar del Plata, Argentina. Crabs were collected by hand from the field and, after the acclimatization phase, were moved to a circular fiberglass tank adopting the following trial configuration: 1 male alone; 1 female alone; 1 male and 1 female; 2 males and 1 female; and 2 females and 1 male (each trial consisted of 3 replicates). In total, 15 experimental trials were performed using 30 specimens of *N. granulata*, 15 males (carapace width of 30.37 ± 3.1 mm, mean ± SD) and 15 females (carapace width of 27.19 ± 3.2 mm). The trials consisted of 1 h of acoustic recording using a calibrated hydrophone (model 8104, Brüel & Kjær) with a sensitivity of −205.6 ± 4.0 dB re 1 V/μPa in the 0.1-Hz to 80-kHz frequency band. The hydrophone was connected to a digital acquisition card (USGH416HB, Avisoft Bioacoustics) managed by Avisoft Recorder USGH software. Pulse trains and single pulses were analyzed using the routine Pulse Train Analysis (Avisoft-SASLab Pro) automatic method. Overall, 75 pulse trains containing 552 single pulses were recorded during the trials. Signals from crabs showed the following acoustic parameters expressed as median ± 10-90 percentiles: pulse train duration of 0.3 ± 0.07-2.22 s; 5 ± 3-10 pulses in the pulse train; pulse rate of 11.9 ± 4.5-29.63 Hz, determined as the ratio of the number of pulses and the duration of the pulse train; 4.33 ± 2.6-6.2 kHz in peak frequencies; and 179.32 ± 174.56-191.87 dB re 1 µPa in peak amplitude. No signals were recorded from crabs evaluated alone, and all the acoustic emissions were observed in trials with grouped animals (without statistical differences in the number of signals among the group layouts), allowing us to assume a social/reproductive role of the acoustic signals in this crab species. However, further studies are needed to analyze the difference in signal structures depending on sex and animal size.
Noise-Induced Hearing Loss in Marine Mammals: A Review of 20 Years of Temporary Threshold Shift Research

James Finneran  
US Navy Marine Mammal Program, james.finneran@navy.mil

Animals exposed to sufficiently intense sound may exhibit an increased hearing threshold called a noise-induced threshold shift (NITS). If the hearing threshold eventually returns to normal, the NITS is called a temporary threshold shift (TTS). If the hearing threshold does not return to normal but leaves some residual NITS, the remaining NITS is called a permanent threshold shift (PTS). Extensive studies of NITS in humans and small terrestrial mammals have been conducted to identify noise parameters that affect hearing loss and to develop safe exposure guidelines for people. The similarities between the auditory systems of humans and small terrestrial mammals have enabled a large body of data to be collected that is directly applicable to developing noise exposure criteria for people; however, differences between the auditory systems of marine and terrestrial mammals and sound propagation in-air and underwater prohibit direct application of terrestrial damage risk criteria to marine mammals. For these reasons, acoustic exposure guidelines for hearing loss in marine mammals have primarily relied on measurements of NITS in representative marine mammal species rather than extrapolation from terrestrial species. The first documented NITS in a marine mammal occurred in 1996, when Kastak and Schusterman (1996) reported small amounts of TTS in a harbor seal (*Phoca vitulina*) incidentally exposed to nearby construction noise. Over the next 20 years, the number of publications related to marine mammal TTS has grown exponentially as additional researchers examined the growth and recovery of TTS in marine mammals exposed to noise with various sound pressure levels, frequencies, durations, and temporal patterns. Although the experimental paradigms have been similar, the various groups examining TTS in marine mammals have used different species, exposure parameters, and testing methods, highlighting the need for periodic review and synthesis of the data. This talk reviews the methods employed by the groups conducting marine mammal TTS experiments and the relationships between the experimental conditions, noise exposure parameters, and the observed TTS. Where possible, data from the different laboratories/experiments are pooled to provide a more complete picture of the state of knowledge at this time for the effects of noise on pinniped and odontocete hearing.

Modeling the Risk of Noise Exposure to Marine Life During Offshore Wind Farm Construction and Operation

Thomas Folegot
Quiet-Oceans, thomas.folegot@quiet-oceans.com

Alain Norro
Royal Belgian Institute of Natural Sciences, anorro@naturalsciences.be

Dominique Clorennec
Quiet-Oceans, dominique.clorennec@quiet-oceans.com

Frank Thomsen
DHI, frth@dhigroup.com

The MaRVEN project, funded by the European Commission Directorate for Research and Innovation, has provided a review of the available literature related to the environmental impacts of marine renewable energy devices and an in-depth analysis of studies on the environmental effects of noise, vibrations, and electromagnetic emissions during installation and operation of wind, wave, and tidal energy devices. A dedicated risk modeling study has been conducted to address the gap identified in various noise impact assessments that have been undertaken at specific sites across marine renewable energy (MRE) projects in EU waters, specifically from the point of view of detectability of the noise by marine life. A generic approach was proposed to evaluate the area of audibility, the so-called noise footprint, to guide future environment impact assessments conducted across EU waters and illustrated through an exemplar risk assessment case study based on offshore wind farms in Belgian waters. The study demonstrated that the area of detectability largely depended on the existing environmental conditions (i.e., sediment type and bathymetry) in addition to the noise generated by the other maritime activities occurring in the area but that were not related to MRE projects. Basing the exemplar risk assessment on the Belgian offshore wind farm case study, it was confirmed that there were large areas where there was the potential for behavioral responses of harbor porpoises, midfrequency species, and pinnipeds. However, during construction, the combined effect of the bathymetry and the noise generated by shipping in this Belgian particular example was predicted to be of greater relevance to the porpoises along the coastline where the noise emitted from a single strike did not add to the soundscape for at least half of the time. Hence, this illustrated the importance of understanding the existing precise background soundscape context when assessing the risk of pile driving to sensitive receptors. It also highlighted that the quantification of the footprint for a single strike defines the geographical limits for cumulative effects from multiple strikes. For operational noise, a similar generic methodology to quantify the cumulative area of detectability has been proposed and applied to the particular case of the three wind farms operating in Belgian waters. The results suggest that the area of detectability for operational noise will be mainly limited by the fact that the other anthropogenic pressure will dominate the soundscape most of time for this particular case.
A multidisciplinary approach bringing together experts of the naval industry, underwater acoustics, and bioacoustics was developed in the framework of Project AQUO (Achieve QUieter Oceans by shipping noise footprint reduction), which started in October 2012 for 3 years to provide stakeholders of the maritime domain with the most promising strategies for the mitigation of the impact of shipping noise on the marine fauna. The proposed mitigation measures studied were not only technical (i.e., in relation to ship design) but also operational through ship navigational parameters settings and/or ship traffic control in localized areas. Fulfilling individual requirements could be achieved by an improvement in design of future vessels and for existing vessels by proper maintenance and adapting operational settings. For shipping noise, an individual reduction solution will lead to a cumulative reduction at the basin scale according to the environmental parameters and the characteristics of the maritime activities. To determine this cumulative effect, a series of simulations was carried out using a noise footprint assessment model derived from the Quonops noise prediction tool. The indicators of the impact on marine life were expressed in maps by spatiotemporal statistical quantities, not only in terms of noise levels but also directly related to bioacoustic criteria. The results will be shown at basin scale for the three pilot areas located in the Atlantic Ocean and the Mediterranean Sea. The responsibility to define local, national, or regional regulations belongs to the European Commission, the member states, or marine area managers. AQUO has provided them with a generic methodology and an operational tool to quantify the global efficiency of future decisions to achieve good environmental status.
Boat Noise Reduces Acoustic Active Space in the Lusitanian Toadfish *Halobatrachus didactylus*

Paulo J. Fonseca  
Departamento de Biologia Animal and cE3c (Centre for Ecology, Evolution and Environmental Changes), Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal, pjfonseca@fc.ul.pt

Clara M. Amorim  
MARE (Marine and Environmental Sciences Centre), ISPA-Instituto Universitário, Lisbon, Portugal, amorim@ispa.pt

Daniel Alves  
Departamento de Biologia Animal and cE3c (Centre for Ecology, Evolution and Environmental Changes), Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal, dbalves@fc.ul.pt

Anthropogenic noise is considered of global concern because increasing ocean background noise due to human activities is impacting various aspects of aquatic life. One of the most prevalent anthropogenic noise sources are boat engines. Although motorboat traffic has dramatically increased in the last few decades, information on the impact of boat noise on the communication of aquatic animals is still scarce. We tested the impact of boat noise on the communication active space of a vocal teleost, the Lusitanian toadfish (*Halobatrachus didactylus*). To achieve this goal, we compared, using the auditory evoked potentials technique, the maximum distance a fish can perceive the conspecific advertisement signal, the boat whistle, before and after embedding the acoustic signal in boat noise recorded in the natural habitat. We used noise from two different types of boat, a small motorboat, and a ferryboat. We found that at ~2 m water depth, the active space ranged between 6 and 10 m depending on the boat whistle spectral characteristics. Noise from the small motorboat and from the ferryboat reduced the communication range to ~2.5-4 m and 7-8.5 m, respectively. These results demonstrate that boat noise can severely reduce the acoustic active space of this fish and, in places of heavy boat traffic, it may influence mate finding depending on the boat noise characteristics.
Methods of predicting the acoustic exposure from anthropogenic sources on animals have become increasingly sophisticated by simulating animal behavior and considering hearing sensitivities. In addition, a long-standing issue in the prediction and regulation of acoustic exposures is the question of how many exposures occur during an activity and how those exposures are distributed over individual animals. The draft NOAA guidance recommends a 24-hour sound accumulation period, which is then scaled by the number of days of the activity for an overall exposure estimate. This method produces a good estimate of the predicted number of exposures, but it does not assess the number of animals that experience multiple exposures, which may be significant in a resident or nonmigratory population. A sensitivity study was conducted to evaluate the effects of (1) source movement, (2) animal movement, and (3) hearing sensitivities on (4) exposure estimates both at the individual animal level and for the overall survey. Three airgun-array vessel-movement patterns (stationary, 2-D seismic survey, and 3-D seismic survey) were modeled for a Gulf of Mexico location, each with a one-month duration in which individual animals were tracked for the entire simulation. During each simulation, animal movement was modeled for a low-frequency hearing mysticete, a shallow-diving midfrequency hearing dolphin, a deep-diving midfrequency hearing whale, and a high-frequency hearing whale. Each animal’s behavior was modeled as (1) horizontally stationary but diving vertically, (2) full 4-D (moving horizontally and diving vertically), and (3) 4-D with aversion to sound pressure level. The aversion response was defined by a cumulative distribution function that had aversion probabilities in which 5% of animals would avert when they experienced a received SPL of 140 dB, 50% at 160 dB, and 95% at 180 dB. The effect of hearing sensitivity was evaluated using three auditory filter functions: none, M-weighting, and draft NOAA guidance. Preliminary results show that 4-D motion animats received lower sound levels than horizontally stationary animats. Inclusion of aversion to sound source and auditory-weighting filters also reduced exposure levels. Preliminary results with a stationary source and full movement animats found that exposed individuals received an average of 1.5 daily exposures during a 1-month period. This preliminary finding represents one particular scenario and is not generalizable to other projects or areas. The full analysis of all permutations in this project will provide insight into the sensitivities of these parameters on animat-based models.
Effects of Anthropogenic Noise on the Acoustic Call Rate of a Freshwater Insect, *Sigara dorsalis*

**Kevin French**  
Marine and Freshwater Research Centre, Galway-Mayo Institute of Technology, kevin.french@research.gmit.ie

**Joanne O’Brien**  
Department of Natural Sciences, Galway-Mayo Institute of Technology, joanne.obrien@gmit.ie

**Martin Gammell**  
Department of Natural Sciences, Galway-Mayo Institute of Technology, martin.gammell@gmit.ie

The effects of noise on aquatic habitats and species is mainly focused on marine mammals, fish, and marine invertebrates. Few studies have considered the effects of noise in freshwater environments, especially assessing the effects on freshwater invertebrates, particularly species that use acoustic communication. Under the EU Water Framework Directive, noise is not recognized as a pollutant as it is under the EU Marine Strategy Framework Directive. The impacts of noise on freshwater organisms could be similar to those in marine and terrestrial habitats and therefore should be considered under our current policies. *Sigara dorsalis* is a species of water boatman and a member of the Corixidae family. They are known to be preyed on by many ecologically and commercially important fish species, such as the brown trout, and it is why fishermen try to emulate them using artificial flies. *S. dorsalis* are known to produce sounds by stridulation using pegs on their forefemora, which they scrape along the plectrum located on the head. This process produces a pulse of sound and is used by *S. dorsalis* during mate selection. Should increases in anthropogenic noise impact on *S. dorsalis* during the mating period, they could lead to a decrease in densities and in turn impact on higher trophic organisms through decreased availability of prey. To assess the potential impact of noise on *S. dorsalis*, controlled noise-exposure experiments were carried out in a laboratory. All specimens used during experiments were collected from a rural site where the potential previous exposure to anthropogenic sounds was minimal. Playback experiments were conducted using a range of anthropogenic sounds found in freshwater aquatic environments, including boat engine noise, traffic (roads), construction, and forestry noise, all of which can be or are found near many shallow freshwater habitats that insects such as *S. dorsalis* inhabit. Experiments were structured to allow behavioral and acoustic observations in response to increased sound in the environment over various durations. Call rates were estimated before, during, and after exposure, and recovery time was also estimated. This study was the first assessment of the potential effect of anthropogenic noise on *S. dorsalis*, and the results suggest that environmental policies should address noise in freshwater habitats.
A Sound System for US Exclusive Economic Zone Waters, NOAA’s Ocean Noise Reference Station Network

Jason Gedamke, Office of Science and Technology, NOAA Fisheries, jason.gedamke@noaa.gov; Holger Klinck, NOAA/PMEL/CIMRS, Cornell University, holger.klinck@noaa.gov; Robert P. Dziak, NOAA/PMEL/CIMRS, robert.p.dziak@noaa.gov; Jay Barlow, SWFSC, NOAA Fisheries, jay.barlow@noaa.gov; Catherine Berchok, AFSC, NOAA Fisheries, catherine.berchok@noaa.gov; Leila Hatch, NOAA NOS-Stellwagen Bank NMS, leila.hatch@noaa.gov; Brad Hanson, Samara Haver, Joseph Haxel, Marla Holt, Haru Matsumoto, Megan McKenna, Christian Meinig, David K. Mellinger, Erin Oleson, Melissa Soldevilla, Sofie Van Parijs

Long-term, deep-ocean acoustic measurements from fixed hydrophone stations have documented a substantial increase in ambient-noise levels (10-12 dB) in the 25- to 50-Hz frequency range in the eastern North Pacific since the 1950s, primarily associated with increased commercial ship traffic. The potential impacts of rising ocean noise levels have raised concern for marine species that rely on acoustic sensing for a variety of essential life history functions, including prey detection, navigation, and reproduction. Long-term trends in underwater noise levels in the US exclusive economic zone (EEZ), however, remain largely unknown because of a lack of adequate time series measurements. To address this need, a unique across-agency partnership between NOAA’s Office of Oceanic and Atmospheric Research, National Marine Fisheries Service; the National Ocean Service, Office of National Marine Sanctuaries; and the National Park Service was initiated to establish the first comprehensive network of ocean noise reference stations aimed at establishing a baseline of sound-level measurements and monitoring long-term changes and trends in the underwater ambient-sound field across the US EEZ. In 2014, implementation of this network began with the deployment of identical autonomous hydrophone systems at 11 reference station sites. Instruments were developed in-house at the Pacific Marine Environmental Laboratory to ensure proper calibration and consistency of the collected data sets. Each instrument records acoustic data up to 2.5 kHz continuously with a 2-year life span before recovery/redeployment is necessary. The instruments were deployed across the US EEZ and in four national marine sanctuaries (NMS), and one national park with 9 deepwater (500-900 m) and 2 shallow-water locations. Sites include (1) the Beaufort Sea, (2) the Gulf of Alaska, (3) the Olympic Coast NMS, (4) the Hawaiian Islands, (5) the Channel Islands NMS, (6) the Gulf of Mexico, (7) the southeast Atlantic Coast, (8) the northeast Atlantic Coast, (9) the Stellwagen Bank NMS, (10) the National Park of American Samoa, and (11) the Cordell Bank NMS. In late 2015, the first 4 instruments were successfully recovered and redeployed to maintain long-term monitoring. Standardized data analyses routines are being developed to provide a comparison of mean sound levels and annual, seasonal, and monthly percentile power spectrum density-level plots between sites. In addition, creation of a long-term acoustic data archive is underway at the National Centers for Environmental Information to provide a full archive for this and other passive acoustic data. Finally, expansion of this network to leverage the investments of other federal agencies is being explored to ultimately establish an ongoing network of ~30 sites to characterize ocean noise trends throughout the US EEZ.
Visualization of Spatially Explicit Acoustic Layers in an Underwater Soundscape

Jennifer L. Giard  
Marine Acoustics, Inc., jenn.giard@marineacoustics.com

Kathleen J. Vigness-Raposa  
Marine Acoustics, Inc., kathleen.vigness@marineacoustics.com

Adam S. Frankel  
Marine Acoustics, Inc., adam.frankel@marineacoustics.com

William T. Ellison  
Marine Acoustics, Inc., bill.ellison@marineacoustics.com

Soundscapes, or acoustic scenes, emphasize the way in which the acoustic environment is perceived by an individual or species. The potential effects of anthropogenic underwater sounds on marine mammals are usually assessed on the basis of exposure to one sound source. Recently published research modeling underwater noise exposure and assessing its impact on marine life has extended the typical single source/single species absolute received-level approach to defining exposure in a variety of ways including relative levels of exposure, such as loudness, signal-to-noise ratio, and sensation level; metrics for evaluating chronic elevation in background noise; and cumulative exposure to multiple and dissimilar sound sources as well as the potential for animals to selectively avoid a particular source and other behavioral changes. Incorporating these concepts into an overall acoustic scene analysis requires a more holistic and multidimensional approach that addresses the relationships among noise environment, animal hearing and behavior, and anthropogenic sound sources. VizSEAL (visualization of spatially explicit acoustic layers) is a user-friendly interactive tool that has been developed to consider each facet of the soundscape in a spatially explicit manner. The exemplar is the underwater environment of the Gulf of Mexico with layers for ambient oceanographic and meteorological noise, shipping, and distant anthropogenic sources in which exposure to a nearby seismic survey is filtered by the animal’s hearing sensitivity, sensation level, and nominal loudness of the signal.
Sound Sources for Seismic Surveys and How They Are Used

Bob Gisiner
IAGC, bob.gisiner@iagc.org

Marine seismic surveys use sound to visualize the geological structure beneath the ocean bottom for geological research, for site selection for offshore structures like wind farm pylons, and to search for oil and gas deposits. The most commonly used sound source is a compressed air cylinder, commonly referred to as an “airgun,” a misleading name because no explosive or blast wave is involved. The compressed air sources are typically arranged in horizontal planar arrays of multiple elements towed near the surface. During surveys, the arrays are towed at moderate speeds (~2.5 m/s) and are typically activated at intervals of 10 to 20 or more seconds, depending on the depth of the geological structures of interest and the dimensions of the listening array. The planar array of compressed air sources is designed to produce a coherent wave front vertically and produces less loud and less coherent patterns of sound laterally. Examples of array designs, source waveforms, and both modeled and measured sound fields will be provided.

Alternative sources of acoustic or vibratory energy, both historical and proposed, will also be reviewed, including explosives, marine vibrator type sources, distributed arrays, and others. Aspects of the process from invention to commercial application will be discussed, using examples from systems currently in different stages of development. The source arrays may either be fixed (for example, hung from a rig) or be towed behind a vessel in specific patterns, depending on the information needed. Fixed receiver systems may often be used to periodically monitor an oil or gas field in a very specific location over years or decades of the life of the field. Towed receiver arrays may also be used for this purpose but are more commonly used for the following types of data collection in which both the sources and the receivers are towed. Large-area, coarse-scale surveys, referred to as 2-D surveys, are used to image geological features over large distances. Surveys intended to identify specific small features likely associated with oil or gas deposits will cover smaller areas with more tightly spaced lines and include 3-D surveys, 4-D (periodically repeated “time-lapse” 3-D), and wide azimuth (WAZ) surveys (in which multiple receiving array vessels are used to obtain better resolution and to “look under” overlying acoustically dense structures like salt domes or surface obstructions such as rigs). Examples of the different types of surveys, survey areas, and durations will be provided.

Catalina Gomez  
Department of Fisheries and Oceans, St. John’s, Newfoundland and Labrador, Canada,  
Catalina.Gomez@dfo-mpo.gc.ca

Jack W. Lawson  
Department of Fisheries and Oceans, St. John’s, Newfoundland and Labrador, Canada,  
Jack.Lawson@dfo-mpo.gc.ca

Andrew J. Wright  
George Mason University, United States, marinebrit@gmail.com

Alejandro Buren  
Department of Fisheries and Oceans, St. John’s, Newfoundland and Labrador, Canada,  
Alejandro.Buren@dfo-mpo.gc.ca

Dominic Tollit  
SMRU Consulting North America, Vancouver, British Columbia, Canada,  
djt@smruconsulting.com

Véronique Lesage  
Fisheries and Oceans Canada, Mont-Joli, Quebec, Canada, Veronique.Lesage@dfo-mpo.gc.ca

Man-made sounds are known to cause marine mammals to interrupt their feeding, alter their vocalizations, and be displaced from important habitats, among other behavioral responses. The current paradigm used to evaluate these behavioral impacts and regulate activities that may cause them is based on establishing allowable sound loudness thresholds to which marine mammal populations can be safely exposed (received sound levels [RSLs]). The importance of considering the context of exposure, in addition to the RSL, led us to conduct a comprehensive, up-to-date systematic literature review (372 papers) and meta-analysis (205 data cases). The review summarized in detail the critical and complex role of the context of exposure. The meta-analysis revealed that the severity of behavioral responses of cetaceans (measured via a linear severity scale) was best explained by the interaction between man-made sound sources (continuous, sonar, or seismic/explosion) and functional hearing group (a proxy for the hearing capabilities of cetaceans). Importantly, the sound loudness received by the animals did not explain the severity level of behavioral reactions; more severe behavioral scores were not consistently related with higher RSLs and vice versa. This indicates that there is no scientific justification for a generalized predictive model of behavioral impact measured via a linear severity scale based on RSL. Consequently, monitoring and regulating sublethal impacts on marine mammals to man-made sounds should not rely entirely on RSL thresholds. Although this review represents the most thorough assessment of its type to date, it was not possible to incorporate any statistical assessment of context of exposure due to the specificities and lack of standardization across studies. Accordingly, it may remain impossible to incorporate context until more well-designed studies are undertaken. As a starting point to develop an alternative framework on man-made sound assessment, we recommend a simple approach focused on a measure of physical and acoustic habitat loss.
Activities such as large-diameter pile driving and underwater explosions pose acute risks of injury or damage for marine mammals. Current observer-based mitigation methods are expensive and likely to be ineffective. Using aversive sound to temporarily move vulnerable animals out of an exclusion zone may provide more effective mitigation, especially when the exclusion zones are large, the animals are difficult to detect, or the operations occur at night or in poor weather (Gordon et al., 2007). However, establishing the efficacy and safety of this approach requires rigorous tests of candidate signals in realistic field conditions (Herschel et al., 2013). We report a series of controlled-exposure experimental (CEE) trials carried out to assess seal responses to aversive sounds. Twenty-three adult harbor seals were fitted with UHF/Fastloc-GPS transmitters. These tags both provide near-real-time data to a research vessel at sea and also downloaded archived data to shore stations. The seals were tracked at sea using a motor-sailing vessel that allowed quiet approaches to set up CEE trials with a range of scenarios including different ranges, locations, and behavioral states. Aversive signals tested were an ADD (Lofitech) and killer whale calls. One hundred and thirteen seal CEEs were achieved. Generally, seals showed “managed” avoidance and not “panicked” responses. The clearest responses were to the ADD, with maximum response ranges of ~3,000 m (estimated received level was 111 dB). All seals within 998 m (estimated received level was 132 dB) showed an avoidance response. Seals directly approaching the source detoured to skirt around it, and their nearest approach was occasionally closer than the initial response range. Responses to killer whale calls were less consistent, with responses scored at ranges as high as 4.5 km but other instances with no response at ranges of <200 m. A binary logistic regression showed that for the ADD, the effect of range was highly significant while animal age class, gender, behavior at the time of playback, and the number of previous exposures were not. No parameters, not even range, were significant predictors of response for the killer whale exposures. These preliminary trials are encouraging, suggesting that aversive sounds could be used as part of an effective mitigation method. Issues still to be addressed include the closer approaches by animals transiting past sound sources. Further trials should also be conducted in offshore areas more typical of wind farm sites and, of course, with a wider range of species. This work, in particular the methodology, is applicable to understanding and investigating the responses to other anthropogenic sounds such as sonar.


Acoustic Particle Motion Measurement for Bioacousticians: Principles and Pitfalls

Michael Gray
University of Oxford, michael.gray@eng.ox.ac.uk

Peter Rogers
Georgia Institute of Technology, peterhrogers@me.com

David Zeddies
JASCO Applied Sciences, david.zeddies@jasco.com

All fish species can detect acoustic particle motion, whereas only some species additionally sense acoustic pressure. Proper measurement of the acoustic particle motion vector is therefore critical when studying hearing and noise impacts. Measurement of particle motion in any of its forms (acceleration, velocity, or displacement) is subject to a range of errors whose significance depends on the sound source and the environment in which it is recorded. Although the principles of particle motion measurement have primarily been developed assuming free-field planar waves, such fields are rarely encountered in practice, and the assumption of plane wave conditions can lead to measurement errors and flawed study conclusions. In this paper, we present a unified treatment of underwater acoustic particle motion measurement by (1) reviewing the properties of acoustic fields in commonly encountered source/environment scenarios, (2) describing potential error sources and quantifying their magnitudes, and (3) providing detailed guidelines and recommendations for bioacoustic studies.
Cetacean watching from tour boats has increased in recent years and has been promoted as an ethically viable alternative to cetacean viewing in captive facilities or directed take. However, short- and long-term impacts of this industry on the behavior and energetic expenditure of cetaceans have been documented. Although multiple studies have investigated the acoustic response of dolphins to marine tourism, there are several covariates that could also explain some of these results and should be considered simultaneously. Here, we investigate whether common bottlenose dolphins (*Tursiops truncatus*) inhabiting Walvis Bay, Namibia, vary their whistle parameters in relation to boat presence, surface behavior, and/or group composition. When dolphins were in the presence of tour boats and the research vessel, we detected an upward shift in several whistle frequency parameters of up to 1.99 kHz. No changes were demonstrated in the frequency range, number of inflection points, or duration of whistles. A similar, though less pronounced, difference was observed in response to engine noise generated by the research vessel in idle, suggesting that noise alone plays an important role in driving this shift in whistle frequency. Additionally, a strong effect of surface behavior was observed, with the greatest difference in whistle parameters detected between resting and other behavioral states that are associated with higher degrees of emotional arousal. Group composition also contributed to the variation observed, with the impact of boats dependent on whether calves were present or not. Overall, these results demonstrate high natural variation in the frequency parameters of whistles utilized by dolphins over varying behavioral states and group composition. Anthropogenic impact in the form of marine tour boats can influence the vocalization parameters of dolphins, and such changes could have a long-term impact if they reduce the communication range of whistles or increase energy expenditure.
Interping Sound Field from a Simulated Midfrequency Active Sonar, and What We Don’t Know About Marine Mammal Tonal Masking

Shane Guan
Department of Mechanical Engineering, The Catholic University of America, 68guan@cua.edu

Brandon Southall
SEA, Inc., brandon.southall@sea-inc.net

Jay Barlow
Southwest Fisheries Science Center, NMFS, jay.barlow@noaa.gov

Joseph Vignola
Department of Mechanical Engineering, The Catholic University of America, vignola@cua.edu

John Judge
Department of Mechanical Engineering, The Catholic University of America, judge@cua.edu

Diego Turo
Department of Mechanical Engineering, The Catholic University of America, turo@cua.edu

Research in human psychoacoustics shows that tonal noise can have masking effects beyond the frequency band of that sound. However, few studies of marine mammals have addressed the potential acoustic masking effects of anthropogenic tonal sources such as the midfrequency active sonar (MFAS) used by the Navy. This study investigates the characteristics of the sound field during the 2013 and 2014 Southern California Behavioral Response Study using drifting acoustic-recording buoys. Acoustic data were collected before, during, and after simulated MFAS playbacks. A numerical approach, incremental computation method, was developed to quantify the interping sound field during the MFAS playback. In addition, comparisons were made between interping sound field and natural background in 3 distinctive frequency bands: low frequency (<3 kHz), MFAS frequency (3–4.5 kHz), and high frequency (>4.5 kHz). The results showed significantly elevated sound pressure levels (SPLs) in the interping interval of the MFAS frequency band when compared with the natural background levels before and after playbacks. No difference was observed between interping SPLs and natural background levels in the low- and high-frequency bands. In addition, the duration of elevated interping sound field depends on the MFAS source distance. At a distance of 900–1,300 m from the source, the interping sound field was observed to remain 5 dB above the natural background levels for ~15 s, or 65%, of the entire interping interval. At a distance of 2,000 m, the 5-dB elevation of the interping SPLs only lasted for ~7 s, or 30%, of the interping interval. The prolonged elevation of the sound field beyond the brief sonar ping at such large distances is most likely due to volume reverberation of the marine environment, although multipath propagation can also be a contributor. This phenomenon underscores the need for further studies on the potential acoustic masking to the auditory systems of marine mammals.
Data from marine mammal observer (MMO) reports from the United Kingdom and adjacent waters between 1994 and 2010 were examined to assess the effects of seismic operations on marine mammals and compliance with the JNCC seismic guidelines. Data were examined for any specific response to the soft start procedure as well examining overall trends in compliance and implementation of the guidelines, comprising analysis of data from both visual and passive acoustic monitoring (PAM).

There was evidence that the soft start procedure may be an effective mitigation measure, with overall detection rates of several species/species groups during the soft start being significantly lower than when the airguns were not firing. On surveys with “large arrays” (airgun volume of 500 or more in.³), more marine mammals were observed demonstrating avoidance behavior (e.g., avoiding or traveling away from the survey vessel) during the soft start than at any other time.

Most species examined showed some response to firing in general (either soft start or full power) on surveys with “large arrays.” This included the first indication that beaked whales may respond to airgun activity because lower detection rates were observed when large arrays were active. The responses of marine mammals were less evident with “small arrays” (<500 in.³), but the detection rates of sperm whales and harbor porpoises were lower during active operations.

Analysis of compliance and implementation of the guidelines highlighted that visual monitoring overall was more effective than PAM at detecting marine mammals and noted potential areas of improvement for both PAM technology as well as PAM operators. Recommendations of where the seismic guidelines could be improved were highlighted, including, for example, strengthening and clarifying some of the existing mitigation measures, guidance on the use of PAM, and further training elements for both MMO and PAM operators to ensure that the guidelines are fully implemented. Such areas are currently being considered by the JNCC in revising the seismic guidelines.
American National Standards Institute (ANSI) published standard S12.64-2009 (reaffirmed in 2014) describing procedures for measuring underwater sound from ships. Port Metro Vancouver and Transport Canada in collaboration with JASCO Applied Sciences and Ocean Networks Canada (ONC), installed a real-time underwater listening station along the northbound (incoming) shipping route to Port of Vancouver, British Columbia in 173 m water depth. A key purpose of this station is to measure acoustic source levels of vessels using methods conforming as closely as possible to S12.64-2009.

The underwater listening station consists of two JASCO AMAR Observer acoustic acquisition systems, each connected to a tetrahedral array of four GeoSpectrum M36-100 hydrophones. All eight hydrophones are sampled at 64 kHz (24-bit) and data are streamed to shore through ONC’s VENUS underwater observatory network. Passing vessels are tracked acoustically and by a dedicated vessel Automatic Identification System (AIS) installed on shore. ONC’s system also collects real-time salinity, temperature, and water current data at the listening station site.

Vessel pilots are requested to sail ships, consisting mainly of containerships and cargo ships and ferries, through a defined measurement zone passing 250-550 m from the hydrophone arrays. Only one pass is made per vessel trip. AIS and acoustic data are used in concert to identify the location and time of closest point of approach of the vessel’s acoustic centre, and its velocity. The data windowing and analysis methods outlined in S12.64-2009 are applied automatically to calculate 1/3-octave band source levels. The entire process conforms as closely as possible to the methods of the standard, recognizing limitations of water depth, proximity of hydrophones to the seabed, and ability to monitor only single vessel passes.

This presentation discusses the characteristics of the acoustic data as they relate to Lloyd’s mirror (sea surface) and seabed reflection interference. We investigate the sensitivity of results to the choice of the measurement track start and end locations, data averaging times and back-propagation methods as specified in the standard. We will discuss how acoustic models were applied to account for seabed reflections that are not considered in S12.64-2009. We discuss the differences between Radiated Noise Level (RNL) and Monopole Source Level (MSL), the latter of which accounts for surface reflected sound energy in the back-propagation of received levels but is not included in the standard.
Our understanding of the importance of sound to aquatic animals for communication, prey and predator detection, navigation, and other fundamental purposes is increasing concurrently with the number and variety of anthropogenic noise-producing activities in the marine environment. Concern regarding the effects of noise on marine life has expanded beyond the acute impacts associated with exposure to intense noise events (e.g., physical injury, hearing impairment, and behavioral disturbance) to include the chronic impacts associated with rising background noise and its interference with the ability of marine animals to detect critical acoustic cues. The US National Oceanic and Atmospheric Administration is the lead US federal agency responsible for reducing the impacts of noise on marine species. Additionally, NOAA conducts science to better understand the aquatic environment and ecosystem function, including noise-related impacts. Finally, these science activities can include vessels and technologies that generate noise. Given these roles, in 2012, NOAA identified the need for a comprehensive and integrated agency vision to address noise impacts over the coming decade. The NOAA Ocean Noise Strategy (ONS) identified four long-term goals: (1) coordinating management activity across the agency to effectively reduce noise impacts to species and their habitats, (2) prioritizing science to understand the noise impacts over ecologically relevant scales, (3) supporting the development of decision-support tools, and (4) improving the agency’s noise-related education, outreach, and stakeholder engagement. A fundamental theme of the ONS is the agency’s recognition of the need to conserve the quality of the acoustic habitat in addition to minimizing the more direct adverse physical and behavioral impacts of noise on protected species. In Spring 2016, NOAA’s National Marine Fisheries Service released draft policy and procedural directives for public review that assert a further commitment by the NMFS to the goals of the ONS and call on NMFS programs to identify the next steps toward their achievement. Additionally, NOAA released a draft ONS roadmap that summarizes the science that supports the Strategy’s goals, presents the agency’s capacities to address ocean noise impacts, and recommends key next steps. In this talk, we present examples of ONS activities that are currently ongoing, summarize the status of the Spring 2016 public review, and outline priority next steps for the ONS initiative.
“Vibrogram” Spectra Can Be Obtained Using Shaking Tank Tests

Dick Hazelwood
R & V Hazelwood Associates LLP, dick@r-vhazelwood.co.uk

Most noise studies relate to the sensitivity of creatures to acoustic pressures, even with increasing evidence that the water particle velocities can be more relevant. This makes sense when away from boundaries, where the water motion is small compared with the pressure. Viewed as a V/P ratio, with velocity V and pressure P both as scalar magnitudes, the free field ratio ≈ 0.65 μm/s per Pa in sea water.

This increases dramatically when near a seabed being shaken by passing seismic interface waves. Models predict V/P increases (> x12) within the water close to a layered seabed. The model uses measured values of shear velocities given by Hamilton. These realistic ground roll wavelets may thus be important to creatures such as crabs.

Inertial sensors such as accelerometers and geophones respond to vibration rather than pressure, and this response mode can also be tested for benthic creatures. If tests minimise pressure, the response will be to shaking only. This simplicity can inform the analysis of the biological complexity.

Laboratory tests cannot entirely mimic travelling waves, but standing waves can be used within tanks. For creatures small by comparison to a wavelength, a simpler mimic can be made by shaking the whole tank. This simulates a water particle, with almost rigid body uniform motion and release of almost all acoustic pressure. Whilst all air bubbles must be eliminated, oxygen can still be dissolved in a realistic manner. Rapid visible responses can be used to plot vibrogram spectra, analogous to audiograms of pressure thresholds.
Hawaiian spinner dolphins display predictable daily behavior, using shallow bays to rest during the daytime. The frequency and intensity of the interaction between humans and dolphins in these resting bays has prompted concern over the effects of these interactions on the animals. All previous research on the potential response of Hawaiian spinner dolphins to human activity in the bays has been conducted visually at the surface. In this study, we take a different approach and evaluate whether dolphins acoustically respond to human activity using a combination of passive acoustic monitoring and vessel-based visual surveys in four resting bays. We used days ($n = 99$) and hours ($n = 641$) when dolphins were confirmed present between January 9, 2011 and August 15, 2012, using hourly visual scan information and metrics generated from the fifteen 30-second recordings made every hour. Previous research found that the dolphins were predictably silent during rest and that acoustic activity matched the general behavioral state of the dolphins. Therefore, we expected to see higher dolphin whistle activity before and after peak resting time and low activity to indicate rest. The daily pattern of dolphin whistle activity in two of the four bays, Bay 2 and Bay 4, matched what we expected. However, in Bay 1 and Bay 3, we did not find a drop in dolphin whistle activity, indicating that the dolphins aren’t achieving deep rest in these two bays. With regard to the acoustic response of the animals to human activity, Bay 1 showed a positive relationship between dolphin whistle activity and the number of vessels and swimmer/snorkelers present in the bay. Bay 4 also showed a positive relationship between dolphin whistle activity and the number of swimmer/snorkelers. However, the general pattern of dolphin acoustic activity in Bay 4, as in Bay 2, indicates that the dolphins may still be able to achieve rest even with these effects. Bay 2, the bay with the most vessels and kayaks, showed no effect of these activities on dolphin whistle activity and also less sound generated per vessel present compared with Bay 1. Human activities in Bay 1, the bay with the greatest response, are dolphin-centric while activities in Bay 2, the busiest bay, are not dolphin-centric. This indicates that the key factor is not the sheer presence of human activities nor the magnitude of the activity but rather the directed interactions with the dolphins that elicit a response.
A New Paradigm for Underwater Noise Management in Coastal Areas: Acoustic Compensation

Kathy Heise
Research Associate, Vancouver Aquarium, kathy.heise@vanaqua.org

Lance Barrett-Lennard
Senior Research Scientist, Vancouver Aquarium

Terrestrial restoration ecology has advanced steadily since the 1970s as concern about the loss of biological diversity has grown. This has led to measures that offset the degradation or destruction of the habitat by creating, enhancing, restoring, or protecting compensatory habitats. A second, related conservation measure involves mitigating damage caused by one type of activity to compensate for damage caused by another. Carbon-trading schemes operate on this transference principle. Both measures are intended to ensure no net loss of ecosystem services. We suggest similar approaches could be used in managing developments that increase anthropogenic underwater noise in urbanized coastal areas where noise has been identified as a threat to marine mammals, fish, and invertebrates. Such projects generally introduce noise during construction and operations, and, increasingly, environmental assessments consider their potential impacts. They generally attempt to show that the impact of underwater noise will, after various mitigation measures, have little impact. However, models used in this process are constrained by key uncertainties in how and in what contexts marine animals use sound. The inferences they draw are therefore weak and estimates of the impacts are poorly supported, particularly the impacts caused by masking. In view of (1) the difficulties associated with assessing underwater noise and its impacts, (2) the growth of activities that produce noise, and (3) the availability of cost-effective methods to reduce sources of anthropogenic noise, we believe that it would be precautionary to use compensatory measures to cap, and possibly reduce, human-caused underwater noise. Such an acoustic compensation paradigm would likely include a mitigation transference component but, in some cases, could also include habitat compensation (the establishment of ecologically important quiet zones to offset zones of high noise). There are several ways in which such approaches might work. Noise levels within frequency ranges that impact marine animals could be measured and capped at present levels. Approval of new developments that increase noise could be contingent on the implementation of programs to make compensatory reductions in noise produced by existing activities. For example, ports developing new terminals might institute incentive or disincentive programs to quiet existing operations. This is easiest to imagine in the case of ships, where a small proportion of vessels produce a relatively large proportion of overall shipping noise. A cap-and-trade scheme by which terminal operators or shipping companies trade noise credits could also be considered.
Traditionally, responses by beaked whales to Navy sonar have been assessed two ways. The first are controlled-exposure studies in which individual animals are tagged and then exposed to simulated or real sonars and the other is by counting the number of dives that occur on Navy ranges and comparing dive counts before, during, and after sonar training events. In this analysis, data from six Navy training events that occurred in 2011-2013 were examined to identify changes in foraging behavior by individual Blainville’s beaked whale (Mesoplodon densirostris) groups that were detected within 30 minutes of the onset or cessation of sonar. In addition, received levels were estimated and the distance and bearing of the ship were calculated to determine if impacts differed based on the proximity and movement of the ship. One hundred and fifty-one groups that met the initial criteria were identified; of these, 66 may have ceased foraging at the onset of sonar or began foraging after the cessation of sonar, while 85 did not appear to respond. Ship distances of the groups that may have responded ranged between 2.5 and 50.3 km (mean 28.2 km), whereas distances for animals that did not respond were between 13.1 and 51.3 km (mean 33.0 km). Received levels were estimated for the groups that may have responded; estimated levels ranged from 102 to 161 dB re 1 µPa at 1 km depth and from 116 to 161 dB re 1 µPa at the surface (mean 142 and 147 dB re 1 µPa, respectively). These individual responses and implications to long-term consequences will be examined in detail to look for patterns that could be more broadly applied to the population as a whole.
Expansion of human activities at sea and acknowledgement of underwater noise as a marine pollutant have led to increasing focus on how to quantify noise loads in marine ecosystems. Vessel noise is the most wide-spread contribution to anthropogenic noise worldwide and a common approach to estimate the noise load from shipping is to use tracking data from the Automatic Identification System (AIS) as a proxy for shipping intensity. Maps of areas with high shipping intensity can then be coupled with maps of the density of marine species to identify high risk areas, where mitigation efforts should be prioritized. However, since AIS transmitters are only required onboard passenger ships and vessels above 300 tons (gross tonnage), the contributions from a number of other ship types, most importantly smaller pleasure boats and fishing vessels, are unaccounted for. This means that the noise load may be considerably underestimated in some areas, if only based on AIS data.

