# 3rd PROGRAMME REVIEW MEETING

## of the E&P Sound & Marine Life Joint Industry Programme

**9 - 14 September 2018**
**The Hague, Netherlands**
**Carlton Beach**

E&P SOUND & MARINE LIFE PROGRAMME

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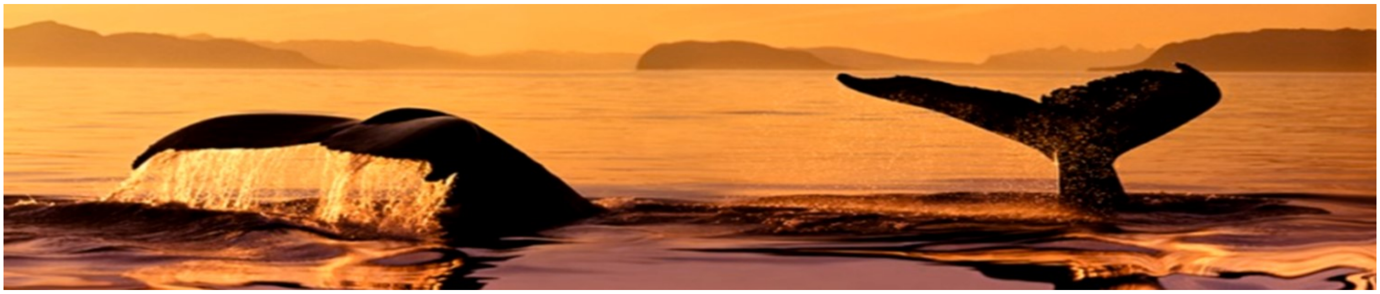
# About the E&P Sound & Marine Life



***Photo, courtesy of Gary Isaksen***

***The Joint Industry Programme, or JIP, supports research to help increase understanding of the effect of sound on marine life generated by oil and gas exploration and production activity. The research helps governments make regulatory decisions based on the best science and the industry develop effective mitigation strategies. This helps us supply much needed energy to people around the world.***

We firmly believe that effective policy must stem from good, independent science. Increased understanding of the effect of sound generated by exploration and production activity on marine life both helps governments make regulatory decisions based on sound science and the industry develop effective mitigation strategies.

While the sea is filled with a wide variety of natural and man-made sounds there has been a particular focus on sound generated by seismic surveys. Seismic studies are absolutely vital to the industry as they create sound waves that bounce off different rock strata, just as submarines determine their location. The process of using seismic sound sources and capturing the data is known as a seismic survey. Interpretation of the seismic survey data allows exploration teams to understand the geology beneath the ocean floor. Seismic surveys are part of a suite of tools that help to define if an area is prospective for oil and gas and if there are locations that merit drilling. As such seismic surveys help to define the number of wells we have to drill and limit our activity in the marine environment.

As a result, a wide group of international oil companies, the International Association of Oil and Gas Producers (IOGP) and the International Association of Geophysical Contractors committed in 2005 to found a Joint Industry Programme (JIP) to identify and conduct a research programme that improves understanding of the potential impact of Exploration and Production (E&P) sound on marine life.

The JIP has deliberately structured itself to ensure that it is democratic, scientific, impartial and open to expert opinion. Like many democratic governments the JIP has two principal chambers: The Executive Committee (ExCom) and the Technical Management Committee (TMC).

The ExCom, made up of environmental and business managers and industry scientists, co-ordinates and approves funding based on their combined decades of experience of operating in marine environments. Every partner company has a member on the ExCom.

The TMC defines and supports the research projects and reports to the ExCom.

This dual structure ensures that all members of the JIP are represented and every effort is made to ensure that decisions are made by consensus.

In addition to the two primary committees every research project is managed on a more day-to-day basis by a Project Support Group (PSG). This is made up of research personnel from each company, who work alongside the researchers in order to share ideas, explain industry practice and monitor project focus and delivery.