Here, we link AIS data with actual noise recordings to test the applicability of AIS tracking data to predict noise load. Recordings were obtained from acoustic loggers deployed in three shallow Danish marine areas (10-30 m water depth) under the BIAS project. Results show that even when no ships carrying AIS were close to the recording stations, noise levels could be significantly elevated above ambient noise, highlighting that AIS data alone cannot explain all variations in noise load. Some of this residual variation can be explained by environmental factors (i.e. rain and wind). However, to test the hypothesis that vessels not carrying AIS also contribute significantly to the unexplained noise load, we tracked smaller boats with theodolite from a coastal high point to obtain a true measure of total vessel intensity, while continuously recording underwater noise. We find that these smaller boats to a large extent contribute to the noise load in marine recreational areas. Our results highlight that the noise contributions from vessels without AIS should be taken into account, when assessing the environmental pressure from ship noise. This missing, but pertinent noise metric can become available by equipping all motorized vessels with AIS or similar tracking systems. Linking these data with actual measurements of vessel noise, in particular in areas with high recreational activity, will improve our abilities to adequately pinpoint high risk areas to improve management efforts.
Comparing the Metabolic Costs of Different Sound Types in Bottlenose Dolphins

Marla M. Holt  
Northwest Fisheries Science Center, NMFS, NOAA, marla.holt@noaa.gov
Dawn P. Noren  
Northwest Fisheries Science Center, NMFS, NOAA, dawn.noren@noaa.gov
Robin C. Dunkin  
University of California, Santa Cruz, rdunkin@ucsc.edu
Terrie M. Williams  
University of California, Santa Cruz, tmwillia@ucsc.edu

Cetaceans produce different types of sounds that vary according to behavioral context. They also modify their acoustic signals in the presence of noise. We recently estimated the metabolic cost of both social sound and click production as well as vocal modification costs in two captive bottlenose dolphins using flow-through respirometry methods. For both sound types, metabolic rates (MRs) significantly increased as vocal effort increased, illustrating a modest cost of vocal modification. Using these data, metabolic costs can be extrapolated to more typical (higher) values of free-ranging dolphins and compared among sound types. However, cost comparisons are complicated by important differences in methodology and the average emitted acoustic energy among sound-type trials. In this investigation, existing data were analyzed specifically to scale and compare costs with these differences taken into account. All trials consisted of 10 min of baseline rest, followed by 2 min of sound production, followed by 10 min of recovery. For social sound trials, dolphins remained at the water surface for all trial periods, whereas in click trials, the dolphins generated clicks while submerged. Control trials during the click production experiment were run that mimicked other trials, but the subject remained silent while submerged to account for MR changes due to submergence. The total metabolic cost of sound production was calculated above appropriate baseline values (baseline rest for social sound trials and submerged silence for click trials) and was significantly related to vocal effort as the cumulative energy flux density (EFD) level in decibels re 1 µPa²·s (adjusted to on-axis source levels) of all signals produced on a per trial basis. Click trials and social sound trials were analyzed separately. Using these results, it is estimated that for a 2-min sound production bout, metabolic costs of whistling at average EFDs and repetition rates reported in the literature for free-ranging bottlenose dolphins would be ~1.5-3 times the costs of clicking at field typical EFDs and repetitions rates. Furthermore, the metabolic cost of producing whistles is ~1.5-4 times the cost of producing clicks of equal radiated energy (assuming whistles are omnidirectional while click have a directivity index of 26 dB). Interestingly, previous work has shown that whistles require higher intranasal air pressures compared with clicks, potentially explaining their higher energetic cost of production. Importantly, these data allow for quantitative assessments of relative biological costs of acoustic responses to anthropogenic disturbance across a range of behavioral contexts and disturbance scenarios.
Source Levels and Spectral Characteristics of Sound Produced During Pile Driving at US East Coast Navy Installations

Cara F. Hotchkin
NAVFAC Atlantic, cara.hotchkin@navy.mil

Jacqueline Bort Thornton
NAVFAC Atlantic

Anurag Kumar
NAVFAC EXWC

Michael Richlen
HDR

Keith Pommerenck
Illingworth & Rodkin, Inc.

Pile installation and extraction are major sources of underwater noise along coastlines and offshore as a part of facility maintenance, oil and gas extraction, and wind-energy development. In the United States, most pile driving occurs on relatively small piles near the coastline during construction of bridges and piers. These projects often overlap the ranges of marine and aquatic species that may be vulnerable to physiological and behavioral impacts from underwater sound. Efforts to mitigate the impacts of such sound include modeling the estimated ranges to the possible impacts, adding observers to detect protected species and limit driving while they are present, and adding physical mitigations like bubble curtains to reduce sound around pilings. Most of these mitigations depend on knowing the source level of the sound, which can be estimated from measurements of similar pile types in other locations. Although a large database of sound source levels from pile installation exists along the US West Coast, very few measurements of pile-driving source levels have been made in the different bathymetric and geological conditions along the US East Coast. This project utilized the same methods that have been used to gather data from the West Coast to measure sound source levels during pile installation and extraction at five naval installations along the US East Coast. Underwater and airborne measurements were taken from a variety of pile types, including steel pipe, steel H-type, concrete, and timber pilings during both installation and extraction. Additionally, because of changes to the regulatory criteria put forth by the US National Marine Fisheries Service for addressing the potential effects of underwater sound to marine mammals, average spectral data in one-third octave bands were analyzed for the available pile types. Source levels varied with installation method, location, and pile type. Frequency spectra indicated that sound energy is concentrated below 500 Hz but that sound from pile driving can be detected up to at least 20 kHz. Measurements from locations ~200 m from the incident pile allowed for estimation of propagation equations at these locations. Source levels, spectral data, and measurements of time required to install and extract piles will be applied to US Navy compliance efforts to reduce the potential impacts from pile driving on marine species.
Near Real-Time Passive Acoustic Monitoring of Baleen Whales from Autonomous Platforms in the Gulf of Maine

Cara F. Hotchkin
NAVFAC Atlantic, cara.hotchkin@navy.mil

Sofie Van Parijs
Northeast Fisheries Science Center, NOAA

Julianne Gurnee
Northeast Fisheries Science Center, NOAA

Jacqueline Bort Thornton
NAVFAC Atlantic

Mark Baumgartner
Woods Hole Oceanographic Institution

The Navy regularly conducts studies of marine mammal distribution and occurrence in association with training exercises to better monitor potential interactions between marine mammals and naval activities. These studies include visual and acoustic monitoring methods; however, such methods have significant drawbacks. Visual surveys are expensive and cannot be conducted during periods of poor visibility. Although traditional passive acoustic recorders can be used to detect vocalizing animals regardless of weather conditions, recordings can only be accessed after recovery of the recording instrument. The goals of this study were to demonstrate the monitoring and detection capabilities of autonomous platforms in conducting near real-time passive acoustic monitoring of baleen whales and to develop best practices for integrating such detections into visual monitoring programs. The demonstration includes three platforms: a moored buoy, a Slocum glider, and a Liquid Robotics, Inc., wave glider. Each platform uses a digital acoustic-monitoring instrument (DMON) equipped with the low-frequency detection and classification system (LFDCS) to detect, classify, and report vocalizations from four baleen whale species (fin, right, sei, and humpback whales) in near real-time via iridium satellite. Collocated visual and acoustic surveys allow for ground-truthing of detections and comparisons of platform accuracy. Visual survey methods include land-based surveys near the moored buoy, ship-based surveys in the vicinity of the Slocum and wave gliders in May 2015 and 2016, and aerial surveys of the entire region. All four species were detected by each platform during the 2015 acoustic surveys and visually validated for a subset of detections; the effects of platform noise (flow, mechanical, tidal) on detectability varied by species. Occurrence estimates from near real-time and archival audio recorded by the Slocum glider during the Spring 2015 deployment were compared to evaluate the accuracy of the LFDCS in indicating species presence. Results indicate that real-time detections can predict species presence with low false alarm rates over both daily and fine-scale analysis periods. Increased detectability on short time scales, platform location flexibility, and the potential for integration with visual surveys make near real-time acoustic surveys from autonomous platforms a good candidate for future navy surveys and monitoring efforts.
Standardization of Auditory Evoked Potential Hearing Tests in Small Odontocetes

Dorian S. Houser  
National Marine Mammal Foundation, dorian.houser@nmmf.org  

Jason Mulsow  
National Marine Mammal Foundation, jason.mulsow@nmmf.org

Understanding hearing in marine mammals is critical for purposes of assessing impacts due to anthropogenic noise exposure and establishing noise exposure mitigation procedures. The use of auditory evoked potentials (AEPs) has dramatically increased the rate at which information on hearing capabilities in marine mammals can be obtained. It has enabled audiometric information to be obtained from species that had until recently been untested as well as population-level audiometry of commonly held or commonly stranded species (e.g., common and bottlenose dolphins). However, AEP methodologies vary across researchers and laboratories and can result in large differences in threshold estimates for the same species or even the same individual. Some investigators utilize objective statistical methods (e.g., magnitude squared coherence) for detecting AEPs, whereas others utilize subjective methods (e.g., visualization of waveforms). Multiple methods also exist for estimating thresholds and for calibrating acoustic stimuli used in testing. Collectively, this has resulted in broad variability in the reported literature on thresholds from individuals within a species or within closely related species (e.g., delphinids), which complicates determining appropriate hearing sensitivities for environmental stewardship purposes. Before the standardization of hearing test methods in humans, similar issues were faced by audiologists interested in pooling data across studies for analytical purposes and for establishing damage risk criteria. Standardization of hearing test approaches in humans was a step forward in enabling comparability of data obtained by a diverse group of researchers and clinical audiologists. Currently, an effort is underway to standardize AEP hearing test methods for small odontocete cetaceans. The standards working group under the Acoustical Society of America Committee on Standards (ASACOS) S3/SC1 (Bioacoustics) was established during the summer of 2015, and work began on the draft standard tentatively entitled Procedure for the Auditory Evoked Potential (AEP) Testing of Toothed Whale Hearing. Progress has been made on initial components of the standard, and the standard is expected for submission to the Accredited Standards Committee on Bioacoustics for review and voting in 2017. Working group participation remains open to interested parties, including members of the stakeholder communities (e.g., military, industry, and scientific).
The amount of anthropogenic sounds in the aquatic environment has increased in the last decades. High-intensity impulsive sounds produced by activities such as detonation of explosives, pile driving, and seismic surveys can have detrimental effects on fish. Especially fish close to the sound source can suffer from permanent hearing loss, physical harm, and even death. Such dramatic effects might be mitigated by temporarily deterring fish before activities that produce these high-intensity sounds. We are currently studying whether fish can be deterred by the playback of pure tones and whether varying pitch can induce stronger horizontal avoidance and delay habituation. For this, we are using a floating study island that supports an octagonal net with a diameter of 12 m. Groups of four tagged European seabass are released in this pen and exposed to six different sound treatments with pure tones of different amplitudes and either a constant or varying pitch. This floating study island was already used in a similar study in which exposures of brown noise were used to mimic anthropogenic sounds. These exposures induced several behavioral responses in European seabass, including horizontal spatial avoidance (Neo, Hubert, Bolle, Winter, ten Cate, and Slabbekoorn, submitted). Therefore, we expect that our current experiment will provide further insight in sound features that deter fish.
Effects of Startling Sounds on Marine Mammal Behavior

Vincent M. Janik
SMRU, Scottish Oceans Institute, University of St. Andrews, vj@st-and.ac.uk

Thomas Götz
SMRU, Scottish Oceans Institute, University of St. Andrews, tg45@st-and.ac.uk

Many anthropogenic noise sources produce signals with a very sharp onset time. Examples are pile driving, echo sounders, naval sonar, and airguns. The startle response is mediated by a simple oligosynaptic reflex arc in the brain stem. The traditional view is that the reflex is triggered if a signal reaches a level of at least 80 dB above the hearing threshold within <20 ms of its onset (Götz and Janik, 2013). The response is a sudden flinch that in itself does not necessarily lead to avoidance of a sound source. However, in pinnipeds, repeated exposure to such sounds leads to flight responses that become more pronounced over time. Captive gray seals avoided an area that elicited startle reactions after a few exposures even when they were food motivated (Götz and Janik, 2011). In a two-month field experiment, we showed that wild harbor seals also consistently avoided the startling zone around such a sound source (Götz and Janik, 2015). Emission of startling sounds around a fish farm led to a sustained decrease in seal predation on farmed fish for a whole year with no sign of habituation over that time period (Götz and Janik, 2016). These sustained reactions show that mammals are sensitized to startling sounds and that they consistently avoid them. Cetaceans also show startle responses and are likely to respond in the same way as pinnipeds because the startle reflex arc is conserved in all mammals tested to date. Because startle reactions start to occur at levels below those eliciting temporary threshold shifts, we need to consider rise time in addition to the effects of received level when trying to understand reactions to anthropogenic noise. We will review all the evidence for startle responses in marine mammals and highlight several mitigation strategies that can help to minimize startle effects. These do not always require the modification of the source signal but can utilize additional sounds that modulate the reflex.

The sound levels introduced in the marine environment by offshore industry and commercial shipping have greatly increased in the last few decades. The scientific evidence of the potential negative effects of current underwater sound levels has encouraged regulatory agencies to establish and redefine mitigation strategies to minimize the impact on marine animals. Seismic surveys can be especially damaging because they use loud sources during extended periods and over large areas.

The sound source verification methodology (SSV) maps the sound field produced by an acoustic source in water, using a combination of models and field measurements (Heath and Wyatt, 2014). The mapped sound levels are eventually used to estimate the exclusion zones, areas around the source where the sound levels exceed a particular threshold with a proved impact on marine species. The SSV procedure consists of three main stages: (1) presurvey modeling, where modeled exclusion zones are provisionally implemented in the mitigation plan, until field measurements are available; (2) sound field mapping, carried out by different deployment techniques and sampling methods; and (3) model validation and refinement, where the presurvey model is verified and updated based on field measurements. The SSV is a very powerful tool to define exclusion areas that are truly representative of each operational and environmental situation, as shown in several deployments (Jiménez et al., 2015).

The way regulations specify how exclusion zones should be determined varies from country to country: some use specific distances from the source while others use threshold levels (Erbe, 2013). The lack of regulatory agreement, along with the necessity for limited, simple exclusion zones that can be practically monitored, might lead to oversimplifications. Exclusion zones can show large variations in shape and coverage by the effect of bathymetry (e.g., shallow water and varying slopes), environmental conditions (e.g., freshwater or colder water intrusions), source and receiver positions, or the hearing sensitivity of the animal. The exclusion zone approach is a key part of the mitigation strategy, and, as such, a special effort must be put on creating methods to accurately calculate these zones and effectively integrate them in the survey mitigation plan.

We show, through measurements and models, the effects on the exclusion zones of some of the main environmental and biological factors: bathymetry, geology, receiver depth, hearing response, and sound level metric. These analyses are complemented with recommendations on the cases where additional exclusion zones should be defined.

A dual-camera system, high definition/thermal imaging (HD/TI), was tested as a marine mammal monitoring technique aboard a seismic vessel. The camera system collected video data for offline analysis postsurvey. The monitoring of performance focused on its ability to detect marine mammals compared with known visual sightings (marine mammal observers [MMOs]) in daylight and passive acoustic monitoring (PAM) detections at night. The technical performance of the camera system was excellent, and data were obtained for a 70-day duration of deployment. However, due to time constraints for the analysis (in excess of 1,703 hours), data were selected from the entire data set. Three whole days were chosen to allow performance assessment over whole 24-hour periods. These three days were selected for analysis because they had the most sea states of 4 or lower. Video analysis was conducted independent of visual and acoustic monitoring by analysts who had in-field marine mammal survey experience. In comparing detection rates, caution is required given the small data set. There are also fundamental limitations to comparing visual and acoustic detections that should be kept in mind. In addition, false HD and IR detections cannot be ruled out, but this possibility was minimized by the conservative approach taken and the ability to replay sightings for confirmation. At night, 26 hours and 45 minutes of overlapping survey time were recorded, revealing 14 PAM detections and 13 TI detections. In daylight, 46 hours and 40 minutes of overlapping survey time were recorded, revealing 15 MMO sightings, 11 IR detections, and 7 HD sightings. As a combined system, HD and IR yielded 14 sightings. We also calculated the average number of hours between detection by each method from the available data over the entire survey. TI was the best performer with 2 hours and 50 minutes (from 71 hours and 11 minutes of data). Combined HD/TI was second with 2 hours and 53 minutes (from 49 hours and 3 minutes). PAM followed with 3 hours and 33 minutes (from 978 hours and 18 minutes). HD yielded a sighting an average of every 4 hours and 27 minutes (from 49 hours and 3 minutes). Last, MMOs achieved 5 hours and 49 minutes (from 1,466 hours and 9 minutes). The comparable detection rates by the dual-camera system against MMOs and PAM provide firm “proof of concept.” The results indicate a future for HD/IR as a supplementary method to existing marine mammal monitoring techniques.
Remote Passive Acoustic Monitoring for Mitigation

Phil Johnston  
Seiche Ltd., p.johnston@seiche.com  
Sherry Baruwa  
Seiche Ltd., s.baruwa@seiche.com  
Roy Wyatt  
Seiche Ltd., r.wyatt@seiche.com

Regulatory requirements for effective monitoring of marine mammals for mitigation purposes have increased and the use of passive acoustic monitoring (PAM) has become standard practice in some areas. This necessitates more environmental specialists going offshore and brings implications on bunk space and safety as well as the availability of experienced operators. Remote PAM (RPAM) is a new technology that enables acoustic monitoring of marine mammals at an on-shore location. Acoustic data is transferred in real time via a satellite link from an at-sea PAM system such as a seismic vessel. From anywhere in the world, a RPAM operator can then detect vocalizing whales and dolphins without the need for personnel offshore. From Seiche’s RPAM base in Devon, UK, four full-scale projects have now been completed. Over 12,000 hours of acoustic surveying have been conducted from seismic vessels off Australia, Malaysia, Trinidad and Tobago, the United States, and Canada. Of this, sole mitigation monitoring has been provided for 600 hours. A total of 943 acoustic detections of several species of marine mammals have now been recorded remotely. RPAM delivers a consistent stream of data at a quality comparable to the signal received on the vessel. Detection rates have been near identical to those onboard, and there is the additional benefit that a second opinion is available, e.g., on confirmation, detection, and localization of marine mammals. Remote operators have on-site access to technical and biological expertise and this enables accelerated training. A key asset that RPAM offers is the provision of support to onboard operator from experts viewing the same signal. This is in real time, using instant chat messaging, emails, and telephone communications. This aspect has already proved vital in ensuring that robust decisions are made for mitigation, such as seismic shutdowns. Given that the requirement for local personnel is increasing quicker than the existing pool of expert PAM operators, this ability of RPAM will prove particularly valuable. With an ever greater need for high-quality environmental mitigation for acoustic disturbance, RPAM has a huge potential.
Because of the extreme distances that sound can travel through water, many marine species rely on the soundscape for auditory information on predator or prey locations, inter- and intraspecific communication, navigation routes, and habitat selection. These species not only take advantage of the prevailing sounds but also contribute to the soundscape through their own vocalizations. Certain sounds have been shown to have negative effects on marine species, resulting in elevated stress levels, unbalanced predator-prey interactions, and disruption of communication. Unfortunately, the vast majority of soundscape studies have been biased toward marine mammals, and only recently has attention been directed toward the potential repercussions of noise on fish and other marine organisms. In an attempt to determine the implications changes to the soundscape may have on the marine community, we conducted a meta-analysis addressing the effects of marine noise on fish behavior and physiology. Focusing primarily on the role that biological or anthropogenic sounds may play in altering reproductive success, foraging activities, predatory-prey interactions, and body composition, our analysis identified 2,817 potentially relevant papers of which 186 were analyzed. The results indicate that noise source as well as frequency and duration are key factors in determining both the duration and the severity of a species response. Depending on the source, species may respond with decreased foraging activities, increased susceptibility to predation, and/or alterations to body composition. Our analysis also identified an overarching bias toward lab studies that utilized unrealistic sound sources played from systems that were likely to result in high levels of reverberation. This is likely due to the difficulties associated with generating a realistic testing environment within a controlled setting. As a result, we developed a planar wave tank that generates a realistic soundscape environment and allows us to monitor the species response within a controlled setting. Our initial experiments have focused on the behavioral changes that occur when tidepool sculpins (Oligocottus maculatus) are exposed to sounds of either anthropogenic, biotic, or abiotic origin collected from various Ocean Networks Canada hydrophones. The results of these experiments, in combination with the meta-analysis, will lead to a greater understanding of how marine fishes respond to changes in the marine soundscape on an individual and a community level. This understanding will help identify potential areas of concern in regard to increasing anthropogenic effects on the prevailing soundscape.
Hydroacoustic Measurements During Construction of the First US Offshore Wind Farm: Methodologies to Address Regulatory Requirements

Erik Kalapinski  
Tetra Tech, erik.kalapinski@tetratech.com  
Kristjan Varnik  
Tetra Tech, kristjan.varnik@tetratech.com

The rules and regulations governing underwater noise from offshore wind farm development in the United States have not been as explicit as in other countries and regions. In this context, it is important to disseminate information about the relevant noise sources, constantly evolving guideline criteria, and the noise measurement and data analysis procedures to ensure timely reporting. With the increasing movement in the development of this renewable energy resource, in particular, in areas off the East Coast of the United States, the need for reliable measurement and data analysis methodologies to address is of critical importance. The foundations for the first offshore wind farm in the United States have been installed. Tetra Tech, Inc., in partnership with JASCO Applied Sciences, performed the hydroacoustic monitoring for the Block Island wind farm located offshore in Rhode Island. The collected measurement data were used for model verification purposes and confirmation of the monitoring zones appropriateness. The overall purpose of the monitoring program was to support the protection of marine mammals, sea turtles, and Atlantic sturgeon that may traverse the area during construction and to comply with the permits and authorizations as issued by the US Army Corps of Engineers and the National Marine Fisheries Service, National Oceanic and Atmospheric Administration. The hydroacoustic monitoring field program occurred in distinct two stages. The first involved short-term monitoring of the installation of the first complete wind turbine generator foundation using both mobile real-time and static-monitoring techniques and required both rapid data dissemination and daily reporting. Long-term monitoring of the remaining four wind turbine foundations with static recorders was completed to document variability in the data set. Received sound levels measured at predetermined distances were used to assess site-specific propagation characteristics and to verify the ranges to the relevant sound exposure thresholds. Measurements were completed using a combination of fixed bottom-mounted autonomous acoustic recorders and vessel-mounted hydrophone arrays. All of the objectives of the monitoring activities were met, including the field verification the modeled result of the noise levels for injury/mortality and behavior disturbance as established during the environmental permitting process. This involved the evaluation of multiple metrics including the site-specific apparent sound source levels of pile-driving activities and confirmation of the exclusion zone and monitoring zone established to ensure the protection of marine life throughout the construction period.
Temporal and Spatial Variability in Biological Sound Production on Tropical Coral Reefs Is Linked to Biota

Maxwell B. Kaplan  
Woods Hole Oceanographic Institution, mkaplan@whoi.edu  
T. Aran Mooney  
Woods Hole Oceanographic Institution, amooney@whoi.edu  
Marc O. Lammers  
Hawai‘i Institute of Marine Biology, lammers@hawaii.edu  
Eden Zang  
Oceanwide Science Institute, edenzang@gmail.com

Coral reef soundscapes are dynamic, demonstrating amplitude and spectral variability across timescales from seconds to seasons. This biological sound production may reflect the appreciable biodiversity of these ecosystems. To investigate how sounds produced on a given reef relate to abiotic and biotic parameters and how that relationship may change over time, an observational study was started in September 2014. Eight Hawaiian reefs that vary in coral cover, rugosity, and fish assemblages were equipped with acoustic recording devices and temperature loggers that recorded on a 10% duty cycle for 16 months. Benthic and fish visual survey data were collected four times over the course of the study. On average, reefs ranged from 0 to 80% live coral cover, although changes over time were noted, in particular during the major El Nino-related bleaching event of October 2015. Statistical analyses indicated that the true number of fish species present on a given reef was related to the coral cover of that reef. Vessel activity was acoustically detected unevenly across reefs, for example, vessels were acoustically present almost every day at a popular snorkeling reef but were rare in a protected area closed to boats, which indicates that exposure of reef fauna to vessel noise will vary by reef. Acoustic analyses were carried out in two frequency bands (50-1,000 Hz and 2-20 kHz) that corresponded to the dominant spectral features of the major sound-producing taxa on these reefs, fish and snapping shrimp, respectively. In the low-frequency band, the presence of humpback whales (December to April) was the major predictor of sound level, whereas in the high-frequency band, sound level closely tracked water temperature. At high frequencies, sound levels were higher during the new moon than during the full moon at all reefs, whereas responses varied by reef at low frequencies. This divergence may reflect differences in the fish species present on the reefs and their soniferous behaviors. Diel trends in sound production were present in both frequency bands, but the strength of this diel trend varied within reefs over time and among reefs, which may also reflect differences in the species assemblages present. These results indicate that soundscape trends can be linked to traditional visual underwater surveys. Furthermore, long-term acoustic recordings can capture the substantial acoustic variability present in coral reef ecosystems.
Signal Detection by Harbor Seals (*Phoca vitulina*) in Amplitude-Modulated Noise: Toward a More Realistic Assessment of Masking

Ron Kastelein  
SEAMARCO, Julianalaan 46, 3843 CC Harderwijk, The Netherlands, researchteam@zonnets.nl
Shirley Van de Voorde  
SEAMARCO, shirleyvandevoorde@gmail.com
Lean Helder-Hoek  
SEAMARCO, leanhoek@hotmail.com

Masking occurs when one sound (the noise) interferes with the detection by an animal of another sound (the signal). The degree of interference depends on the relative amplitudes of the two sounds and on the degree of difference between the frequencies of the signal and noise; masking is greatest when the two sounds overlap in spectrum. The lowest signal-to-noise ratio at which an animal can detect a tonal signal in a broadband continuous Gaussian masking noise is defined as the critical signal-to-noise ratio (or critical ratio [CR]). So far, mainly masking due to continuous random Gaussian white noise has been studied in harbor seals. The CRs derived in these studies, when used in environmental impact assessment models, result in overestimation of the masking effect of most natural and anthropogenic noises because most noise fluctuates in amplitude (wave noise at the beach, noise caused by wind, propeller noise of ships, blade noise of windmills). Therefore, to assess masking more realistically, information is needed about the masking effect of noise that varies over time in both amplitude and spectrum. The goal of the present study was to determine the masking effect of Gaussian white noise that was modulated in amplitude at various frequencies (0.125, 0.250, 0.5, 1, 2, 5, 10, 20, 40, 80, and 90 Hz and constant-amplitude Gaussian noise) and varied in modulation depth, noise bandwidth, and sound pressure level (SPL). Seals were asked to detect signals of different durations (0.5, 1, and 2 s) in the masking noises. Two hearing signal frequencies were tested: a 4-kHz tone in a one-third octave noise band around that frequency and a 32-kHz tone in a one-third octave noise band around that frequency. The hearing thresholds of both animals in the tested noise conditions were virtually identical. Masking release was shown for all amplitude modulation frequencies but varied between modulation frequencies. The amplitude modulation frequency range could be divided into 3 ranges: up to a modulation frequency of 1 Hz (where the timing of the signal relative to the sinusoidal amplitude-modulating noise affected the hearing threshold), 2-20 Hz in which the hearing thresholds increased with increasing modulation frequency, and 40-90 Hz modulation in which the hearing threshold increased less when the modulation frequency increased.
Sensitivity of Noise Exposure Metrics to Acoustic Modeling Errors and Uncertainties

Ronald Kessel
Maritime Way Scientific, rkessel@maritimeway.ca

Acoustic modeling is used to estimate the underwater noise fields from seismic exploration, blasting, and piling operations and thereby safe stand-off distances, exposure levels, and take probabilities for marine animals. As with computer modeling generally, questions immediately arise about model accuracy. Is the model sufficiently accurate? As the statistician George Box famously quipped, “All models are wrong, but some are useful.” Thus a model is sufficiently accurate if it does not undermine the objectives of its particular application. The utility of underwater noise modeling lies in its computation of relevant noise metrics. A significant source of error and uncertainty in those metrics is the error and uncertainty in the underwater acoustic propagation conditions, which are forecast or assumed at the time of modeling, and are, in any case, at best only partially and approximately known. The errors and uncertainty in noise metrics depend in large part on their sensitivity to perturbations in parameters that characterize the propagation conditions (seafloor reflectivity, sound-speed velocity profile, bathymetry, tide level, and so forth). This paper addresses the question of sufficient accuracy for noise propagation modeling in practical terms. Although proof of sufficient accuracy is very difficult and rare in practice, it is possible to identify allowances for inaccuracy in modeling provided by the nature of the noise metrics themselves. Here it is shown how statistical noise metrics like take probability and maximum exposure generally have, by virtue of their statistical treatment of noise fields, lower sensitivity to propagation conditions than a single realization of the noise field itself. Thus it is shown that statistical noise metrics generally do double duty by (1) making allowances for errors and uncertainties in propagation conditions and, at the same time, (2) reducing their sensitivity to those errors and uncertainties. Linear sensitivity theory is used to show that the sensitivity of statistical noise metrics to propagation conditions ultimately depends on the sensitivity of the metrics to the mean noise energy, even if the noise metrics are based on extrema.
A Port-Led Collaborative Initiative: Working to Reduce Cumulative Noise Impacts of Commercial Vessel Activity on an Endangered Resident Killer Whale Population

Melanie Knight
ECHO Program Coordinator, Port Metro Vancouver, melanie.knight@portmetrovancouver.com

Orla Robinson
ECHO Program Manager, Vancouver Fraser Port Authority, orla.robinson@portmetrovancouver.com

The Enhancing Cetacean Habitat and Observation (ECHO) Program is a Vancouver Port Authority-led collaborative initiative aimed at better understanding and managing the cumulative impact of commercial vessel activities on at-risk whales throughout the southern coast of British Columbia, Canada, and shared US waters. Underwater noise produced by commercial vessels has been identified by the ECHO Program as an important issue for consideration in terms of the possible impact on marine fauna. With primary shipping routes to the port transiting the critical habitat for an endangered resident killer whale population comprising just 85 individuals, the collaborative initiative is advancing a series of individual research projects to inform the development of mitigation and management options that will lead to a quantifiable reduction in noise impacts from the vessels. This presentation will describe a number of the underwater noise research projects that are being advanced by the ECHO Program, including development of a regional acoustic model to quantify the respective ocean noise contributions in a range of regional vessel sectors and to assess their potential impact on killer whales and deployment of an underwater listening station in the inbound shipping lane to measure the source levels of different vessel types arriving at and operating within port jurisdiction. The listening station also performs ambient underwater noise measurements and marine mammal detections. The listening station will further help with the testing of possible future vessel noise mitigation solutions as well as the ground-truthing and refining of the regional acoustic model. A description of the preliminary results will be provided, and the potential application of such acoustic models and measurement systems to other managers, regulators, and scientists will be discussed.
Effects of Anthropogenic Noise on Foraging Efficiency in Harbor Porpoises

Annebelle Kok
Leiden University, a.c.m.kok@biology.leidenuniv.nl

R. A. Kastelein
SEAMARCO, Harderwijk, The Netherlands, researchteam@zonnet.nl

Pam Engelberts
Leiden University, pamengelberts@hotmail.com

Lean Hoek
SEAMARCO, Harderwijk, The Netherlands, seamarco@versatel.nl

Fleur Visser
Kelp Marine Research, Leiden University, fleurvisser@gmail.com

Hans Slabbekoorn
Leiden University, h.w.slabbekoorn@biology.leidenuniv.nl

Man-made sound in the oceans has been growing strongly over the past decades, with potentially large consequences for marine mammal populations and their prey. Behavioral responses to noise may lead to a cessation of vital activities such as foraging or area avoidance or reduced abilities to catch prey or escape predators. The challenges of studying cetaceans and their prey at sea and the species-specific and context-dependent nature of responses currently leave large data gaps in our understanding of potential disturbance by different noise sources. Predator and prey behavioral responses to noise, leading to reduced foraging and energy intake in particular, have been identified as a strong concern, marking key research areas. A decrease in foraging efficiency can be especially detrimental for small odontocetes, such as harbor porpoises. Their low volume-to-surface ratio induces a relatively high energy demand and having a small body means less room for fat storage. Harbor porpoises hunt with sound. Because their echolocation frequency is higher than most anthropogenic noise (120-150 kHz), the effects are most likely induced by an attention shift rather than masking, making it more difficult to focus on the task at hand. Here, we present the results of a study where two captive harbor porpoises were tested for their susceptibility to disturbance by anthropogenic noise in terms of foraging efficiency. Foraging is made up of three steps: encountering a suitable foraging patch, finding a prey, and finally catching and eating the prey. Consequently, first, we investigated the possible tendency to avoid a pool area with playback of low-frequency noise, which could affect the prey encounter rate. Second, we tested whether noise levels above and below the avoidance threshold had a detrimental effect (increased search time) on a prey search task. Third, with the same noise levels, we tested their ability to catch a dead prey dropping through the water behind a net. The results provide evidence for the possible effects of moderate noise levels during the three stages of foraging: spatial effects, changes in search time for prey, and influences on catch rate. Our data can be used to evaluate the potential consequences of sound pollution on the energy balance of small odontocetes.
Comparison of Soundscape Contributors Between Two Neighboring Southern Right Whale Nursing Areas Along the Eastern Cape Coast, South Africa

Renee P. Koper
Nelson Mandela Metropolitan University, Port Elizabeth, South Africa,
renee.koper@nmmu.ac.za

Christine Erbe
Centre for Marine Science and Technology, Curtin University, Perth, Australia,
C.Erbe@curtin.edu.au

Derek R. du Preez
Nelson Mandela Metropolitan University, Port Elizabeth, South Africa,
derek.dupreez@nmmu.ac.za

Stephanie Plön
Nelson Mandela Metropolitan University, Port Elizabeth, South Africa,
stephanie.plon@nmmu.ac.za

The population of southern right whales that annually migrates towards the South African coast during their breeding season is currently increasing at an average rate of 6.8% per annum. Consequently, the range of this population is expanding to pre-whaling limits, including the Eastern Cape coast, South Africa. A three-year study in Algoa Bay (2008-2011) revealed that 38.8% of all southern right whale sightings were mother-calf pairs. Local observations also confirmed the presence of mother-calf pairs in St. Francis Bay, 80 km East of Algoa Bay. This could indicate that both bays might be an important nursery area for this species. However, the establishment of a new commercial Port in Algoa Bay in 2009 raised concerns as to whether the acoustic environment might have an effect on the habitat selection as well as behavior of mother-calf pairs. As a first step to address this concern we analysed acoustic data over a four-week period (i.e. April–May 2015) during the arrival of the southern right whales. Manual inspections of 1 min sound samples, time series of 1/3 Octave Band Levels (OBL), and Power Spectral Density (PSD) percentile plots were used to identify prominent soundscape contributors within bays as well as to compare contributors between bays. Noise levels and wind had a strong (i.e. >0.7) correlation at 800-1600 Hz and at 100-2500 Hz in Algoa Bay and St. Francis Bay, respectively. Large vessels dominate the soundscape within Algoa Bay at 20-100 Hz, whereas only small vessels were detected in St. Francis dominating at 100-3000 Hz. Snapping shrimps dominated both soundscapes >3000 Hz. Regardless of the difference in anthropogenic contributors, the number of individual mother-calf pair sightings over the entire whale season (i.e. April-November) per 100 km of search effort were 1.6 and 1.4 for Algoa Bay and St. Francis Bay, respectively. These preliminary results suggest that there is no effect of soundscape on the habitat selection of southern right whale mother-calf pairs. Currently more data is gathered to establish a long-term trend and behavioral data is analysed.
It has been shown that pile-driving sound for offshore wind farm foundations can affect harbor porpoises and harbor seals at considerable distances from the source. As pile driving reaches comparably high sound pressure levels at mainly low frequencies, there is also a high potential to affect low-frequency cetaceans such as baleen whales as well. Yet, the risks of marine renewable energy device (MRED) construction and operation to low-frequency cetaceans are unknown. Thus, a comprehensive impact assessment of MREDS has not been possible today. In the MaRVEN study (European Commission Directorate General for Research and Innovation), we reviewed the available scientific evidence and significance of the impacts of marine renewable noise emissions on marine life. We also performed measurements and noise modeling across Europe to close the knowledge gaps. Here, we place the findings of the measurements in the context of a risk assessment of low-frequency cetaceans. Detailed and long-term measurements during construction of an offshore wind farm in the German Bight show that, at frequencies below 1 kHz, pile-driving noise was exceeding ambient sound at distances of at least 60 km from the source. These results were obtained for a 3-m-diameter pile being driven into the bottom. Conducted measurements during operation of a single-wave device and a tidal test turbine suggest that noise emitted due to operation, although strongly dependent on the ambient-noise levels at a site, can be detected by low-frequency cetaceans. The results obtained emphasize the need for future research in terms of MRED noise effects on low-frequency cetaceans on both an individual and population level.
Managing Vessel Noise: Trade-Off Considerations

Cecilia S. Krahforst  
Coastal Resources Management, East Carolina University, Greenville, NC 27858,  
krahforstc06@students.ecu.edu  
David K. Loomis  
Department of Recreation and Leisure and The Institute of Coastal Science and Policy, East  
Carolina University, Greenville, NC 27858, loomisd@ecu.edu  
Joseph J. Luczkovich  
Department of Biology and The Institute of Coastal Science and Policy, East Carolina  
University, Greenville, NC 27858, luczkovichj@ecu.edu

Vessel noise from recreational, commercial, and industrial boat traffic is known to impact marine life. Vessel noise directly impacts animals via acoustic disturbance by masking intraspecific communication, often during peak reproductive periods that commonly coincide with peak boat activity (summer months). Vessel noise also impacts animals by reducing habitat quality, including calving grounds for marine mammals as well as nursery and spawning grounds for fishes. These impacts threaten ecosystem health, including the availability of fishery resources and other ecosystem services. The purpose of this research is to determine the management considerations associated with underwater noise. In the United States, noise is regulated by the Federal Energy Regulatory Commission, which addresses the noise associated with underwater construction activities. However, the only Federal Act that directly requires management of vessel noise is the Whale Conservation and Protection Study Act that only addresses the noise generated from commercial fishing vessel activities impacting marine mammals. All other forms of noise generated from vessel traffic remain unregulated by the US government. Federal laws do require the regulation of the physical interactions between marine life and vessels as well as the preservation of habitats that conserve animal health, reproductive activities, and growth. However, management initiatives must also be valued socially, economically, and ecologically. In this paper, we review how vessel noise impacts ecosystem services and explore the trade-offs associated with proposed noise management strategies. Some examples of management strategies include increased boating costs to reduce engine noise, altered channel positions to reduce noise in critical habitats, and motorboat-prohibited marine protected areas. The benefits and costs of each type of protection plan are explored, with a particular focus on identifying future research initiatives to gauge socially acceptable trade-offs to enhance the management of our coastal ecosystems.
Impact of Vessel Noise on Fish Communication, Reproduction, and Larval Development

Cecilia S. Krahforst
Coastal Resources Management Program, East Carolina University Greenville, NC 27858, krahforstc06@students.ecu.edu

M. W. Sprague
Department of Physics, East Carolina University Greenville, NC 27858, spraguem@ecu.edu

Meganne Rose
Department of Biology, East Carolina University Greenville, NC 27858, megannerose14@gmail.com

Maddie Heater
Department of Biology, The University of North Carolina at Chapel Hill, 120 South Road, Chapel Hill, NC 27599, madheater@gmail.com

Michael L. Fine
Department of Biology, Virginia Commonwealth University, 821 West Franklin Street, Richmond, VA 23284, mfine@vcu.edu

Joseph J. Luczkovich
Department of Biology and The Institute of Coastal Science and Policy, East Carolina University, Greenville, NC 27858, luczkovichj@ecu.edu

The number of boats and their ambient-noise input in coastal estuaries has increased since the 1950s. Boats overlap the acoustic communication and hearing ranges of fishes and can minimize a fish’s ability to find suitable mates and locate and capture prey. Here we use the oyster toadfish (*Opsanus tau*) to explore how the soundscape alters male courtship call rates, female reproductive output, and larval development. In 2013, toadfish colonized artificial dens in the field. Six sound types were played to these toadfish from an underwater speaker: snapping shrimp sounds (SN; control), low-frequency (LFD) and high-frequency (HFD) bottlenose dolphin biosonar, large-vessel (LV) and outboard motorboat (OB) noises, and a combination of anthropogenic and predator sound (LV+LFD). Toadfish calling rates were quantified before, during, and after noise exposure. Calling rates declined during playback compared with preexposure levels ($P \leq 0.042$). The acoustic disturbance effect followed the order SN$^a$ < OB$^{a,b}$ < LV$^{b,c}$ < LFD$^{b,c}$ < HFD$^c$ < LV+LFD$^c$ (superscripts indicate not significant means). In March 2014, artificial dens were deployed in the field both near (7 m) and far (35 m) from vessel channels. These positions were selected based on an acoustic propagation experiment, which showed that vessel noise was higher than ambient-noise level ($\Delta = 20$ dB re 1 $\mu$Pa) at 7 m and near ambient-noise level by 20 m from the channel. Each den was checked every 9 days from May through August for toadfish and embryos. Noisy sites had fewer embryos than quiet sites ($P < 0.001$), and there were less embryos near than far from the channel ($P = 0.04$). In 2015, toadfish embryos were collected from the field and transferred to laboratory tanks. The embryo batches were exposed to either a boat noise or natural soundscape. After developing, the toadfish were tested for near-field frequency sensitivity (10-500 Hz) using a vibrating rod and an infrared video camera. Their attraction behavior was measured by counting the number of times the juvenile made contact with the vibrating rod. The preliminary results indicate that fish from the natural soundscapes were 8.3 times more likely to contact the rod between 20 and 70 Hz than fish reared in boat noise soundscapes ($\Delta = 0.22$, $F = 4.35$, $P = 0.04$). These differences were primarily driven by 40 ($\Delta = 0.38$, $F = 5.23$, $P = 0.028$) and 50 Hz ($\Delta = 0.42$, $F = 3.94$, $P = 0.055$). The vibrating rod represents a proxy for a moving food source and juvenile toadfish food items, such as amphipods and nematodes that move at rates <60 Hz. These results suggest that vessel noise is altering fish behavior and is likely impacting stocks.
Especially at depths, marine mammals may rely exclusively on their passive acoustic capabilities to successfully perceive their environment and the threats in it and then safely navigate past those potential dangers. This passive approach can provide the needed view of the surrounding environment without the necessity for these marine mammals to reveal themselves acoustically with vocal transmissions. Understanding the possible methodologies employed by these marine mammals to obtain, analyze, and optimize the requisite acoustic data is challenging. Humans typically rely on visual cues and nearly instantaneous positional and velocity data when evaluating the environment. However, one of the few exceptions to this rule about human perception is the process by which manned submarines transit from relatively safe depths through depths where collisions can potentially occur and into the very shallow depths where visual observations are available again and can be made via a periscope. This paper will identify and explore the terminology, logic, and processes used by submariners to passively assess their environment in these situations and will then suggest several ways in which marine mammals may be employing similar techniques to achieve similar results.
Ten Years of Behavioral-Response Studies in Norwegian Waters: Key Achievements and the Way Forward

Frans-Peter A. Lam, TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK The Hague, The Netherlands, Frans-Peter.Lam@tno.nl; Peter H. Kvadsheim, Maritime Systems Division, Norwegian Defence Research Establishment (FFI), Horten 3191, Norway, Petter-Helgevold.Kvadsheim@ffi.no; Patrick J. O. Miller, Sea Mammal Research Unit (SMRU), University of St. Andrews, St. Andrews, Fife KY16 8LB, UK, pm29@st-andrews.ac.uk; Peter L. Tyack, Sea Mammal Research Unit (SMRU), University of St. Andrews, St. Andrews, Fife KY16 8LB, UK, plt@st-andrews.ac.uk; Fleur Visser, KMR, Loniusstraat 9, 1624 CJ Hoorn, The Netherlands, fvisser@kelpmarineresearch.com; Charlotte Curé, CEREMA Dter Est, Acoustics Group, Laboratoire de Strasbourg, 11 rue Jean Mentelin, BP09, 67035 Strasbourg cedex 02, France, charlotte.cure@cerema.fr; Paul J. Wensveen, Sea Mammal Research unit (SMRU), University of St Andrews, St Andrews, Fife, KY16 8LB, UK pw234@st-andrews.ac.uk; Lise D. Sivle, IMR, P.O. Box 1870 Nordnes, NO-5870 Bergen, Norway; Lars Kleivane, Maritime Systems Division, Norwegian Defence Research Establishment (FFI), Horten 3191, Norway Lars.Kleivane@ffi.no; Saana Isojunnno, Sea Mammal Research unit (SMRU), University of St Andrews, St Andrews, Fife, KY16 8LB, UK si66@st-andrews.ac.uk; Alexander M. von Benda-Beckmann, TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK, The Hague, The Netherlands. VonBenda@tno.nl; Sander P. van IJsselmuide, TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK, The Hague, The Netherlands. Sander.VanIjsselmuide@tno.nl; Rune Roland Hansen, Department of Biosciences, University of Oslo. NO-0316 OSLO, Norway r.r.hansen@ibv.uio.no; René P.A. Dekeling Defence Materiel Organisation DMO, The Hague, the Netherlands RPA.Dekeling@mindef.nl

In 2015, the second phase of the 3S Project (Sea Mammals, Sonar, and Safety) was finalized, studying, since 2006, the behavioral responses of cetaceans and herring to naval sonar sound. After 10 years of research, a wide range of knowledge has been obtained (e.g., Kvadsheim et al., 2015). The experimental setup (technology and protocols) for conducting controlled behavioral response studies (BRSs) at sea have been developed and refined and many exposure experiments have been carried out. With interactions among similar BRS projects and the MOCHA project (e.g., Harris et al., 2016), state-of-the-art analysis and statistical methods were applied. Results were obtained on a variety of topics, including the baseline behavior of herring and six marine mammal species and their behavioral responses to naval sonar and predator sounds, acoustic dose-response relationships for most species, and testing of the efficacy of ramping up the sonar system as a mitigation measure. Behavioral responses were seen across all six species, but response thresholds varied with species and context. Bottlenose whales had a greater spatial and temporal scale of responses; pilot whales appeared to be the least responsive. Many responses were judged to be of potential biological significance based on their life function and consistency with responses to predator playback. Derivation of dose-response functions were a key outcome, and acoustic dose-response functions for four species were developed (killer whales, sperm whales, pilot whales, and humpback whales), whereas for bottlenose whales and minke whales, sample sizes were too small to achieve this. For killer whales, BRS results were also consistent with observations during a full-scale naval exercise. Modeling and experimental approaches verified that ramp-up can reduce the risk of acute effects, but effectiveness depends on individual responses. Deep divers were predicted to have a greater overall risk of developing decompression sickness, and individual animals responded to sonar in a way that might further increase risk. Our studies on prey showed that herring do not respond to naval sonar at levels that are likely to lead to population-level effects. Important methods were developed (tagging tools, acoustic detection and tracking, social behavioral protocol, and statistical methods to analyze BRS data). These results have been published (or are in review) in over 30 peer-reviewed papers and are currently already being used in risk assessment and regulation of sonar usage within several national navies. The way forward for future research (and the third phase of the 3S Project) will be discussed.


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Response by Coastal Dolphins to Naval Mine Exercise (MINEX) Training Activities off Virginia Beach, US

Marc Lammers  
Hawai‘i Institute of Marine Biology, lammers@hawaii.edu

Marian Howe  
Hawai‘i Institute of Marine Biology, Merra.Howe@gmail.com

Amy Engelhaupt  
HDR, Inc., amyengelhaupt@gmail.com

Eden Zang  
Oceanwide Science Institute, edenzang@gmail.com

Lisa Munger  
Oceanwide Science Institute, lmunger@hawaii.edu

Eva Nosal  
University of Hawai‘i, nosal@hawaii.edu

Joel Bell  
NAVFAC-Atlantic joel.t.bell@navy.mil

The naval forces of many nations conduct mine detonation exercises in coastal waters as part of their regular training. These exercises have the potential to disturb, injure, or even kill marine mammals occurring in the same area. To address concerns about this possibility at the US Navy’s Virginia Capes (VACAPES) Range Complex, an effort was conducted to monitor odontocete activity at the mine exercise (MINEX) training range using passive acoustic methods. The objectives of the project were to document the daily and seasonal patterns of occurrence of dolphins in the VACAPES MINEX training area, to detect explosions related to MINEX activities, and to investigate potential behavioral and acoustic responses of dolphins to MINEX events. Up to four ecological acoustic recorders programmed to achieve continuous monitoring were deployed at various distances from the known “epicenter” of training events and were refurbished approximately every two months. Dolphins were detected near the training area year-round, with ~97% of monitored days containing some dolphin acoustic signals. However, there was also clear seasonal variability, with a consistent period of low occurrence or reduced acoustic activity during the winter months. The results also indicate that dolphins exhibit an acoustic and/or behavioral response after a MINEX event. Acoustic activity levels ~1 km from the epicenter of training were examined for 34 training events and were found to be, on average, lower during both the day of and the day after the event, suggesting that the animals either reduced their signaling, left the area, or both. Conversely, dolphin acoustic activity levels during the second day after a training event were higher than either the day before, the day of, or the first day after an event. In addition, the data examined to date suggest that dolphins may follow a pattern of redistribution away from the epicenter after a MINEX training event. There is evidence that dolphins are more acoustically active or abundant 3 km from the epicenter during the day of and the day after an event than the day before it. These results underscore the value of long-term monitoring to inform the military on the potential impacts on marine mammal populations from training activities involving underwater detonations.
The eSource is a new type of seismic airgun that has a greatly reduced acoustic output at high frequencies. The high frequencies originate from the rising edge of the emitted acoustic pulse and the reduction has been achieved by a significant redesign of the mechanism that controls the air release. The potential environmental benefit of such a source is obtained without sacrificing the quality of the seismic image. The eSource was developed jointly by Schlumberger and Teledyne-Bolt. It may be purchased through Teledyne-Bolt for use by any seismic survey vessel. The famous paper by Southall et al. (2007) led the way in redefining criteria for the risk of injury to marine mammals, and the draft guidelines from NOAA (2015), with their more stringent requirements on high-frequency sound, have drawn this issue into a sharper focus. Several authors have made use of these various criteria in assessing the effect of seismic airguns (see references in Coste et al., 2014). They have also been in the design of the eSource (Laws, 2013). The high-frequency output originates primarily from the rising edge at the start of the airgun acoustic pulse as the compressed air flows out of the airgun ports. A 3-D computational fluid dynamics (CFD) computer model was used to simulate the airgun release mechanism and the air flows. A new airgun design was then created to generate the required smoother pulse shape (Coste et al., 2014; Gerez et al., 2015). The CFD simulation led to a new hardware design, which was built and experimentally tested; the test results were then used to verify and update the CFD model. Several cycles of this optimization and hardware verification have converged on a radical redesign of the airgun while still utilizing the technological advancements and maintaining the proven reliability of established airgun designs. At seismic imaging frequencies (typically <100 Hz), the eSource and the standard airgun generate almost the same energy spectrum. This means that the seismic image is largely unaffected. The reduced high-frequency output, pulse steepness, and peak pressure of the eSource result in a reduced zone of potential injury for marine mammals when, for example, the NOAA criteria are applied.

Three types of eSource are available with varying degrees of high-frequency reduction.
Within the UK North Sea, there are more than 20 wind farms currently proposed, with 17 projects either consented to or in the preconstruction phase. The UK National Policy Statement for Renewable Energy Infrastructure (EN-3) requires plans and projects to undertake a cumulative impact assessment (CIA) for marine mammals. This presents developers with a huge challenge in ensuring that the assessment is appropriate, evidence based, and realistic. This study outlines the steps for approaching the CIA for harbor porpoises and underwater noise in the North Sea. We highlight how different approaches to the CIA can lead to large variation in both the complexity of the assessment and the conclusions drawn with respect to the significance of impacts. The proposed harbor porpoise possible special area of conservation (pSAC) will also require consideration of in-combination impacts in the context of that designation, and the implications of this are also discussed. The first challenge of the CIA is to identify the criteria to be used to determine which plans and projects should be screened into the assessment. This should primarily be driven by the stage in the planning process at which the projects are; however, this approach may result in an unrealistic (overly conservative) representation of what to include in the CIA. For example, a review of entire North Sea identified over 100 offshore wind farm plans or projects that required consideration in relation to harbor porpoises before the inclusion of non-wind farm projects. The evidence base for the CIA also needs to be taken into account; this should reflect the confidence in the existing assessments used to inform the CIA. The evidence-based approach aims to refine the list of projects for inclusion in the assessment based on the level of certainty and confidence in the potential impacts. For example, where a project’s baseline data or assessment methods are out-of-date, it may be appropriate to exclude or update the inclusion of such a project in the assessment. The final challenge is the definition of a realistic worst-case scenario. During its assessment, each project must consider its own worst-case scenario. In applying project-level information, the CIAs therefore consider multiple worst cases, which may result in unrealistic estimates of potential magnitude of effect and a multitude of “what if” scenarios. This provides a huge challenge to developers, and ultimately regulators, in determining an appropriate, evidence-based, and realistic worst-case approach to the CIA.
Importance of Ultrasonic Field Direction for Guiding Juvenile Blueback Herring Past Hydroelectric Turbines

Ben Lenz  
New York Power Authority, benjamin.lenz@nypa.gov

Chris Gurshin  
Normandeau Associates, Inc.

Michael Taylor  
Normandeau Associates, Inc. (former employer)

Matt Balge  
Normandeau Associates, Inc.

Populations of anadromous blueback herring, *Alosa aestivalis*, have been depleted from historic levels. Measures to reduce mortality from many sources, including entrainment by hydroelectric turbines, are considered to be important to restore populations back to sustainable levels. At the Crescent Hydroelectric Project (Crescent), Mohawk River, New York, ultrasound (122-128 kHz) was produced to deter out-migrating blueback herring adults and juveniles to sea from entering the intake channel to the Crescent headrace and turbines where mortality may occur. To increase the deterrence rate observed in 2008, the sound field was extended further upriver to expose juvenile blueback herring to an increasing sound gradient as they migrate downriver and allow them more time to avoid the intake channel. When juvenile blueback herring were present upstream of Crescent from September 8 to October 10, 2012, and exposed to an ultrasonic field, the catch per unit effort (CPUE) by pelagic trawling in the main channel downriver of the ultrasound was 94% of the CPUE in the upriver trawl region and 250% of the CPUE in the intake channel. Repeated mobile acoustic surveys revealed that the total abundance of juvenile blueback herring averaged 35 times higher in the downriver main channel region than in the intake channel region. During the peak migration period from September 20 to October 14, continuous monitoring by fixed-location horizontal transducers revealed that 76% of the cumulative net downstream passage of juvenile blueback herring at the upriver site occurred through the downriver site in the main channel, thus bypassing the turbines. This was significantly higher than expected, assuming that entrainment is proportional to river flow and higher than the proportion observed in presence of the previous ultrasound field. These results demonstrate significantly improved downstream passage at Crescent for the majority of out-migrating juvenile blueback herring.
Getting off the Decision Carousel: Case Study of Marine Sound and Marine Mammals

Jill Lewandowski
US Bureau of Ocean Energy Management and George Mason University,
jill.lewandowski@boem.gov

Marine sound and its potential for effects on marine mammals is a seemingly intractable problem. Despite years of scientific and regulatory efforts, the controversy still continues and parties are increasingly frustrated on why a better solution cannot be found. Ultimately, progress on this issue will fail unless all parties better understand what is driving the conflict, the actions of those involved, and what is needed to move people and groups from established positions to more effective collaborations. This presentation will provide results from a review of 230 documents and the conduct of 58 semistructured, in-depth interviews with stakeholders engaged on this issue. Specifically, the presentation will explain where and why the greatest conflict exists, how “groups” are perceiving each other, and what groups and individuals see as the path forward. Although focused on marine mammals and sound, research results elucidate the role of conflict in environmental issues and provide lessons for productively addressing conflict to reach more meaningful and sustainable outcomes.
The Indo-Pacific humpback dolphin (*Sousa chinensis*) is a nearshore small odontocete, which is widely distributed in the coastal waters of the Indo-Pacific region including southeast China. Conservation of the humpback dolphins in Chinese waters has been on the agenda of local scientific and conservation communities since the 1980s, despite little research, including bioacoustic research, being conducted. Research on biosonar and hearing of the humpback dolphins has only been initiated in recent years. Our recent studies indicated that the biosonar clicks of the wild humpback dolphins in Sanniang Bay, China, were of short duration, with a 95% energy duration of 22 µs and broadband ultrasonic pulses with a mean peak frequency of 109.0 kHz, similar to those produced by other whistling dolphins of similar body size. However, the click source levels of the humpback dolphins, which ranged from 177.1 to 207.3 dB, with an average of 187.7 dB re 1 µPa peak-to-peak, appear to be lower than those of other whistling dolphins, which were over 220 dB re 1 µPa peak-to-peak. The hearing-sensitive frequency range of the humpback dolphins is generally higher than 5 kHz and lower than 120 kHz, with possible age-related hearing loss for old dolphins, and at frequencies lower and higher than the sensitive frequency range, hearing thresholds increased steeply. The humpback dolphin could therefore be characterized as a midfrequency cetacean, which operates sounds in the mid- to high-frequency range. Any sufficiently intense sounds with mid- to high-frequency components could have deleterious effects on the humpback dolphins through interference on the behavior of the animals and with the ability of the animals to detect signals from conspecifics and echoes of echolocation clicks. Recently, we recorded noise made by a small high-speed boat by using a broadband recording system in a dolphin-watching area, focusing on the effects on humpback dolphins in Sanniang Bay, China. It was found that the high-speed boat produced substantial mid- to high-frequency noise components with frequencies to >100 kHz, measured at three speeds: ~40, 30, and 15 km/h. The noise from the boat raised the ambient-noise levels from ~5 to 47 dB, with the root-mean-square (RMS) across frequency bands ranging from 1 to 125 kHz at a distance of 20 to 85 m, with louder levels recorded at higher speeds and at closer distances. To conclude, the noise produced by the small high-speed boat could be heard by *Sousa chinensis* and therefore potentially had adverse effects on the dolphins.
Loudly Heard, Little Seen, and Rarely Understood: Spatiotemporal Variation and Environmental Drivers of Sound Production by Snapping Shrimp, the Noisiest Animals in the Sea

Ashlee Lillis
Woods Hole Oceanographic Institution, ashlee@whoi.edu

T. Aran Mooney
Woods Hole Oceanographic Institution, amooney@whoi.edu

Snapping shrimp (family Alpheidae) are abundant crevice-dwelling crustaceans, comprising several hundred species in tropical and temperate habitats worldwide. The short-duration broadband “snap” generated by the collapse of a cavitation bubble on the rapid closure of their specialized claw is among the loudest bioacoustic sound in the marine environment. Because these shrimp can form large high-density aggregations, their colonies create a pervasive and continuous crackling in many coastal environments, and variation in snapping shrimp acoustic activity can substantially alter ambient-sound levels at a given location or time. Despite their fundamental contribution to the soundscape of many marine habitats and probable influence on myriad acoustically mediated ecological processes, relatively little is known about snapping shrimp sound production patterns, the underlying behavioral ecology, or environmental factors. Recent advances in recording capacity and increased efforts to sample coastal habitat soundscapes at high spatiotemporal resolution have provided acoustic data sets that reveal complex dynamics in snapping shrimp sound production. Our analyses of soundscape data from tropical coral reefs and temperate coastal habitats show that snap rates generally exhibit diurnal and crepuscular rhythms but that these rhythms can vary over short spatial scales (e.g., opposite diurnal patterns between nearby reefs) and shift substantially over time (e.g., daytime versus nighttime dominance during different seasons). These snapping shrimp sound production patterns correlate to abiotic variables such as water temperature, light, and DO, but the nature of these relationships and underlying causal mechanisms remain unclear. Our ongoing lab experiments to investigate snapping patterns in *Alpheus heterochaelis* found that isolated individuals produced snaps in the absence of external provocation and that their basal snap rate was dependent on water temperature, time of day, and sex of the shrimp. Interestingly, the spontaneous snapping observed indicates that snaps are used by the shrimp for purposes other than the aggressive and territorial interactions that are more commonly known; the functions of these snaps have yet to be explored. By combining a detailed snap analysis of field recordings and manipulative lab experiments, progress is being made toward understanding the complex interactions between sound-producing behaviors and the environmental factors that drive variation in snapping shrimp-dominated soundscapes. Establishing the acoustic ecology of key soniferous organisms is imperative to assess when and where soundscapes influence ecological processes and how human impacts alter these linkages. Moreover, these studies provide information essential to the effective use of soundscape characteristics for passive acoustic monitoring of marine communities.
The marine environment in the Bay of Fundy hosts a dynamic and diverse soundscape that is a fundamental component of the local ecosystem. The emergence of new anthropogenic marine activities and infrastructure, such as tidal turbine installations, introduces new sound sources that change or disrupt the existing acoustic environment, but the full extent of these changes is not well understood and is not predictable. To better evaluate the effects of future tidal energy development on the local soundscape in Grand Passage, Nova Scotia, a thorough understanding of the predevelopment characteristics must be established. This research quantifies and analyzes the acoustic environment as a dynamic compilation of various discrete and semicontinuous sound sources to characterize the soundscape as a function of its governing biological and physical processes and conditions. Passive acoustic measurements have been conducted using long-term moored omnidirectional hydrophones, a moored 5-channel array, and drifting hydrophone arrays, enabling identification of dominant signals and source direction, assessment of broadband noise sources, estimation of pseudonoise masking effects due to turbulent flow, and analysis of diurnal, daily, seasonal, and annual variability as well as spatial variability within the study area. The results provide a comprehensive baseline assessment that will support accurate evaluation of anthropogenic acoustic impacts.
The Lombard Effect in Fishes: How Boat Noise Impacts Oyster Toadfish Calling Rates and Vocalization Amplitudes in Natural Experiments

Joseph J. Luczkovich
East Carolina University, luczkovichj@ecu.edu

Cecilia S. Krahforst
East Carolina University, krahforstc06@students.ecu.edu

Kelsey Kelly
East Carolina University, kelleyk@alumni.ecu.edu

Mark W. Sprague
East Carolina University, spraguem@ecu.edu

The Lombard effect (an involuntary increase in vocal levels in noisy environments so as to be audible above the background noise) has been shown for humans, birds, marine mammals, and now in fishes. Here we use experimental playbacks of vessel noise and other natural sounds in the normal soundscape of the oyster toadfish (Opsanus tau). Experiments were conducted in areas adjacent to noisy boat channels and in a quiet marine reserve area. We played back large-vessel noise, outboard motor noise, dolphin sounds (predators on toadfish), and snapping shrimp sounds (natural sound) for 600 s and recorded the vocalizations made by the toadfish in experimental dens during 600-s periods before and after the playback period. We subtracted the background noise levels in a reference period measured just before each vocalization to obtain a signal-to-noise ratio (SNR) for each vocalization. There was no change in the fundamental frequency of calls before, during, and after the playback periods (average frequency was 224-233 Hz). The amplitude of vocalizations increased when we played back natural and anthropogenic sound types (vessel sounds). Average toadfish call sound pressure levels (SPL dB) increased as a function of reference-level background noise. Because background noise levels increased in the environment, the toadfish calls were louder after subtracting the reference noise level for each call detected, and we observed that the SNR was 9 dB above background before we played back the sounds, 5 dB during playbacks, and 11 dB after the playbacks. The amplitude of the calls increased by 2 dB after playbacks relative to before playbacks, demonstrating the Lombard effect in toadfish. This effect was persistent when data were restricted to just vessel noises, although no boat whistle calls were detected during large-vessel playbacks. Toadfish males were limited in their ability to overcome noise using the Lombard effect because the SNR of boat whistle calls decreased with increasing ambient noise, eventually falling below the critical ratio of signal to background noise. These results agree with recent work on oyster toadfish (Fine and Waybright, 2015), which found that individual toadfish could not alter their fundamental frequency at all but were capable of increasing amplitude by up to 15 dB. The impact on communication of toadfish males when calling to females may be masked by loud vessels, but the Lombard effect response can increase their SPL in noisy environments, up to a point. At that point, noise may impact reproductive success.

We present results of static acoustic monitoring of harbor porpoises at the research platform FINO 3 in the German Bight, North Sea, conducted since May 2012. The objective was part of a larger scale FINO 3 project and investigated the presence of harbor porpoises, looking at seasonal and daily pattern and at possible changes caused by construction activities of an offshore wind farm near the FINO 3 platform. Two click detectors (C-PODs) were moored at about 11 and 15 m depth to record the high-frequency clicks. In parallel, a vertical hydrophone chain was installed to mainly measure underwater noise related to the construction works. Parts of the hydrophone chain data were recorded with a high sampling rate to enable a comparison with the C-POD data. Additionally, a camera was installed on the platform aiming at the C-POD mooring to detect harbor porpoises visually at the same time. Only under calm weather and sea state conditions was a detection possible. An automatic detection algorithm was developed. In general, the data (measured in detection positive minutes [DPM]) showed a high rate of occurrence of harbor porpoises during all the years. Seasonal maxima of DPM were recorded during the summer (June to August) and winter (January to March), and low values were observed during spring (May). The daily pattern showed higher activity during daylight hours. The diurnal rhythm of recorded click activity could be related to the local feeding behavior and vertical movements of the preferred prey. In 2013 when the construction work at the offshore wind farm nearby took place, the registered maximum DPM were lower than in 2012 and 2014, but the database is too poor to affirm a direct correlation.
Echo Sounder Radiation Modeling in the Context of Acoustical Impact Assessment for Marine Mammal Protection

Xavier Lurton  
Ifremer-Underwater Acoustics Laboratory, xavier.lurton@ifremer.fr  
Yves Le Gall  
Ifremer-Underwater Acoustics Laboratory, yves.le.gall@ifremer.fr

For about two decades, attention has been focusing on the impact of anthropogenic sound sources on marine life, particularly marine mammals. Several cetacean stranding events, observed in the past, have been linked to operations of high-power military sonar, raising considerable reactions in public opinion and leading to mitigation measures by the concerned navies, later extended to the oil and gas industry using airgun-type seismic sources. On the other hand, fisheries, oceanography, and seafloor mapping make extensive use of echo sounders, and the use of low-frequency multibeam echo sounders has been suspected of being the cause of one stranding event. This paper aims to present the magnitude and the spatial structure of the sound field radiated by echo sounders (multibeam echo sounders [MBESs], single-beam echo sounders [SBESs], and subbottom profilers [SBPs]) in relation to their potential impact on marine mammals. The echo sounder signal characteristics and its geometrical radiation patterns are first summarized according to the various configurations met today (including multisector and multiswath MBESs). This provides the 3-D radiated field for one ping (Lurton, 2015), expressed along classical metrics of sound pressure level (SPL), and sound exposure level (SEL). The model is then extended to the more realistic case of the SEL cumulated along a survey line, integrating the contribution of pings transmitted along the ship's run. Numerical results from case studies are then compared with currently accepted threshold values for marine mammal sound exposure in terms of both maximum received SPL and cumulative SEL. The main conclusions are that although the MBES may indeed transmit at a high SPL (up to 240 dB re 1 µPa at 1 m), the very short duration of their pulses (typically a few milliseconds) and their strong spatial selectivity (typically 1°) make them unlikely to exceed the auditory damage thresholds currently used today (Southall et al., 2007; Finneran, 2015) except at unrealistically short distances or long exposures. Similar conclusions are drawn for the SBES, with a higher ping rate but a narrower radiation extent. For the SBP, the detrimental effect of wider transmission lobes, longer modulated signals, and higher ping rate is actually mitigated by a lower SPL magnitude and its specific-frequency range. The general conclusion is that the use of echo sounders, whatever their type, characteristics, and settings, is not prone to raise a significant impact on marine mammals in terms of physiological damage according to the present status of scientific knowledge.

Localized Changes in Underwater Noise Produced by the Generator of a Stationary Sailing Vessel

Claire P. Lusted-Koslowski  
Department of Engineering, University of Derby, clairelustedk@hotmail.co.uk  
Julius J. B. Piercy  
University of Essex, juliuspiercy@gmail.com  
Adam J. Hill  
Department of Engineering, University of Derby, a.hill@derby.ac.uk

The study of underwater vessel noise over the past 60 years has predominantly focused on the increase in ambient noise caused by the propulsion mechanisms of large commercial vessels. Studies have identified that the continuous rise of ambient-noise levels in open waters is linked to the increase in size and strength of anthropogenic sound sources. Few studies have investigated the noise contribution of smaller vessels or ambient-noise levels present in coastal and in-shore waters. This study aims to identify the level of noise common to noncommercial harbors by studying the noise emissions of a diesel generator onboard an ~70-m sailing vessel. Propagation patterns reveal an unconventional shape (specific to the precise location of the noise source on board the vessel) unlike those of standard geometric spreading models, as typically assumed when predicting vessel noise emission. Harbor attributes (including water depth, water temperature, ground sediment, and structural material components) showed altered level and frequency characteristics of underwater noise. Measurements taken in eight harbors around northern Europe were statistically analyzed to identify the primary factors influencing near-field sound propagation. In each harbor, a hydrophone was used to record the sound produced by the onboard generator in six positions around the vessel and at two depths below the water surface, in accordance to the vessel structure. Statistical analysis of the measurements identified common trends in each harbor and the impact of localized aspects, causing for variance between the measurement levels and tonal elements. Signal strength at each location around the vessel highlights the nonstandard propagation pattern of the generator noise and the complexity of the acoustic field surrounding a stationary vessel. The way in which sound spreads should thus not be assumed to have equal strength emanating from the entire length of the vessel. These findings may be expanded on to better predict the way in which sound spreads from a vessel, regardless of type classification and size. By identifying harbor attributes that cause greater underwater noise levels, progress may be made to avoid such structures in the future, ultimately reducing the detrimental impact on the marine environment.
Behavioral Responses of Belugas to Seismic Surveys

Oleg Lyamin  
University of California, Los Angeles, olyamin@ucla.edu

Dmitri Glazov  
Severtsov Institute of Ecology and Evolution, Moscow, Russia

Oksana Golenok  
Lomonosov Moscow State University, Moscow, Russia

Nikolai Shabalin  
Center of Marine Research, Moscow State University, Moscow, Russia

Faina Mel’nikova  
Severtsov Institute of Ecology and Evolution, Moscow, Russia

Evgeni Nazarenko  
Severtsov Institute of Ecology and Evolution, Moscow, Russia

Alena Vishnyakova  
Lomonosov Moscow State University, Moscow, Russia

Lev Mukhametov  
Severtsov Institute of Ecology and Evolution, Moscow, Russia

Mikhail Tokarev  
Center of Marine Research, Moscow State University, Moscow, Russia

Vyacheslav Rozhnov  
Severtsov Institute of Ecology and Evolution, Moscow, Russia

There is limited information on the effect of anthropogenic noise on the beluga. The aim of this study was to evaluate the impact of sparker (a sound source used in marine seismic surveys) on behavior and breathing rate in belugas. The subjects were two adult captive belugas housed in a spacious octagonal enclosure (size: 8.5 m; depth: 6 m) in the White Sea. The belugas were exposed to trains of underwater impulses of the sparker (pulse length: 200 ms; frequency: 2 Hz; peak intensity: 105-165 dB; band: 200-4,000 Hz; duration: 6-130 min). The sounds were emitted from a small vessel that passed the enclosure or drifted at a distance. Due to the small number of exposures (a total of 8), the response was evaluated when comparing each measurement (percent of different behaviors, position of animals in the enclosure, and the pattern of breathing) with the three-sigma ranges of the corresponding parameter during the control preexposure periods. Under baseline conditions, the behavior of belugas represented an alternation of resting and floating at the surface and submergings and slow swimming or rest at depth. Consequently, the pattern of breathing was highly stereotypic, manifesting an alternation of periods of regular breathing (up to 85% of all breathing pauses ranged between 2 and 20 s) and apneas longer than 60 s (a maximum of 370 s). The behavioral response of belugas to the sparker with a peak intensity of 120-165 dB and duration up to 24 min was shallow diving and fast erratic swimming at the part of the enclosure that was opposite the vessel. At the same time, the range of breathing pauses narrowed (the majority pauses were between 1 and 120 s) and the stereotypic breathing pattern diminished. Those changes were significant (based on the criteria described) without features of habituation while the noise continued. The behavior of belugas returned to normal within 20-30 min after the noise cancellation. The behavioral and breathing changes were not always parallel because the belugas took longer apneas during erratic swimming when exposed. The sparker noise with a peak intensity between 106 and 112 dB and lasting between 70 and 130 min did not cause significant changes. To conclude, the sparker noise with a peak intensity exceeding 120 dB altered the behavior and pattern of breathing in belugas. The response appeared to be nonspecific because it might be caused by other unexpected stimuli (e.g., small motorboats).
Cardiac Response to Acoustic Noise in Belugas

Oleg Lyamin
University of California, Los Angeles, olyamin@ucla.edu

Lev Mukhametov
Severtsov Institute of Ecology and Evolution, Moscow, Russia

Daniil Ostras
Kharkiv National University, Kharkiv, Ukraine

Vladislav Rozhnov
Severtsov Institute of Ecology and Evolution, Moscow, Russia

It is known that continuous noise may cause health issues to humans and land mammals, including cardiovascular diseases. The objective of this report is to summarize the cardiac response in 5 captive belugas to different types of acoustic noise, including an octave band noise (9.5-108 kHz, 140-175 dB, 1-100 min) and several types of low-frequency anthropogenic noise (ships, airguns, and military sonars; 0.1-5 kHz, 140-175 dB, 1-30 min). The cardiac response of belugas to the onset of noise resembles the "acoustic startle response" featuring either heart rate (HR) tachycardia or bradycardia. The most expressed recorded tachycardia manifested a HR acceleration greater than twofold of the baseline level for a period of >5 min without evidence for habituation over several consecutive presentations. It was recorded in one-year-old calf when exposed to an octave band acoustic noise (19-27 kHz, 150-165 dB). The spectral analysis of HR variability revealed the features of stress as described in humans and land mammals. A less pronounced response was observed in older belugas. A similar tachycardiac response was recorded in belugas when exposed to shipping noise, whereas the magnitude of the response quickly attenuated after several presentations. The bradycardiac response in belugas represents a sharp HR deceleration (as low as 8 beats/min) at the noise onset followed by a period of reduced HR (<20 beats/min) and recovery to the normal arrhythmic HR pattern while the noise still continued. Exposure to mid-frequency sonar and seismic noise also tended to cause apneas and bradycardia in belugas. As in the case of the shipping noise, the magnitude of cardiac response to sonars and airguns was generally less pronounced when compared with the octave band noise at the same intensities. The response to continuous noise may include a decrease in the HR variability and the disappearance of respiratory sinus arrhythmia (a respiratory act without an increase in instantaneous HR). In conclusion, the cardiac response of belugas to acoustic noise is highly variable. It clearly has all the features of startle and stress response. The magnitude of the response depends on the animal's age, health, and prior experience as well as the parameters of the noise. Continuous noise may cause prolonged alteration of the normal HR pattern and the health effects of such long changes of HR are not known. HR can be used as a measure of physiological response to fatiguing acoustic noise in the beluga and other cetaceans.
Recent efforts have been undertaken within the Agreement on the Conservation of Cetaceans in the Black Sea, the Mediterranean Sea, and the contiguous Atlantic area (ACCOBAMS) with the aim of understanding, assessing, and regulating underwater noise inputs into the agreement area. In 2014, a cooperation between ACCOBAMS and the convention for the protection of the Mediterranean Sea and its coastal region against pollution (Barcelona Convention) led to the development of a Mediterranean-wide strategy for assessing and monitoring underwater noise. This strategy was developed in the framework of the ecosystem approach (EcAp) project. EcAp is an initiative of the Barcelona Convention having the same overall objective of the Marine Strategy Framework Directive (MSFD) of the European Union, i.e., achieving and/or maintaining a good environmental status (GES), and a similar methodological framework. Underwater noise is indeed one of the several factors to consider for assessing the environmental status of the Mediterranean Sea. The strategy developed by ACCOBAMS proposed a methodology aimed at being consistent with the recommendations from the Task Group on Noise of the European Commission and has been approved by different technical meetings of the Barcelona Convention in 2015. Subsequently, ACCOBAMS supported the first preliminary basinwide assessment of the spatial and temporal distribution of noise-producing human activities in the Mediterranean Sea. The objective of this work was to gather an overview of the occurrence of the activities identified as being of the highest risk for marine wildlife and particularly for cetaceans. Although not exhaustive, this study put together a large amount of data on where and when noise sources were used for a period from 2005 to 2015, highlighted areas where activities producing noise accumulated, and presented overlaps with important cetacean habitats. This overview can now serve as a first discussion ground concerning the need for conservation measures as well as monitoring and assessment programs. Also, the results of this project can be used for supporting the discussions concerning the definition of GES relative to underwater noise, which is relevant for the EcAp initiative and the MSFD process. In conclusion, actions undertaken thus far in the Mediterranean Sea yielded the first important results for addressing the noise issue at a regional sea scale. However, such efforts also pointed out the urgent need for tools aimed at collecting best quality data and for standards for data collection and processing.
Description of a Flotilla of Recreational Activities During the Summer Season in Calvi Bay (Corsica, France) by Underwater Passive Acoustics: Automatic Detection and Classification of Vessels and Evaluation of the Impact of Radiated Noise in a Protected Area

Caroline Magnier
PhD Student, cmagnier@rtsys.fr

Cedric Gervaise
GIPSA Lab-CHORUS, cedric.gervaise@chorusacoustics.com

Luc Simon
RTSYS, lsimon@rtsys.fr

Located in Corsica (France), Calvi Bay is a coastal environment sheltering species and natural habitats protected by the Natura 2000 program as the Posidonia oceanica meadows. This ecosystem suffers a strong anthropic pressure during the summer season. In addition to the small fishing activity present throughout the year, this bay becomes a privileged place of recreational activities during summer. This flotilla is composed of vessels of different sizes: jet skis, zodiacs, sailboats only using driving force, medium and big yachts, and shuttles. In the framework of the program STARE-CAPMED, several studies have been conducted to evaluate the impact of human activity on the ecosystem of Calvi Bay. Abadie (2012) evaluated the impact of anchoring on the evolution of Posidonia in this bay. This article focuses on the acoustic pressure due to the radiated noise from vessels.

An opportunistic acoustic recording to obtain data on the radiated noise from vessels present in Calvi Bay was conducted from July 5-10, 2015. The acoustic recorder was placed over the Posidonia meadows at a depth of 30 m. A protocol of ground truths gave an estimate of the total number of vessels crossing the bay of between 280 and 550 vessels per day. Acoustic data recorded 603 vessels that radiated noise during this period. However, only 189 vessels had a sufficient proximity to the recorder, and an acoustic signature clearly identified those to be kept for this study. These acoustic data permitted an automatic detection and classification of vessels in this bay. Radiated noise from vessels is classified into three general classes based only on acoustic proprieties: the presence of harmonics in high frequency (fundamental frequency of 760 Hz for some zodiacs), the presence of rays in low frequency, and the absence of a dominant ray.

Several acoustic measures estimated the impact of noise on the local ecosystem: the M-weighting level (Southall et al., 2007), the dB\text{ht} level (Nedwell et al., 2007), and the duration of “acoustic rest” and “acoustic stress” on organisms. The sound exposure level (SEL) daily average value estimated in the absence of anthropic activities was 124.4 dB (SEL\text{30s}). The duration where this level was higher than 127 dB SEL\text{30s} was between 6 and 37.5 minutes (128 minutes during the entire period), whereas the duration where this level was higher than 134 dB SEL\text{30s} (“stress on organisms”) was between 0 and 5 minutes (9 minutes during the entire period).


Two passive acoustic data sets collected with near-bottom high-frequency acoustic recording packages (HARPs) have been analyzed for fin whale vocalizations in relation to ship passages. Both data sets, one over Sur Ridge, about 25 nm west of Point Sur, CA, and the other at Thirtymile Bank, about 25 nm west of Point Loma, CA, were collected at about 800 m. Both sites are located near commercial shipping lanes, and both data sets commonly detect fin whales. Preliminary analysis showed that intensity of fin whale vocalizations can change in response to ship noise. Two types of responses have been detected: the whale either ceased or considerably reduced its vocalizations or the vocalization intensity became elevated. Both responses are abrupt, i.e., there is no gradual change in the intensity, and both last for a short period of time after ship passage. Both response types observed in the two data sets were compared using the power spectral density at three frequencies: 12, 20, and 33 Hz. To further investigate the observed response in fin whale vocal behavior, we employed a two-step computer vision-based classifier developed for blue and fin whale calls, which allowed for denoising and extracting of individual calls and thus for quantifying the response in terms of received level, frequency content, and intercall interval. Specifically, we focused on three main questions. (1) How statistically significant was the observed change in the vocal behavior compared with the background variability in the vocalization intensity and call patterns? (2) How do we estimate and account for the uncertainty in the relative positions of the receiver, whale(s), and a ship, which produce the overlapping signatures in the acoustic recordings? (3) Can the observed response be explained by a fin whale physically “escaping” from the direct path of the ship noise propagation? The last two questions were answered by combining the observations with modeling of sound propagation loss using the Bellhop model under real environmental conditions. The present research lays out a foundation for detecting and quantifying the vocal response of other cetacean species, both baleen and toothed whales, as observed in passive acoustic data.
Coastal Dolphins and Noisy Environments: Sound Sources, Soundscape Variability, and Dolphin Behavioral Responses

Sarah A. Marley  
Centre for Marine Science and Technology (CMST), Curtin University,  
sarah.marley86@gmail.com

Chandra P. Salgado Kent  
Centre for Marine Science and Technology (CMST), Curtin University,  
c.salgado@cmst.curtin.edu.au

Christine Erbe  
Centre for Marine Science and Technology (CMST), Curtin University,  
c.erbe@curtin.edu.au

Human waterborne activities emit noise into the marine environment. This is of particular concern with regard to the potential impact on cetaceans due to their acoustic specializations. Yet few previous studies have considered the acoustic characteristics of marine habitats to explain cetacean occurrence, instead relying on geographical features and environmental variables. As underwater noise levels increasingly become considered an indicator of habitat quality, there is a need to characterize soundscapes with regard to their cetacean fauna and examine animal responses to “noisy” environments.