**External Advisors**

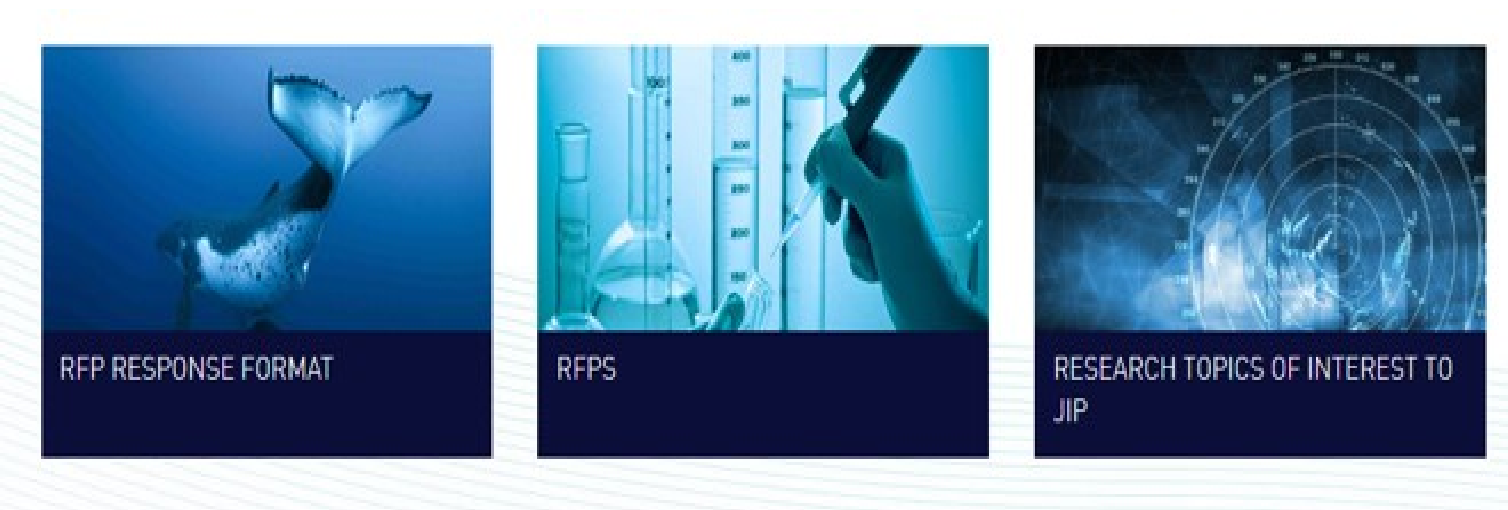
Collaboration is one of the founding principles of the JIP, and we have deliberately engaged world-leading scientists to guide our research to ensure that it conforms to the highest standards. With this aim in mind the EC has appointed an external advisory panel made up of recognised experts from outside the industry (regulators, academics, NGOs and scientists). The external advisory panel provides regular review of the programme's direction and scope of work. Their independent voices ensure the credibility and authority of the research.

**JIP Accomplishments**

100+ Research studies since 2006
Funding $60M USD to date
Guidance from regulators, academic researchers, NGO's
Significant scientific progress & broad respect
More than 120 peer-reviewed publications
Website and Research Library Database

**JIP Objectives**

Support planning of E&P projects and risk assessments.
Provide the basis for appropriate operational measures that are protective of marine life.
Inform policy and regulatory development.



# Programme Review Meeting Schedule and Abstracts

## Monday, 10 September 2018

***Session Chair: K. Broker***

13:30 JIP introduction & overview – **G. Isaksen**

13:45 Potential use of JIP research in better regulation of underwater sound – **M. Tasker**

13:55 BOEM and BRAHSS – **J. Lewandowski**

14:00 The Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS): Background and Introduction – **D. Cato**

14:25 Towards a Risk Assessment Framework/Protocol for Implementing the Data-Driven Population Consequences of (Acoustic) Disturbance (PCAD/PCoD) Model/Approach – **D. Costa**

14:50 Discussion

15:00 Coffee

## Tuesday, 11 September 2018

***Session Chair: P. Evans***

8:30 Introduction to JIP projects: behavioral response – **G. Wolinsky**

8:40 BRAHSS: Considerations for experimental design of a large-scale behavioral response study – **R. Dunlop**

8:55 Air gun signal propagation during BRAHSS experiments with humpback whales off Queensland and Western Australia – R. McCauley / **D. Cato**

9:15 BRAHSS: The behavioral responses of migrating humpback whales to air guns: results – **R. Dunlop**

9:45 BRAHSS: summary of presentations and conclusions – **D. Cato**

10:00 Coffee Break

10:30 PCAD4Cod" Impact of seismic survey sound exposure on fishes: popula-
tion- level modelling and empirical data collection – **H. Slabbekoorn**

10:55 Towards a Risk Assessment Framework/Protocol for Implementing the Data-Driven Population Consequences of (Acoustic) Disturbance (PCAD/PCoD) Model/Approach – **D. Costa**

11:25 Discussion

11:45 Lunch

## Wednesday, 12 September 2018

***Session Chair: M. Tasker***

10:00 Introduction to JIP project: physical and physiological – **K. Speirs**

10:10 Re-Evaluating Marine Mammal Noise Exposure Criteria: A Decade Following the Southall et al. (2007) Expert Panel – **B. Southall**

10:35 The influence of temporally varying noise from seismic air guns on the detection of underwater sounds by seals – **C. Reichmuth**

10:55 Comprehensive Models of Hearing in Two Species of Mysticetes- **D. Ketten**

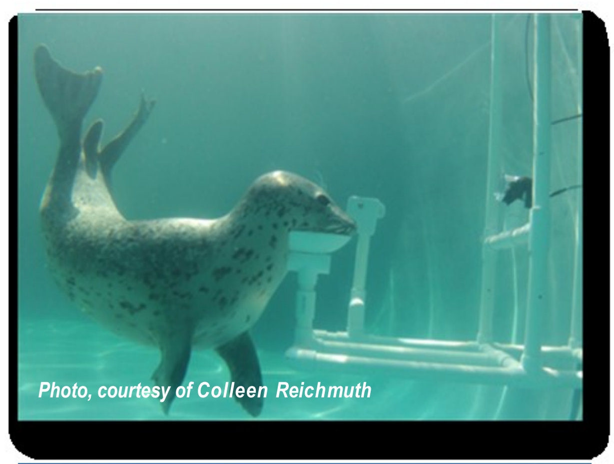
11:20 Temporary hearing threshold shift in a harbor porpoise (Phocoena phocoena) due to exposure to airgun sounds – **R. Kastelein**

11:45 Auditory detection, masking, and temporary threshold shift in bearded seals (Erignathus barbatus) – **C. Reichmuth**

12:05 Discussion

12:30 Lunch

***Photo, courtesy of Jennifer Liebeler Michael***



***Photo, courtesy of Colleen Reichmuth***

***Photo, courtesy of BRAHSS***

# Programme Review Meeting Schedule and Abstracts

## Thursday, 13 September2018 — *Session Chair: O. Boebel*

8:30 Overview of Mitigation & Monitoring – **D. Hedgeland**

8:45 BRAHSS: logistics, mitigation, field operations and safety – **M. Noad**

9:10 Low Visibility Real-time Monitoring Techniques Review – **U. Verfuss**

9:30 The 3-D-V Array: A volumetric, digital towed hydrophone array system capable of bearing and location estimation in 3-D space – **T. Norris**

9:50 Coffee

10:20 AVADECAF: Assessing the ViAbility of Density Estimation for Cetaceans from passive Acoustic Fixed sensors (DECAF) throughout the Life Cycle of an Offshore E&P Field Development – **C. Booth**

10:40 Evaluation of DECAF Methods Using an Existing Eight-Year Fixed Acoustic Monitoring and Localization Dataset,Deployed During E&P Activities Along the Arctic Continental Shelf.- **L. Thomas**

11:00 Discussion

11:30 Lunch

## Friday, 14 September 2018 — *Session Chair: J. Miksis-Olds*

8:30 Overview of Sound Source Characterisation and Propagation – **M. Jenkerson**

8:45 Broadband airgun-source characterisation: the Svein Vaage dataset – **M. Prior**

9:05 3-dimensional seismic source characterization study – **N. Sidorovskaia**

9:25 Terminology, measurement, processing and reporting standards for assessing effects of underwater sound on aquatic life – **M. Ainslie**

9:45 Acoustic Impacts on Marine Fauna from Marine Vibroseis Technologies - **D. Zeddies**

10:05 Discussion

10:30 Coffee

*Session Chair: G. Isaksen*

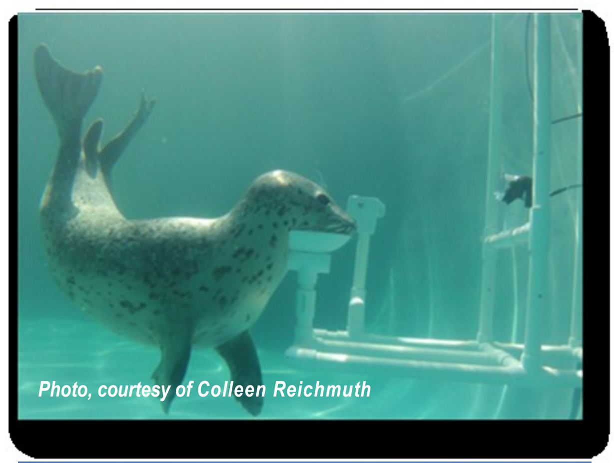
11:00 Discussion of JIP Research through Phase III – **R. Gisiner**

11:30 Phase IV Plans – **K. Speirs**

11:45 Closing Comments – **K. Broker**

11:55 Lunch

Photo, courtesy of Jennifer Liebeler Michael



Photo, courtesy of Colleen Reichmuth

Photo, courtesy of BRAHSS

**The Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS): Background and Introduction**

**Douglas H. Cato** (1), Michael J. Noad (2), Rebecca A. Dunlop (2), Robert McCauley (3), Erick Kniest (4), David Paton (5) and Robert Slade (5)

(1) School of Geosciences, University of Sydney and Defence Science & Technology Group, (2) Cetacean Ecology and Acoustic Lab.,The University of Queensland, Australia. (3) Centre for Marine Science and Technology, Curtin University Australia. (4) School of Engineering, University of Newcastle, Australia. (5) Blue Planet Marine, Australia.