The overall aim of this study is to identify the response of coastal dolphins to environments rich in anthropogenic sound. The Swan-Canning River system in Western Australia is home to a resident community of Indo-Pacific bottlenose dolphins (Tursiops aduncus) but is also a site regularly used for various human activities. Data were collected from November 2013 to July 2015 using a combination of acoustic and visual survey techniques. Autonomous underwater acoustic recorders were deployed at several locations within the river system. At two of these sites, land-based visual observations were conducted using a theodolite to track the activities of dolphins, vessels, and dredging platforms.

Acoustic data were analyzed using weekly spectrograms, power spectral density percentile plots, octave band levels, and generalized estimating equations. These identified several sound sources that strongly influenced the underwater soundscape, namely wind, snapping shrimp, and vessel traffic. The sounds of bridge traffic, waves, fish, machinery, dolphins, and precipitation also contributed to the acoustic environment. Furthermore, three of these sound sources (boats, waves, and fish) were found to vary at a range of temporal scales within sites, with evidence of spatial variation between sites. Land-based observations revealed high levels of vessel traffic at both sites; consequently, visual data were used to investigate the behavioral response of dolphins to anthropogenic activities and associated noise. Generalized additive modeling showed that dolphin presence/absence, relative abundance, and occupancy time varied in response to environmental and anthropogenic variables. Moreover, the significance of these variables differed between sites.

These results highlight the variability of marine soundscapes, both temporally and spatially, even within the same system. Sound sources contributing to these soundscapes have been shown to influence the occurrence and potentially the behavior of dolphins utilizing these areas. However, dolphin responses vary according to site. Thus, this study emphasizes the need to consider context in behavioral-response studies in terms of habitat type studied, explanatory variables considered, and response variables selected.
Opportunistic Behavioral-Response Studies of Two Species of Baleen Whales, Fin Whales (*Balaenoptera physalus*), and Minke Whales (*Balaenoptera acutorostrata*) in Response to US Navy Sonar Training in the Central Pacific Ocean

**Stephen Martin**  
National Marine Mammal Foundation, steve.martin@nmmpfoundation.org  
**Cameron Martin**  
National Marine Mammal Foundation, cameron.martin@nmmpfoundation.org  
**Brian Matsuyama**  
National Marine Mammal Foundation, brian.matsuyama@nmmpfoundation.org

Opportunistic behavioral responses of two species of baleen whales, fin whales (*Balaenoptera physalus*) and minke whales (*Balaenoptera acutorostrata*), to disturbances from US Navy midfrequency active sonar training at the Pacific Missile Range Facility, Kauai, Hawai‘i, are being studied utilizing passive acoustic recordings. Automated passive acoustic detection, classification, localization, and tracking analyses of the data have shown a behavioral response in terms of a reduction, or cessation, of minke whale “boing” calling in response to US Navy training over relatively large areas of the ocean (i.e., 3,780 km²). The reduced calling is also expressed in terms of reduced densities by utilizing acoustically localized individual whale counts. Individual ship-whale encounters for both species of whales will be presented, with estimated received levels that the whales were exposed to from midfrequency active sonar (MFAS; estimated as high as 166 dB re 1 µPa). In some cases, the animals appeared to have a longer call interval after the initial exposure before ceasing calling. In other cases, the animals also appeared to begin calling again after the initial exposure and temporary cessation of calling; however, as training activities progressed, calling ceased completely. Additional data need to be analyzed to determine if the longer intercall interval observations are statistically different from variations found in normal behaviors, which also include some extended intercall intervals. Swim patterns derived from the passive localizations of calls during sonar activity are also analyzed to determine if differences exist from the robust baselines of the normal variations in the swim pattern kinematics of the whales. The obvious disadvantages of this approach are the lack of experimental controls and the lack of information when whales are not calling. However, the approach offers multiple advantages such as the involvement of actual naval sonar training, the monitoring is noninvasive to whales, large areas of the ocean are monitored simultaneously, relatively low costs are involved, and robust baselines of normal whale behaviors may be established from large quantities of baseline data for comparison for determination of behavioral responses from MFAS disturbances.
Comparison of Psychophysical Methods Used to Determine the In-Air Hearing Threshold of the Great Cormorant (*Phalacrocorax carbo sinensis*)

Alyssa Maxwell  
University of Southern Denmark, maxwell_a@live.ca  
Kirstin Anderson Hansen  
University of Southern Denmark  
Ole Næsby Larsen  
University of Southern Denmark  
Magnus Wahlberg  
University of Southern Denmark

The need to increase the knowledge and understanding of marine animal hearing has come with the ever-expanding human presence in their natural environment. A group of animals that are usually forgotten during these studies are the marine birds. The goal of this study is to explore the hearing capabilities of the great cormorant (*Phalacrocorax carbo sinensis*) by comparing results from two psychophysical studies using staircases and methods of constants to present stimuli. Experiments were made on a captive cormorant trained with positive reinforcement. Hearing thresholds were ~20 dB higher using staircases than when using method of constants. This indicates that the experimental methodology has a huge impact on the derived hearing thresholds in this case. Because the cormorant is globally distributed, this information plays an important role in the development of cormorant deterrent devices for fishery use as well as for understanding the impact that the increasing anthropogenic noise has on them as an amphibious species.
Airgun and Airgun Array Near-Field Measurements in Biological Exposure Experiments: Small-Scale Variability in Sound Transmission Regimens, Ground Motion, and Ramp-Up Scenarios

Robert McCauley
CMST, Curtin University, r.mccauley@cmst.curtin.edu.au

Douglas H. Cato
University of Sydney, Sydney, NSW, Australia, doug.cato@sydney.edu.au

Michael Noad
Cetacean Ecology and Acoustics Laboratory, University of Queensland, Gatton, QLD, Australia, mnoad@uq.edu.au

Rebecca Dunlop
Cetacean Ecology and Acoustics Laboratory, University of Queensland, Gatton, QLD, Australia, r.dunlop@uq.edu.au

Ryan Day
Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia, ryan.day@utas.edu.au

Jayson Semmens
Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia, jayson.semmens@utas.edu.au

From 2010 to 2015, field experiments were undertaken in Australia on the biological impacts of airgun sources. Study sites were east of Peregian Beach, North Queensland (10-50 m depth); west of Dongara, Western Australia (30-50 m), and in Storm Bay, southern Tasmania (10-36 m). Individual airguns, gun clusters, and airgun arrays from 20 to 3,130 in.³ were measured using calibrated seabed or midwater sensors (hydrophones and 3-axis geophones). The 3,130-in.³ airgun array pressure signals at short range (<1 km) were complicated, comprising individual signals from discrete guns or gun clusters spread over 311 ± 11 ms (±95%), with peak-to-peak levels to 194 dB re 1 µPa and maximum sound exposure levels >174 dB re 1 µPa²·s. All sites showed local differences in sound transmission regimens at hundreds of meter to kilometer scales because of differences in water depth, bathymetry slope, or seabed type. The Peregian Beach site was a mosaic of reef interspersed with varying thicknesses of sand. The reefs had ~7 dB/km higher loss rates than those observed over sand only, which greatly influenced experimental airgun exposures. Off Dongara, airgun signal loss rates increased westward (further offshore). None of the sites had uniform sound transmission regimens; all required comprehensive studies to evaluate the exposures received by test animals. Geophone measurements revealed expected airgun energy traveling through the seabed ahead of the waterborne signal but also intense ground motion 40-80 ms after the waterborne arrival. It was as though the ground had been stuck; maximum acceleration magnitudes up to 69 ms⁻² (150-in.³ airgun at a 37-m range) were measured, although the values were typically 1-3 ms⁻² for the 150-in.³ airgun at 6-50 m and 0.2-0.4 ms⁻² for the 3,130-in.³ array at 477-750 m. The single 150-in.³ airgun groundborne acceleration magnitude was 3.7 times less than the 3,130-in.³ array at a similar range. Extensive modeling and measurements of airgun array ramp-up configurations were made to design 4-6 dB ramp-up steps of a 3,130-in.³ array. Source modeling did not predict ramp-up steps well until the model output was combined with sound transmission modeling. This was due to low-frequency energy not transmitting well in the duct available. This presentation will highlight some of the intricacies of airgun array sound transmission phenomena, the importance of measuring this in studies of the impact of the sounds on marine animals, and the relevance for biological impact studies.
Great Barrier Reef Marine Soundscapes: Lizard Island, a Coral Reef Case Study

Jamie McWilliam
Centre for Marine Science and Technology, Curtin University, mcwilliamjamie@gmail.com

Rob McCauley
Centre for Marine Science and Technology, Curtin University, r.mccauley@curtin.edu.au

Christine Erbe
Centre for Marine Science and Technology, Curtin University, c.erbe@curtin.edu.au

Miles Parsons
Centre for Marine Science and Technology, Curtin University, miles.parsons@curtin.edu.au

Euan Harvey
Curtin University, euan.harvey@curtin.edu.au

In the past decade, the study of marine soundscapes has acquired a growing level of social and academic awareness. Advancements in technology and ecological modeling have provided significant opportunities to progress research and initiate long-term monitoring programs, but substantial knowledge gaps remain in the following key areas: soundcape spatiotemporal patterns, methodology, and sound source identification. This presentation will provide a synopsis of the soundscapes recorded around Lizard Island. Great Barrier Reef marine soundscapes have received limited attention and coverage, making this a rare and important study. Sets of continuous sound recordings were collected at field sites across a number of seasons (2014-2016). Several prominent fish choruses were identified at specific locations around the island, exhibiting a range of different temporal patterns. The most prevalent and prominent chorus started just before sunset and was composed of a series of rapid pulse grunts (30 ms) with energy centered between 500 and 700 Hz. Around the new moon, chorus levels reached up to 120 dB re 1 µPa. Cyclone Nathan struck Lizard Island in March 2015 causing widespread damage to the Island's surrounding coral reef. The cyclone produced high-level broadband noise as it passed overhead. A comparison of reef soundscapes before and after the cyclone found that the fish chorus recorded in March 2015 appeared again in October, November, and December 2015 in the same area where large-scale cyclone damage of the reef occurred, suggesting that chorusing fish are a transient species. Simultaneously measuring environmental covariables at a site is an important step in identifying soundscape contributors and explaining observed patterns. Environmental covariables, wind speed, temperature, and relative light levels were collected at field sites in a 10-min duty cycle. Additional information on salinity, pH, and tide height was obtained from open-access meteorological and oceanographic data sets. The influence of a temporal sampling regimen will be presented by comparing spatial variation over fine-scale windows (5, 10, 30, 60, 180, 300, 900, 1,200, and 3,600 s) for four separate field sites. The influence of anthropogenic activity, principally ship-radiated broadband noise from a nearby commercial shipping lane, had a significant and prolonged influence on the underlying soundscape. Masking of fish choruses for several hours north and south of the Island was a common occurrence in the presence of passing ships. Potential impacts of this will be discussed.
Could We Have Simpler (But More Adequate) Noise Risk Assessments for Geophysical Surveys?

Sónia Mendes  
Joint Nature Conservation Committee, sonia.mendes@jncc.gov.uk

Francesca Marubini  
Hartley Anderson Limited, fm2@hartleyanderson.com

Noise risk assessments for geophysical surveys are routinely carried out as part of permitting regimens to inform, for example, the size of the mitigation and effects zone. In the United Kingdom, the need for guidance on how to undertake these assessments has been acknowledged by regulators, advisers, and industry. The assessments vary greatly in their level of detail and in how they are conducted and presented. Yet in the majority of cases, the same conclusions have been reached, mainly that the risk of auditory injury to marine mammals is limited to the first few hundred meters from the sound source, i.e., within the 500- to 1,000-m standard mitigation zones. Such consistent outcome puts into question the added value of all these detailed noise assessments, particularly if one could make some generalizations, for example, on the appropriate mitigation zone for a certain group of surveys and environmental conditions. This project looked at whether guidance could be provided by category of geophysical survey, risk and level of uncertainty, advising on the level of information needed for permitting for each of the categories. Three base reviews were undertaken: (1) of the main conclusions, areas of uncertainty and inconsistencies in a sample of noise assessments; (2) of existing injury threshold criteria; and (3) of the types of geophysical surveys routinely carried out in UK waters. In addition, noise modeling was carried out for several typical scenarios corresponding to the most likely combination of survey (including equipment and operating parameters), location and duration, to estimate a possible range of sound exposure footprints with respect to marine mammal auditory injury. Building on this work, the guidance will formulate the type of information and detail necessary to adequately assess the risk and decide on mitigation for each scenario. The guidance will also consider those cases when the survey proposed is not consistent with any single “typical scenario” and/or the associated uncertainty does not allow for conclusions to be drawn on the most adequate mitigation and residual risk to species without a more detailed assessment. The implementation of this guidance should result in noise assessments that are shorter, clearer, focused, pragmatic, and appropriate to the type and scale of the activity, the sensitivities of the species affected, and the uncertainties around the potential risk.
Anthropogenic noise in the world’s oceans is increasing the ambient background levels at an alarming rate. Given the mounting evidence that sound plays an important role in the life history of many fish species, understanding how increasing noise levels affects the natural behavior of fish is critical. Here we used baited underwater video stations (BUVs) to compare the behavior of fish inside and outside a temperate marine reserve in the presence of motorboat noise at shallow (5-m) and deep (20-m) sites. The interactions of New Zealand snapper (Pagrus auratus) with the bait jar was quantified before, during, and after an approach by a semirigid boat equipped with a 4-stroke 60-HP outboard motor. The BUV hydrophone recorded sound pressure levels (SPLs) with a background noise ranging from 106.9 to 112.9 dB re 1 µPa and with boat noise peaking at 129.3 dB re 1 µPa SPL in shallow sites and 123.1 dB re 1 µPa SPL at the deep locations. Fish number and interactions with the bait jar increased for approximately the first 15 min after deployment before reaching a steady state but decreased significantly in the presence of boat noise in areas outside the reserve. Fish number and behavior returned to preboat levels soon after the boat left the area. In most sites in the reserve, boat noise had little effect on fish number and feeding. The reserve fish are not under fishing pressure, and their tolerance of the boat presence is consistent with previous observations that the fish are “bolder” than conspecifics outside the reserve. The nonreserve fish either left the area or stopped moving/feeding that could be indicative of the association of boat presence with fishing pressure or that the sound pressure levels temporarily reduced/masked sensory input. The study shows that short, transient boat passes can affect fish behavior.
Anthropogenic noise levels in continental shelf seas may be rising as shipping, offshore construction, and other noise-generating human activities become more prevalent. A number of adverse effects from exposure to such noise have been documented in acoustically sensitive marine organisms, which may have consequences for the functioning of marine ecosystems. Policymakers and environmental managers are developing responses to this risk but are constrained by a lack of data on noise levels. Here, we present a joint monitoring project to quantify levels of noise in the marine environment in the United Kingdom, using existing data sets, in support of the UK’s policy objectives under the EU Marine Strategy Framework Directive. Ambient-noise recordings were made during 2013-2014 at 12 sites around the UK coast. Median noise levels ranged between 81.5 and 95.5 dB re 1 µPa for octave-separated one-third octave frequency bands centered between 63 and 500 Hz. Levels of anthropogenic noise varied between the monitoring sites and regions, with little influence from man-made noise in the Celtic Sea and a number of sites with persistent noise from vessels in the northern and southern North Sea. An assessment of acoustical metrics found that the RMS level (the conventional metric used for mean sound level) was highly skewed by the presence of outliers and exceeded the 97th percentile at some frequencies. It is therefore recommended that environmental indicators of anthropogenic noise use percentiles to ensure that indicators are statistically robust. The monitoring effort is limited by available resources, and so there is a need to focus and prioritize monitoring programs. To achieve this, we suggest that the sites of conservation importance for acoustically sensitive species and areas of high shipping density be prioritized. The data reported here provide an initial baseline of noise levels in UK waters, which can be used to assess future trends in noise pollution.
Some acoustic deterrents help reduce marine mammal interactions with fisheries and aquacultures, but they also contribute to an increasing level of underwater noise. In the Southern California Bight, a variety of US West Coast fisheries (e.g., purse seiners) use commercially produced explosive deterrents, commonly known as “seal bombs,” to protect the fishing gear and catch from pinniped predation and potentially also to aid in separating catch species. Passive acoustic monitoring (PAM) data collected over the past 10 years (2005–2015) at multiple sites within the Southern California Bight have revealed first insights into the large number of small-charge underwater detonations generated by explosive deterrents. Maximum explosion counts exceeded 32,000 per month and 550 per hour at a recording site near Catalina Island. The majority of these explosions occurred at night; this pattern was consistent for all PAM sites and deployment years. By comparing spatial and temporal patterns of explosions with daily operating hours and commercial fisheries landings data, a significant relationship with the California market squid (Doryteuthis opalescens) purse seine fishery was found. Sound pressure levels of seal bombs were estimated at 220–235 dB re 1 µPa at 1 m (peak-to-peak). Such high levels, in combination with the persistence of reoccurring explosions, indicate the potential to affect the behavior of aquatic animals. No long-term studies on the effects of explosive deterrents exist. Quantification of noise levels, sound propagation models, and modeling the effects on, e.g., cetacean acoustic behavior will be required to judge the necessity for possible adaptations of procedures regarding the use of explosive deterrents to enhance sustainability of these economically important fisheries.
Seal Scarers Do Not Scare Seals: A Study on the Effects of Seal Scarer Sounds on Harbor Seals

Lonnie Mikkelsen  
Aarhus University, lomi@bios.au.dk

Line Hermannsen  
Aarhus University, lihe@bios.au.dk

Jakob Tougaard  
Aarhus University, jat@bios.au.dk

Seal scarers are loud underwater sound emitters designed to deter seals from fishing gear and aquaculture installations to avoid depredation on fish. In addition, seal scarers are also extensively used as mitigation tools to deter marine mammals from loud and potentially dangerous sound sources, such as pile driving or underwater explosions. Mitigation is achieved by deploying a seal scarer before the main activity (e.g., pile driving) so that marine mammals are deterred out to safe distances before the main event occurs. The effectiveness of these devices for mitigation is, however, not well-known and relies on their ability to deter animals effectively. To test this effectiveness on seals, we conducted a visual study on the Island of Anholt, Denmark, where harbor seals were exposed to 500-ms tone bursts at 12 kHz, simulating that of a seal scarer. Output levels of the sounds were reduced (source level of 165 dB re 1 µPa peak to peak) in comparison to commercial devices to maintain avoidance responses within our visual range. Simultaneously with noise exposures, seals were positioned with a theodolite from the nearby lighthouse (40 m above sea level). In total, 13 sound exposure trials were conducted over a 3-week period in September 2015, with a maximum of 3 exposures conducted per day. In contrast to expectations, seals were not scared by the seal scarer sounds and they did not avoid the area around the loudspeaker when the sound was on. In fact, several seals were observed moving closer to the loudspeaker during trials, often being only 20 m from the noise source. These results show that seals may not effectively be deterred by seal scarer sounds, at least at the sound level used in this study, and may instead be attracted by the sounds. This is in sharp contrast to reactions seen in harbor porpoises, which react strongly to seal scarers, having implications for mitigation practices in locations where deterrence of both species is desired. With the seal scarers currently used, there is thus a conflict between obtaining sufficient deterrence for seals without increasing the deterrence of porpoises to undesired levels. Current mitigation measures using deterrent devices should thus be reevaluated to ensure that the deterrence effects on different target species are balanced.
Sri Lankan pygmy blue whale calls consist of three components: (1) low-frequency pulsive unit, (2) frequency-modulated (FM) upsweep, and (3) long tonal downsweep. The (~100-Hz) tonal downsweep is the most distinct of the call units and lasts 20-30 s. The FM component has up to three visible upsweeps, with energy concentrated at ~40 Hz, 50 Hz, and 60 Hz. Spectral characteristics of the tonal downsweep and FM upsweeps, along with long-term patterns of environmental sound levels, were analyzed from the Comprehensive Nuclear-Test-Ban Treaty International Monitoring Station at Diego Garcia in the Indian Ocean from 2002 to 2012. Average weekly spectral frequency peaks and ambient-sound levels were computed. The peak frequency of Sri Lankan pygmy blue whale tonal calls decreased from ~107 Hz to 100 Hz over a decade, corresponding to a 0.55Hz/year rate of decrease. To date, this is the largest rate of frequency decrease observed for any blue whale population. Over the same time period, the frequency content of the FM upsweeps did not significantly change. The differential shift of one call component in a stereotyped song sequence suggests voluntary control and purposeful modification of the tonal downsweep. Analysis of the ambient-sound levels in the vocalization and adjacent bands did not exhibit equivalent patterns in amplitude trends. Regression analysis showed no increase in the 100- to 107-Hz ambient noise or in the compensated peak amplitude levels of the tonal downsweeps, eliminating the presence of a Lombard effect. The 60-Hz component of the call appears more stable over time, making this a stronger candidate for targeted auto detection compared with the ~100-Hz tonal component. Potential drivers of the observed trends will be discussed.

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Acoustic and Seismic Measurements of Pile Driving for the First Offshore Wind Farm in the United States

James H. Miller, University of Rhode Island, miller@uri.edu; Gopu R. Potty, University of Rhode Island, potty@egr.uri.edu; John W. King, University of Rhode Island, jwking@uri.edu; Dennis R. Gallien, HDR, Inc., Dennis.Gallien@hdrinc.com; Anwar A. Khan, HDR, Inc., Anwar.Khan@hdrinc.com; Jamey Elliot, HDR, Inc., James.B.Elliott@hdrinc.com; Kathleen Vigness-Raposa, Marine Acoustics, Inc. kathleen.vigness@marineacoustics.com; Jennifer L. Giard, Marine Acoustics, Inc. Jenn.Giard@marineacoustics.com; Adam S. Frankel, Marine Acoustics, Inc., adam.frankel@marineacoustics.com; Tim Mason, Subacoustech Environmental Ltd Tim.Mason@subacoustech.com; Arthur N. Popper, University of Maryland apopper@umd.edu; Anthony D. Hawkins, Loughine Ltd a.hawkins@btconnect.com; Steven E. Crocker, Naval Undersea Warfare Center – Newport steven.e.crocker@gmail.com; YT Lin, Woods Hole Oceanographic Institution, ytlin@whoi.edu; Arthur Newhall, Woods Hole Oceanographic Institution, anewhall@whoi.edu; Mark Baumgartner, Woods Hole Oceanographic Institution mbaumgartner@whoi.edu

Underwater acoustic and seismic signals from pile driving were monitored in September and October 2015 using multiple sensors during the construction of the US first offshore wind farm located 3 nm off Block Island, RI. The 30-megawatt Block Island Wind Farm (BIWF) consists of 5 turbines in water depths of ~30 m and is scheduled to be online in 2016. The substructure for each of these turbines consists of a jacket-type construction with 4 piles driven at an angle of ~13° to the vertical to pin the structure to the seabed. The underwater acoustic measurement platforms consisted of a towed array consisting of eight hydrophones, two fixed moorings with four hydrophones each, a fixed sensor package and a mobile sensor for measuring particle velocity, and boat-deployed dipping hydrophones. The hydrophone array was towed from a position 1 km from the pile-driving location to a 7-km distance from the construction. The fixed moorings were deployed at 10 km and 15 km from the pile location. The fixed moorings consisted of 4 hydrophones, each at depths of 10, 15, 20, and 25 m. Near-field measurements of the underwater acoustic signals, including particle velocity from the pile driving, were collected with a tetrahedral hydrophone array deployed 500 m from the pile-driving location ~1 m above the seabed. In addition, seismic signals from the pile driving were measured with a three-axis geophone placed on the seafloor. The boat-deployed dipping hydrophones sampled the acoustic field at locations from 0.5 km to 20 km from the pile-driving locations. Based on these acoustic measurements and propagation modeling, the acoustic pressure field as a function of range and depth from the pile was estimated. The transition from fast-rise-time impulsive signals at close range to slow-rise-time nonimpulsive signals at longer ranges will be addressed using kurtosis. The levels of all sensors varied by more than 10 dB and kurtosis by a factor of ~3 as a function of time at the same range. It is hypothesized that the rake of the individual piles was the cause of this time dependence. This study will provide the required information to qualify the different zones of potential marine mammal effects (zones of injury, behavioral effects, etc.) and to estimate exposure to fishes and other species.

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Hearing Sensitivity and Variability in a Wild Odontocete Population (Beluga Whales) and the Relationship of Hearing Loss to Echolocation

T. Aran Mooney  
Woods Hole Oceanographic Institution, amooney@whoi.edu

Manuel Castellote  
National Marine Mammal Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service

Lori Quakenbush  
Alaska Department of Fish and Game

Roderick Hobbs  
National Marine Mammal Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service

Caroline Goertz  
Alaska SeaLife Center

Eric Gaglione  
Georgia Aquarium

Maxwell B. Kaplan Woods Hole Oceanographic Institution

Hearing and echolocation are considered the primary sensory modalities in odontocetes. To understand and predict the impacts of anthropogenic noise, we must know the natural hearing ability at the population level (which includes variability among individuals). Yet auditory sensitivity, including the extent and rate of natural hearing loss, is little known for most cetacean species and is essentially unknown for wild cetacean populations. The goals of this work were (1) to establish the mean audiogram and variance of wild beluga whales to define what a natural population hears and how sound sensitivities differ among individuals and (2) to evaluate, for the first time, how the hearing abilities of wild belugas relate to their respective echolocation click parameters to inform how hearing loss may impact other sensory modalities. Audiograms were collected from 17 wild belugas during capture-release events in Bristol Bay, AK, using auditory evoked potentials in the frequency range of 4-150 kHz. Echolocation clicks were measured on-axis at 1 m using a 3-channel acoustic recorder. Habitat background noise levels were characterized. Belugas generally showed excellent sensitivity (<60 dB) from 45 to 100 kHz and most (76%) heard up to at least 120 kHz, relatively high compared with studies on some captive and stranded odontocete species. Hearing thresholds at lower frequencies (4-11 kHz) tracked the low environmental noise levels (70 dB/Hz), suggesting that quiet habitats may support consistently high population hearing sensitivity; conversely, some impaired hearing sensitivity measured elsewhere may result from high background noise. Echolocation clicks showed peak and center frequencies between 45 and 120 kHz; median values were relatively high (100 kHz), correlating to their generally sensitive high-frequency hearing. Individuals tended to produce clicks with intensities centered in frequencies of best hearing; however, the variability in click power spectra increased in individuals with less sensitivity and high-frequency hearing loss. This suggests that hearing deficits can result in a greater click variability, perhaps due to less control when sounds are poorly heard or the need to utilize a greater range to find an effective signal. These audiograms more than triple the data for beluga whales as a species and provide the beginning of population-level auditory data for a wild odontocete. Beluga audiograms show substantial (20- to 40-dB) variation but less than that of bottlenose dolphins, suggesting differences between populations or species and demonstrates the need for comparative data. Finally, it appears that hearing loss influences variability in sound production (i.e., click characteristics). Although this suggests that the hearing range might be predicted from click variability, such effects substantially broaden the potential impact that noise can have on sensory and bioacoustic modalities.
Motion in the Ocean: Characterization of Particle Motion in Humpback Whale Song and Its Potential in Communication

T. Aran Mooney  
Woods Hole Oceanographic Institution, amooney@whoi.edu  
Maxwell B. Kaplan  
Woods Hole Oceanographic Institution, mkaplan@whoi.edu  
Marc O. Lammers  
University of Hawai‘i, lammers@hawaii.edu

Acoustic communication can rapidly transfer a substantial amount of information, yet emitted signals must be conveyed and detected with enough clarity to allow appropriate physiological and behavioral responses. Many mysticete calls such as the humpback whale (*Megaptera novaeangliae*) song can be detected over large distances as a result of the propagating wave of acoustic pressure emitted from the whale. In whales and other mammals, we have a poor understanding of the acoustic particle motion component of these signals. Similar to other mammals with large ossicles fused to the skull, particle motion, an inherent component of sound, might also play an important role in mysticete communication and may similarly be masked or otherwise impacted by noise. Instruments such as DIFAR sonobuoys use particle velocity to localize whales over many kilometers, indicating that this cue may similarly be used by whales to detect and localize each other. To explore the particle velocity properties of the humpback whale song, three singing humpback whales were recorded from a vessel off Maui, HI, in March 2015, using a sensor that contained a digital magnetometer, a triaxial accelerometer (to measure 3-D particle velocity), and an omnidirectional hydrophone. Each whale was recorded at close range (<200 m) for 40 min. The median magnitude of the acoustic particle velocity signal was substantial (64.5 dB re 1 m/s) for song components with a median pressure of 135.4 dB re 1 µPa. As vessel and sensor gradually drifted away or toward the whales, acoustic particle velocity and sound pressure correspondingly decreased or increased (range, 49.3-77.9 dB re 1 m/s and 118.4-148.1 dB re 1 µPa, respectively), reflecting the change in position and distance of the whale with reference to the sensor. The particle velocity signals were high even at our maximal 200 m distance from the whale, indicating this cue is substantial well into the far field. These results demonstrate that there are predictable trends in the acoustic particle motion signal component and that this component of song is an acoustic cue available to nearby animals. As a vector that may decrease predictably from the singer source, acoustic velocity could aid whales in determining the bearing and relative distance of vocalizing animals, both valuable for communication. This vibratory nature of sound also supports bone conduction as a mode for whale hearing. These data also suggest that we must also consider and quantify the particle motion component of anthropogenic noise sources because of its potential role in masking communication.
Review of Seismic Survey Mitigation and Monitoring Measures for Cetacean Species at Risk

**Hilary Moors-Murphy**  
Fisheries and Oceans Canada, Hilary.Moors-Murphy@dfo-mpo.gc.ca

**James Theriault**  
Defense R&D Canada Atlantic and Fisheries and Oceans Canada, jim.theriault@drdc-rddc.gc.ca

On March 25-27, 2014, Fisheries and Oceans Canada (DFO) held the Canadian Science Advisory Secretariat national peer-review meeting, “Review of Mitigation and Monitoring Measures for Seismic Survey Activities in and near the Habitat of Cetacean Species at Risk” (DFO, 2014). Participants included DFO scientists and managers, academic experts, consulting experts, offshore petroleum board members, environmental organizations, and others. The objectives of this meeting were to review sound exposure criteria for avoiding impacts prohibited under the Species at Risk Act (SARA) on listed cetaceans, which include the killing, harming, and harassment of endangered or threatened individuals and destruction of their critical habitat; to determine whether the application of the current requirements outlined in the Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment (SOCP) are likely to avoid these SARA-prohibited impacts; and to identify modifications to the measures of the SOCP or additional mitigation and monitoring measures that could be used to avoid SARA-prohibited impacts. Although uncertainties about the impacts of seismic noise on cetaceans prevented establishment of thresholds for avoiding SARA-prohibited impacts (Theriault and Moors-Murphy, 2015), it was recognized that implementation of cautionary and reliable risk-reducing mitigation measures is the most effective approach for minimizing potential negative effects (DFO, 2015). It was concluded that most of the mitigation measures of the SOCP likely reduce the potential negative impacts of seismic airgun sounds on individuals but to varying degrees of effectiveness and with some caveats. For example, the SOCP focuses on reducing significant adverse effects on individuals and populations through efforts to avoid potential physical injury to animals in close proximity of operating airguns but does not provide specific mitigation measures for reducing SARA-prohibited impacts that may occur at greater ranges from the sound source (i.e., beyond the safety zone), including impacts on important habitats. Several additional mitigation and monitoring measures were thus recommended (DFO, 2015). This talk will provide an overview of the recommendations suggested to enhance the effectiveness of the SOCP for avoiding SARA-prohibited impacts on listed cetaceans.


Implementing a protocol to detect whether whales may suffer from acoustic trauma is key to understand the sensitivity of these species to anthropogenic noise. Analysis of the odontocete cochlea by Scanning Electron Microscopy (SEM) is currently giving us a very high resolution imaging of the organ of Corti reticular lamina. However, preparation of specimens for SEM (including dehydration) causes shrinkage of the tissue. Here, we present results obtained by an alternative technique, immunofluorescence, for harbor porpoise, common dolphin and beluga ears fixed in 10% neutral buffered formalin, approximately 1 to 7 hours post-mortem. The inner ears were decalcified with 14% EDTA and dissected using the whole-mount technique, allowing the isolation of the organ of Corti in intact cochlear half turns. We used an antibody against Prestin to label outer hair cells. This motor protein is specific to outer hair cells but was also found, surprisingly, in the apical cellular region of inner hair cells. An anti-Myosin VI antibody labeled hair cell cuticular plate and stereocilia; missing hair cells were clearly identified with an ³X² shape pattern as a result of the growth of supporting cells after hair cell death. In addition, an anti-Sox 2 antibody was specific for marking the nucleus of supporting cells while an anti-Neurofilament 200 kD antibody was specific for type-I afferent innervation. We conclude from our study that: 1) the immunofluorescence technique is suitable for labeling different cell types within the organ of Corti and its associated innervation with minimal artifacts in those cases when ears can be collected and fixed very soon after death (maximum around 6-7 hours post-mortem) and 2) Myosin VI labeling is particularly appropriate to detect hair cell loss in odontocete species such as harbor porpoise, common dolphin and beluga.
Implementing Multiple Digital Platforms to Effectively Communicate Research on Underwater Acoustics

Holly Morin  
Graduate School of Oceanography, University of Rhode Island, holly_morin@uri.edu

Christopher Knowlton  
Graduate School of Oceanography, University of Rhode Island, cknowlton@uri.edu

Gail Scowcroft  
Graduate School of Oceanography, University of Rhode Island, gailscow@uri.edu

Kathleen J. Vigness-Raposa  
Marine Acoustics, Inc., kathleen.vigness@marineacoustics.com

James H. Miller  
Ocean Engineering, University of Rhode Island, miller@uri.edu

Darlene R. Ketten  
Jefferson Science Fellow, National Academy of Sciences and US Department of State, Harvard University Medical School, and Woods Hole Oceanographic Institution, KettenDR@state.gov

Arthur N. Popper  
Department of Biology, University of Maryland, apopper@umd.edu

The Discovery of Sound in the Sea (DOSITS) project has produced a comprehensive set of resources on underwater sound. The DOSITS website (www.dosits.org) was launched in 2002. Its content has been identified and developed through a series of needs assessments targeting diverse audiences. Over the last 14 years, the project has increased the diversity of digital platforms used to meet its objective of communicating accurate, peer-reviewed science to diverse audiences. Since the DOSITS site was launched, there has been a great increase in Internet accessibility, both in terms of the number of people connected and in bandwidth available. At the same time, a sea of change has occurred in website technologies, making it easier to provide an incredible range of media and interfaces. In the last six years, the platforms or methods by which people can access digital media and the devices used to access that media have greatly proliferated. These changes provide opportunities and challenges for those communicating science. As researchers strive to effectively communicate the broader impacts of their work and bring scientific results to specific audiences, such as the international regulatory community, it is necessary to address the diverse digital platforms available. The DOSITS team now uses many digital platforms including websites, electronic books, live webinars, and online videos. The current DOSITS website bears little resemblance to the initial 2002 version. It has become a mobile friendly platform with vivid imagery, spectrogram animations, and other enhancements. The DOSITS content is also available in a digital iBook with high-resolution imagery, videos, and sound files, all in an interactive, touch-and-play format. The project conducts live informational webinars that offer a structured opportunity for participants to not only learn from experts in underwater acoustics but also directly ask questions and explore more deeply their topic of interest. Finally, DOSITS has developed short, informational videos on focused topics as a new digital resource. The evolution of the DOSITS project to leverage multiple digital platforms allows different audiences to access DOSITS content in forms that best meet their information needs at a preferred time. A review of these methods will be provided, including the challenges and successes surrounding each digital platform in a lessons-learned format that will help other researchers communicate their research more effectively.
Low-Frequency Noise Alters Dolphin Biosonar Click Level: Evidence for the Lombard Effect

Jason Mulsow  
National Marine Mammal Foundation, jason.mulsow@nmmf.org  
James J. Finneran  
US Navy Marine Mammal Program, james.finneran@navy.mil

Efforts to predict and mitigate the effects of noise on aquatic life have increasingly focused on auditory masking, where the detection or identification of an acoustic signal is impeded by background noise. The most studied vocal modification employed to overcome masking is the Lombard effect, where vocalization amplitudes increase in proportion to noise levels (Lombard, 1911; Scheifele et al., 2005; Holt et al., 2009). For anthropogenic noise sources that are often low frequency in nature, it is usually assumed that the masking and Lombard effects in odontocetes are limited to low-frequency, interindividual communication signals and have relatively little impact on high-frequency biosonar signals. This assumption is supported by data demonstrating that overlap of vocalization and noise frequencies is necessary to induce the Lombard effect (Stowe and Golob, 2013). This study tested the hypothesis that low-frequency noise can induce a Lombard effect in bottlenose dolphin (Tursiops truncatus) echolocation signals (“clicks”). A dolphin was trained to perform a target-change detection task, and subject performance and click acoustic parameters were recorded. On ~25% of the trials, spectrally “pink” noise was presented. Three combinations of noise bandwidth and one-third octave band sound pressure level were used: 0.6-5 kHz at 130 dB re 1 μPa, 0.6-10 kHz at 120 dB re 1 μPa, and 0.6-10 kHz at 130 dB re 1 μPa. This experimental design allowed for a controlled assessment of any potential Lombard effect; noise and click parameters were precisely measured, and there was a definite motivation by the dolphin to perceive the target change (i.e., effectively autocommunicate). The dolphin correctly detected the target change and withheld a response during control intervals on all trials. Increases in click level, synchronous with noise onset, were observed for all noise conditions. This increase was greatest for the 0.6-10 kHz at 130 dB re 1 μPa condition and smallest for the 0.6-5 kHz at 130 dB re 1 μPa condition. Comparable increases in click level were not observed when noise was not presented. These results suggest that background noise considered to be below the echolocation frequency range may alter click level in this species. It seems unlikely that this alteration is a result of the masking of click or echo frequency content due to the near absence of energy below 10 kHz in clicks. These preliminary data suggest that low-frequency noise may indeed affect high-frequency echolocation behavior in odontocetes.