Seismic surveys are widely used throughout the world's ocean, producing high level impulsive sounds. There is considerable uncertainty about the significance of the behavioral responses of whales to these sounds, in spite of many studies. Ramp-up is widely used in mitigation, but little is known about its effectiveness. BRAHSS is a recently completed, six year project studying the behavioral response of humpback whales (Megaptera novaeangliae) to a range of seismic air gun sources, including a 20 cu in (0.33 L) air gun, a small array and a full commercial array of 3,130 cu in (51.3 L). The overall aim was to provide information to reduce the uncertainty in evaluating impacts of seismic surveys through a series of well controlled, rigorous experiments. The objectives were (a) to determine the response of humpback whales to seismic sources, (b) to determine the effectiveness of ramp-up and (c) to infer longer term biological significance of the responses. The humpback whales with new born calves were migrating southwards along the Australian coastlines from the tropical breeding grounds and showed behavior typical of migration and breeding. Arrays were towed along fixed line transects rather than approaching individual whales. The extensive knowledge of the biology, physical and acoustic behavior of these whale populations from previous work provided a robust context for assessing the results. This paper wilt provide a background and introduction to the project and the following papers will provide

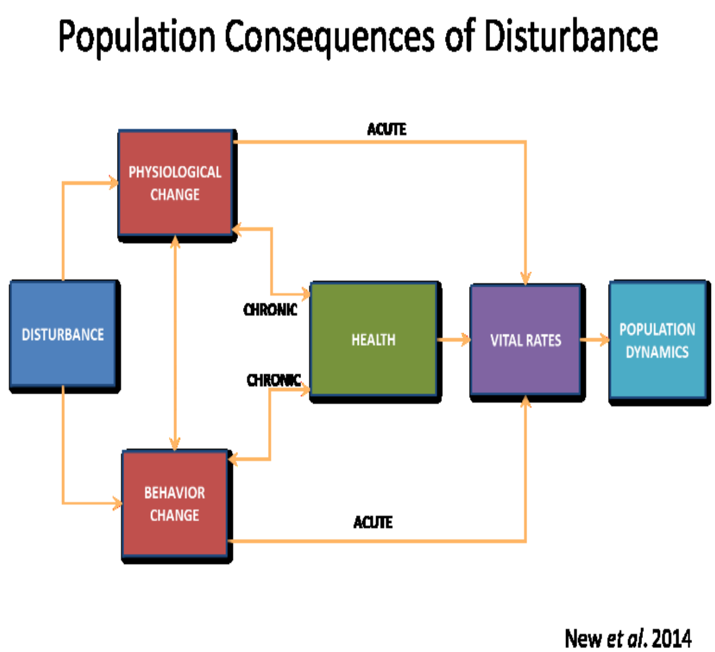
*Photo, courtesy of BRAHSS*

**Towards a Risk Assessment Framework/Protocol for Implementing the Data-Driven Population Consequences of (Acoustic) Disturbance (PCAD/PCoD) Model/Approach**

**D. Costa** (1), L. Schwarz (1), L. Huckstadt (1), E. McHuron (1), M. Mangel (1), L. Huckstadt (1), S. Villegas-Amtmann (1). E. Pirotta (2), L. New

(1) University of California Santa Cruz, (2) Washington State University

The Population Consequences of Acoustic Disturbance (PCAD) is a conceptual model that links animal behavioral responses to sound, these behavioral reactions to life functions, life functions to vital rates, and changes in vital rates to population level change through a series of transfer functions. PCoD (Population Consequences of Disturbance) superseded PCAD and broadened the range of stressors that cause disturbance. In PCoD, the central focus is what type and level of stressor could lead to a change in body condition or fitness that in turn could result in changes in vital rates leading to population effects. As with PCAD this approach is designed to couple behavioral response studies with some estimation of if and when these short-term and sometimes subtle behavioral responses may affect a population. Two approaches have been used: i) a data-driven approach that uses a bioenergetics model and a population dynamic model to identify disturbance scenarios that can potentially cause biologically significant or population-level responses. The second approach is used when the data for a bioenergetics model are not available they are estimated through an expert elicitation process. The goal is to develop risk assessment tool(s) that can be used to focus research and mitigation activities on situations that are likely to be of higher risk. Initially, these efforts focused on data rich species such as elephant seals and blue whales, but has been extended to California sea lions, harbor porpoises, minke, sperm, beaked and gray whales. This presentation will provide an overview of the progress made.



***BRAHSS: Considerations for experimental design of a large-scale behavioral response study***

**Dunlop, R.A.** (1), Noad, M.J. (1), McCauley, R.D. (2) and Cato, D.H. (3)

(1) Cetacean Ecology and Acoustic Lab., The University of Queensland, Gatton, Qld 4343 Australia. (2) Centre for Marine Science and Technology, Curtin University Australia. (3) School of Geosciences, University of Sydney and Defence Science &Technology Group, Australia.

Behavioral response studies aim to quantify and interpret the response of animals to various acoustic sources, e.g. conspecific signals or anthropogenic noise. In the marine environment, these experiments are especially challenging and expensive due to the logistic difficulties in working at sea. Many species of marine mammal cannot be held in captivity, therefore the major challenge is to create a well-controlled laboratory-based experiment that can be carried out in their natural environment. These experiments must account for factors that cannot be controlled for; è.g. differences in the social and physical environment of the experimental animals, changes in these parameters as the experiments progress, and potential responses to other noise sources. This means a large dataset, including adequate controls and baseline data, is necessary, translating to increased time spent in the field and expense. A major series of experiments in Australian waters (BRAHSS) aimed to test the behavioral impact of noise from seismic air gun arrays on migrating humpback whales. These experiments attempted to mimic a laboratory-based experiment as much as logistically possible, whilst measuring, and accounting for, factors than could not be controlled for. A pre-field power analysis indicated the sample size required. Experimental results found that groups behaviorally responded to changes in their social and physical environment as well as the source vessel (vessel noise). Behavioral reactions to the air gun were highly variable in type, and magnitude. Due to these multiple sources of variance, the large dataset, and complex design, was necessary to complete a robust analysis.

***Air gun signal propagation during BRAHSS experiments with humpback whales off Queensland and Western Australia***

McCauley, R. D (1), **Cato, D. H.** (2), Noad, M. J. (3) and Dunlop. R. A (3)

(1) Centre Marine Science and Technology, Curtin University, GPO Box U 1987, Perth, WA 6845, Australia. (2) School of Geosciences, University of Sydney and Defence Science and Technology Group, Australia. (3) Cetacean Ecology and Acoustic Lab., The University of Queensland, Australia.

Over 2010 to 2014 experiments were conducted off Peregian Beach, Queensland (- 26.5° S) and off Dongara, Western Australia (- 29.25° S), to establish the response of southerly migrating humpback whales to marine seismic surveys. Off Peregian Beach seismic sources used were a 20 cu in single air gun, a 6 gun cluster (2.1 m tow, x 1.3 m abeam) with stages of 20, 60, 140 or 440 cu in or a 3D seismic array with ramp up stages of 40, 250, 500 and 1440 cu in to full power at 3130 cu in. Off Dongara, the 6 gun cluster was used. Sound propagation properties differed between and within sites. The seabed at Peregian was a mosaic of deep sand, an exposed soft rock or reefs, or shallow sand (< 2 m) over the soft rock. Sound propagation across areas of shallow sand over rock and exposed rock (or reef) exceeded that over deep sand by - 3.5, 7.4 dB / km respectively. Seabed slope and water depth were also important. The 3130 cu in source was highly directional, with levels increasing by 10-15 dB as the array passed abeam. The Dongara site was a gradation of thin sand over limestone to deeper sand over limestone on moving offshore, with sound propagation here worse (greater losses) than off Peregian. Predicting received air gun signal levels at humpback whales for all shots was a challenge in each of these highly heterogeneous environments with the added complexity of source directionality for the 3130 cu in source.

***BRAHSS: The behavioral responses of migrating humpback whales to air guns: results***

**Dunlop, R.A.** (1), Noad, M.J. (1), McCauley, R. (2) and Cato, D.H. (3)

(1) Cetacean Ecology and Acoustic Lab., The University of Queensland, Gatton, Qld 4343Australia. (2) Centre for Marine Science and Technology, Curtin University Australia. (3) School of Geosciences, University of Sydney and Defence Science &Technology Group, Australia.

Despite concerns on the effects of noise from seismic survey air guns on cetaceans, there remains considerable uncertainty in the biological significance of any response. This study quantifies and interprets the response of migrating humpback whales (Megaptera novaeangliae) to different air gun arrays, including a 3130 cu in full commercial array. We compare the behavioral responses to active trials, with responses to control trials (source vessel towing the array while silent) and baseline studies of normal behavior in the absence of the vessel. No abnormal behaviors were recorded during any of the trials. However, in response to the active seismic array and the controls, the whales displayed changes in some measured behaviors, mainly migratory movement and dive parameters. Changes in respiration rate were also found in response to the full commercial array, though these changes were of a similar magnitude to changes in baseline groups being joined by other animals. The most consistent result between the different experiments (using different array sources) was the reduced progression southwards. For some cohorts, they migrated, during the active trials, at speeds below typical migratory speeds. This response was more likely to occur within 4 km from the arrays at received levels over 135 dB re 1μPa2.s demonstrating that response was influenced by proximity to the source as well as received level. A simple dose-response relationship was not apparent indicating that there is still much to be learned about the response of these whales to seismic surveys.