Silver (*Hypothalmichthys molitrix*) and bighead (*H. nobilis*) carp are invasive fish species that negatively impact aquatic ecosystems throughout the Mississippi River Basin. These species compete with native paddlefish (*Polyodon spathula*), gizzard shad (*Dorosoma cepedianum*), and bigmouth buffalo (*Ictiobus cyprinellus*) for food and space. State and federal agencies are evaluating the use of acoustical barriers as a tool for an integrated pest management system to block the expansion of these species into the Laurentian Great Lakes. Acoustical deterrents broadcasting a high-frequency (1-Hz to 10-kHz), underwater outboard motor sound have been effective (>90%) at deterring bighead and silver carp in a controlled setting; however, the impacts this sound would have on native species has not been assessed. In a series of controlled experiments, the swimming behaviors of a native ostariophysian (e.g., fathead minnow *Pimephales promelas*), invasive ostariophysians (e.g., bighead carp), and native nonostariophysians (e.g., paddlefish) were monitored in response to an outboard motor sound. Invasive carp demonstrated consistent negative phonotaxis (37 consecutive responses) to the motorboat sound. The nonostariophysians did not react to the stimulus and native ostariophysians were inconsistent in their response behavior; on average, responding less than two times. The observed responses were likely due to the increased hearing range and sensitivity of ostariophysians relative to nonostariophysians due to the presence of Weberian ossicles in ostariophysians. Based on these results, native nonostariophysians may not be negatively impacted by the placement of an anthropogenic sound barrier in a river. Funding was provided by US Geological Survey and the Minnesota Environment and Natural Resources Trust Fund.
Environmental Noise Pollution: Human Exposure and Mitigation

Enda Murphy
Planning and Environmental Policy, School of Architecture, Planning Building, Richview Clonskeagh, Dublin 14, ei.dcu@yhprum.adne

In Europe public attitude surveys show that environmental noise is often rated as a significant environmental and public health concern by citizens. In the academy, there is a growing body of evidence which highlights the link between prolonged exposure to environmental noise and negative health outcomes. These include increased annoyance, sleep disturbance, cardiovascular disease, tinnitus, and cognitive impairment in children, among others. The WHO has recently estimated that one in five individuals in Europe suffer from sleep disturbance as a result of traffic noise alone. In terms of mitigation, the EU adopted legislation - the Environmental Noise Directive - in 2002 which has compelled EU nations to create strategic noise maps and noise actions plans of major cities, roads, railways, airports and industrial sites within their territories as well as to estimate the level of population exposure therein. In policy terms, the legislation is highly progressive and is a genuine attempt to gauge the extent of the noise exposure problem at an EU level. Within this context, the current paper explores the recent evidence base for the noise-health relationship placing specific focus on the role of transportation noise. It also critically analyses the success of the European Noise Directive highlighting the results from the first two rounds of strategic noise mapping (2007 and 2012) as an exemplar of the extent or otherwise of progress in noise mitigation within the EU. Emphasis will also be placed on recent studies in Ireland which examine the extent of industrial/transportation noise in the city as well as recent work assessing the role of new technology in aiding environmental noise pollution monitoring through citizen engagement and pervasive sensing approaches. In this regard, the role of smartphones as low-cost environmental noise monitoring devices is explored for the future.
Passenger Ship Source-Level Determination in a Shallow-Water Environment

Mirko Mustonen
Department of Mechanics, Tallinn University of Technology, mirkomustonen@gmail.com

Aleksander Klauson
Department of Mechanics, Tallinn University of Technology, aleksander.klauson@ttu.ee

Thomas Folegot
Quiet-Oceans, thomas.folegot@quiet-oceans.com

Dominique Clorennec
Quiet-Oceans, dominique.clorennec@gmail.com

Janek Laanearu
Department of Mechanics, Tallinn University of Technology, janek.laanearu@ttu.ee

Madis Ratassepp
Department of Mechanics, Tallinn University of Technology, madis.ratassepp@ttu.ee

Shipping constitutes a major source of low-frequency (5- to 500-Hz) ambient underwater noise. For a better understanding of the sound radiation from an individual ship, one has to study the spectral and spatial distribution of the ship’s underwater radiated noise and its source level (SL). This information can be obtained directly by using standard measurement procedures (ISO/PAS, 2012). Such procedures have given good results for the measurement of noise from large ships in deepwater conditions (Arveson and Vendittis, 2000), where the back calculation of the SL from the received level (RL) can be accomplished using spherical spread law for determining the transmission loss (TL). This approach is not always valid in shallow-water conditions, where the dependence of the TL on distance must be determined by applying a more sophisticated modeling of the underwater sound propagation, as in the parabolic equation method (Collins, 1993). In frames of the BIAS Life+ project (Sigray et al., 2016), the ambient-noise measurements in the Baltic Sea were carried out in the entire year 2014. Nearly 40 underwater noise recorders were deployed all over the Baltic Sea. The ambient-noise measurements revealed the dominance of shipping noise in the underwater noise recordings. The shipping noise sources were identified by temporal tracking of the distances of the ships from the measuring hydrophone using ship traffic data from an automatic identification system (AIS). One of the noise measurement positions was near the busy commercial shipping lanes in the Gulf of Finland (GoF), where some passenger ships traveling between Tallinn and Helsinki pass several times a day, thus providing a large amount of data. Using this large data set of recorded, identified, and positionally tracked ship noise events, it is possible to assess the TL between the measurement point and each tracked location of the ship. For the modeling, one must determine the acoustical characteristics of the water column and the sea bottom. Given that the bathymetry of the GoF is quite uneven and azimuthally variable, this is a challenge. The problem can be approached using some average values of the essential acoustical properties of both the water column and the sea bottom to estimate the attenuation rate of the measured ship noise data. Once the dependence of the TL on the azimuth and range is estimated, it can be used for the back calculation of the SL, allowing the ship’s radiated underwater noise SL directivity patterns in shallow-water conditions to be found.


Three Odontocete Species Dampen Hearing Levels When Warned of Impending Loud Sound

P. E. Nachtigall
University of Hawai‘i, Hawai‘i Institute of Marine Biology, nachtiga@hawaii.edu

A. Ya Supin
Severtsov Institute, Russian Academy of Sciences

A. F. Pacini
Severtsov Institute, Russian Academy of Sciences

Hearing sensitivity change was investigated when a warning sound preceded a loud sound in the false killer whale (Pseudorca crassidens) bottlenose dolphin (Tursiops truncatus) and the beluga whale (Delphinapterus leucas). Hearing sensitivity was measured using pip-train test stimuli and auditory evoked potential recording. When the test/warning stimuli preceded a loud sound, hearing thresholds before the loud sound increased relative to the baseline. The threshold generally increased 12-15 dB. Experiments to reveal underlying processes for hearing change using an extinction test, in which only the warning sound and not the loud sounds were presented, revealed that the most likely process for change was that the animals quickly learned to dampen hearing in anticipation of loud sound. Work with the beluga whale, showed little initial hearing recovery during three experimental extinction sessions followed by a jump-like return to the baseline thresholds. The low exposure level producing the hearing-dampening effect in the beluga whale (156 dB re 1 microPa² in each trial), and the recovery during the extinction process, are considered as evidence that the observed hearing threshold increases were not a result of the unconditioned effect of the loud sound (like TTS) and were instead a manifestation of a classically conditioned dampening of hearing when the whale anticipated the quick appearance of a loud sound. Experiments with multiple frequencies of exposure and shift provided evidence of different amounts of hearing change depending on frequency, indicating that the hearing sensation level changes were not likely due to a simple stapedial reflex. When warned, all three species rapidly learned to internally ‘plug their ears’ in anticipation of loud sounds when warning and loud sounds were simply paired in time. Given that such a wide variety of odontocetes demonstrate quick hearing change with a simple warning, it seems reasonable to suggest that some hearing protection might be afforded to wild animals by providing warning signals. Loud navy sonars could be preceded by a much quieter warning pulse and multiple airgun arrays could simply fire a single gun before the rest to allow free swimming odontocetes the opportunity to learn to adjust and protect their hearing.


A Novel Automated Identification System-Based Approach To Modeling Vessel Noise Emissions

Sarah T. V. Neenan
University of Southampton, stvn1e12@soton.ac.uk
Paul R. White
University of Southampton, prw@isvr.soton.ac.uk
Timothy G. Leighton
University of Southampton, T.G.Leighton@soton.ac.uk
Peter J. Shaw
University of Southampton, P.J.Shaw@soton.ac.uk

Concern about the impacts of noise pollution on fish has primarily focused on acute effects of noise, for example, those caused by pile driving, that could lead to instantaneous consequences and direct physical harm, such as tissue damage. The rising number of research and management efforts to combat marine noise pollution has led to an increasing awareness of the long-term chronic effects of ocean noise and changes in underwater soundscapes. Vessel noise emissions have played a large part in the increase of ocean ambient noise over recent decades and have been observed to impact fish behaviors through decreased forging efficiency, changes in vocalizations, and altered schooling behaviors. Such behavioral changes have the potential to instigate effects at the population level. Recent research has highlighted the importance of soundscape characterization, modeling, and mapping. Models and noise maps are seen as valuable tools for generating comprehensive results at low costs. Consequently, the model-based approach to research represents a powerful way to evaluate noise levels. This research is the first model to evaluate vessel noise pollution in waters surrounding the United Kingdom at a large temporal (yearly) and spatial scale (hundreds of kilometers) using an automated identification system (AIS) and online static vessel data. The vessel noise map is calculated using source levels of individual ships to produce noise emissions at each AIS transmission point along a vessel transit line. The accumulation and propagation of these transit line emissions, in 1-km grid squares, will produce a cumulative noise map of the waters surrounding the United Kingdom. The applications of this map are manyfold and include evaluating the efficiency of marine protected areas to mitigate the impacts of noise pollution; assessing the effects of vessel noise barriers on fish migrations; showing how vessel noise can influence the spatial distributions of fish species; and determining the noise-related consequences of altering the shipping lanes. The ocean vessel noise map will be made readily available to aid with marine planning and developing mitigation strategies.
Sound Exposure Changes European Seabass Behavior in a Large Outdoor Floating Pen: Investigation into Several Modulating Factors

Erol Neo
Leiden University and IMARES, Wageningen University, erolneo@gmail.com

Jeroen Hubert
Leiden University, j.hubert.2@umail.leidenuniv.nl

Loes Bolle
IMARES, Wageningen University, Loes.bolle@wur.nl

Carel Ten Cate
Leiden University, c.j.ten.cate@biology.leidenuniv.nl

Hans Slabbekoorn
Leiden University, H.W.Slabbeek@biology.leidenuniv.nl

Underwater sound from human activities may affect fish behavior negatively and threaten the stability of fish stocks. However, some fundamental understanding is still lacking for adequate impact assessments and potential mitigation strategies. For example, little is known about the potential contribution of the temporal features of sound, the efficacy of ramp-up procedures, the extent of fish habituation to sound exposure, and the influence of environmental contexts on the impacts. Using a semi-natural set-up, we conducted two experiments on European seabass in an outdoor pen. In the first experiment, we tested the effects of sound intermittency, pulse interval regularity and the efficacy of a 'ramp-up' procedure. In the second experiment, we tested if the fish habituated to eight consecutive exposure trials and if behavioral changes were influenced by the time of the day. Upon sound exposure, the fish increased swimming speed and depth, and swam away from the sound source. The behavioral readouts were generally consistent with earlier research, but the changes and recovery were not significantly influenced by sound intermittency and interval regularity. Furthermore, the ‘ramp-up’ procedure caused startle response but did not drive fish away as expected. Our results also showed that behavioral changes were stronger at night than at daytime. Moreover, the fish not only habituated to sound exposure within a session, they also reduced their response to consecutive sessions, showing between-session habituation. Our results provide important insights into factors that may modulate sound impacts, and carries implications that can inform mitigating strategies.
Comparing Models of Humpback Whale Response to Small Airgun Arrays and Testing the Efficacy of “Ramp-Up”

Michael Noad  
The University of Queensland, mnoad@uq.edu.au  
Rebecca Dunlop  
The University of Queensland, r.dunlop@uq.edu.au  
Robert McCauley  
Curtin University  
Douglas Cato  
University of Sydney, doug.cato@sydney.edu.au

“Ramp-up” or “soft start” is a technique used by industry that theoretically reduces acoustic impacts on marine mammals and other animals. During ramp-up, acoustic sources are started at a low level and then increased until full operating power is reached. In theory, this allows animals to move away from the source before being exposed to full power, reducing acoustic exposure. To test behavioral responses to ramp-up, Dunlop et al. (2016) exposed migrating humpback whales to a small array of seismic airguns with two experimental treatments: (1) a ramp-up comprising 20 in.\(^3\), 60 in.\(^3\), 140 in.\(^3\), and 440 in.\(^3\) and (2) a “constant source” 140 in.\(^3\) array with no ramp-up. In both treatments, groups of whales significantly changed their movements, presumably to avoid the source. In the current study, we propose five possible models for behavioral responses of whales to acoustic sources and use this experimental evidence as well as new data on cumulative levels to test these. Tested models include animals moving away from the source (1) due to the proximity of an intimidating source (proximity model); (2) only when the levels reach a certain level (dose-response model); (3) when they perceive the increasing nature of the sound and move away in anticipation of higher levels to come (cognitive model); (4) at higher levels for ramp-up than for a constant source (desensitization model); and (5) when they are startled by starting the source at a sufficiently high level (startle model). Behavioral reactions to the airguns generally occurred within the first 10 min of exposure and were not significantly different in magnitude between treatments (Dunlop et al., 2016). This best supports the proximity model, with whales reacting quickly to the presence of a disturbing acoustic stimulus rather than to a particular level (dose model) or step-in level (cognitive, desensitization, and startle models). Cumulative received levels, however, were also not significantly different between the two treatments, which better supports the dose model, suggesting that both proximity and cumulative (rather than “per shot”) dose may be important factors in regulating the whales’ responses to airguns. Although this study provides little support for the efficacy of ramp-up in terms of limiting a cumulative dose compared with a constant source, other tests of efficacy are required. These would expose whales to higher levels and test the degree to which cumulative levels are reduced by their response compared with no response.

Acoustic Particle Motion and Pressure Observed During a 100-kg TNT Depth-Charge Exercise

Andreas Nöjd
FOI, Swedish Defence Research Agency, andreas.nojd@foi.se
Mathias H. Andersson
FOI, Swedish Defence Research Agency, mathias.andersson@foi.se

The research on the impact of anthropogenic noise on aquatic life is at a stage where for some species, even psychologically driven responses are mapped to some extent, whereas for others, thresholds for fatal injuries are still unknown. Ethics, funding, and experimental difficulties all cause these discrepancies and sometimes makes for a slow progress, but one thing is clear, as the response database of aquatic animals is filling up so must the database of source characteristics. A particular void of data is source characteristics in terms of particle motion; another is more detailed information of an emitted acoustic pressure time series because not only is the pulse peak amplitude important, but also, e.g., the energy and the rise time are important as well as other potentially important parameters unknown today. This study focuses on collecting and interpreting particle motion and acoustic pressure times series during underwater detonations of a series of 100-kg TNT depth charges. The particle motion measurements are made using accelerometers that are housed in a nearly neutral buoyant sphere suspended in the water volume.

The detonation of underwater explosives cause several far-reaching acoustic pulses, of which the strongest in amplitude by far is the shock wave formed during the explosion. It is characterized by a seemingly infinite rise time and an exponential decay during at least its first time constant. After the initial blast, other pulses are consecutively generated by oscillation of a gas bubble containing by-products of the chemical reaction. Although weaker in amplitude, these pulses can be more energetic that the shock wave and are therefore of interest when quantities such as SEL single pulse and SEL cumulative for sound pressure and the particle motion equivalent are important. In addition to these pulses, wave propagation via the bottom can be important in certain cases.

Because depth charges of the kind studied here are commonly used during antisubmarine warfare exercises, the potential environmental impact clearly motivates a risk assessment. In addition, the detonation weight is in the same order of magnitude as most submerged mines.
Comparative and Cumulative Energetic Costs of Odontocete Responses to Anthropogenic Disturbance

Dawn P. Noren
Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, dawn.noren@noaa.gov

Marla M. Holt
Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA, marla.holt@noaa.gov

Robin C. Dunkin
University of California, Santa Cruz, rdunkin@ucsc.edu

Nicole M. Thometz
University of California, Santa Cruz, nthometz@ucsc.edu

Terrie M. Williams
University of California, Santa Cruz, tmwillia@ucsc.edu

Odontocetes respond to vessels and anthropogenic sound by modifying vocal behavior, surface active behaviors, dive patterns, swim speed, direction of travel, and activity budgets. However, the consequences of these responses are often difficult to quantify in biological currencies. One method to assess the biological significance of disturbance is to measure the energetic costs of responses. In previous work, we measured the metabolic costs of performing surface-active behaviors, producing and modifying communicative sounds and echolocation clicks, and swimming over a range of speeds in delphinids. Building on our previous work, we estimated the energetic costs of published responses to anthropogenic disturbance, including sonar and vessel noise, for several odontocete species (bottlenose dolphin, killer whale, harbor porpoise, and beaked whales). Exposure scenarios and behavioral responses vary across odontocetes. For example, killer whales and bottlenose dolphins increase surface-active behaviors, alter acoustic signals, and modify activity budgets in response to vessels. Beaked whales respond to both vessels and sonar by modifying acoustic signal production and dive behavior. Harbor porpoises increase surface-active behaviors, respiration rate, and swimming speed in response to sonar. Using a novel approach, we quantified the metabolic costs of responses on a fine temporal scale that can be scaled to estimate the total energetic costs of a range of exposure scenarios for a diverse group of cetaceans. The energetic impact varies across species and scenarios, and cumulative costs are dependent on the frequency of exposure. For example, the cumulative energetic cost of ephemeral and low-cost responses to vessel noise (e.g., performing tail slaps, performing one to two breaches, increasing whistle rate and amplitude) combined with the energetic cost of changing swim speed with activity state modification increases daily energy expenditure by <3% in killer whales. In addition, the previously reported 18-67% reduction in bottlenose dolphin and killer whale foraging activity in the presence of vessels has the potential to significantly reduce individuals’ daily energy acquisition. Indeed, across all odontocete species, decreased energy acquisition as a result of reduced foraging has a larger energetic impact on the energy balance of individuals than the energy expenditure associated with other observed behavioral responses. This work provides a powerful tool to investigate the biological significance of multiple behavioral responses that are likely to occur in response to anthropogenic disturbance. This is critical for linking short-term impacts to long-term, population-level consequences and informs models such as the population consequences of acoustic disturbance model.
Effects of Pile Driving on Bottlenose Dolphins in the Shannon Estuary Special Area of Conservation, Ireland

Joanne O'Brien  
Galway-Mayo Institute of Technology, joanne.obrien@gmit.ie

Simon D. Berrow  
Galway-Mayo Institute of Technology, simon.berrow@gmit.ie

The Shannon Estuary located on the West Coast of Ireland forms the largest estuarine complex in Ireland, covering an area of 500 km² of navigable water, extending for 100 km, from Limerick City to Loop Head, County Clare. The estuary is one of Europe’s principal deepwater berths catering to ships of up to 200,000 deadweight tonnage. It has six main terminals that handle up to 1,000 ships, carrying 12 million tons of cargo per annum. Additionally, a car and passenger ferry operates year-round between Killimer, County Clare, and Tarbert, County Kerry, and the estuary has two licensed dolphin-watching vessels operating between April and October. Fishing activity also takes place in the estuary, with potting being the most notable. Industries located along the Shannon Estuary include power generation plants at Moneypoint, County Clare, and Tarbert, County Kerry, and a bauxite refinery at Auginish. Moneypoint power station, which is Ireland’s largest electricity-generating station (coal powered) has been the focus of long-term (since 2008) static acoustic monitoring (SAM) of *Tursiops truncatus* (bottlenose dolphin) using C-PODs, which are automated click detectors. The Shannon Estuary is an important habitat for a resident group of bottlenose dolphins and is currently one of two designated special areas of conservation (SACs) (lower River Shannon, site code 2165) for this species in Ireland. The most recent estimate of dolphin abundance in the estuary stands at 107 individuals (95% CI = 83-131). As part of its duty to target carbon emissions and as part of Ireland’s commitment on greenhouse gases under the Kyoto Protocol (Commission Decision 2005/166/EC), Moneypoint power station is developing a wind farm on site. During the installation of piles for the wind farm foundations, dolphin presence was monitored at the vicinity using C-PODs. This facilitated the BACI concept, where a deep understating of site usage was already known “before” construction due to the long-term monitoring program in place. SAM continued at the site during and “after” construction (allowing for a comparison between pre- and postconstruction presence). Comparisons were also made between a “control” site (which consisted of a similar site further upriver) and the “impact” site (where construction took place off Moneypoint). This study was the first assessment of the potential effect of pile driving on the behavior of this discrete population at a known foraging area where baseline monitoring showed dolphins to be present on 88% of days monitored.
The Regulatory and Legal Environment of Underwater Noise

Daniel Owen
Fenners Chambers, Cambridge, UK, daniel.owen@fennerschambers.com

This presentation will use two case studies to illustrate the regulatory framework for underwater noise. Using the case studies, the presentation will seek to draw out some general principles of relevance to Theme 6. Both case studies relate to international organizations, namely the International Maritime Organization (IMO) and the International Seabed Authority (ISA). In 2014, the Marine Environment Protection Committee (MEPC) of the IMO approved guidelines on ship-sourced ocean noise (Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life [MEPC.1/Circ.833]). This presentation will first summarize the steps in the evolution of the IMO’s guidelines, with some thoughts about the possible next steps in the regulation of this sound source. It will then consider another economic activity, namely exploration and exploitation of mineral resources in areas beyond national jurisdiction. This activity falls within the mandate of the ISA. As mineral exploration moves toward exploitation, questions may arise about the ocean noise generated by that exploitation. The presentation will consider the regulatory options available to the ISA and will seek to make a comparison with the IMO process.
Evidence of Hearing Loss Due to Dynamite Fishing in Two Species of Odontocetes

Aude F. Pacini  
Hawai‘i Institute of Marine Biology, University of Hawai‘i at Manoa, aude@hawaii.edu

Paul E. Nachtigall  
Hawai‘i Institute of Marine Biology, University of Hawai‘i at Manoa, nachtiga@hawaii.edu

Adam Smith  
Hawai‘i Institute of Marine Biology, University of Hawai‘i at Manoa, adambsmi@hawaii.edu

Leo Suarez  
Marine Mammal Stranding Network, ljasuarez@oceanadventure.com.ph

Lem Aragones  
Institute of Environmental Science and Meteorology, University of the Philippines, laragones@iesm.upd.edu.ph

Carlo Magno  
Ocean Adventure, cgmagno@oceanadventure.com.ph

Gail Laule  
Marine Mammal Stranding Network/Wildlife in Need, gelaule@oceanadventure.com.ph

An important effort has been invested into understanding the effects of anthropogenic sound on marine life. These efforts primarily focus on large geographically distributed events such as naval exercises and oil exploration. However, smaller local and regional activities are rarely quantified or taken into account when investigating population and ecosystem stressors. Blast fishing is an illegal and unsustainable practice that is often reported in southeast Asia and Africa. The effects on fish and reef-building corals are well documented, yet there is limited information on the effects on other larger species and near-shore predators. In recent years, several strandings in the Philippines have increasingly been temporally linked to underwater explosions associated with blast fishing. The goal of this study was to measure the hearing of stranded dolphins, including two spinner dolphins (*Stenella longirostris*) and two rough-toothed dolphins (*Steno bredanensis*), that were rehabilitated in Subic Bay at Ocean Adventure Dolphin Rescue Center in cooperation with the Philippines Marine Mammal Stranding Network and Wildlife in Need. Hearing measurements were conducted using noninvasive auditory brain stem responses (ABRs). Test stimuli consisted of tone pips ranging from 8 to 128 kHz. To date, all the results on stranded animals with vestibular clinical signs indicated elevated thresholds and various degrees of hearing loss, including three individuals with severe hearing impairment beyond 22.5 kHz. These results provide evidence of hearing loss associated with impulsive sound exposure.
Bryde’s Whale Behavioral Metrics in the Southern California Bight from Acoustic Array Tracking

Camille Pagniello  
Scripps Institution of Oceanography, University of California, San Diego, cpagniello@ucsd.edu

Ana Širović  
Scripps Institution of Oceanography, University of California, San Diego, asirovic@ucsd.edu

Sean Wiggins  
Scripps Institution of Oceanography, University of California, San Diego, swiggins@ucsd.edu

Gerald D’Spain  
Scripps Institution of Oceanography, University of California, San Diego, gdspain@ucsd.edu

John Hildebrand  
Scripps Institution of Oceanography, University of California, San Diego, jahildebrand@ucsd.edu

The Southern California Bight (SCB) is a highly productive ecosystem and thus attracts a variety of cetaceans, including Bryde’s whales (*Balaenoptera edeni*). This species of baleen whale is present in the SCB, primarily for foraging, from spring until the beginning of winter. The SCB is an area of high anthropogenic activity where ocean noise is dominated by low-frequency (<100-Hz) sound from commercial shipping as well as higher frequency (above 1-kHz) sounds from sonar activity. Passive acoustic methods can be used to track vocalizing marine mammals to study their behavior, including changes in response to man-made noise. Several encounters of Bryde’s whales were tracked using a large-aperture (~1-km element spacing) seafloor array of five hydrophones mounted on autonomous high-frequency acoustic recording packages (HARPs) deployed over a 2-mo period from December 2010 to February 2011. Bryde’s whale Be4 calls within an area of 25 km² were detected in these recordings by a human analyst. Encounter durations ranged from 0.5 to 5 h. Time difference of arrivals (TDOAs) of a call between each hydrophone pair were computed by cross-correlating time series waveforms. A 5-km × 5-km × 1.3-km search box with 25-m grid spacing was defined within which a homogeneous sound speed and acoustic propagation model was used to calculate sets of modeled TDOAs for each grid point. To find the location of each whale call, the grid point with the smallest least squares difference between the set of measured and modeled TDOAs was used. Successive locations provided tracks from which sound source levels, swimming speeds, and calling rates were estimated, all biologically important behaviors that can be monitored for changes from before, during, and after anthropogenic events. These results provide a quantitative foundation required for sound impact studies as well as a population density estimate of this species in the SCB.
Underwater Sound Measurement Data During Diamond-Wire Cutting

Tanja Pangerc
National Physical Laboratory, tanja.pangerc@npl.co.uk

Acoustic data were analyzed for underwater noise from a conductor severance operation using diamond-wire cutting. Three autonomous recorders deployed at distances of 100 m, 250 m, and 800 m from an oil and gas platform acquired data for a period spanning several hours, including the relatively short period that corresponded to the time of the conductor termination with a 36-in. diamond-wire cutting machine. The analysis revealed that the noise from the diamond-wire cutting was not a dominant feature in the measured data at the three recorder locations. Analysis showed an increase in one-third octave band spectral density levels at a time that generally corresponded to the start and end of the cutting operation. An increase of up to ~15 dB was detectable in the one-third octave band level at frequencies above 5 kHz. There was no apparent increase in one-third octave band levels at frequencies below 5 kHz that could be associated with cutting. No tonal components in the data could be directly attributed to the diamond-wire cutting process. In general, the analysis indicated that the radiated noise from the diamond-wire cutting process of the conductor was not easily detectable above the background noise.
The Stellwagen Bank National Marine Sanctuary, located in a highly urbanized coastal area off the coast of Massachusetts in the United States, serves as an important foraging habitat for North Atlantic humpback whales (*Megaptera novaeangliae*; Friedlaender et al., 2009). During the summer months, large numbers of both recreational and commercial vessels are present in the vicinity of foraging humpback whales. Humpback whales produce a wide variety of low-frequency (<1-kHz) nonsong social sounds associated with foraging behavior (Stimpert et al., 2009; Parks et al., 2014). These signals are produced at lower amplitudes than song and, as such, may be subject to significant masking from noise from vessels in the area. The goals of this study were to (1) characterize the contribution of anthropogenic sound sources to the acoustic environment of foraging humpback whales both during daytime and nighttime hours and (2) document changes in the acoustic behavior of whales in the presence of ship noise. A total of 17 noninvasive DTAGs (acoustic recording suction-cup tags) were attached for a period of >12 hours between 2004 and 2016. All tag attachments spanned both daytime and nighttime hours. This study allows us to start to consider the long-term acoustic environment experienced by free-ranging cetaceans in urbanized habitats and to document the behavioral responses of individuals to shifting background noise levels.


Similar to geophysical and anthropogenic noise, biological contributions to soundscapes can vary considerably in frequency content, time, and intensity. Fish calls and choruses contribute significantly to marine biological noise. These acoustic phenomena occur over a wide range of timescales, providing prime examples of contributions that prove so difficult to sample and delineate in long-term soundscape monitoring. An individual fish may produce intense tonal or impulsive signals at regular intervals from seconds to hours and pause unexpectedly in between for undefined times. Chorusing fish can raise ambient noise by tens of decibels for periods of hours to days. The Centre for Marine Science and Technology has acquired data sets of underwater noise from around Australia for over two decades. Multiple calling patterns have been compared with environmental correlates to understand what may drive the fish calls at various recording locations and timescales and will be described in this presentation. Darwin Harbour, for example, experiences several fish choruses (nine described to date) that relate to seasonal (wet/dry), semilunar and lunar, and diurnal (solar, tidal) cycles, often in chorus presence, timing, and/or level (up to 40 dB re 1 µPa above broadband ambient levels). Chorus levels of Terapontids here can peak several hours apart over the space of only a few days. Temporal and frequency partitioning of calling can be nonexistent or be a complicated relationship of the choruses present at the time. Mulloway in the Swan River, Perth, increase noise levels every day around sunset for months, but peak calling location moves upstream/downstream. Meanwhile, off Onslow, the location of one fish chorus has been observed moving tens of kilometers onshore/offshore over a matter of days, and off Port Hedland, seven different fish choruses exist at various times of year. These offer a few examples of the timescales over which biological sources can occur and highlight the need for the application of appropriate temporal sampling regimens. Detecting, delineating, and understanding these patterns is a complex task and a metric from which they can be teased out would be an invaluable tool. A frequency- and timescale-specific index is described that indicates the complexity of the soundscape while also assessing the impacts of sampling duration. Examples are given from the above-mentioned Australian soundscapes.
Anthropological noise impact on marine life can be hard to estimate, and field measurements are expensive and offer only limited insight into the total soundscape resulting from human activity in a given scenario. Modeling tools such as dBSea are available and implement recognized acoustic propagation models (parabolic equation, normal modes, and ray tracing). In addition to modeling noise, dBSea can incorporate animal audiograms to account for specific spectral sensitivities and sediment properties to better estimate environmental impact. Even though models are useful tools for estimating soundscapes, they require careful tuning of parameters to produce accurate and thus acceptable results. It is essential for models to be tested against real-world data to ensure model validity, and, indeed, their use cannot be merited without such evaluation. Good use of modeling essentially “makes the most” of the data and can often produce very accurate estimates of noise distribution from very little empirical data. Here we evaluate the predictive capabilities of dBSea against a set of controlled scenarios and recorded industrial noise in Irish waters. The data are of varied character and have multiple origins. Long-term data were provided from the permanent hydrophone mounted in the Smartbay testing facility in Galway Bay. It provides background noise levels for a range of weather and traffic states. Opportunistic source-level recording and estimation (modeled as oscillating monopoles) came from data from an Ocean Instruments Soundtrap deployed in close proximity to the shipping lanes. Additional deployments from a small vessel recorded noise levels at a range of distances and across different depths and bathymetry. These measurements along with the recordings from the Smartbay unit provide the data for performance evaluation of the three advanced solvers in dBSea. On this basis, we give recommendations for robust parameter settings. We also suggest a systematic approach to classify inaccuracies to improve later use of this and other models to facilitate anthropogenic impact assessment.
Soundscape of a Pristine High-Latitude Ocean Area: One Year of Observations from the Lofoten-Vesterålen Cabled Ocean Observatory

Geir Pedersen
Christian Michelsen Research, geir.pedersen@cmr.no

Espen Storheim
Nansen Environmental and Remote Sensing Center

Lise Doksaeter Sivle
Institute of Marine Research

Rune Hauge
Christian Michelsen Research

Lofoten-Vesterålen is a vital area for key marine species in Norwegian waters and the foundation for many important fisheries as well as an important feeding area for marine mammals. This area is under increasing pressure from human activity, such as shipping, in addition to being a highly interesting area for future petroleum developments. Establishing a proper acoustic baseline before further development in this area is thus of high importance. A cabled ocean observatory in Lofoten-Vesterålen (LoVe) has been in place since 2014, and an extension of the existing observatory, consisting of one node with a variety of sensors including a wide-bandwidth hydrophone, will be established in 2017. Experiences from one year of operation are reported, and underwater sound recordings from October 2014 to November 2015 from the existing infrastructure were analyzed to examine the most prominent contributors to the soundscape. This is done through exploratory data analysis using hydrophone data and data from auxiliary sensors connected to the observatory as well as data from external sources such as AIS and meteorological stations. Transiting vessels and fishing vessels contribute to the overall soundscape throughout the period, as does sound generated by wind and precipitation. Biological sources contribute periodically with identified sounds from, e.g., sperm, humpback, and killer whales. Sensors in the observatory, echo sounders with a center frequency of 70 kHz and acoustic doppler current profilers (ADCPs) with a center frequency of 193 kHz, contribute in the high-frequency range. Future opportunities with the LoVe observatory are also discussed. The expansion of LoVe starts in 2017 and will greatly expand the network capabilities for underwater acoustic monitoring and targeted scientific studies.
The Lloyd's mirror effect is a local acoustic interaction that sometimes occurs at the ocean surface that can cause changes to acoustic signals. The surface-reflected signal with the direct-path waveform interference fringes can be observed in a spectrogram. Fin whales produce a variety of sounds but the most common and most studied is the 20-Hz "regular" call. Many studies have found a variation in some spectral characteristics of this call that seem to reflect geographic differences. However, the type of habitat, receiver, and whale depth and range variability on the spectral measurements of the call due to the Lloyd's mirror effect may occur. These effects would be more prominent within the “interference field,” with a boundary less than the distance from the sound source and with a calling whale close to the surface and at a low sea state. Using a sample of sequences of 20-Hz fin whale calls with estimated locations, our study aimed to (1) show and analyze differences of spectral parameters due to the Lloyd's mirror effect and (2) infer about the depth of the vocalizing whale. The composite spectrograms of the sequences (calls side by side and without intervals) showed that they were not homogeneous, and very different spectral characteristics of the calls could be identified within the same bout. The spectrograms also revealed a similar interference pattern (Lloyd’s mirror effect) that explained these differences. An understanding of the occurrence and the effects of this interference is important for studies of acoustic signals in the ocean, such as marine mammal sounds, that rely on a good characterization of the signals. We then used BELLHOP to model the transmission loss due to the Lloyd’s mirror effect as applied to a fin whale call generated close to the surface and recorded at the sea bottom by an instrument. Models obtained with BELLHOP for a source depth varying between 10 and 500 m were compared with the interference patterns identified in the composite spectrogram. This comparison allowed us to have an estimate of the depth at which the whales were calling. Our results show that some differences measured in fin whale calls are due to the effects of acoustic propagation. In addition, it shows potential as an approach to estimate the depth of calling whales without invasive methods.
Biophony in a Mussel Farm: Soundscape and Man-Made Noise Levels

Marta Picciulin
marta.picciulin@gmail.com

Silvia Colla
Center for Estuarine and Coastal Marine Sciences (CEMAS), Department of Environmental Sciences, Informatics and Statistics, University Ca’ Foscari Venice, slvcolla@gmail.com

Riccardo Fiorin
Laguna Project snc, riccardo.fiorin@lagunaproject.it

Fabio Pranovi
Center for Estuarine and Coastal Marine Sciences (CEMAS), Department of Environmental Sciences, Informatics and Statistics, University Ca’ Foscari Venice, fpranovi@unive.it

Stefano Malavasi
Center for Estuarine and Coastal Marine Sciences (CEMAS), Department of Environmental Sciences, Informatics and Statistics, University Ca’ Foscari Venice, mala@unive.it

During Summer 2015, four nighttime passive acoustic monitoring surveys were conducted in a partially decommissioned mussel farm located in the Venetian littoral zone (northern Adriatic Sea, Italy). A qualitative and quantitative analysis of the main biophonical and anthrophony sources was carried out, with particular reference to those acoustic features characterizing the local biophony as well as the spectral contents and levels characterizing man-made noise that is likely to affect the aquatic communities. Passive acoustic monitoring proved to be successful in characterizing the local ecosystem conditions over both temporal and special scales. Different soundscape features were found to be associated with different microhabitats (muddy bottom vs. artificial bottom structures). The biophonical sources associated with the spawning of important vocal species, with special regard to the sonic family of the Sciaenidae, were used as a biological indicator of a typical fish community. The results of this study suggest that the artificial bottom structures may work as fishery aggregated devices (FADs), where fish might utilize them for different ecosystem services such as food and shelter as well as a spawning and nursery area.
Cetaceans are facing extreme pressure from humans within their natural environments. Shifts in habitat use by cetaceans as well as changes to their distribution patterns are often listed as impacts from anthropogenic noise that can have profound effects both ecologically and economically for communities dependent on ecotourism. Using passive acoustic monitoring, we investigated how changes to a biological soundscape may alter dolphin distribution by studying the relationship between fish choruses, vessel noise, and Indo-Pacific humpback dolphin (*Sousa chinensis*) detection rates in the Pearl River Estuary, China. Analyses of over 20,000 recordings revealed temporal and spatial variation within fish choruses (ranging between $95.5 \pm 84.9$ [mean ± SD] and $138.9 \pm 70.9$ calls/2 min, duration between 50 and 346 min/night, and increases in background sound pressure levels between $3 \pm 2$ and $30 \pm 4$ dB), vessel presence (between 15 and 66% of a 24-h day), and dolphin detection rates between an average of $0.5 \pm 0.9$ (± SD) and $2 \pm 1.0$ detections/day over 125 days. Linear regression models revealed a significant correlation ($P < 0.05$) between fish choruses (call rate, chorus duration, and chorus sound pressure level) and dolphin detection rates; however, no relationship between fish choruses and vessel presence or dolphin detection rates and vessel presence were observed ($P > 0.05$). Furthermore, fewer dolphins were detected at sites where fish activity was less intense ($P < 0.05$). Thus fish activity rather than vessels may influence the distribution of dolphins within the Pearl River Estuary. These findings suggest that detrimental changes to fish populations from coastal developments may lead to potential shifts in habitat use for Indo-Pacific humpback dolphins.
The KwaZulu-Natal (KZN) Sharks Board in Durban, South Africa, has been managing bather protection nets off KZN’s most popular beaches since the 1950s to mitigate shark-human interaction. The number of nets deployed has varied over time, reaching a maximum in the early 1990s when the combined net length was 44 km (Dudley and Cliff, 1993). The nets function by fishing for potentially dangerous sharks but also take a bycatch of other marine megafauna, including the Indo-Pacific bottlenose dolphin *Tursiops aduncus*. In an effort to mitigate *T. aduncus* bycatch, acoustic deterrence devices (pingers) were installed at selected beaches on the KZN North Coast between 1993 and 2006. We investigated the spatial, temporal, and life history patterns of bottlenose dolphins caught between 1980 and 2009 and assessed long-term catch trends in relation to pinger deployments (1993-2006). A total of 1,034 animals were caught between 1980 and 2009 (annual mean ± SD of 34.5 ± 13.59). The mean annual catch rate was 0.94 ± 0.30 dolphins/km of net, and there was no significant linear trend in catch per unit effort (CPUE; *n* = 30 yr; *P* = 0.066). Comparing bycatch at beaches with pingers (impact) and at nearby beaches without pingers (control) for seven years before and seven years after pinger installation, we found that the average annual CPUE at impact beaches increased from 0.57/km of net before pinger deployment to 1.68/km of net after the introduction of pingers but decreased at control beaches from 1.53 to 0.53/km of net, respectively. A minimum of 1 pinger per net of 220 m length was deployed. We present dolphin bycatch patterns as a function of year, season, El Nino, and the presence of the annual sardine run (influx of migratory sardines) and highlight the importance of environmental covariates. We present source levels and emission beam patterns of pingers and discuss the observed outcomes of intentional behavior modification by acoustic devices, which are not only used on bather protection nets but also as a warning device around anthropogenic operations that temporarily emit strong levels of underwater noise.

The Maintenance of PAMGuard Software to Detect, Localize, and Classify Marine Mammals

Rachael Plunkett
SMRU Consulting, rp@smruconsulting.com

Douglas Gillespie
SMRU, dg50@st-andrews.ac.uk

Jamie MacAulay
SMRU, jdjm@st-andrews.ac.uk

Passive acoustic monitoring (PAM) is widely used as a tool in the mitigation of the potential effects of underwater sound on marine mammals. Marine mammal vocalizations vary enormously in frequency and duration from the 10- to 15-Hz, 15-s duration moans of blue whales to the ultrasonic 130-kHz, 100-µs duration echolocations clicks of porpoises. Different processing algorithms and hardware configurations are required to detect and localize such a diverse range of sound types. Mitigation exercises, by their very nature, also tend to take place in a highly variable noise environment, so a system that allows easy operator intervention and checking of detection results is essential if high rates of false alarm are to be avoided.

PAMGuard was created to provide a standard software infrastructure for the detection, classification, and localization (DCL) of marine mammal vocalizations. PAMGuard supports a wide range of sound acquisition devices and multiple channels of data can be processed in real time at sample rates in excess of 500 kS/s. The Java-based software is free to download and is open source, providing a rapid development environment for new DCL algorithms. The software undergoes a continuous process of improvement and bug fixing to ensure compatibility with new versions of Windows, Java, and external hardware. In addition, we support other PAMGuard developers around the world. To date, maintenance and support for PAMGuard has been provided through direct exploration and production (E&P) industry funding via the International Association of Oil & Gas Producers (IOGP) Sound and Marine Life Joint Industry Programme. Funds are used to provide basic support to industry users, fix any reported bugs, and provide general maintenance. Maintenance funding is now transitioning to a voluntary contribution system that will operate based on payments from the owners of the PAM equipment that employ the PAMGuard software. Currently, these arrangements are being implemented within the oil and gas industry, particularly for seismic surveys, but it is hoped that it will be adopted by other offshore users, including the renewable energy sector, in the near future. Examples of recent maintenance activities are the provision of a new database interface and Java 8- and 64-bit compatible software versions. We are also working to alter the plug-in architecture, making it easier for developers to distribute bespoke modules. An improved real-time target motion localization module will also be released later this year. Additional information is available at www.pamguard.org.
Sound Exposure Level Measurements and Model Predictions for a Marine Seismic Airgun Array in a Shallow-Water Environment.