***BRAHSS: summary of presentations and conclusions***

**Cato, D. H.** (1), Noad, M. J. (2), Dunlop, R. A. (2), McCauley, R. D. (3), Kniest, E. (4), Paton, D. (5) and Slade, R. (5)

(1) School of Geosciences, University of Sydney and Defence Science &Technology Group, NSW 2006, Australia. (2) Cetacean Ecology and Acoustic Lab.,The University of Queensland, Australia. (3) Centre for Marine Science and Technology, Curtin University Australia. (4) School of Engineering, University of Newcastle, Australia. (5) Blue Planet Marine, Australia.

This paper summarizes the results presented in the previous papers and reviews the strengths and weaknesses of the project and the lessons learnt. It also considers implications for future research and for management. The project demonstrates the importance of having expert staff covering all of the disciplines involved, the need for a balanced experimental design with treatment, controls and baseline data of normal behavior, observers blind to the treatment, and the measurement of the acoustic characteristics of the sites and the sources. Multiple observation and measurement platforms allowed comparison of the relative effectiveness of each platform to be determined. Using a range of air gun sources allowed a much better understanding of response and also allowed the proximity of the source to the whales to be included in the dose response estimates by ensuring a range of received levels at any proximity. The results show trends in behavioral responses that could be applied to management, including the design of ramp-up, but it is important to keep in mind that the results are trends with considerable variation in responses between individuals. This study was limited to one species of whale showing only some of their possible behavioral states and so there will be limitations in applying the results to other species and types of behaviors. The results and experience of BRAHSS should allow the development of simpler experimental protocols that can be applied to studies with other species.

*"PCAD4Cod" Impact of seismic survey sound exposure on fishes: population-level modelling and empirical data collection*

**H. Slabbekoorn**

Institute of Biology, Leiden University

Seismic surveys are necessary to explore the floor of seas and oceans but yield potential conflict with aquatic life. Seismic survey sound pulses can affect fishes in multiple ways. At close range, extreme over-exposure may induce physical injury and death. Beyond this close range, but within the audible range, there may be behavioural and physiological effects that are more subtle than physical injury or death, but that may apply to many more individual fish. The more subtle effects of anthropogenic sound exposure for many individuals have been recognized as important for 'Population Consequences of Acoustic Disturbance'. However, well replicated and controlled studies do not exist. In a JIP-funded project, we therefore integrate existing and new field data into models of energy-flow, individual behaviour and population dynamics. The overall key objectives can be summarized as: 1. A fully integrated project with energy budget and population modelling and empirical data collection (using a PCAD-model type framework); 2. First time ever impact study of a real-size seismic survey on free-ranging fish using individual tags for weeks before, during and after; 3. Direct comparison of behaviour in the wild with behaviour and physiology in captive outdoor conditions for adult and juvenile life stages; and 4. Measurement and modelling of natural patterns of particle motion and the modification of these patterns by human-made sound. The results so far and plans for the coming year will be reported. A one year desk study yielded an overview of the literature and insights, which was followed by a first practical year with modelling and pilot data collection, while another year of modelling and experimental work is still to come.

***Towards a Risk Assessment Framework/Protocol for Implementing the Data-Driven Population Consequences of (Acoustic) Disturbance (PCAD/PCoD) Model/Approach***

**Costa, D.** (1), Schwarz, L. (1), Huckstadt, L. (1), McHuron, E. (1), Mangel, M. (1), Huckstadt, L. (1), Villegas-Amtmann, S. (1). Pirotta, E. (2), New, L. (2),

(1) University of California Santa Cruz, (2) Washington State University

We have developed bioenergetic models to implement the PCoD framework to identify disturbance scenarios that can potentially cause population-level responses. With support from the JIP we developed a genera! Stochastic Dynamic Programming (SDP) model for the effect of acoustic disturbance on marine mammals; and then specifically applied this model to California sea lions and blue whales. A bioenergetics approach focuses on behavioral changes that reduce foraging or increase energetic costs. These bioenergetics models were coupled with tracking data from humpback and blue whales, California sea lions and northern elephant seals to look at likelihood (probability) of exposure (proportion of the population exposed) and the context of animals exposed to sound (e.g., proportion of individual foraging time exposed). Together this approach allows for a framework where worst-case scenarios can be examined to look at effects of sound exposure. Such a scenario assumes that animals are unable to adjust their behavior to minimize the impacts of exposure, and any exposure would result in no foraging behavior and the associated reduction in energy intake for the entire duration of exposure. If the worst-case scenario leads to acceptable risks, the scenario is screened out from further risk assessment. Due to the large number of marine mammal species and populations, it is impractical, and in many cases may not be necessary, to develop a data-driven model for each group. Instead, a tiered approach is more practical where we examine whether there is a potential for a worst-case scenario to result in a population-level impact.

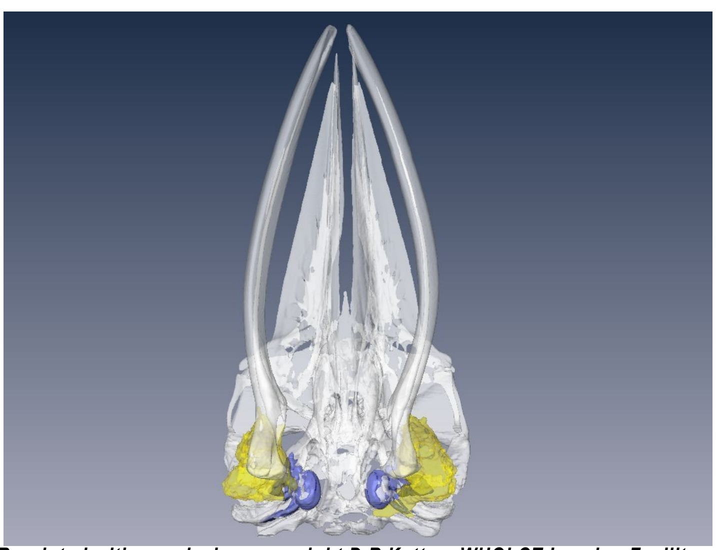
*Photo, courtesy of Kystmagasinet, Bergen, Norway*

### *Re-Evaluating Marine Mammal Noise Exposure Criteria: A Decade Following the Southall et al. (2007) Expert Panel*

**Southall, B.L (**1,2), Bejder, L. (3), Bowles, A.E. (4), Ellison, W.T. (5), Finneran, J.J. (6), Gentry, R.L. (7), Greene, Jr., C.R. (8), Ketten, D.R. (9, 10), Miller, J.H., Nachtigall, P.E. (3), Nowacek,D.P. (12), Reichmuth, C. (2), and Tyack, P.L. (13)

(1) Southall Environmental Associates, Inc, (2) Institute of Marine Sciences, Long Marine Laboratory, University of California, Santa Cruz, (3) University of Hawaii, Institute of Marine Biology, (4) Hubbs SeaWorld Research Institute, (5) Marine Acoustics. Inc., (6) United States Navy Marine Mammal Program, (7) ProScience Consulting, (8) Greeneridge Sciences, Inc., (9) Woods Hole Oceanographic Institution, (10) Harvard Medical School, (11) University of Rhode Island, (12) Duke University Marine Laboratory, (13) University of St Andrews

Exposure criteria in Southall et al. (2007) were based on limited data and presented as an iterative process intended for on-going review and revision. Major progress has been made in the last decade on the effects of noise on marine mammals, particularly in new studies of hearing for previously untested species and auditory and behavioral effects of noise. Members of the original expert panel, as well as several additional experts in key areas, are currently re-evaluating exposure criteria for three focal topics: auditory responses, propagation effects on received sound characteristics, and behavioral impacts. First, quantitative exposure criteria were derived to predict auditory effects for marine mammal species in air and water, grouped by hearing characteristics, auditory anatomy, and sound production. Revised auditory weighting functions were calculated and TTS/PTS onset levels predicted for all groups. Second, sound propagation-dependent changes in received frequency spectra were evaluated to derive a measurement-based method of estimating whether Impulsive stimuli (at source) may become less- or non-impulsive at distance, and thus be evaluated with different exposure criteria. Finally, methods for evaluating the occurrence and severity of behavioral responses to noise were revised. Broadly-applicable behavioral response criteria as a function of received level were again deemed infeasible. Instead, response severity was expressed in terms of biological vital rates, with noise exposure characterized by a wider range of acoustic metrics and contextual covariates. The results are applicable to both acute and longer-term noise exposure scenarios.