Mark K Prior
TNO, The Netherlands, mark.prior@tno.nl
Michael A Ainslie
TNO, The Netherlands, michael.ainslie@tno.nl
Bas Binnerts
TNO, The Netherlands, bas.binnerts@tno.nl
Stefania Giodini
TNO, The Netherlands, stefania.giodini@tno.nl
Ozkan Sertlek
TNO, The Netherlands, ozkan.sertlek@tno.nl

Marine seismic surveys are widely used for hydrocarbon exploration and reservoir monitoring, and the potential impact on marine life of airgun signals is a subject of active research. This impact is a combination of physical acoustic, physiological, and behavioral factors, and an important step in the process of predicting it is the calculation of the acoustic field incident at long ranges from airguns as quantified by the energy-related metric of sound exposure level (SEL). The environmental impact of airgun surveys is strongly influenced by sound in a higher frequency range (~100-500 Hz) than is normally considered in seismic data processing. Such sound can become trapped in the water column and propagate to horizontal ranges equivalent to a large number of water depths. Models capable of predicting the generation and propagation of this sound are under development, and there is a requirement for their validation by intermodel comparison in well-described test cases and by comparison with measured data. Measurements of SEL spectra associated with signals transmitted by a marine seismic airgun array are compared with predictions made by a computer model. Sound pressure was recorded at 3 receivers moored in a shallow-water (35-m) region of the North Sea while a seismic survey vessel transmitted signals in a “drive-by” track geometry. The measurements illustrate how SEL varies as a function of source receiver range and bearing relative to tow direction. A computer model is used to predict the far-field signature of individual airguns, which are then combined to obtain the far-field signature of the airgun array as a function of bearing and elevation. This source description is coupled with an acoustic propagation model to predict SEL for source receiver geometries matching the experimental scenario. Model measurement agreement is shown to be generally good (±1 dB) at ranges up to 1 km, corresponding to a distance of ~30 water depths from the source. At longer ranges, the agreement between measurements and predictions depends on circumstances. In some cases, there is agreement about the uncertainty of inputs (±3 dB) out to 3 km. In others, there is a discrepancy of up to 10 dB at longer ranges. Agreement varies between approaching and receding geometries. The reason for this discrepancy is not yet known.
Scallop Condition Remains Unchanged After Marine Seismic Survey

Rachel Przeslawski  
Geoscience Australia, rachel.przeslawski@ga.gov.au

Andrew Carroll  
Geoscience Australia, andrew.carroll@ga.gov.au

Matt Edmunds  
Australian Marine Ecology, matt@marine-ecology.com.au

Peter D. Nichols  
CSIRO, Peter.Nichols@csiro.au

Stefan Williams  
University of Sydney, Peter.Nichols@csiro.au

Fisheries groups worldwide are concerned that seismic operations negatively affect catch rates within a given area, although there is a lack of field-based scientific evidence. In Australia, marine seismic surveys have been attributed to mass mortalities of benthic invertebrates, including the commercial scallop *Pecten fumatus*. In April 2015, Geoscience Australia (GA) commissioned a 2-D seismic survey in the Gippsland region (southeast Australia) as part of the Australian Government’s National CO2 Infrastructure Program. GA also used the survey as an opportunity to conduct field-based experiments investigating the potential impacts on marine organisms. Moored hydrophones recorded noise before and during the seismic survey. An autonomous underwater vehicle (AUV) was used to evaluate the effectiveness of seafloor images to inform scallop monitoring, with deployment over two time periods (2 months after operations and 10 months after operations). In addition, benthic sampling was undertaken using a commercial scallop dredge both before and after the seismic survey, from which a variety of biological and biochemical variables were analyzed. Data were collected from an experimental zone (0-1 km from seismic operations) and a control zone (>10 km from seismic operations). The highest sound exposure level recorded by the hydrophones was 146 dB re 1 µPa²s at 51 m water depth at a distance of 1.4 km from the airguns. Although commercial scallops were not abundant in the study area, analysis of AUV images revealed no significant differences in commercial scallop types (live, clapper, dead shell, other) between experimental and control zones. Similarly, analysis of dredged scallops showed no detectable change in shell size, meat size and condition, gonad size and condition, or biochemical indices. Both AUV and dredging data showed strong spatial patterns, with significant differences between sites. Our study confirms previous work in Australia showing no evidence of immediate mortality of scallops in the field, but it also shows no evidence of long-term (10-months) or sublethal effects. For future investigations of short-term effects, we recommend in situ studies that focus on the underlying mechanisms of potential impacts (i.e., physiological responses) rather than gross metrics such as mortality or size. Physiological responses to stressors may not be as immediately obvious as mortality or behavioral responses, but they are equally important to provide early indications of negative effects as well as to explain the underlying mechanisms behind mortality events and reduced catch.
Sounds, Source Levels and Acoustic Localization of “Feeding Workups”

Rosalyn L. Putland
Leigh Marine Laboratory, Institute of Marine Science, University of Auckland, NZ,
rput037@aucklanduni.ac.nz

Craig A. Radford
Leigh Marine Laboratory, Institute of Marine Science, University of Auckland, NZ,
c.radford@auckland.ac.nz

John Atkins
Leigh Marine Laboratory, Institute of Marine Science, University of Auckland, NZ,
j.atkins@auckland.ac.nz

The novel application of localizing biological sound sources within interspecies feeding events could provide insight into the competitive dynamics of acoustic ecology. During a so-called “feeding workup,” dolphins round up the fish, attracting diving gannets and subsequently attracting whales and large pelagic predators. Our theory is that this is a process whereby the noise produced by schooling fish, dolphins, and gannets, which can potentially be heard a significant distance away, alerts other species to the presence of food. Using a drifting GPS hydrophone array allows us to calculate the source level and position of the key sound contributors during feeding events as well as to conduct a comparative analysis into the current techniques for sound localization. Importantly, by knowing the source level of specific sound signatures, we aim to determine the distance and its effective range over which a feeding workup is likely to be acoustically detectable. Based on a preliminary analysis, our hypothesis is that diving gannets provide the key and most dominant acoustic cue within a feeding workup and that their sound alerts other seabirds, large pelagic fish, and whales to join the feeding frenzy.
Seismic Surveys and Gray Whales near Sakhalin Island: Findings from Multivariate Analyses of Monitoring Data from the 2010 Astokh Geophysical Survey

Roberto Racca  
JASCO Applied Sciences, roberto.racca@jasco.com  
Judy Muir  
Muir Ecological Services Ltd., jemuir@telus.net  
Gzilenn Gailey  
Texas A&M University, GGailey@cascadiaresearch.org  
Koen Bröker  
Shell Global Solutions and Groningen Institute for Evolutionary Life Sciences, University of Groningen, Koen.Broker@shell.com

At the previous Aquatic Noise conference, Racca and Austin (2016) described use of pre-season acoustic modelling in the monitoring and mitigation plan design for a 2010 seismic survey conducted near the feeding grounds of gray whales *Eschrichtius robustus* off north-eastern Sakhalin Island, Russia. This plan involved unprecedented monitoring and protection measures, justified by the critically endangered status of that subpopulation. Monitoring yielded high quality underwater sound recordings at eleven locations and systematic shore-based visual observations of nearshore distribution and movement / respiration behaviors during the early part of the whales’ summer feeding season. These data were used in three multivariate analyses (MVAs) that investigated effects of sound from the seismic survey on i) gray whale distance from shore, ii) occupancy/abundance in daily 1 km² density surfaces, and iii) 17 behavior response variables. Environmental and non-acoustic covariates were also considered. Post-season acoustic modelling enabled estimation of sound metrics (both instantaneous and cumulative) in one-minute time steps at locations that included points directly offshore the monitoring stations, centroids of density surface cells, and individual gray whale paths. The acoustic recordings provided measurement-based correction factors that were used to refine modelling results for seismic pulses. The modeled time series allowed sound covariates to be estimated at appropriate temporal and spatial scales for the MVAs, and in addition enabled testing the effects of patterns of sound exposure over selected time periods in the density surface MVA. Acoustic modelling also provided estimates of sound levels from the vessels associated with the seismic survey for use in the behavior MVA. Distance from shore analyses gave no evidence that seismic pulses caused a distributional shift in either direction, whilst the density surface MVA found highest occupancy in areas with moderate sound exposure and suggested that slightly decreased densities were associated with a low-high-low pattern of sound exposure over the previous 3 days. Observed shifts in occupancy and density could also reflect changes in the prey distribution, data for which were not available. The behavioral analyses found no significant association between movement / respiration response variables and the seismic survey and vessel noise variables that were considered. Results from power analyses found insufficient sample sizes to detect subtle to moderate behavioral changes, but sufficient to detect large changes related to noise exposure. A set of seismic surveys conducted in 2015 over a longer period of the feeding season may provide more substantive evidence in future analyses.

For over 50 years, the mechanism and even existence of crustacean hearing has been fiercely debated. The lack of convincing evidence for how they hear is especially embarrassing given the tremendous advancements made in our understanding of crustacean behavior that clearly shows they produce sounds and can respond to acoustic cues. We hypothesize that the crustacean statocyst is the primary hearing organ used by crustaceans of the decapod family. Using medical imaging technology, microCT, and auditory evoked potentials (AEPs), we characterized the form and function of the statocyst organ in the paddle crab, Ovalipes catherus. The statocyst structure is found at the base of the antenna and is a narrow canal system with a statolith consisting of only a few grains of sand. The hearing ability of the paddle crab was measured in response to both an underwater speaker stimulus (pressure and particle motion) and a pure particle motion stimulus (shaker table). Paddle crabs were most sensitive to the lower frequencies (100–200 Hz) in response to the speaker stimulus and most sensitive to pure particle motion at 400 Hz. All AEP responses to both the speaker stimulus and particle motion stimulus disappeared when the statocysts were ablated. This provides strong evidence that the statocyst is indeed the primary hearing organ for the range of frequencies studied. In conclusion, we propose that there might be a fundamental difference between the statocyst structure and the sensitivity of different members of the decapod order.
Big Gear for a Big Whale: Localizing Vocalizing Blue Whales (*Balaenoptera musculus*) Using a Large Hydrophone Array

**Marianne Rasmussen**
Institute for Terrestrial and Aquatic Wildlife Research (ITAW) and The University of Iceland’s Research Center in Husavik, Marianne.Helene.Rasmussen@tiho-hannover.de

**Magnus Wahlberg**
University of Southern Denmark, magnus@biology.sdu.dk

**Henriette Schack**
HBS Consulting, henriette.b.schack@gmail.com

**Nina Bircher**
University of Southern Denmark, nibir13@student.sdu.dk

**Maria Iversen**
The University of Iceland’s Research Center in Husavik, phocoena@hotmail.com

**Ursula Siebert**
Institute for Terrestrial and Aquatic Wildlife Research (ITAW), University of Veterinary Medicine Hannover, Foundation, ursula.siebert@tiho-hannover.de

Blue whales (*Balaenoptera musculus*) feed in Skjálfandi Bay, Iceland, every year during the month of June. Here we used a large hydrophone array spreading over 1.5–3 km to localize blue whale calls off Húsavík in June to July 2015. The aim of the project was to study communication in blue whales as well as how their communication would be affected by external noise (as for example, ship noise) in terms of masking of their signals. Three sailing vessels and a speed boat were used as platforms for the recordings. Each recording vessel had a calibrated hydrophone connected to a digital recorder. The underwater sounds were recorded in one channel and a frequency shift-keyed GPS signal in the other channel. The hydrophone was lowered to a depth of 30 m from each recording vessel. All recordings were made in sea state 3 or less. During the recordings, the boats were separated by either 500 m or 1 km in either the north-south or east-west direction. Recordings were conducted during both nighttime and daytime to include data from lot of boat traffic (“noisy” scenario) and without (“natural” scenario). Data were collected on 10 different recording trips. We recorded 84 downsweep calls. The down-sweep blue whale calls could be used for acoustic localizations for source-level estimates. Source-level estimates were between 185 and 190 dB re 1 µPa and thereby up to 30 dB higher than estimates previously obtained in the same study location using acoustic tags. However, the source levels are within the same range as that reported in the Southern Ocean. One possibility could be that the animals increase the volume of the sound when there are many other calling animals around or that generally blue whales would adjust their calling volume according to background noise.
Auditory and Behavioral Responses of Arctic Seals to Seismic Signals

Colleen Reichmuth  
University of California, Santa Cruz, coll@ucsc.edu  
Asila Ghoul  
University of California, Santa Cruz, asila@ucsc.edu  
Andrew Rouse  
University of California, Santa Cruz and SEA, Inc., arouse@ucsc.edu  
Jillian Sills  
University of California, Santa Cruz, jmsills@ucsc.edu  
Brandon Southall  
SEA Inc., brandon.southall@sea-inc.net

Following a series of experiments to describe the auditory capabilities of spotted and ringed seals (Sills et al., 2014, 2015), we sought to determine the effects of signal impulse noise exposure on hearing in these Arctic species. We applied behavioral methods to measure the sensitivity thresholds at 100 Hz before and immediately after voluntary exposure to impulsive noise produced by a seismic airgun. Auditory responses were determined from psychoacoustic data, and behavioral responses were scored from video recordings. Four successive exposure conditions of increasing levels were tested, with received sound exposure levels (SEls) extending from 165 to 181 dB re 1 μPa²·s and peak-to-peak sound pressure levels (SPLs) from 190 to 207 dB re 1 μPa. We found no evidence that these single seismic exposures influenced hearing, including at SELs that exceeded those previously predicted to cause temporary threshold shift (TTS). After training at low-exposure levels, relatively mild behavioral responses were observed during testing at higher exposure levels. This suggests that individuals can learn to tolerate loud, impulsive sounds but does not necessarily imply that similar sounds would not elicit stronger behavioral responses in wild seals. The absence of an observed TTS in this study confirms that current regulatory guidelines for single-impulse noise exposures are conservative for seals. Additional studies using multiple impulses and/or higher exposure levels are needed to quantify exposure conditions that do produce measurable changes in hearing sensitivity.


A Review of the Legislation Applied to Seismic Surveys for Mitigation of the Effects on Marine Mammals in Latin America

María Vanesaa Reyes  
Whale and Dolphin Conservation, vanesa.reyes@whales.org  
Sarah J. Dolman  
Whale and Dolphin Conservation, sarah.dolman@whales.org

Marine seismic surveys for oil and gas exploration are in expansion worldwide. The potential effects of airgun sound on marine life, especially marine mammals, are of great concern. Cetaceans rely on sound for relevant aspects of their lives such as communication, foraging, navigation, and predator avoidance. In many countries, these activities proceed without a robust assessment of their environmental impact and an effective mitigation plan to minimize impacts on marine ecosystems. A review of legislation establishing guidelines for mitigation of impacts on cetaceans of noise generated during seismic surveys was undertaken for Latin American (LA) countries. Seismic survey mitigation remains unlegislated in most of the countries in the region. Only Brazil and Peru have enforced statutory guidelines within their national waters. Environmental authorities of Colombia enforced adoption of JNCC Seismic Guidelines but there is no formal legislation. Some countries and oil companies voluntarily adopted mitigation measures set in the legislation of developed countries. Environmental impact assessments (EIAs) are mandatory to obtain environmental licenses for oil and gas exploration in the region, with variable levels of public consultation among countries. Argentina, Colombia, Mexico, and Peru have specific rules for the presentation of EIAs for oil and gas exploration and production that include the requisite of an environmental management plan with mitigation measures for the identified impacts and monitoring plans. However, such rules fail to include cumulative impacts and modeling of the generated sound field, including local propagation features that are essential to accurately determine the appropriate management, including exclusion zones, for cetaceans. Currently, mitigation guidelines that have been broadly used as “best practice,” such as JNCC Guidelines and the New Zealand Code of Conduct, are being revised due to the limited effectiveness of some measures. Recently, it has been suggested that a global noise management framework is required, given the expansion of seismic surveys and transboundary nature of underwater noise. In this paper, we discuss the flaws in current mitigation measures adopted by LA countries and make suggestions toward the development of standardized international guidelines for these activities to better protect cetaceans from the impact of seismic noise pollution.
Predicted and Measured Hydroacoustic Levels for the Pier E3 Implosion Relative to Criteria for Fishes and Marine Mammals

James A. Reyff  
Illingworth & Rodkin, Inc., jreyff@illingworthrodkin.com  
Paul Donavan  
Illingworth & Rodkin, Inc., pdonavan@illingworthrodkin.com

The California Department of Transportation is currently removing the 3.4-kilometer old eastern span of the San Francisco-Oakland Bay Bridge that was recently replaced. This portion of the old bridge was supported by 23 concrete piers. The largest, Pier E3, is 41 meters long by 26 meters wide and extends 70 meters down through ~15 meters of water into the bay mud. After careful consideration of demolition options, the Department imploded Pier E3. A blast attenuation system (BAS), consisting of a wide bubble stream, was used to minimize the underwater sound levels in the water surrounding the pier. The implosion event consisted of 588 individual charge detonations that ranged from 22 to 13 kilograms per delay spaced 9 milliseconds apart. The entire event lasted less than 6 seconds. As part the permitting process for the Pier E3 implosion, expected hydroacoustic levels were predicted to identify potential effect zones and extensive biological monitoring was conducted to minimize harm to the environment. Challenges of predicting underwater sound levels included predicting the level of confinement for each charge, the effectiveness of the BAS, and the propagation of the sounds. The predicted impact areas were developed with regard to specified criteria for fish and marine mammals that included peak pressure and sound exposure levels (SEls). Extensive measurements of underwater sound pressures were conducted at distances from 8 to over 1,200 meters from the pier. For peak pressure, the measured levels were slightly higher than estimated, whereas for the SEL, the measured levels were somewhat lower than estimated. Although there were 135 individual detonations of the larger 22-kilogram charges, the highest peak pressures varied in level by 10 to 15 decibels during the course of the implosion. In this paper, the methods for predicting the levels, the measured results, analysis of the data, and the performance of the BAS are reviewed. The biological monitoring effort for this implosion included a live fish-cage study, where salmonids in cages were exposed to the implosion at distances of about 45 to over 900 meters. The acoustic measurements are also extrapolated to estimate the levels at the positions used for the caged-fish study.
Underwater noise from anthropogenic sources has been increasing dramatically for the past few decades. Its impacts on marine mammals have been widely studied, but little is known of the effects of noise on fishes and invertebrates. Marine anthropogenic noise at low frequencies overlaps with the fishes’ hearing range and peak sound production that can reduce their communication space and result in habitat loss. In addition to increasing stress levels and impairing the ability of fish to detect prey and predators, intense noise can cause tissue damage, temporary hearing loss, and reduced survival. This study is part of a Marine Environmental Observation Prediction and Response Network (MEOPAR) project that focuses on quantifying and comparing vessel noise from recordings at three locations: SGaan Kinghlas-Bowie Seamount Marine Protected Area (SKB MPA), Sachs Harbour (Amundsen Gulf), and the Salish Sea. Acoustic data were collected by Fisheries and Oceans Canada (DFO) at SKB MPA with an autonomous recorder between July 2011 and July 2013. Our project focuses on inspecting these data in search of fish sounds to determine the presence of sound-producing fish species and the seasonality of their acoustic behavior. An automatic detector is being used to highlight acoustic episodes that are more likely to contain fish sounds. Automatic detections are being verified manually as well as by a systematic blind analysis of parts of the data to compare manual versus automatic analysis. We will then correlate these detections with the MEOPAR ocean soundscape quantifications to identify potential acoustic threats to deepwater habitats of Pacific fishes. The same procedure could be applied to other locations facing increased anthropogenic noise. This study addresses the need to cover the knowledge gaps in fish acoustic behavior and quantify the baseline soundscape in coastal and deepwater habitats of Pacific fishes to inform managers of the impact of multiple stressors so they can set maximum thresholds in target habitats to be protected.
Exposure of Benthic Invertebrates to Sediment Vibration: From Laboratory Experiments to Small-Scale Pile Driving in the Field

Louise Roberts
Institute of Estuarine and Coastal Studies (IECS), University of Hull, Louise.Roberts@hull.ac.uk

Harry Harding
School of Biological Sciences and Cabot Institute, University of Bristol, harry.harding@bristol.ac.uk

Irene Voellmy
School of Biological Sciences and Cabot Institute, University of Bristol, irene.voellmy@gmail.com

Rick Bruintjes
Biosciences, College of Life and Environmental Sciences, University of Exeter, r.bruintjes@exeter.ac.uk

Steve Simpson
Biosciences, College of Life and Environmental Sciences, University of Exeter, s.simpson@exeter.ac.uk

Andrew Radford
School of Biological Sciences and Cabot Institute, University of Bristol, Andy.Radford@bristol.ac.uk

Thomas Breithaupt
T.Breithaupt@hull.ac.uk School of Biological, Biomedical and Environmental Sciences, University of Hull.

Michael Elliott, Institute of Estuarine and Coastal Studies (IECS), University of Hull Mike.Elliott@hull.ac.uk

Human activities directly interacting with the seabed, such as drilling and pile driving, can produce significant vibrations that have the potential to impact benthic invertebrates within the vicinity of the activity. Vibrations can be used by marine invertebrates to detect environmental cues, predators, and conspecifics. Therefore, any additional stimuli may interfere with crucial behaviors such as foraging and predation avoidance, yet the significance of these changes and the sensitivity to such stimuli are largely unknown. Here the responsiveness of benthic invertebrates to substrate-borne vibration is discussed in relation to laboratory and field trial methodologies using two species, the blue mussel (Mytilus edulis) and common marine hermit crab (Pagurus bernhardus), as examples. In controlled laboratory conditions, sensory threshold curves were produced by exposure to sinusoidal vibrations of varied amplitudes and frequencies produced by an electromagnetic shaker. In field conditions, the same two species were exposed to a small-scale pile-driving operation. The use of behavioral indicators such as movement and startle responses are discussed as a method of reception detection in addition to biochemical oxygen demand (BOD) change. The measurement and sensors required for sediment vibration quantification are discussed in the context of the work, for example, use of tridirectional geophones and accelerometers to measure ambient or vibration exposures. Response and threshold data were related to data from the literature measured in the vicinity of anthropogenic sources, allowing a link between responsiveness and real-life vibration levels. The impact of anthropogenic activities on sediment-dwelling invertebrates has received relatively little research, yet the data here from complementary field and laboratory studies suggest that such activities are likely to impact key coastal species that play important roles within the marine environment.
Plainfin midshipman fish (*Porichthys notatus*) nest in the shallow intertidal zone off the West Coast of British Columbia and the United States. Males attract females by producing an acoustic advertisement call that is multiharmonic with a fundamental frequency (*F₀*) that ranges from 70 to 100 Hz. Females localize calling mates at depths <1 m. The wavelength of the call’s *F₀* is much larger than water depth so all normal modes are cut off, which would suggest extremely poor waterborne sound propagation. Several experiments performed in a large concrete tank with similar water depth have shown that midshipman females exhibit phonotaxis toward a sinusoidal sound source radiating at frequencies from 75 to 100 Hz (Coffin et al., 2014). This phonotaxic behavior was shown to incorporate resolution of the 180° ambiguity and requires an intact swim bladder. This implies that they are using pressure as well as particle motion to perform the localization. The time-averaged acoustic intensity can be determined from the pressure and particle velocity, and the sign of this quantity is what ultimately resolves the 180° ambiguity. We have made measurements of acoustic propagation for both pressure and particle motion for a water depth of ~0.75 m in the intertidal zones where midshipman fish are known to nest as well as those zones where midshipman do not nest. We compare the results for nesting and nonnesting beaches with each other and with data obtained for similar depths and frequencies in a large concrete tank. The quantities compared include the ratio of the particle motion to pressure components (i.e., the kinetic to potential energy ratio), the magnitude and sign of the time-averaged intensity, and the propagation loss for particle motion, pressure, and intensity. The objectives of this research are (1) to determine how realistic it is to test the localization capabilities of the midshipman fish in tanks and (2) to investigate whether there are acoustic reasons why midshipman nest at some beaches but not at other, seemingly similar, nearby beaches. It is found that the kinetic-to-potential energy ratio is 30 dB larger than the plane wave value both in situ and in the tank, but that the pressure and particle velocity fields decay much more slowly in situ than they do in the tank. There appear to be significant differences between the results for nesting beaches and some of the results for the nonnesting beaches.

An Integrated Computational Model of Estuarine Dolphin (*Sotalia guianensis*) Behavioral Responses to the Sound Fields Produced by Natural and Anthropogenic Noise Sources

**Mario M. Rollo**  
Biosciences Institute, Sao Paulo State University, Coastal Campus, P.O. Box 73601, Sao Vicente-SP, 11380-972 Brazil, mario.rollo@icloud.com

**Amanda Jodas**  
Biosciences Institute, Sao Paulo State University, Coastal Campus, P.O. Box 73601, Sao Vicente-SP, 11380-972 Brazil

**Rebecca G. Natal**  
Biosciences Institute, Sao Paulo State University, Coastal Campus, P.O. Box 73601, Sao Vicente-SP, 11380-972 Brazil

There has been an increasing concern on the consequences of continuous exposure of marine mammals to noise from anthropogenic sources. On the other hand, we know relatively little about how they adjust their movements and acoustic behavior to deal with the variability of natural sound fields. Therefore, modeling the sound propagation in the ocean is essential to assess the potential risk of these interfering noises on the survival of marine mammal populations. We aimed to use estuarine dolphins, *Sotalia guianensis*, as a biological model of interaction with natural and man-made noise fields integrated with complex environmental data. We performed simulations at ESME Workbench, a computational modeling environment developed by the Office of Naval Research and Boston University Hearing Research Center. ESME brings together in a single framework advanced models of sound propagation running in a spatially bounded environment on simulated individual animals (animats), whose behavioral state transitions were retrieved from peer-reviewed scientific literature sources and converted in Marine Mammal Movement and Behavior (3MB) algorithms. The target study area was a semienclosed estuarine-coastal system in Cananeia, southeastern Brazil. Because there was no available specific 3MB for estuarine dolphins, we employed a generic small odontocete model. Transmission loss profiles produced by ESME from fishing and recreational boats demonstrated that, in general, the sound attenuation was relatively fast in the area and their effects on the movement and distribution of the target species seemed limited. Our simulations indicated that the dolphins did not suffer significant behavioral stress from being exposed to local ambient noise. We still need more accurate, finer resolution environmental data; a stronger effort on building a specific 3MB algorithm for this species; and an increasing experience on the use of ESME’s programmable tools for testing dolphin aversion to sound exposure to improve our conclusions.
Bubble Curtains Efficiently Reduce Temporary Habitat Loss for Harbor Porpoises During Pile Driving

Armin Rose  
BioConsult SH GmbH & Co. KG, Schobueller Strasse 36, D-25813 Husum, Germany, a.rose@bioconsult-sh.de

Michael Bellmann  
Institute of Technical and Applied Physics (ITAP) GmbH, Marie-Curie-Straße 8, D-26129 Oldenburg, Germany, bellmann@itap.de

Ansgar Diederichs  
BioConsult SH GmbH & Co. KG, Schobueller Strasse 36, D-25813 Husum, Germany, a.diederichs@bioconsult-sh.de

Jens Oldeland  
Biocentre Klein Flottbek and Botanical Garden, University of Hamburg, Ohnhorststrasse 18, D-22609 Hamburg, Germany, fbda005@uni-hamburg.de

Georg Nehls  
BioConsult SH GmbH & Co. KG, Schobueller Strasse 36, D-25813 Husum, Germany, g.nehls@bioconsult-sh.de

Marine organisms can be seriously affected by underwater noise. Because a considerable number of offshore wind farms (OWFs) are about to be constructed in the North Sea during the next years, a substantial proportion of research is nowadays addressed to the possible effects of noise on marine mammals during OFW construction and on how to reduce their impact. We investigated the efficiency of noise mitigation by different configurations of circular big bubble curtains (BBCs) regarding their ability to reduce temporary habitat loss for harbor porpoises (*Phocoena phocoena*) during pile-driving operations for the OWFs Borkum West II (BW2) and Global Tech I (GT1). Offshore wind turbines (OWTs) for these wind farms, positioned 45 km (BW2) and 170 km (GT1) north of Borkum Island in the North Sea, were founded on tripod constructions (piles, 2.5 m diameter) at water depth of 30 m (BW2) or 40 m (GT1). At BW2, noise attenuation by the most efficient bubble curtain configuration, BBC2 (200 m length; holes: 30 cm distance, 1.5 mm diameter) was about 11 dB for the sound exposure level (SEL) at a 750-m distance from piling, whereas configuration BBC1 (200 m length; holes: 150 cm distance, 3.5 mm diameter) reduced sound emissions by 8 dB on average. The bubble curtain configuration investigated at GT1 resembled the BBC2 of BW2, but the hose was longer (800 m length; holes: 25-30 cm distance, 1.7 mm diameter); sound emissions were reduced by 9 dB on average. All investigated bubble curtains operated under airflows of ~0.3 (range 0.23–0.35) m³·min⁻¹·tube⁻¹. The reduction in temporarily lost habitats was computed (1) by modeling the relationship of the SEL to the distance from piling, then combining this model curve with sound levels of initial significant displacement of porpoises with and without BBC, and (2) by directly modeling porpoise detection rates against the distance from the pilings with and without BBCs. For BW2, a reduction in temporarily lost habitats for harbor porpoises was ~78% for piling under BBC1 and 90% under BBC2 compared with the reference piling. For the bubble curtain used at GT1, the reduction was 73%. The better performance of BBC2 at BW2 might have been caused by shallower water depths. Overall, the results demonstrate that bubble curtains have the capability to significantly reduce temporary habitat loss for a marine mammal species listed in the EU Habitats Directive.
Oil Industry and Noise Pollution in the Humpback Whale (*Megaptera novaeangliae*)
Acoustic Environment in the Southwestern Atlantic Breeding Ground

Marcos Rossi-Santos
Universidade Federal do Reconcavo da Bahia and Instituto Baleia Jubarte,
marcos.rossi@ufrb.edu.br

The present work aims to assess acoustic overlapping between the humpback whale song and anthropogenic sounds around oil and gas platforms through spectral description and frequency comparison. Whales were monitored systematically in northeastern Brazil (11° S, 37° W to 14° S, 38° W). Acoustic and behavioral data were collected from 2007 to 2009, focusing on humpback occurrence around oil platforms. Diverse anthropogenic noises were registered in a similar frequency range as recorded cetacean sounds, which suggests overlapping of acoustic niches. Noise pollution from oil and gas production may potentially affect this species communication, with implications for distribution and behavior in their breeding area. This paper is the first report of acoustic overlapping of oil platforms and cetaceans in the southwestern Atlantic Ocean. Given increasing gas and oil exploitation, efforts to improve the development and use of these acoustic methods is recommended to mitigate impacts on the marine life.
Whale-Watching Noise Effects on the Behavior of Humpback Whales (*Megaptera novaeangliae*) in the Brazilian Breeding Ground

**Marcos Rossi-Santos**  
Universidade Federal do Reconcavo da Bahia and Instituto Baleia Jubarte,  
marcos.rossi@ufrb.edu.br

Whale-watching tourism is increasingly growing in the world, mostly due to the charisma that cetaceans exert on humans as well as the constant conservationist appeal that shows a strong argument to the no return of commercial whaling. Nonetheless, if this activity is not sustainable, it may harm cetacean populations, from behavioral changes to physiological injuries. In a long-term study about the acoustic ecology of the humpback whale (*Megaptera novaeangliae*) in their breeding ground off northeastern Brazil, behavioral and acoustic data were collected during a whale-watching boat approach in Praia do Forte, a tourist traditional center. Frequency measurements indicated the potential impacts in the surface and underwater behavior of the humpbacks, masking important biological sounds when these animals come to breeding areas. Implications for the species as well as environmental conservation are discussed along with educational awareness and more use of nonintrusive research tools as the modern acoustic methods.
Temporary Threshold Shift Induced for Pure Tones at 25 or 28 kHz on Harbor Porpoise Hearing

Andreas Ruser
Institute for Terrestrial and Aquatic Wildlife Research (ITAW), University of Veterinary Medicine Hannover, Foundation, Germany, andreas.ruser@tiho-hannover.de

Magnus Wahlberg
University of Southern Denmark, Kerteminde, Denmark, Magnus@biology.sdu.dk

Mathias H. Andersson
Swedish Defence Research Agency, Stockholm, Sweden, mathias.andersson@foi.se

Jakob Hoyer Christensen
Fjord&Bælt, Kerteminde, Denmark, jakob@fjord-baelt.dk

Ursula Siebert
Institute for Terrestrial and Aquatic Wildlife Research (ITAW), University of Veterinary Medicine Hannover, Ursula.Siebert@tiho-hannover.de

Harbor porpoises rely on their hearing ability and show behavioral reactions to anthropogenic sound sources. Like other mammals, when exposed to strong sound pulses, they experience a brief reduction in their hearing ability to detect environmental sounds and therefore potential important information to survive. It has been suggested that this so-called temporary threshold shift (TTS) could be used as a standardized limit of tolerance for exposure to human sound sources. Therefore, there are several recent studies investigating TTS in porpoises exposed to various types of anthropogenic noise. However, most of these studies have focused on rather low-frequency signals, below 10 kHz, but there are other frequently occurring sound sources in the oceans such as, e.g., echo sounders, high-speed ferries, and naval sonars in the frequency range of 20-50 kHz. Here we estimated the onset of TTS in a harbor porpoise exposed to 25- or 28-kHz tonal sound stimuli of 0.5 and 3.5 s duration by measuring the auditory brain stem response. The study was made at Fjord&Bælt, where three harbor porpoises are kept in the harbor of Kerteminde, Denmark. The porpoise pen is connected to the harbor through a series of nets so that the animals experience ambient sound levels and water temperatures year-round. The average ambient-noise levels during the trials are not expected to have had a great influence on the TTS data derived here. For both fatiguing signals, we found the onset of TTS at 141 dB re 1 µPa²·s, which is much lower than the onset of TTS at lower frequencies. This fits well with the prediction that the onset of TTS is related to the hearing sensitivity at the exposure frequency.
In March 2014, APPEA, the Australian oil and gas industry, and Curtin University commenced a project to review information on the most recent research in Australia on the potential effects of underwater marine sound and vibration produced by oil and gas activities on marine mammals, marine reptiles, penguins, fish, and invertebrates. A compilation specifically focused on Australian marine fauna has not been produced in over a decade. This project is a component of APPEA’s Marine Environmental Science Program aimed at helping environmental planning processes, allowing information not widely available to be more readily accessible, and identifying significant gaps in current knowledge. To achieve a rigorous review, a systematic process for searching published peer-reviewed articles and gray literature was applied. Over 30 studies in the last few decades investigating effects of human activities on marine fauna were identified. Although a few notable studies focused on oil and gas industry activity noise, most were on the effects of other noise-producing human activities. Most studies focused on particular species of marine mammals, fish, and invertebrates, which was driven by Environment Protection and Biodiversity Conservation (EPBC) Act 1999 requirements and stakeholders’ interest in particular species. From those studies reviewed here, most had a focus on assessing the behavioral responses of underwater noise on large marine fauna or the behavior, mortality, and physiological effects on fish and invertebrates. For behavioral studies on megafauna, only one study separated the effects of noise from the structure producing it. Also, only a few key studies measured noise characteristics and levels and were undertaken with a robust sample size and experimental design (including controls). Key comprehensive studies were those with specific objectives relating to the impact of underwater noise from oil and gas activities. These large research programs included two studies on humpback whale behavioral responses and two on fish and one on invertebrate behavior, physiological, and/or auditory and nonauditory injury. Responses varied from none to damage to the auditory system in fishes and no to the short-term behavioral response in marine mammals. Although there were some consistencies, there was variability among studies likely attributable to species-specific responses and/or varying experimental design. Some of the high-quality research reported on here was obtained from consulting reports. This study highlights that the current knowledge continues to be limited as well as the importance of publication and data sharing to improve our knowledge base, to accelerate the distribution of results, and to enhance the science transfer to management.
Loudness-Dependent Behavioral Responses, Predator Evasion, and Habituation to Sound by the Longfin Squid (*Doryteuthis pealeii*)

**Julia Samson**  
University of North Carolina at Chapel Hill, julia@unc.edu  
**T. Aran Mooney**  
Woods Hole Oceanographic Institution, amooney@whoi.edu

Nearly all investigations of noise and sound use in aquatic animals have examined vertebrates despite the dominant role of marine invertebrates in species diversity, habitat used, and total biomass. Cephalopods, and squid in particular, play a central role in many trophic webs as a key link between top predators and smaller deepwater prey. Their behavioral responses to noise may thus have widespread consequences on food webs and ecosystems. Linking these reactions to sound is essential to determine the function of acoustics in their life history and community interactions. Although squid have demonstrated physiological responses to sound, vital behavioral responses are largely anecdotal but would reflect both perception and functional use. This work sought to address the range of sounds that elicit behavioral responses in squid *Doryteuthis* (formerly *Loligo*) *pealeii*, the types of responses generated, and how responses may change over multiple sound exposures. Responses to tone pips were recorded with high-definition and high-speed cameras, and stimuli were measured in acceleration and sound pressure. Squid responded to sounds from 80 to 1,000 Hz, with response rates diminishing at the higher ends of this frequency range. A range of response types characteristic of predator evasion were evoked. They varied from protean (inking misdirection) and jetting (fleeing) to body pattern changes (diematic startle of predators) and mild fin movements. Inking was confined to the lower frequencies and highest sound levels (mean 6.75 m/s²); jetting was also induced by higher sound levels but was more widespread in frequency. Both inking and jetting are typically induced by ambush predators. Animals responded to the lowest sound levels (0.001 m/s²) in the 200- to 400-Hz range via pattern changes and fin movements (responses to cruising predators). Response latencies were variable and could occur as rapidly as 0.01 s but were more often 0.1-0.3 s (and generally faster for body pattern change compared with jetting). Compared with cuttlefish, squid typically required higher sound levels to exhibit behavioral responses, perhaps suggesting poorer sensitivity or an adaptation to their more schooling, pelagic life history. Potential habituation to sound was examined using repeated 200-Hz tones at 2 sound intensities. Response intensity decreased rapidly (ca. 4-6 trials), indicating a potential for habituation and perhaps minimal aversion to some repeated noise. Overall, the results suggest that squid sound use was linked, at least partly, to ecologically relevant predator evasion. Squid responded to specific sounds as if they were predator contexts, suggesting perception. Amplitude- and frequency-dependent response types reflected an intensity of perceived threat, indicating an apparent relative loudness concept to squid sound detection.
Analysis of the Acoustic, Electric, and Magnetic Background Noise in a High-Activity Area in the Mediterranean Sea

Antonio Sanchez-Garcia
SAES, a.sanchez@electronica-submarina.com
Francisco Javier Rodrigo-Saura
SAES, f.rodrigo@electronica-submarina.com

The growing human activity in the marine environment is generating an increasing impact on this field in general and on the marine fauna in particular. This activity produces a wide variety of kinds of pollution, some of which, as in the case of hydrocarbon or plastic spills, have traditionally been treated, but other ones, such as underwater energy radiation, has started to receive generalized attention from the scientific community and society in general much more recently. This radiation, with a potential negative impact on marine fauna as reflected in the Marine Strategy Framework Directive (MSFD), is not limited to acoustic influence but also to other influences such as electric and magnetic ones. On this basis, it becomes necessary to have at our disposal systems that let us register and analyze these influences to determine their levels, evolution, and potential damage on marine fauna. In this context, this study shows the outcome of the analysis of the acoustic, electric, and magnetic background noise from a set of measurement campaigns that took place in an environment of intense human activity in the Mediterranean Sea. These analyses show very significant increments in this radiation in comparison with the values reported in the international literature. Additionally, and on the basis of the gained experience, an autonomous integrated system to detect and analyze acoustic, electric, and magnetic radiation is presented.
Influence of Shipping Noise on the Acoustic Activity of the Harbor Porpoise Phocoena phocoena

Joanna Sarnocińska
University of Southern Denmark, asia.sarenka88@gmail.com

Magnus Wahlberg
Marine Biological Research Center, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark, magnus@biology.sdu.dk

Jakob Tougaard
Institut for Bioscience, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark, jat@dmu.dk

Ship traffic has grown over the past decades, and it is expected that it will continue and with it also the noise caused by shipping. More recent studies showed that ships also generate high-frequency components that could potentially mask harbor porpoise (Phocoena phocoena) signals and disturb their foraging and communication. Here we investigate the effect of shipping noise on the acoustic activity of harbor porpoises. Noise was characterized in terms of an average of 1-min frequency content and intensity. Recordings of underwater noise and acoustic activity of porpoises were made in two Danish straits (Great Belt and Little Belt) using acoustic data loggers. In total, eight deployments were made from June to November 2015. Two different data loggers were used: SoundTraps (model HF), both for underwater shipping noise and porpoise detection (analyzed using PAMGUARD), and C-PODs. The porpoises reacted to the shipping noise. With increasing levels of low-frequency (<20-kHz) noise, the number of echolocation clicks decreased. With increasing levels of mid- to high-frequency (20- to 100-kHz) noise in the range of 81-93 dB re 1 μPa RMS, the number of clicks increased, but after exceeding this noise range, a decrease in clicks was observed. There were no signs of the animals adapting to shipping noise, even though ships were passing within 1 km several times every hour. Noise from ships may thus have a larger effect on harbor porpoises than has previously been assumed.

This study also examined the performance of C-PODs under varying ambient-noise conditions because of boat passages. Sometimes the C-POD results were similar to those from PAMGUARD but sometimes not. These findings indicate that in studies of the effects from boat noise on cetaceans, the C-POD will not generate trustworthy results.
The Watkins Marine Mammal Sound Database: An Online, Freely Accessible Resource

Laela Sayigh
Woods Hole Oceanographic Institution, Woods Hole, MA 02543, lsayigh@whoi.edu

Mary Ann Daher
Woods Hole Oceanographic Institution, Woods Hole, MA 02543, maryann.daher@gmail.com

Julie Allen
Woods Hole Oceanographic Institution, Woods Hole, MA 02543, jallen@whoi.edu

Helen Gordon
Woods Hole Oceanographic Institution, Woods Hole, MA 02543, hgordon@whoi.edu

Katherine Joyce
Woods Hole Oceanographic Institution, Woods Hole, MA 02543, kjoyce@whoi.edu

Peter Tyack
Sea Mammal Research Unit, Department of Biology, University of St. Andrews, St. Andrews KY16 8LB, UK, plt@st-andrews.ac.uk

One of the founding fathers of marine mammal bioacoustics, William Watkins, carried out pioneering work at the Woods Hole Oceanographic Institution for more than four decades, laying the groundwork for our field today. One of the lasting achievements of his career was the Watkins Marine Mammal Sound Database, a resource that contains more than 2,000 unique recordings of 76 species of marine mammals, with almost 16,000 annotated digital sound clips. These recordings have enormous historical and scientific value. They provide sounds professionally identified as produced by particular marine mammal species in defined geographic regions during specific seasons, which can be used as reference data sets for marine mammal detection from the growing amount of passive acoustic monitoring (PAM) data that are being collected worldwide. In addition, the archive contains recordings that span 7 decades, from the 1940s to the 2000s, and includes the very first recordings of 51 species of marine mammals. These data provide a rich resource to efforts aimed at examining long-term changes in vocal production that may be related to changes in ambient-noise levels as well as serving as a voucher collection for many species. This resource is now fully accessible online, which was Watkins’ goal, at http://www.whoi.edu/watkinssounds. Users can browse and download from any of three tabs: a “Best of” collection of 1,695 sound cuts, the full collection of 15,945 sound cuts, or the 1,755 digitized master tapes. Metadata associated with each file are also available, including information about the species recorded, other species present in the recording, location, date, recording equipment, and sample rate of the digitized file. The Watkins Marine Mammal Sound Database enables investigators, educators, students, and the public worldwide to freely and easily access acoustic samples from identified species of marine mammals and place these samples in a geographic and temporal context.
Developing and Implementing National Acoustic Guidance: Processes, Challenges, and Lessons Learned

Amy R. Scholik-Schlomer
NOAA Fisheries, amy.scholik@noaa.gov

The National Oceanic and Atmospheric Administration (NOAA) has been in the process of developing national acoustic guidance (Guidance) for marine mammals for several years. The first guidance document produced addresses the effects of noise on marine mammal hearing via updated acoustic thresholds for the onset of permanent and temporary threshold shifts. This Guidance is intended to be used by NOAA managers and applicants to better predict acoustic exposures that have the potential to trigger certain requirements under one or more of NOAA’s statutes (e.g., US Marine Mammal Protection Act, Endangered Species Act). Although the Guidance’s acoustic thresholds often get a lot of attention because of the overall “take” numbers they help generate, they are but one tool to be utilized within a larger impact assessment to help evaluate the effects of a proposed activity on marine mammals and make findings required by our various statutes.

To develop updated acoustic thresholds within the Guidance, NOAA compiled, interpreted, and synthesized the best available information on the effects of anthropogenic sound on marine mammal hearing. However, dealing with sparse data and uncertainty is an ever-present challenge, especially with the numerous protected marine species under NOAA’s jurisdiction. Furthermore, science is continually changing and becoming more complicated as more is learned. Thus, the Guidance’s updated acoustic thresholds are more sophisticated than our previous acoustic thresholds. This added complexity is an important consideration for applicants who have formerly relied on simple acoustic thresholds to evaluate the potential impacts. The development of user-friendly tools as well as how to ease the transition to updated Guidance are fundamental issues for the regulatory community that are not often considered by most outside this realm.

Developing national guidance also included critical independent peer review and stakeholder/public input, which focused on both the technical and policy applications of the document. These processes ensured that NOAA transparently addressed and considered all aspects of implementing the acoustic thresholds before finalizing the Guidance.

As NOAA moves from the Guidance’s development to the implementation stage, we are entering a new phase that consists of its own inherent issues and challenges associated with the practicality of employing more complex science to real-world applications. Through the Guidance’s development, NOAA has learned several valuable lessons, which will help improve the process of updating this document as well as drafting future guidance (e.g., updated acoustic thresholds for marine mammal behavioral impacts and effects of noise on protected fishes and sea turtles).
Airgun Sounds in Antarctic Waters: Measurement and Simulation

Max Schuster  
DW-ShipConsult GmbH, schuster@dw-sc.de

Brian Miller  
Australian Antarctic Division, Brian.Miller@aad.gov.au

Russell Leaper  
University of Aberdeen, r.c.leaper@abdn.ac.uk

Matthias Fischer  
DW-ShipConsult GmbH, fischer@dw-sc.de

Low-frequency sounds from seismic airguns are emitted at very high sound pressure levels. Therefore the acoustic signature is audible over hundreds and sometimes up to thousands of kilometers. Because of complex sound propagation paths in the sea, impulsive noise distorts to quasi-continuous ambient noise over long ranges. The time gaps in between individual shots become shorter as the length of the events increases. A previous study focused on Antarctic waters showed that especially vocalizations from low-frequency cetaceans are prone to a high degree of masking by airgun sounds. In a follow-up project, these numerical simulations are validated by means of acoustic recordings. Sounds from seismic airguns were recorded by coincidence during a blue whale survey based on acoustic DIFAR buoys. Because of the high number of deployed DIFAR buoys, the measured data are a vast repository to validate the results from numerical calculations of sound propagation. Many details of the survey are well documented, such as the distance between source and receiver as well as the configuration of applied airgun arrays. This information significantly reduces uncertainties of input parameters for the numerical calculation. This presentation summarizes the first conclusions from the data evaluation, with special focus on the absolute levels and signal-to-noise ratios of seismic airgun sounds. On this basis, simulation results from earlier studies are reassessed and conclusions are drawn for future assessment of low-frequency masking.
Since the introduction of the population consequences of disturbance (PCoD) conceptual model, the consequences of energy lost due to reduced foraging or increased energetic output have become a central component of modeling efforts to determine when a disturbance is biologically significant. Although aspects of this approach have been applied to a variety of marine mammals, data sets on northern elephant seals in Año Nuevo, CA, and bottlenose dolphins in Sarasota Bay, FL, are the most complete. The data come from mark-recapture efforts, assessments of health, and behavioral observations. Most important, these long-term data span several environmental disturbances (El Niño for elephant seals and red tide for bottlenose dolphins), allowing us to quantify how behavior, physiology, and vital rates change with natural reductions in prey. Although complete PCoD models are possible with large data sets, health metrics in particular can be difficult or impossible to collect for many species. The limitation can be especially true for income breeders who make decisions about resource allocation on short timescales. In addition, PCoD models to date have assumed the worst-case scenario, in that animals exposed to a disturbance do not have the ability to compensate for lost foraging opportunities (Costa et al., 2016). Stochastic dynamic programming (SDP) provides an approach to model the foraging behavior of animals in the absence of disturbance and to examine the potential compensatory behavioral mechanisms that individuals can employ in the presence of a disturbance (McHuron, Costa, Schwarz, and Mangel, Submitted). Combined with knowledge of the energetic requirements of individuals, SDP models can provide an index of animal condition, an important measure of health. However, SDP bioenergetic models present some important data needs. First, they require an understanding of the energetic landscape in which a species lives and how individuals respond to that landscape in the context of disturbance and potentially predation. Specifically, time-activity budgets, movement probabilities between habitats, and metabolic rates are needed on a timescale appropriate for energy acquisition, ideally on a daily scale. Energetic requirements for capital breeders are also needed on a larger timescale because energy input is decoupled from energy output during fasting. This approach is currently being implemented for California sea lions and gray whales, with the potential to groundtruth SDP models by comparing them with current elephant seal and bottlenose dolphin models.

Shipping Noise and Seismic Airgun Surveys in the Ionian Sea: Long-Term Observations and Potential Impact on Mediterranean Fin Whale

Virginia Sciacca
Dipartimento di Scienze Biologiche e Ambientali, University of Messina, Messina, Italy, and
Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare (INFN), Catania, Italy, vsciacc@unime.it

Salvatore Viola
Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare (INFN), Catania, Italy, sviol@lns.infn.it

Francesco Caruso
Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare (INFN), Catania, Italy, and Bioacoustics Lab,
IAMC Capo Granitola, National Research Council, Torretta Granitola (TP), Italy, fcaruso@unime.it

Emilio De Domenico
Dipartimento di Scienze Biologiche e Ambientali, University of Messina, Messina, Italy, edd@unime.it

Gianni Pavan
Centro Interdisciplinare di Bioacustica e Ricerche Ambientali (CIBRA), University of Pavia, Pavia, Italy,
gianni.pavan@unipv.it

Giorgio Riccobene
Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare (INFN), Catania, Italy, riccobene@lns.infn.it

The Mediterranean fin whale (Balaenoptera physalus) population is classified as “vulnerable” by the Red List of the International Union for Conservation of Nature. Many threats affect fin whale survival within the Mediterranean Sea. Among these, anthropogenic noise represents an issue of growing concern. Both auditory and behavioral effects have been observed worldwide on fin whale populations in relation to local increases of background noise (Clark et al., 2009; Castellote et al., 2010). Since 2012, the acoustic sensors installed offshore in eastern Sicily, onboard deep-sea infrastructures, give us the opportunity to monitor anthropogenic underwater noise in relation to fin whale acoustic presence. In particular, the cabled deep-sea multidisciplinary observatory, “NEMO-SN1,” was deployed in the Ionian Sea (37.54765° N, 15.3975° E), at a depth of 2,100 m. The observatory was equipped with a low-frequency hydrophone that continuously acquired data from July 2012 to May 2013. About 7,200 hours of acoustic data were analyzed by means of custom MATLAB codes and spectrogram display (Sciacca et al., 2015). The average values and percentile distribution of the noise power spectral density were measured on all the acquired data (1 Hz-1,000 Hz) and separately in a contour of ~6 seconds around each airgun pulse detected. Both shipping noise and seismic airgun pulses have highly contributed to the low-frequency background noise. In ~50% of the analyzed time, the results indicated that the received levels of acoustic noise exceed the limits proposed by the European Marine Strategy Framework Directive (Directive 2008/56/EC). Moreover, our results show high median values of noise within the fin whale emission frequency band (one-third frequency band centered at 20 Hz) and calls were more frequently detected in low background noise conditions. Airgun pulses were detected on a daily base in 4 of the 10 analyzed months. Considering the typical received PSD levels, we may hypothesize that the airgun pulses were produced at a distance of several hundred kilometers from the location of the sensor. In a single day, airgun pulses were also detected in the presence of fin whale calls. The correlation between noise levels and fin whale acoustic presence represents a fundamental study in understanding the effects of noise on the behavior of the species. Further observations are required to comprehend the impact of airgun sounds on fin whales in the Ionian Sea. Nevertheless, our results support recent studies that underline the urgent need of long-term and large-scale observations (Nowacek et al., 2015).


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Spatial, Spectral, and Temporal Distribution of Sound for Selected Sound Sources in the Dutch North Sea

Özkan Sertlek  
IBL, University of Leiden, The Netherlands, osertlek@gmail.com

Hans Slabbekoorn  
IBL, University of Leiden, The Netherlands, H.W.Slabbekoorn@biology.leidenuniv.nl

Carel ten Cate  
IBL, University of Leiden, The Netherlands, c.j.ten.cate@biology.leidenuniv.nl

Michael A. Ainslie  
Acoustic and Sonar Group, TNO, The Netherlands, michael.ainslie@tno.nl

In recent years, there has been a growing interest in the potential impact of sound on marine life. An increase in human activities such as shipping, detonations, seismic surveys, pile driving, and dredging has increased the contribution to the sound budget from anthropogenic sources, but we have very little insight into the overall energy contribution, distribution in space, frequency, and time for the various sources (Ainslie et al, 2009). Furthermore, the potential impact on marine life will depend on taxon-specific variety in distribution temporally, geographically, and within the water column as well as on overlap with taxon-specific hearing ranges.

Sound mapping by mathematical methods provides a practical way to estimate the contribution of individual sources to the overall soundscape and allows exploration of potential for taxon-specific impact. We explored the spatial, spectral, and temporal distribution of four selected sound sources in the Dutch North Sea (wind, shipping, explosions, and seismic airguns). To overcome the computational load problems associated with multiple sources, multiple receivers, and multiple frequencies, we developed an analytical hybrid propagation model based on Weston's energy flux and mode theories for use in shallow water (Sertlek and Ainslie, 2014). The use of this propagation model allows sound mapping at high spatial and spectral resolution.

In this work, we calculated annually averaged sound maps for the selected sound sources (wind, shipping, explosions, and seismic surveys) in the Dutch North Sea. Then, we ranked these selected sound sources according to their averaged contribution to the total acoustic energy in the Dutch North Sea over a two-year time period in various frequency bands between 100 Hz and 100 kHz. The sound maps can be used to zoom into species-specific exposure probabilities through weighted sound mapping based on typical swimming depths and hearing ranges (Slabbekoorn et al., 2010). These applications reveal the flexibility and scope of sound mapping and should become a practical tool for biologists, conservationists, policy makers, and legislators.

Effects of Sound Exposure on Behavior of Captive Zebrafish

Saeed Shafiei Sabet
Institute of Biology Leiden (IBL), Leiden, The Netherlands, s.shafiei.sabet@biology.leidenuniv.nl

Kees Wesdorp
Institute of Biology Leiden (IBL), Leiden, The Netherlands, keeswesdorp@gmail.com

Dirk van Dooren
Institute of Biology Leiden (IBL), Leiden, The Netherlands, dirkvandooren22@gmail.com

Hans Slabbekoorn
Institute of Biology Leiden (IBL), Leiden, The Netherlands, h.w.slabbekoorn@biology.leidenuniv.nl

Sounds generated by human activities due to urbanization, industrialization, and transportation have increased ambient-noise levels in marine and freshwater habitats worldwide. Fishes may use sounds to communicate with conspecifics, defend their territory, avoid predators, and locate foraging areas and may therefore be affected through disturbance, deterrence, and masking (Shafiei Sabet et al., 2016a). There are also many fish kept in indoor conditions that may be noisy, and there is a general lack of knowledge about the effects of sound exposure on their spatial distribution and swimming behavior within the confinement of their fish tanks.

We used two different experimental setups to test individual zebrafish (Danio rerio) response behavior to experimental sound exposure. In the first experiment, we used an elongated fish tank (200 cm × 50 cm × 50 cm), which allowed us to create a gradient of sound pressure levels through the tank, especially close to the active speaker. In the second experiment, we used a dual tank set up with two tanks (75 cm × 50 cm × 50 cm each) connected by a plastic tube, by which we were able to create more discrete transitions in sound conditions.

Our findings revealed several behavioral response patterns on sound exposure that indicated anxiety and that were similar in both experiments: startle responses, reflected in immediate increases in swimming speed, followed by a general slowdown and sometimes complete freezing. We did not find any significant lateral displacement to playback away from the speakers on the left or right side in either setup. We only found that zebrafish avoided the area directly in front of the active speaker (<10 cm) in the second experiment. It is likely that sound field conditions vary in such a complex way that there are no cues available to the fish to sense the direction of the sound source.

In conclusion, we believe that sound exposure can have a significant and considerable impact on swimming patterns and anxiety levels in captive zebrafish. This can have consequences in the short term for individual well-being and in the long term for individual growth and reproductive output. However, this requires more long-term studies into habituation and chronic stress. It should also be clear that the acoustic environment in laboratories should be taken into account for any acoustic or nonacoustic study with behavioral measurements as the readout. Importantly, horizontal displacement is not likely to be a useful measurement for any noise impact study in captivity (Neo et al., 2015; Shafiei Sabet et al., 2016b,c).


Endocrinal Responses To Long-Term Acoustical Stress In Milkfish (*Chanos chanos*)

Yi-Ta Shao  
Institute of Marine Biology National Taiwan Ocean University, itshao@mail.ntou.edu.tw  
Chih-An Wei  
Institute of Marine Biology National Taiwan Ocean University  
Tzu-Hao Lin  
Institute of Ecology and Evolutionary Biology, National Taiwan University  
Yung-Che Tseng  
Department of Life Science National Taiwan Normal University  
Kwang-Tsao Shao  
Biodiversity Research Center Academia Sinica

Strong underwater acoustic noise from shipping, seismic experiments, or sonar has been known to cause hearing loss and actual stress in teleosts. However, the long-term physiological effects of relatively weak but continuous ambient sound on fish are less well understood. In the present study, milkfish, *Chanos chanos*, were exposed to wind farm noise under either weak (109 dB re 1 μPa at 125 Hz; ~10-100 m away from the wind farm) or strong (138 dB re 1 μPa at 125 Hz; near the wind farm) conditions for 1, 3, and 7 days. Compared with the control group (80 dB re 1 μPa at 125 Hz), the fish under strong noise conditions had higher plasma cortisol levels than the other groups in the first 24 h. After the first day, the plasma cortisol levels of the fish in the strong group returned to the resting levels quickly, but the noise exposure increased both head kidney cyp11b1 (11β-hydroxylase, which converted 11-deoxycortisol to cortisol) mRNA levels on the 3rd and 7th days. Nevertheless, there was no difference found either in plasma cortisol levels or in cyp11b1 mRNA levels between the control fish and the fish under weak noise conditions at all time points. Moreover, noise exposure did not change hypothalamus corticotropin-releasing hormone (crh) mRNA levels in the entire experiment. This study showed that continuous noise may upregulate the gene that is related to cortisol biosynthesis, which possibly made the fish more susceptible to other stressors. However, hypothalamus crh expression may not be involved in the regulation pathway. Furthermore, the influence of continuous ambient sound was, of course, dependent on the sensory ability of the animals. As earlier ABR results have shown, sound pressure from the offshore wind farm noise in the weak noise condition was far lower than the hearing thresholds of milkfish.
Group Behavior and Reaction to an Acoustic Stimulus of a Small Cypriniform Fish

Matthew Short
University of Southampton, ms6e13@soton.ac.uk

Paul Kemp
University of Southampton, p.kemp@soton.ac.uk

Paul White
University of Southampton, prw@isvr.soton.ac.uk

Tim Leighton
University of Southampton, t.g.leighton@soton.ac.uk

Interpreting their surroundings and detecting threats and opportunities is key for all animals, and among the senses used by fish, the auditory system can provide the clearest information. Therefore, understanding how fish react to acoustic stimuli may be effective in the development of behavioral deterrents designed to prevent ingress into hazardous areas. This presentation will outline a study that aimed to determine how a complex acoustic environment influences the behavior of an individual and a school of five fish. Quantifying the link between group behavior and the reaction to sound would have serious implications on future experimental designs within the fisheries acoustics field because of the added complexity of behavioral interaction. Experiments were conducted in a section of a flume (75 × 45 × 45 cm) constructed of glass panels in a metal frame. The sound field was generated by underwater speakers placed in the flume but outside the experimental section. The acoustic stimulus consisted of 1-kHz tonal signal, with a maximum sound pressure level of 115 dB re 1 µPa. The acoustic field was mapped by scanning with a hydrophone to attempt to correlate fish location and the acoustic field. Control (no sound) and treatment (sound on) conditions were tested with the European minnow (Phoxinus phoxinus), a schooling species with well-developed hearing. Behavior was monitored with overhead video cameras and quantified using video-tracking software. Fish placement within the experimental area, continuous swimming speed, and total distance traveled were compared between treatment and control trials and individuals and groups of fish. Although no difference in swimming behavior or placement of the fish was observed between the control and treatment groups, it is important that future research involve a wider range of frequencies and intensities and a flume with a more rigid construction to enable a sound field with a simpler spatial distribution to be created. Such lessons learned and applied to future research are of importance if progress toward more robust fish-deterrent systems are to be developed for species occurring in aggregations, aiding to their conservation and management.
Decadal Evolution of the Northern Gulf of Mexico Soundscapes

Natalia A. Sidorovskaia
Department of Physics, University of Louisiana at Lafayette, nas@louisiana.edu

The Gulf of Mexico (GoM) is the home of numerous marine species including top-level predators such as marine mammals. Marine mammals in the northern GoM must coexist with extensive anthropogenic activities responsible for unique regional soundscapes, including oil exploration and production, fishing, and high levels of marine traffic. Understanding how the variability in acoustic soundscapes correlates with marine mammal distribution is critically important for regional conservation and mitigation strategies. Such studies can also assist in forecasting the long-term ecosystem health status and ecosystem response to disturbances of different spatial and temporal extent, including slow variations associated with climate change. In this paper, I analyze the evolution of the GoM soundscapes over the last 15 years based on regional archival passive acoustic data collected by the Littoral Acoustic Demonstration Center-Gulf Ecological Modeling and Monitoring (LADC-GEMM). Broadband acoustic noise in the industrially active GoM area is analyzed on short-term and long-term timescales and includes seasonal and weather-related variations and soundscapes of industrial seismic exploration surveys. When data allow, ambient-noise levels are correlated with acoustic encounters of endangered sperm whales and beaked whales in the region.

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BIAS: Toward Establishing Good Environmental Status on a Baltic Sea Regional Scale

Peter Sigray - Swedish Defense Research Agency, peters@foi.se; Anna Nikolopoulos, AquaBiota Water Research; Mathias Andersson, Swedish Defense Research Agency; Maria Boethling, Federal Maritime and Hydrographic Agency; Julia Carlström, AquaBiota Water Research; Ida Carlen, AquaBiota Water Research; Klaus Betke, ITAP; Jens Fischer, Federal Maritime and Hydrographic Agency; Frida Fyhr, AquaBiota Water Research; Line Hermansen, Århus University; Alkesander Klausen, Tallinn University of Technology; Radek Koza, University of Gdansk; Janek Laanearu, Tallinn University of Technology; Emilia Lalander, Swedish Defense Research Agency; Rainer Matuschek, ITAP; Mirko Mustonen, Tallinn University of Technology; Jukka Pajala, Finnish Environment Institute; Iwona Pawliczka, Hel Marine Station; Leif K G Persson, Swedish Defense Research Agency; Jaroslaw Tegowski, University of Gdansk; Jakob Tougaard, Århus University; Magnus Wahlberg, University of Southern Denmark

The EU LIFE+ project Baltic Sea Information on the Acoustic Soundscape (BIAS) started in September 2012 to support a regional management of underwater noise in the Baltic Sea, in line with the EU roadmap for the Marine Strategy Framework Directive (MSFD) and the general recognition that a regional handling of ambient noise (Descriptor 11) is advantageous or even necessary for regions such as the Baltic Sea. BIAS was directed exclusively toward the Descriptor Criterion 11.2 - Continuous Low Frequency Sound, aimed at the establishment of a regional implementation plan with regional standards, methodologies, and tools allowing for cross-border handling of acoustic data and associated results. The objectives for BIAS were formulated to create the framework for an efficient joint management of underwater sound in the Baltic Sea by elucidating and solving the major challenges in the implementation of Descriptor 11.2, specifically in this region but with outcomes relevant also for other marine regions. As the first implementation of a joint monitoring program across national borders, BIAS performed one year of measurements (2014) with 38 acoustic sensors deployed across the Baltic Sea by six nations. The measurements as well as the postprocessing of the measurement data were subject to standard field procedures, quality control, and signal-processing routines, all established within BIAS and published as standards. The measured acoustic data on low-frequency continuous sound were used to establish modeled noise maps for the project area, providing the first views of the Baltic Sea soundscape variation on a monthly basis. It deserves to underline that a large number of maps were produced that will constitute the base for the management of noise. To facilitate an efficient handling of noise, a geographic information system (GIS)-based online tool was outlined, visualizing the measured data and the modeled maps in terms of values and measures recommended for the implementation of the MSFD descriptor within the context of good environmental status (GES). This tool aggregates data one step closer to the management of GES.
Listening for Signals in Seismic Noise: A Case Study of Masking in Arctic Seals

Jillian Sills
Department of Ocean Sciences, University of California, Santa Cruz, jmsills@ucsc.edu

Colleen Reichmuth
Long Marine Laboratory, Institute of Marine Sciences, University of California, Santa Cruz, coll@ucsc.edu

When considering the effects of noise on hearing in marine mammals, the common practice is to apply standard audiometric data to predict how a noise source will influence an individual or species. In the case of auditory masking, critical ratio data, obtained in the laboratory with trained animals and tonal signals within flat-spectrum, continuous noise maskers, are often used for this purpose. Critical ratios can be combined with measured, average one-third octave band noise levels to predict the amplitude of a target signal required for detection above a particular noise background. However, the extent to which this method is appropriate may vary based on the features of the noise source in question. Temporally varying noise, such as that generated by seismic surveys, presents a particular challenge. To address this issue, we trained captive spotted and ringed seals to detect 100-Hz narrowband sweeps embedded within a background of seismic noise recorded 1 and 30 km from an operational airgun array. The results of this complex masking experiment indicate that a one-third octave band plus a critical ratio model is sufficient to predict the extent of masking only in some cases. When one-third octave band noise levels vary significantly in time, it becomes necessary to consider signal-to-noise ratios within time windows shorter than the duration of the target signal. This study addresses the important issue of masking outside of the laboratory and provides much needed information about when it is appropriate to use average noise levels and critical ratio data to predict masking in real environments. Our results can inform best management practices for evaluating the effects of noise on Arctic seals and other marine mammals.
Soundscape Cube: A Holistic Approach to Explore and Compare Acoustic Environments

Yvan Simard
Fisheries and Oceans Canada and ISMER-UQAR, Yvan.Simard@dfo-mpo.gc.ca

Marion Bandet
ISMER UQAR, Marion_Bandet@uqar.ca

Cédric Gervaise
Chaire Chorus, University of Grenoble-Alpes, cedric.gervaise@gipsa-lab.grenoble-inp.fr

Nathalie Roy
Fisheries and Oceans Canada, Nathalie.Roy@dfo-mpo.gc.ca

Florian Aulanier
ISMER-UQAR, Florian.Aulanier@uqar.ca

Soundscapes are characterized by large multiscale variability over space and time that makes their comparison difficult and dependent on the angle of view of the observer and the comparison metrics. Soundscapes are generated by sounds emanating from diverse geophonic, biophonic, and anthropophonic sources and processes, all responding to various triggering factors and environmental forces that are contributing their respective imprints on the mean level and variability at diverse frequencies. This multidimensional and variable nature of soundscapes is often explored along narrow segments of this large range of variability or for addressing selected objectives or particular questions. Such analyses offer a partial view of the actual soundscape characteristics or differences from site to site or periods of time. In contrast, the proposed soundscape cube approach rapidly summarizes the time and frequency variability along a continuum of scales by building a three-dimensional (3-D) statistical image of its content, which can be explored with several zooms and tools. The soundscape is simultaneously summarized along the frequency, time, and SPL quantile dimensions. First, SPL spectral cumulative distribution functions (cdfs) for $N$ time windows ($t$) over a recording period are computed. Second, the $N$ SPL spectral cdfs are stacked along the time axis for generating a 3-D block. Third, this latter 3-D block is converted to a stratified cube where each stratum is made of (frequency × time) SPL spectral quantile surfaces and pixels are colored by their SPL value. This soundscape cube can then be explored by various methods, by navigating and cutting across the three dimensions of the cube, to examine data quality, mean and median levels, trends, anomalies, recurrent features, biophonic and geophonic graininess and speckles, and differences and similarities among such cubes from different sites and years. The soundscape cube can also be split into its ambient- and transient-noise components, which respond to different forcing factors and scales of variability. Identification algorithms can be exploited to classify and tag acoustic events, such as specific sources within the cube. Examples of using the soundscape cube approach are given for underwater long-term recordings from the Canadian Arctic, the St. Lawrence Estuary, and the Mediterranean Sea.
Long-Term Trends in Ambient and Anthropogenic Noise in the Central and Western Pacific Ocean

Ana Sirovic  
Scripps Institution of Oceanography, asirovic@ucsd.edu  
Leah M. Varga  
Scripps Institution of Oceanography  
Erin M. Oleson  
Pacific Islands Fisheries Science Center, NOAA

Multiyear studies of the changes in ambient noise are uncommon, yet they can provide information on the amount of natural variability in the noise that animals are exposed to as well as an idea of changing noise-level trends. To investigate some of these long-term trends in low-frequency (<1,000-Hz) ocean ambient noise, passive acoustic data were collected using high-frequency acoustic recording packages at two locations in the tropical Pacific Ocean. One site was recording in the central Pacific off Kona on the Big Island of Hawai‘i from 2007 to 2015 and the other in the western Pacific near Saipan from 2011 to 2015. In addition, detailed occurrences of two types of transient anthropogenic noise events, nearby boat passages and midfrequency active (MFA) sonar transmissions, were identified at these locations from a period from 2010/2011 to 2012/2013. Characteristics of those anthropogenic sounds including duration, frequency, received levels, and sound exposure levels were measured. Both sites exhibited relatively low levels of ambient noise characteristic of distant shipping (<100 Hz) compared with levels generally reported for the North Pacific. Ambient noise attributable to shipping was generally lowest during the early years of recording at Saipan and increased after mid-2013. At Kona, there was a large level in variability in this part of the noise spectrum but no clear interannual trend. This is likely explained by the fact that most of the low-frequency noise was from nearby boats and was not a result of distant shipping noise. Ambient noise at Kona also had a seasonally variable contribution by various baleen whales. Humpback whales were a particularly prominent component of the soundscape during the winter, with an indication of a change in spectral features of the song over the recording period. Broadband shipping noise, indicative of nearby ships, was found at both sites year-round, but the total number of hours with ships increased over the period of the study. There was a clear diel trend of increased boat activity during daylight hours. The MFA sonar was also detected at both sites. At Kona, MFA sonar occurred intermittently through most of the recording period. The MFA sonar off Saipan was mostly concentrated to a period from Summer 2012 to the Winter 2013. As areas with relatively persistent low level and local sources of anthropogenic noise, these locations may be good places for the study of the impact of these sounds on marine mammals as well as on other marine life.
Analysis of the Protein Content of the Statocyst Endolymph in the Common Cuttlefish (Sepia officinalis): A Contribution to Assess Acoustic Trauma After Exposure to Sound

Marta Solé
Laboratory of Applied Bioacoustics (LAB), Technical University of Catalonia, BarcelonaTech (UPC), Rambla exposició s/n, 08800 Vilanova i la Geltrú, Barcelona, Spain, marta.sole@upc.edu

Marta Monge
Proteomics Laboratory, Vall d’Hebron Institute of Oncology (VHIO), Edifici Collserola, 08035 Barcelona, Spain, mmonge@ir.vhebron.net

Francesc Canals
Proteomics Laboratory, Vall d’Hebron Institute of Oncology (VHIO), Edifici Collserola, 08035 Barcelona, Spain,

Carme Quero
Department of Biological Chemistry and Molecular Modelling, IQAC (CSIC), Jordi Girona 18, 08034 Barcelona, Spain, cqlqob@cid.csic.es

Michel André
Laboratory of Applied Bioacoustics (LAB), Technical University of Catalonia, BarcelonaTech (UPC), Rambla exposició s/n, 08800 Vilanova i la Geltrú, Barcelona, Spain,

Analyses by scanning and transmission electron microscopy techniques revealed lesions on the statocysts of the Mediterranean common cuttlefish (Sepia officinalis) when exposed to low-intensity low-frequency sounds. For the purpose of assessing the effects of exposure to sound on the statocyst endolymph of this species, proteomic analysis of the endolymph before and after sound exposure was performed. We determined the changes in the protein composition of the statocyst endolymph of S. officinalis when sacrificed at different times after sound exposure. Significant differences in protein expression were observed, especially between control and exposed animals 24 h after exposure. A total of 37 proteins were found to be significantly different in exposed specimens, of which 17 were identified to be mostly related to stress and cytoskeleton structure. The endolymph analysis under situations of acoustic stress allowed us to establish the effects at the proteome level and identify the proteins especially sensitive to this type of trauma. The observed changes are known to affect the physiology and functioning of S. officinalis statocysts and alter the sensory information of this species, compromising their survival and role in the oceanic ecosystems.
Influence of Pile Driving on the Feeding Physiology of the Common Mussel *Mytilus edulis* (L.)

Ilaria Spiga  
Newcastle University, ilaria.spiga@gmail.com  
Gary S. Caldwell  
Newcastle University, gary.caldwell@newcastle.ac.uk  
Rick Bruintjes  
University of Exeter, r bruktjes@exeter.ac.uk

Underwater pile driving is typically undertaken during offshore construction, such as during the building of oil and gas platforms, offshore wind farms, and harbors. These structures generally need solid foundations, provided by large steel piles, that are driven into the seabed. Impact pile driving generates waterborne pressure and particle motion, which propagate through both the water column and the seabed. To improve our understanding of the consequences of pile driving on marine organisms, experiments replicating the acoustic and vibration conditions are needed. This should be particularly important for organisms that live on or within the seabed and have limited possibility to relocate, such as bivalve mollusks. Few studies have investigated the potential effects of underwater noise and vibration on marine invertebrates, and studies addressing the responses of bivalves to underwater noise stimuli are in particularly short supply. This is surprising given that bivalves are key components of marine food webs as well as being of considerable economic and nutritional importance. In the current study, the influence of impact pile driving on the feeding physiology of the common mussel (*Mytilus edulis*) was investigated in a semiopen field experiment. An experimental piling setup was constructed using a pile driver and a steel pile. The experiment was conducted in a former shipbuilding dock filled with water and North Sea sediment. Under controlled conditions, individual mussels were exposed to experimental pile driving and ambient conditions, with the possibility to feed on *Tetraselmis suecica*. An indirect clearance method was used to measure the volume of water cleared of suspended microalgae per unit time. Mussels had significantly higher clearance rates during exposure to pile driving compared with individuals tested in ambient conditions. We suggest that mussels under pile-driving conditions physiologically moved from a maintenance state to active metabolism in an attempt to compensate for the initial stress caused by pile driving. The increased clearance rate could enable more active mussels to meet their increased metabolic demands and counterbalance the energetic costs of ventilation and filtration with food intake and digestion. However, if the metabolic demand is not satisfied by food availability, then more active animals may not have the energy resources to sustain increased clearance rates, with potential consequences for individual fitness levels.
Noise Propagation from Vessel Channels into Nearby Fish Nesting Sites in Very Shallow Water

Mark W. Sprague
Department of Physics, East Carolina University, Greenville, NC 27858, spraguem@ecu.edu

Cecelia S. Krahforst
Institute for Coastal Science and Policy, East Carolina University, Greenville, NC 27858, krahforstc06@students.ecu.edu

Joseph J. Luczkovich
Department of Biology and Institute for Coastal Science and Policy, East Carolina University, Greenville, NC 27858

Evidence suggests that vessel noise is associated with changes in fish behavior and physiology. We compared fish sound exposure in two noisy high-vessel traffic areas to fish sound exposure in two quieter areas located in a research reserve and a remote estuary. We measured sound transmission from vessel channels into adjacent fish nesting sites located in very shallow (1- to 2-m) water. We placed hydrophones at each nesting site and recorded sounds played through an underwater speaker in the vessel channel to produce transfer functions for sound propagation from the channel to each nesting site as a function of frequency, allowing us to predict the sound levels in the nesting sites and the sound exposure levels from arbitrary sources. We also recorded ambient sound and sounds from passing vessels at each nesting site. We calculated sound exposure levels for fish at the site from the passing vessels. As expected, the “quiet” areas had lower ambient sound levels than the “noisy” areas. The research reserve quiet area was isolated from the nearby vessel channel by sand bars that blocked the sounds played in the channel by our speaker and those produced by passing vessels. As a result, all sound exposure in this area was due to occasional research and fishing vessels passing through the shallow water. The second quiet area was not acoustically isolated from the nearby vessel channel. Instead, it was located in a remote area with few vessels present; thus it was quiet. This second quiet area and the two noisy sites allowed sound transmission from the deeper vessel channel into the fish nesting sites. Although the cutoff frequencies associated with the water depth at the nesting sites limited the propagation from the channel, low-frequency sounds from boats were detected in the shallow fish nesting sites, resulting in fish sound exposure in shallow water due to vessels in the channel. These sound exposure levels for the fish nesting sites can be compared with the observations of fish behavior and the physiological parameters of fish at the sites to assess the impact of vessel noise.
The effects of prolonged exposure to increasing levels of anthropogenic noise on populations of acoustic signalers are a topic of considerable scientific concern and research focus. Although there is mounting literature on the topic, the effects are still not thoroughly understood, and studies to date have largely focused on terrestrial animals and marine mammals. Low-frequency ocean noise has dramatically increased in the past few decades in certain ocean areas, some of which are important habitats for a number of threatened or endangered marine organisms. One of these areas is the Stellwagen Bank National Marine Sanctuary (SBNMS) that is located off the northeast coast of the United States and in close proximity to a densely populated coastal zone. The sanctuary experiences high anthropogenic activity and, subsequently, increased levels of underwater noise, particularly due to commercial shipping. The SBNMS is an important seasonal feeding ground for a number of endangered and vocally active baleen whales that have been the focus of a considerable amount of acoustic research attention. Specifically, there has been a large amount of work dedicated to documenting the temporally and spatially fluctuating underwater noise field and its potential masking effect on low-frequency whale communication. The sanctuary is also host to a significant number of acoustically active and ecologically and commercially important fish species, such as Atlantic cod and cusk, whose natural populations have been dramatically reduced. Considerable data to support habitat and organism distribution patterns are available within the sanctuary, often at higher resolution than for adjacent waters. Together, this combination of facts and accessible knowledge led us to assess the potential for vulnerability to increased levels of low-frequency underwater noise in important fish species. Using a number of bottom-mounted autonomous acoustic recorders distributed throughout the sanctuary and providing continuous low-frequency recording over the course of a year, we investigated the extent and patterns of acoustic behavior in a number of soniferous fishes in several different habitat types within the SBNMS. These results were then used to take the first steps in assessing these animals’ communication spaces and the alteration of these spaces due to varying levels of background noise. Identifying and better understanding the implications of anthropogenic noise at lower trophic levels is important to advancing the management of this pollutant both within the sanctuary and globally.
Are Current Regulatory Practices Keeping Up with Technology?

Michael Stocker  
Ocean Conservation Research, mstocker@OCR.org  
Suzanne Arnold  
Grey Whale Coalition, suearnold25@icloud.com  
Bruce Martin  
JASCO Applied Sciences, Bruce.Martin@jasco.com  
Chris Clark  
Cornell University, cwc2@cornell.edu  
Michael Jasny  
NRDC, mjasny@nrdc.org

The rapid colonization of the ocean by research, military, energy-harvesting, and extractive industries are introducing many new sources of acoustical energy into the sea. Sound sources such as underwater navigation beacons, multinodal communication networks, continuous seismic and benthic profile surveys, and mechanical noise from wind farms, mining operations, and seafloor hydrocarbon processing are making permanent changes to the marine soundscapes. Concurrently, biological research is revealing that anthropogenic noise produces acute and chronic impacts on most marine taxa including fish, crustaceans, and turtles as well as the traditionally studied marine mammals. However, our understanding of the scale and importance of the impacts of man-made noise has not developed to the point that national and international regulations are in place to protect marine life, a situation that is of great concern to many scientists and marine conservation advocates. This presentation reviews the product of an Ocean Noise Pollution Workshop: Policy, Regulation, and Practice attended by marine research, policy, and regulation professionals to inform the conversation on data gaps and shortcomings in the current regulatory practices.
Using Communication Range Reduction to Index Anthropogenic Noise Masking of Baleen Whale Vocalizations

John Terhune
Department of Biological Sciences, University of New Brunswick, terhune@unb.ca

It is difficult to convey the impact of anthropogenic noise masking on baleen whale communication, especially to laypersons. High-amplitude noises will completely mask vocalizations at close range. Lower amplitude noises will, in a nonlinear manner, reduce the range at which calls can be perceived. The acoustic communication ranges of baleen whales cannot accurately be determined because there are no data on their hearing sensitivity, call recognition thresholds, and critical ratios of tonal and broadband signals. Call detection is primarily limited by background noise. Thus, we can index relative masking effects by measuring noise levels in the one-third octave band frequencies of the calls. This assumes that the maximum communication range will occur at quiet ambient levels (levels exceeded 95% of the time) and for every 4.5-dB increase above this, the range will be reduced by half. The halving of detection distance for each 4.5-dB increase assumes a spreading loss of \(15\log(\text{range})\) and does not consider absorption. Underwater noise levels were recorded for 2 min every 10 min for 127 days near the coast of the Bay of Fundy, Canada, in the summer and fall of 2015. The bottom-mounted autonomous recorder was ~5 km from a ferry route going to Grand Manan Island and in an area frequented by fin whales (\textit{Balaenoptera physalus}). Each ferry crossing took 1.5 h and departures were ~2 h apart from 0730 to 2100. Noise levels were highly variable. The baleen whale median communication ranges when the ferries were not running \((n = 9,144)\) were 30.7% and 21.2% of the maximum at 63 Hz and 125 Hz, respectively. When the ferries were running \((n = 9,144)\), the median ranges dropped to 4.2% and 4.6%, respectively. Communication ranges dropped below 1% for 13% and 9% of the time at 63 Hz and 125 Hz, respectively, when the ferries were running. At 20 Hz, the median communication ranges were 10.0% and 9.7% of the time when the ferries were not and were running, respectively. Thus, the presence of the ferries had little impact on the detection ranges of the 20-Hz fin whale call, but vocalizations at higher frequencies would only be detected at much reduced ranges. Communication range reductions associated with background noise level increases present a means to index masking and thus may aid in quantifying the impact of anthropogenic underwater noise sources on baleen whales and other aquatic animals.
DRAMAD: A Dynamic Risk Assessment Model for Acoustic Disturbance Using Agent-Based Modeling for the Calculation of Sound Exposure

Frank Thomsen
DHI, Agern Alle 5, 2970 Hørsholm, Denmark frth@dhigroup.com

Flemming Hansen
DHI, flemmingthorbjoernhansen@gmail.com

Anders Erichsen
DHI, aer@dhigroup.com

Henrik Skov
DHI, hsk@dhigroup.com

Stefan Heinänen
DHI, she@dhigroup.com

Ramunas Zydelis
DHI, rzy@dhigroup.com

Martin Taaning
DHI, mat@dhigroup.com

Jonas Mortensen
DHI, jbm@dhigroup.com

Henriette Schack
DHI, Henriette.b.schack@gmail.com

Emma Guirey
GENESIS, emma.guirey@genesisoilandgas.com

Jürgen Weissenberger
Statoil, jurw@statoil.com

Man-made sound can impact marine mammals over long ranges due to the very good acoustic properties of water. The effects range from masking of biologically important sounds to injury, usually limited to very high and sustained sound levels. Repeated exposure to lower levels of noise can lead to effects on hearing sensitivity. However, conventional risk assessment frameworks to predict the magnitude of noise-related impacts are based on the concept of static receivers, which can lead to rather unrealistic results. The objective of DRAMAD was to develop a model that accounts for the movements of cetaceans and seals before during and after noise exposure. The study area was the Chukchi Sea and the target species were two cetaceans (bowheads and white whales) and four pinnipeds (bearded, ringed, and spotted seals and walrus). The hydrodynamics of the Chukchi Sea were modeled using MIKE, DHI’s in-house software. We investigated the relationship between environmental variables and species movements using dynamic habitat modeling. Based on this, we modeled the movements of the receivers (individual mammals) in response to environmental variables using agent-based models. The results show good agreement between the simulated distribution and timing of marine mammals and the calculated kernel densities based on observation data. The effect of sound exposure on marine mammals was simulated by using a four-step reaction response, based on literature data, from a weak avoidance reaction at low sound exposure to more severe reactions on swimming speed and directions at higher sound pressure levels. Results showed differences between bowhead and beluga whales, with little effect on the former and large-scale but short-term displacement in the latter. Our study shows that risk assessments that are based on mobile species have a great potential to shed light on the impact of human-generated sound on marine life. Yet, they depend very much on the quality of the input data that is so far limited for a number of variables such as movement patterns, and behavioral and physiological response thresholds. However, a variety of studies are underway that address these questions so that the database informing such models is steadily increasing. Thus, in the future, dynamic risk assessments could be suitable for large-scale risk assessments undertaken by industry and/or regulators to inform environmental impact assessments and marine spatial planning. They also hold great potential to fill in gaps when investigating the population consequences of acoustic disturbance.
Driven to Distraction: Behavioral Impact of Ocean Noise on the European Hermit Crab

Svenja Tidau  
Plymouth University, svenja.tidau@plymouth.ac.uk  
Mark Briffa  
Plymouth University, mark.briffa@plymouth.ac.uk

Recent studies show that anthropogenic noise can have detrimental effects on animal behavior, either through the masking of important sounds in the animal’s environment or through distraction effects. In the sea, the effects of noise pollution have been demonstrated across a range of taxa including mammals, fish, and crustaceans. This study aims to determine whether ocean noise pollution distracts marine hermit crabs, *Pagurus bernhardus*, from their usual shell investigation behaviors. These behaviors are used to assess the quality of the empty gastropod shells on which hermit crabs rely for protection and play a key role in the decision to switch shells.

We randomly assigned individuals to occupy a shell of either 50% or 80% of their optimal shell size (based on crab weight). The crabs were then allowed to repeatedly investigate a new empty shell that was of optimal size. Using a crossover design, we allowed each crab to investigate the new shell five times in the absence and five times in the presence of recorded boat noise, on each occasion recording the focal crab’s shell investigation activities. Both sounds were recorded at Teignmouth, UK. We will be analyzing the data with regard to (1) differences in mean shell investigation behavior among conditions and across observations, (2) differences in the repeatability of behavior among conditions, and (3) differences in within-individual variation in behavior among conditions. As well as providing insights into the average effect of noise pollution, this design will enable us to assess the extent to which hermit crabs might habituate and whether key markers of “animal personality” may be influenced by this form of pollution.

Here, we will give a brief overview about the current stage of research in the field of ocean noise and decapod crustaceans followed by the details of our experimental setup, discussing the challenges of replicating ecologically relevant noise conditions in the lab. We will also present the preliminary results from the experiment described above as well as outlining our planned experiments.
Three Different Ways to Approach Good Environmental Status with Respect To Man-Made Underwater Noise

Jakob Tougaard
Aarhus University, Denmark, jat@bios.au.dk

Line Hermannsen
Aarhus University, Denmark, line.hermannsen@gmail.com

Jukka Pajala
SYKE, Helsinki, Finland, Jukka.Pajala@ymparisto.fi

Mathias Andersson
FOI, Stockholm, Sweden, mathias.andersson@foi.se

Thomas Folegot
Quiet Oceans, Brest, France, thomas.folegot@quiet-oceans.com

Peter Sigray
FOI, Stockholm, Sweden, peter.sigray@foi.se

The EU Marine Strategy Framework Directive includes specific obligations to reach good environmental status (GES) for the European seas, including respect for man-made underwater noise (Descriptor 11). This raises a number of urgent questions about defining GES for underwater noise and especially how to manage GES in situations where there is little knowledge about the long-term impact of noise. Three different frameworks for evaluating GES are offered and discussed. The first approach to GES is based on pressure indicators, i.e., one or more measures of the total amount of underwater noise emitted to an ecosystem without particular regard for the effects of the noise. GES can be assessed by comparing anthropogenic to natural ambient noise. One could define conditions to be good if man-made noise rarely elevates above natural ambient noise, moderate if man-made noise is comparable to and sometimes elevates above natural ambient noise, and poor if man-made noise dominates over natural sources. Examples include assessment of ship noise quantified by a range-reduction factor (or equivalent), expressing a possible reduction in communication distances. The second approach to GES is risk based. The risk from noise exposure can be expressed as the product of abundance of target species, the impact of the noise, and noise exposure. This product allows for identification of areas with high risk, even when little is known about the effects. High risk occurs in areas where the product of abundance and noise exposure is high. Examples of risk-based approaches include models of the impact from pile driving and more heuristic models identifying risk areas from animal abundance and noise exposure maps, such as the projects SAMBAH and BIAS in the Baltic Sea. The third approach to evaluating GES is truly quantitative and based on the long-term impact on animals. If man-made noise negatively affects the conservation status of one or more abundant species in an area, then this area cannot have GES with respect to underwater noise. However, only a very limited number of examples exist where direct links between noise and long-term survival are available, and truly quantitative models, such as the PCoD and DEPONS models, are still in their infancy. For most species, it is unrealistic to obtain good measures of impact in the near future and there is thus a need for adaptation of the two first frameworks for GES to allow for assessment and regulation toward GES in situations dominated by the lack of knowledge about impact.
Arctic Soundscapes During the 2013 and 2014 Seasons

Mike van der Schaar  
Technical University of Catalonia, BarcelonaTech (UPC), mike.vanderschaar@upc.edu

Anja Johansen Haugerud  
Statoil ASA, ANJJH@statoil.com

Jürgen Weissenberger  
Statoil ASA, jurw@statoil.com

Michel André  
Technical University of Catalonia, BarcelonaTech (UPC), michel.andre@upc.edu

Statoil deployed three acoustic recorders from Fall 2013 to Fall 2014 in the arctic region as part of a broad scientific campaign. One recorder was installed in the Barents Sea southeast of Spitsbergen. Two other recorders were installed in the Greenland Sea northeast of Greenland. All recorders were operating at a duty cycle of 2 minutes on and 30 minutes off, sampling at 39,062 Hz, and recording in 24 bits. This presentation will report the acoustic analysis done on the data using SONS-DCL, comparing the results between the different locations and putting emphasis on the differences in received sound levels mostly due to ice movement, anthropogenic sources, and the presence of cetaceans in the different seasons. For the Greenland Sea data, an overview will be presented of the relationship between the received levels and the distance of a detected seismic survey. As for the animal presence, it was found to be minimal during the summer months, although sperm whales were present all year-round and some fin whale calls were received in early summer as well. Bearded seal presence was very seasonal from around April to June at both Spitsbergen and Greenland. The bowhead whale presence in Greenland was especially strong during the winter, with a possible humpback presence at Spitsbergen. But no attempt was made to distinguish humpback and bowhead whale calls. At Spitsbergen, belugas or narwhals were present; at the Greenland recorders, there were fewer dolphin signals, and those found were most likely from white beaked dolphins. A number of unidentified acoustic events were detected as well. These data will be shown here but are also available for playback from a dedicated website.

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The status and potential of autonomous aerial and marine vehicles for marine animal monitoring were reviewed. Focus was laid on state-of-the-art solutions and those in development that are most pertinent to environmental monitoring and were conducted for the oil and gas industry, such as mitigation monitoring (e.g., during seismic surveys), population surveys, and/or tracking marine mammals, sea turtles, and fish to investigate their behavior in relation to anthropogenic sound. Considered were unmanned aerial systems, autonomous underwater vehicles, and autonomous surface vehicles as well as appropriate sensor technology. The requirements that need to be met for conducting mitigation monitoring, population surveys, and animal tracking were assessed to define the appropriate criteria and metrics. These were used to evaluate the applicability and suitability of the autonomous systems for different monitoring activities. Further criteria allowed the evaluation of potential vehicle and sensor combinations, operational capabilities, data processing and transfer aspects, and further considerations to be taken into account during project planning. The results suggest that simple “one-size-fits-all” solutions to use a particular autonomous vehicle system for a certain monitoring task cannot be given because many project-dependent factors need to be considered for the choice of vehicle-type/sensor-type combination, such as the nature of the species or the area to be monitored. The technical and operational details of autonomous platforms need to be tailored to the specific needs of the exploration and production project, e.g., the location of the area of interest, the properties of the platform that the autonomous vehicle will be deployed from, the required survey length, the project budget, and more. Also, the choice of a data relay system is important to match the demands needed for the different monitoring tasks. The study revealed which vehicle types are best to use for which monitoring type in which situation by comparing each class of vehicle and highlighting their particular strengths and weaknesses relating to the specific monitoring tasks. Data gaps and recommendations on what future research should focus on were also identified and will be discussed in the presentation. This work was funded by the International Association of Oil and Gas Producers from the Joint Industry Programme on E&P Sound and Marine Life-Phase III.
Effect of Outboard Motor Sound on Invasive Silver Carp (Hypophthalmichthys molitrix) Jumping Behavior

Brooke J. Vetter
University of Minnesota Duluth, vett0114@d.umn.edu

Allen F. Mensinger
University of Minnesota Duluth, amensing@d.umn.edu

Invasive silver carp (Hypophthalmichthys molitrix) dominate regions of the Mississippi River drainage in North America, outcompete native species, and continue to expand northward, threatening the Laurentian Great Lakes. Silver carp are notorious for their prolific and unusual jumping behavior; however, it is unclear if the fish are reacting to sound pressure or particle motion. Field trials on the Illinois River indicate that silver carp primarily jump behind and away from fast-moving (16-32 km/h) boats with large outboard motors (100-150 hp). These motors emit broadband sound with energy peaks from 0.1 to 2 kHz and from 6 to 10 kHz. Additionally, captive silver carp demonstrated consistent negative phonotaxis (reacting up to 37 times consecutively) to an outboard motor recording (100 hp at 32 km/h). Therefore, it seems the carp react to both sound and vibrations. However, the same sound stimulus at a higher intensity (170 dB re 1 μPa) elicited jumping behavior in wild fish when played from a slow-moving boat (>5 km/h) in the Spoon River near Havana, Illinois. In these trials, the fish jumped 100 m or more in front of the boat, implying that the fish may also be reacting to sound pressure, the far-field component of sound. Furthermore, the fish showed behavioral differences depending on the underwater environment. Sound was effective in dispersing the fish after passing through a river section only three times, but if submerged debris was available, the fish preferred to seek refuge in these areas of cover. This research implies that anthropogenic sound can be used to alter the behavior of silver carp and has implications for deterrent barriers or other uses (e.g., herding fish) that are important to fisheries managers.

This research was supported by the University of Minnesota Duluth, the Minnesota Environment and Natural Resources Trust Fund, and the Illinois Natural History Survey.
Research on underwater sound is critical for understanding the potential acoustic impact on marine life. However, such research can be challenging, requiring complex multidisciplinary approaches. Research results often reach the public through popular media, but these sources sometimes contain misinformation or oversimplify results. To provide a scientifically accurate resource on underwater sound that is understandable for a variety of audiences, the Graduate School of Oceanography at the University of Rhode Island has teamed with Marine Acoustics, Inc., on the Discovery of Sound in the Sea (DOSITS) project. The project’s foundation is a website (www.dosits.org) that is a comprehensive, universally available resource that synthesizes the latest peer-reviewed science on underwater sound in a form accessible to students, educators, reporters, the public, regulators, and decision makers. The site has over 400 pages and is updated semiannually with newly published scientific information after a thorough review by a panel of scientific experts. A current focus of the DOSITS project is resources for the international decision-making community. Recently, two needs assessment surveys were conducted to identify the format and content priorities of government employees, federal and state contractors, nongovernmental organization employees, and industry representatives. Guided by their input, structured tutorials, webinars, and instructional videos were developed to address needs such as science of sound fundamentals, hearing sensitivities, and the potential effects of underwater sound on marine animals. The structured tutorials provide a streamlined, progressive development of knowledge from current scientific information. One tutorial focuses on the potential effects on marine animals from increased background noise and specific sound sources. Another tutorial focuses on the process for determining possible effects of a specific sound source. The webinar series consists of presentations by experts followed by interactive, real-time question-and-answer sessions. All webinars are archived on the DOSITS website as a permanent resource. The five-part series has modules on the science of underwater sound, sound reception by marine mammals and fishes, the effects of sound on marine mammals, and the effects of sound on marine fishes plus a final, combined review webinar with all presenters. In contrast to the detailed webinars, instructional videos provide short (3- to 5-minute) summaries that can be viewed on mobile devices and personal computers. The four current videos cover the fundamentals of underwater sound, sound reception in marine animals, the potential effects on marine life, and mitigation and monitoring methods.
Assessing the Impact of Underwater Clearance of Unexploded Ordnance on Harbor Porpoises \textit{(Phocoena phocoena)} in the Southern North Sea

Alexander M. von Benda-Beckmann, TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK The Hague, The Netherlands, sander.vonbenda@tno.nl; Geert Aarts, IMARES, Wageningen UR, Zuiderhaaks 5, 1797 SH ’t Horntje, The Netherlands, and Department of Aquatic Ecology and Water Quality Management (AEW), Wageningen University, Droevendaalsesteeg 3a, Building 100, 6708 PB Wageningen, The Netherlands, geert.aarts@wur.nl; H. Özkan Sertlek, Institute of Biology Leiden, Leiden University, Sylviusweg 72, 2333 BE Leiden, The Netherlands, and Electronics Engineering Department, Gebze Institute of Technology, P.O. Box 141, 41400 Gebze, Turkey, osertlek@gmail.com; Klaus Lücke, Centre for Marine Science and Technology, Curtin University, GPO Box U1987, Perth, WA 6845, Australia, and IMARES, Wageningen UR, Zuiderhaaks 5, 1797 SH ’t Horntje, The Netherlands, klaus.luecke@curtin.edu.au; Wim C. Verboom, JunoBioacoustics, Dorpsstraat 1-a, 1731RA Winkel, The Netherlands, weverboom@hotmail.com; Ron A. Kastelein, SEAMARCO, Julianalaan 46, 3843 CC Harderwijk, The Netherlands, researchteam@zonnet.nl; Darlene R. Ketten, Harvard Medical School and Hanse Wissenschaftskolleg Institute for Advanced Studies, Neurosciences and Marine Sciences, Delmenhorst, 27753 Germany dketten@whoi.edu; Rob van Bemmelen, IMARES, Wageningen UR, Zuiderhaaks 5, 1797 SH ’t Horntje, the Netherlands rvanbemmelen@gmail.com; Frans-Peter A. Lam, TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK, The Hague, The Netherlands frans-peter.lam@tno.nl; Roger J. Kirkwood, IMARES, Wageningen UR, Zuiderhaaks 5, 1797 SH ’t Horntje, the Netherlands roger.kirkwood@wur.nl; Michael A. Ainslie, TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK, The Hague, The Netherlands Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom michael.ainslie@tno.nl

Large amounts of ordnance were deposited in the North Sea during the Second World War. Much of this unexploded “legacy” ordnance (UXO) that is still present in the North Sea results in frequent encounters for fishermen or is located during ground clearing before construction of offshore wind farms, cable laying, sediment extraction, and dredging. Out of concern for human safety and to avoid damage to equipment, ships, and structures from uncontrolled explosions, reported UXO cleared in the DCS, provided by the Netherlands Ministry of Defence, was used in a propagation model that produced sound maps to estimate potential sound exposures. These were combined with survey-based models of harbor porpoise seasonal distribution on the DCS and contours for a risk intensity threshold that if exceeded are estimated to cause hearing loss in harbor porpoises. It was predicted that in a 1-year period, the 88 explosions that occurred in the DCS very likely caused 1,280, and possibly up to 5,450, permanent hearing loss events, in other words, individual instances of a harbor porpoise predicted to have received sufficient sound exposure to cause permanent hearing loss. The percentage of animals estimated to have suffered from permanent hearing loss per year due to exposure to underwater explosions in the DCS could be at least 1.3% and potentially up to 8.7% of the harbor porpoise population present in the DCS. The large uncertainty range in the estimated impact reflects the limited data available on permanent hearing loss thresholds. This study is the first to address the impact of underwater explosions on the population scale of a marine mammal species.
Acoustic tags attached to marine animals are commonly used to study their behavior. Measuring ambient noise is of interest to understand the responses of marine mammals to anthropogenic underwater sound, characterize their natural soundscape, or assess their potential communication space. Noise of water flowing around the tag reflects the speed of the animal but hinders obtaining reliable ambient-noise measurements. Here we describe a correlation-based method for stereo acoustic tags to separate the relative contributions of flow and ambient noise. The uncorrelated part of the noise measured on DTAG recordings was strongly correlated with animal swim speed, thus providing a robust measure of flow noise over a wider frequency bandwidth than using a single hydrophone. By removing measurements dominated by flow noise, ambient-noise estimates were made for two whale species, a humpback whale (*Megaptera novaeangliae*) and two killer whales (*Orcinus orca*), with DTAGs attached simultaneously. The method is applicable to any multichannel acoustic tag, enabling application to a wide range of marine species.
In this work, experiences with the measurement and monitoring of the underwater noise in Croatia are presented. Historically, underwater noise was measured for the Yugoslav Navy and its purposes, and with the breakup of Yugoslavia, there was a long period of no activity in that field. However, basic equipment and knowledge were preserved. In 2013, Croatia launched a pilot project titled “Consulting services for the definition of the monitoring and observation program for ongoing assessment of the Adriatic Sea,” aimed at defining a monitoring program to comply with the requirements of the Marine Strategy Framework Directive (MSFD). Within that project, measurements of the ambient underwater noise were carried out to examine and define new measurement methodology and techniques and to gather some baseline data. In this work, the temporal and spatial distribution of measurement sites, measurement methodology, and results are presented. Also, the future program for the monitoring of both low- to midfrequency impulsive and low-frequency continuous underwater noise complying with MSFD is presented.
Effect of Anthropogenic Noise Playbacks on the Blue Mussel *Mytilus edulis*

Matthew Wale  
School of Life, Sport, and Social Sciences, Edinburgh Napier University, Edinburgh, UK,  
m.wale@napier.ac.uk

R. A. Briers  
School of Life, Sport, and Social Sciences, Edinburgh Napier University, Edinburgh, UK

M. G. J. Hartl  
Centre for Marine Biodiversity and Biotechnology, Heriot Watt University, Edinburgh, UK

K. Diele  
School of Life, Sport, and Social Sciences, Edinburgh Napier University, Edinburgh, UK, and St. Abbs Marine Station, St. Abbs, UK

Marine invertebrates have received scant attention with regard to their responses to anthropogenic noise despite their pivotal role in marine ecosystems. They are important components of most food webs and perform essential ecosystem services. Preliminary evidence that marine invertebrates can be very sensitive to noise calls for further studies in this context (e.g., reports by the Convention of Biological Diversity and OSPAR). We conducted a series of carefully controlled laboratory experiments to investigate how short-term (up to 6 hours) playback of ship noise affects the blue mussel *Mytilus edulis*. To help understand whether it is affected by underwater noise and also how and why, we employed a mechanistic, integrative approach as set forth by Kight and Swaddle (2011), considering behavioral (valve movement and algal clearance), physiological (oxygen consumption), and biochemical (structural DNA damage and oxidative stress) responses. Comet assay analysis of hemocytes and gill cells demonstrated significantly higher single-strand breaks in the DNA in the cells of mussels exposed to ship noise playback compared with those kept under ambient conditions. Superoxide dismutase (SOD) analysis did not identify an excess of superoxide ions, whereas a thiobarbituric acid-reactive (TBAR) assay revealed increased TBAR substances, indicating lipid peroxidation in the gill epithelia of noise-exposed specimens. Glutathione (GSH) and glutathione peroxidase (GPx) assays to further investigate oxidative stress responses are ongoing, along with the behavioral and physiological tests. This study is the first to show DNA damage in the gills and hemolymph of any marine species in response to anthropogenic noise and highlights the Comet assay as an adequate tool in noise research. It is also, to the best of our knowledge, the first to use oxidative stress endpoints as a biomarker of the effects of underwater noise in marine organisms. Together, the results of this study accentuate the need for biochemical investigation in anthropogenic noise studies.

A Modeling Comparison Between Received Sound Levels Produced by a Marine Vibroseis Array and Those from an Airgun Array for Some Typical Seismic Survey Scenarios

Lindy Weilgart  
Dalhousie University, lweilgar@dal.ca  
Alec J. Duncan  
Curtin University, a.duncan@cmst.curtin.edu.au  
Russell Leaper  
IFAW, russell@ivyt.demon.co.uk  
Michael Jasny  
NRDC, mjasny@nrdoc.org  
Sharon Livermore  
IFAW, mcollis@ifaw.org

Seismic airgun surveys have shown noise impacts on marine life, leading to the search for quieter alternatives such as marine Vibroseis (MV). Modeled underwater sound levels produced by a realistic MV array were compared with those emitted by an airgun array with similar total downward energy output at frequencies up to 100 Hz under 3 scenarios: shallow (100 m water depth), deep (4,000 m water depth), and slope (realistic bathymetry, sloping seabed, 500 m water depth at source). Importantly, changing the horizontal plane layout of the higher frequency (20- to 100-Hz) sources in the MV array reduced sound exposure levels (SELs) by 4 dB. This modified MV array was about 20 dB lower in broadband (to 1,000 Hz) peak-to-peak sound pressure level compared with the airgun array, although this advantage diminished somewhat with range, especially in shallow water. Even so, for all modeled scenarios, out to the maximum range at which peak-to-peak levels were modeled (5 km), airgun array levels were at least 12 dB higher than those from the MV array. SELs were less clear-cut, but for all scenarios modeled and as a consequence of the reduced signal bandwidth of the MV, they were lower and dropped off more rapidly with range from the MV than from the airgun array. This effect was most pronounced for the shallow scenario where lower SELs from the MV first started to become apparent at a range of around 1 km versus 10 km for the deep scenario. For both shallow and deep water, though, SELs from the MV were about 8 dB lower than those produced by the airgun array at a 100-km range. The slope scenario was less conclusive due to the more complex propagation conditions. Overall, we show that a MV array produced lower broadband SELs, especially at long range, and lower peak pressure, especially at short range, than an airgun array, thus confirming the lower acoustic footprint of the MV for the same energy output for geophysical purposes. Although not quantified in this study, the relative benefit of MV in terms of SEL would be much greater for animals with a poor low-frequency hearing response (e.g., mid- and high-frequency-sensitive cetaceans).

Jürgen Weissenberger
Statoil ASA, Trondheim, Norway, jurw@statoil.com

Jan Durinck
Dansk Biokonsult-Marine Observers, Snedsted, Denmark, jan.durinck@gmail.com

Christian Collin-Hansen
Statoil ASA, Trondheim, Norway, chrc@statoil.com

Arve A. Nymo Skogvold
Statoil ASA, Trondheim, Norway, arvn@statoil.com

Terje Barstad Olsen
Statoil ASA, Trondheim, Norway

Harald Wesenberg
Statoil ASA, Trondheim, Norway, hwes@statoil.com

Tom McKeever
Statoil Canada Limited, St Johns, Canada thmc@statoil.com

Daniel Zitterbart
Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany, Daniel.zitterbart@awi.de

Alejandro Cammareri
Fundacion MaryBio, Las Grutas, Argentina, ale@marybio.org

Michael Flau
Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany, michael.flau@awi.de

Marine mammal observers (MMOs) on board seismic vessels are mandatory in many regulatory frameworks. Their task is to observe a safety zone around the seismic sound source for the presence of marine mammals, and the observations are also often used to collect data on species presence in the respective area by using principles for distance sampling methods. For each observation, a set of data must be recorded, such as distance to the observed animal, bearing, date, time, and position. In particular, precise distance measurements are difficult for marine mammals because other methods such as laser range finders and sextants do not work or are difficult to use. MMO personnel also have to constantly track the observed animal and putting the binocular down for angle measurement or data writing is an unwanted interruption to the observation process. To develop an assistance tool for MMO work, we attached a sensor package consisting of a three-axis accelerometer and a three-axis compass to a binocular. When pointing the binocular to the observed object, the inclination and compass bearing are automatically measured and stored on a compact single-board computer (SBC). The SBC is also attached to a GPS for accurate positioning and timing. Thus, with a known height of the observation point, the inclination measurement is used to calculate the distance to the observed object, and the position of the object can then be determined using the measured values, distance, and compass heading from the GPS position of the observation point. Much data relevant for marine mammal observations are thereby registered and stored while the MMO continues to look through the binocular, fulfilling the main task of continuous observations. Data stored on the SBC are accessible via a browser and comments can be added post-observation, e.g., on the species observed, identification numbers, or other data. Results from two field tests will be shown. We also demonstrate the hardware and provide a hardware list that will allow interested parties to produce their own device. The software can be requested from the authors and will be given at no cost for tests. The device is named “Durimeter” to honor the inspiration source behind this device, Jan Durinck.
A Case Study Testing Dynamic Against Static Risk Assessments of Underwater Noise Impacts

Jürgen Weissenberger
Statoil ASA, Hydroveien 67, Herøya, 3905 Porsgrunn, Norway, jurw@statoil.com

Jonas B. Mortensen
DHI Singapore Pte. Ltd., 1 CleanTechLoop, Singapore, Singapore 637141, jbm@dhigroup.com

Flemming Thorborn Hansen
DHI, Agern Alle 5, 2970 Hørsholm, Denmark, flemmingthorbjoernhansen@gmail.com

Frank Thomsen
DHI, Agern Alle 5, 2970 Hørsholm, Denmark, frth@dhigroup.com

Regulations for seismic surveys in the marine environment often require an environmental impact assessment (EIA) before the respective activity gets permission. The aim of this process is to estimate the number of potentially affected animals in relation to established noise exposure criteria. This can be done after either a “static” approach that is based on a concept of nonmoving animals or a “dynamic” paradigm where animal movements are modeled in response to noise and other variables. Our team has made a proof of concept with a dynamic risk assessment model for acoustic disturbance (DRAMAD; see Thomsen et al., this conference). In this study, we test DRAMAD against other risk assessment methods using an existing case of a seismic survey in the Chukchi Sea in 2010. The risk assessment method applied in the EIA used the estimated species density multiplied by the size of the area exposed to certain sound levels. This resulted in a number of marine mammals exposed to sound pressure levels above 160, 180, and 190 dB re 1 µPa. The species density estimates had a comparable coarse temporal and spatial resolution, resulting in huge uncertainty in the number of animals in the different impact zones for the proposed time of the survey. We compare this conventional method with our novel approach where we predict bowhead and beluga whale densities based on a coupled habitat and agent-based model (ABM). The impact sound was introduced into the model as a moving sound source following the planned line pattern for the seismic survey. We first compared scenarios where marine mammals do not respond to received sound levels, followed by the introduction of avoidance behavior into the ABM as a reaction to the introduction of the modeled sound. Our results show that the dynamic method is suited to incorporate temporal displacement into risk assessment. It also became clear that cumulative sound exposure could be assessed in a much more refined way using DRAMAD. Our study demonstrates that habitat and ABM allow for introducing a range of dynamic behavioral reactions to sound into risk assessment as well as the quantification of the impact to resulting migration and distribution patterns. This technique will likely become increasingly important as our knowledge on the behavioral reaction of marine mammals to sound increases in the future.
Dose-Response Functions for Behavioral Responses of Humpback Whales to Naval Sonar: An Overview of Analysis Methods

Paul J. Wensveen
Sea Mammal Research Unit (SMRU), University of St. Andrews, St. Andrews KY16 8LB, UK, pw234@st-andrews.ac.uk

Catriona M. Harris
Centre for Research into Ecological and Environmental Modelling (CREEM), University of St. Andrews, St. Andrews KY16 9LZ, UK, catriona.harris@st-andrews.ac.uk

Len Thomas
Centre for Research into Ecological and Environmental Modelling (CREEM), University of St. Andrews, St. Andrews KY16 9LZ, UK, len.thomas@st-andrews.ac.uk

Petter H. Kvadsheim
Maritime Systems Division, Norwegian Defence Research Establishment (FFI), Horten 3191, Norway, Petter-Helgevold.Kvadsheim@ffi.no

Frans-Peter A. Lam
TNO Acoustics and Sonar, Oude Waalsdorperweg 63, 2597 AK The Hague, The Netherlands, Frans-Peter.Lam@tno.nl

Peter L. Tyack
Sea Mammal Research Unit (SMRU), University of St. Andrews, St. Andrews KY16 8LB, UK, plt@st-andrews.ac.uk

Patrick J.O. Miller
Sea Mammal Research Unit (SMRU), University of St Andrews, St Andrews, KY16 8LB, UK pm29@st-andrews.ac.uk

Effective management of the potential impacts of naval sonar on marine mammals requires risk functions that quantify the relationship between the sound level received by the exposed animal (the dose) and the probability of the animal’s behavioral response. In recent years, such relationships have been reported for a number of marine mammal species using different methodologies for fitting dose-response functions. Here, we present dose-response functions for humpback whales based on behavioral responses observed during controlled sonar exposure experiments. We use this data set to compare several analytical methods that have been developed/implemented in the context of sonar behavioral response studies (BRSs). Ten independent groups of one or two humpback whales were instrumented with multisensor DTAGs and GPS loggers and focally followed for the deployment duration. The whales were exposed to repeated sonar signals in a total of 18 dose-escalation experiments, with an additional 11 control vessel approaches without sonar exposure. Bayesian hierarchical models for individual response types (i.e., avoidance onset, feeding cessation) were fitted to response thresholds identified by human observers. These models accounted for between-animal variation, the influence of contextual covariates such as behavioral state and session order, prior assumptions about the dose at which responses may occur, and censoring when thresholds were observed at the lowest dose or not observed at the highest dose. Functions were generated for sound pressure level, sound exposure level, signal-to-noise ratio, and source-whale distance. In comparison to other marine mammal species, humpback whales appeared to have on average somewhat lower responsiveness. However, the relatively shallow slopes of the dose-response functions indicated that some individuals may respond at relatively low received levels that could be equivalent to long distances from higher power operational sonar sources. Most recently, this Bayesian model structure was extended to include two different response mechanisms, a lower level context-dependent threshold and a threshold dependent on uncomfortable loudness/annoyance. Second, we fitted marginal stratified Cox proportional hazards models to the humpback whale data set, but, in this instance, we have included all response types observed. This methodology is based on survival analysis and is particularly useful for the derivation of dose-response severity functions because it allows for the inclusion of responses of different response intensity categories. The assessment of advantages and limitations of the different methods should be helpful for scientists and regulatory agencies that may use dose-response and dose-response severity functions to predict potential impacts of noisy activities.
As the focus of renewable energy in the United States turns to offshore wind facility development, there is an increasing need for an understanding of potential noise impacts from this development on marine mammals. Pile driving of offshore wind turbines produces loud low-frequency sound that can travel great distances and could potentially harm or disturb marine mammals. As a result, a critical first step is to understand the current baseline ambient-noise levels and the spatiotemporal distribution of marine species that could potentially be impacted. Little is known about the year-round distribution of cetaceans offshore of Maryland. There is a particular concern regarding the potential overlap with the migratory routes of endangered whale species, such as North Atlantic right whales (*Eubalaena glacialis*). We used passive acoustic monitoring to characterize the soundscape and determine the seasonal occurrence, migratory routes, residency patterns, and foraging areas of cetaceans in and around the Maryland offshore wind energy area (WEA). We deployed Cornell University’s marine autonomous recording units (MARUs) to detect whales at 10 sites and C-PODs to detect dolphins at 4 sites ranging from ~10 to 60 km offshore from November 2014 to November 2015. The large whale species most frequently detected were fin whales (*Balaenoptera physalus*), followed by humpback (*Megaptera novaeangliae*), right, and minke (*Balaenoptera acutorostrata*) whales. Fin whales were detected most frequently farther offshore but were detected at all sites on at least 50% of the days per month during the winter (November to March). Right whales were most frequently detected within the Maryland WEA compared with the other sites, indicating that this area is within their migratory route. The temporal variation in dolphin occurrence was modeled, taking into account the autocorrelation in detections. From May to September, dolphins were detected during 99% of days at the site closest to shore, for a median of 7 hours each day, predominantly during dawn and dusk, switching to increased presence offshore in the winter months. Limiting construction to periods when North Atlantic right whales are less likely to occur in the vicinity of the WEA could reduce the potential impact of wind facility development. However, the year-round presence of cetaceans within the area, including endangered North Atlantic right, humpback, and fin whales, indicates that at least some individuals may be within the audible range of pile-driving sounds. Continued monitoring during wind facility construction would help to determine the response of whales to these sounds.
Underwater Noise Mitigation Using a Tunable Resonator System

Mark S. Wochner
AdBm Technologies, Austin, TX, mark@adbmtech.com

Kevin M. Lee
Applied Research Laboratories, The University of Texas at Austin, Austin, TX, kevin.lee@arlut.utexas.edu

Andrew R. McNeese
Applied Research Laboratories, The University of Texas at Austin, Austin, TX, mcneese@arlut.utexas.edu

Preston S. Wilson
Department of Mechanical Engineering and Applied Research Laboratories, The University of Texas at Austin, Austin, TX, pswilson@mail.utexas.edu

This paper covers the development of a tunable acoustic resonance-based underwater noise abatement system for use with marine pile driving, offshore energy production, seismic sources, and ships, among others. The system consists of arrays of underwater air-filled resonators, which surround the noise source and are tuned to optimally attenuate noise in the frequency band of interest. Based on the predictive models for the acoustic dispersion relation in bubbly liquids given by Church (1995) and Commander and Prosperetti (1989), this system has been shown to attenuate sound by up to 50 dB near the resonance frequency of the resonators (Lee and Wilson, 2013). In this investigation, modeling and laboratory tests were used to tune the system for pile-driving applications with a spectral noise peak near 100 Hz. System demonstrations that were conducted at two offshore wind farm construction sites in the North Sea will be discussed. In these tests, a peak sound pressure level reduction of nearly 40 dB was measured around the design frequency, and an almost 20-dB sound exposure level reduction was measured in the 20-Hz to 20-kHz band. The method of deploying these resonator arrays in a simple collapsible framework as well as the operational advantages of this system for pile driving will be described, and details on a fully constructed noise abatement system that will soon be tested will be shared. In addition, concepts for the application of this system to other noise sources as well as future planned demonstrations of the technology will be discussed.


In many areas around the world, seismic surveys and other exploration and production activities are subject to regulatory environmental assessment and permitting. In areas not subject to these requirements, most operators have their own internal processes that guide risk assessment for planning and operational phases. Risk assessments for seismic surveys tend to follow a generic methodology of identifying source properties, modeling sound propagation, identifying potential risk (consequence and likelihood) to sensitive species, and recommending appropriate mitigation measures. However, the complexity of each step of the process varies depending on the proposed activity, known species sensitivity, regulatory requirements, and internal company practices. The detail and type of information required by regulators also varies and complicates the process. In addition, the amount of data available varies considerably and is dependent on species and geography. The combination of these variables contributes to the complexity of risk assessments.

The current general trend for such risk assessment activities is moving toward longer term population consequence methodologies, which are becoming better understood for a potential application in an operational setting. The Exploration and Production Sound and Marine Life Joint Industry Programme (SML JIP) members conducted a review of a generic risk assessment process, which included using the population consequences of disturbance (PCoD)/population consequences of acoustic disturbance (PCAD) framework to identify and evaluate risk assessment data needs. The key findings of this exercise include (1) confirmation that all projects funded by the SML JIP are applicable to the risk assessment process, (2) the majority of SML JIP projects that have multiple outcomes that apply across multiple components of a generic risk assessment process, and (3) SML JIP efforts that have been built on or expanded existing research or vice versa. The SML JIP plans to refresh the risk assessment review at the conclusion of the current phase to assess our efforts and gauge future research priorities.
Evaluating Noise Metrics to Predict Masking in Killer Whales

Jason Wood
SMRU Consulting, jw@smruconsulting.com

Using killer whales as a model, this study aimed to evaluate a number of different noise metrics to determine which is better at predicting masking of social signals in delphinids. Killer whales were chosen because they have been shown to increase the source level of their calls as background noise levels increase in a linear fashion (the Lombard effect). This is direct evidence from a wild population that antimasking strategies are being used to overcome the effects of masking of social signals. Because the relationship between noise levels and signal source levels is linear, the $R^2$ value of this linear regression can be used to estimate which noise metric best predicts antimasking strategies (and by extension masking).

Given the tonal nature of killer whale social calls, one would expect masking to occur when sufficient noise is present in the same cochlear band filter as the tonal peaks. Previous studies have used one-third and one-twelfth octave bands to estimate masking and active space. However, killer whale calls do span a fairly wide range of frequencies (i.e., they often have a number of harmonics and side bands present), and it could be that these are all important in conveying the meaning of the signal. Therefore, it could be argued, as several studies have, that assessing noise levels within frequency bands that span the signal bands would be appropriate. This study therefore measured background noise levels using one-twelfth octave, one-third octave, call frequency band (1-40 kHz), and broadband noise (0.01-96 kHz) as well as M-weighting type II and audiogram weighting and compared the $R^2$ values resulting from regressing these noise measurements with the source level estimate of killer whale calls recorded from a 5-hydrophone fixed array under a variety of noise conditions. Broadband (0.01-96 kHz) noise measurements performed best at predicting antimasking, with an $R^2$ value of 0.87, whereas audiogram weighting performed the worst, with an $R^2$ value of 0.7. How we measure noise has obvious repercussions on estimating the potential impact of noise on marine life. This study demonstrates that one can compare the efficacy of different noise metrics in predicting masking of social calls in killer whales. This kind of approach should be used more widely to test assumptions on appropriate noise metrics for predicting the impact of noise on aquatic life.
Hearing: Human Auditory Perception

William A. Yost
Speech and Hearing Science, Arizona State University, William.yost@asu.edu

The study of hearing is as old as recorded history. There has always been a fascination with sound’s ability to inform humans about the world they inhabit. Sound generated when an object vibrates occurs over time and sounds from different objects physically interact before reaching a listener’s ears. While the peripheral receptors for encoding sound are amazing biological transducers, they only provide a neural code for the sound field generated by sound-producing objects. The auditory brain is required to sort this auditory neural code into information that allows humans to determine what the sound sources are and where they are located. The brain is required to sort the images in an auditory scene. This presentation will review some of what is known about the relationship between the physical variables of sounds and human perception of these sounds. In general, developing such relationships is psychoacoustics. Psychoacoustic topics such as pitch perception, loudness, masking, and sound source localization and the way in which they are studied will be briefly reviewed.
Estimating Required Sampling Rates in Agent-Based Simulations

David Zeddies
JASCO Applied Sciences, David.Zeddies@jasco.com

In the majority of exposure scenarios to anthropogenic noise, the sound sources and animals are not stationary and the sound fields associated with the activities can be complex. The amount of sound that an animal receives depends on where the animal is within the sound field. Because the precise location of animals is not usually known, statistical methods such as Monte Carlo sampling are used in the estimation of exposure during an operation. With Monte Carlo sampling, realistic movement of simulated animals (animats) is convolved with calculated acoustic fields to estimate the received sound level over time. The combined exposure histories of many animats give an estimate of the probability of exposure above a certain threshold, where the probability of an event’s occurrence is proportional to the frequency with which it occurs in the simulation. The more samples, in this case the more animats, the more accurate the exposure estimate. For most operations, exposure levels of concern are infrequent occurrences (e.g., few if any individuals are expected to withstand sound levels above the threshold criteria for injury) and by its very nature, Monte Carlo sampling yields fewer points from which to determine the likelihood of rare events. Often there are no examples at all of rare events in the simulation, so that other than knowing the event is “rare,” its likelihood remains undefined. Increasing the number of samples or repetitions in the simulation to capture a larger quantity of infrequent events is often prohibitively time consuming or resource intensive and does not necessarily result in a reliable likelihood estimate for the rare event. In the present study, we use the statistical distribution of sound levels in the acoustic fields as a way to estimate sampling confidence intervals and determine the minimum number of samples (animats) required to satisfy a chosen tolerance.