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### *The influence of temporally varying noise from seismic air guns on the detection of underwater sounds by seals*

Sills, J.M. and **Reichmuth, C.**

Long Marine Laboratory, Institute of Marine Sciences, University of California Santa Cruz

Standard audiometric data are often applied to predict how noise influences hearing. With regard to auditory masking, critical ratios—obtained using tonal signals and flat-spectrum maskers—can be combined with noise spectral density levels derived from 1/3-octave band levels to predict signal amplitudes required for detection. However, the efficacy of this conventional model of masking may vary based on features of the signal and noise in question. The ability of resource managers to quantify masking from intermittent seismic noise is relevant due to widespread geophysical exploration. To address this, spotted and ringed seals with previously measured critical ratios were trained to detect low-frequency tonal signals within seismic pulses recorded 1 and 30 km from an operational air gun array. The conventional model of masking accurately predicted the extent of masking only in certain cases. When noise amplitude varied significantly in time, the results suggested that detection was driven by higher signal-to-noise ratios within time windows shorter than the full signal duration. This study evaluates when it is appropriate to use average noise levels and critical ratios to predict auditory masking experienced by marine mammals, and suggests how masking models can be improved by incorporating time-based analyses of signals and noise.

### *Comprehensive Models of Hearing in Two Species of Mysticetes*

**Ketten, D. R.** (1, 2), Tubelli, A. A. (3), Zosuls, A. (1), Voysey, G. (1)

(1) Biomedical Engineering, The Hearing Center, Boston University, (2) Woods Hole Oceanographic Institution; (3) Broad Institute of MIT

Mysticetes are expected to be most liable to impacts from low frequency underwater sound sources. Currently there are no in vivo measures of mysticete hearing. Modelling is one alternative for determining hearing characteristics for species-specific risk assessments as well as optimal signals for playbacks and effective electrode and source placements for evoked potential (AEP) and brainstem response (ABR) measures. Models also allow impact simulations and exploration of auditory system component contributions to hearing characteristics.

In this research, we produced inner and middle ear modules for minke (Balaenoptera acutorostrata) and humpback (Megaptera novaeangliae) whale hearing. We employed micro CT, dissection, and histology to calculate inner ear frequency maps (FPMs) of total hearing ranges and frequencies of greatest liability for NIHL (notch). Anatomically derived maps were compared with nanoindentation measures of basilar membrane stiffness gradients. Middle ear measurements of frequency response and stiffness at the stapes footplate were coupled with the morphometrics of the ossicular chain and associated soft tissues obtained from dissection and 3D reconstructions of CT scans for input to finite element models (FEM) to obtain middle ear transfer functions (METF). Frequency response differences were measured also for stimulation of the glove finger vs tympanic bulla to assess bone vs tympanic membrane transfer efficiency. Peak responses differ by species but were generally between 20Hz to 5 kHz for these two species. The study was supported by the Joint Industry Programme on Sound and Marine Life, the Hanse Wissenschaftskollegg ICBM Feliowship, and the Helmholtz International Fellow research programs.

### *Temporary hearing threshold shift in a harbor porpoise (Phocoena phocoena) due to exposure to multiple airgun sounds*

**Kastelein, R. A.** (1), Helder-Hoek, L. (1), Van de Voorde, S. (1), von Benda-Beckmann, A. M. (2), Lam, F. A. (2), Jansen, E. (2), de Jong, C. A. F. (2), and Ainslie, M. A. (2)

(1) SEAMARCO, (2) TNO

The susceptibility of harbor porpoise hearing for airgun sounds used in oil and gas exploration was investigated. Small dedicated air guns (max 10 cubic inch) were developed and a harbor porpoise was exposed to an increase in SELcum, and it was determined at what exposure level Temporary threshold shift (TTS) was observed. Increased SELcum was achieved by increasing the airgun volume (up to 10 cubic inch), pressure, number of simultaneous firing air guns from 1 to 2, increasing the firing pressure (max. of 8 bar = 800 kPa), and increasing the number of pulses (max. of 20). The distance between the porpoise to the airguns was —1m and the depth of the airguns was 1 m. Around 4 dB TTS was observed after exposure to 10 and 20 consecutive pulses from two air guns which fired simultaneously (unweighted SELcum: 188 and 191 dB re 1 µ13a2s; weighted SELcum: 140 and 143 dB re 1 liPa2s, respectively) with mean shot intervals of around 17 s. Recovery occurred within 12 minutes after exposure. Surprisingly, TTS was only observed at 4 kHz, and not at 0.5, 1, and 2 kHz, whereas almost most of the pulse energy was below 1 kHz. This study suggests that the hearing of harbor porpoises is less likely to be damaged by low frequencies (<100 Hz), and advocates for use of a frequency-weighted (i.e. corrected for frequency-dependent TTS susceptibility) SELcum to predict temporarily and permanent threshold shifts. The SELcum required for TTS onset is an important metric as the onset of actual non-recoverable hearing damage is assumed to be related to this. The outcomes of these types of exposure studies are used by regulators to develop fact-based regulations

### *Auditory detection, masking, and temporary threshold shift in bearded seals (Erignathus barbatus)*

Sills, J.M. (1), Southall, B.L. (2), and **Reichmuth, C.** (1)

(1) Long Marine Laboratory, Institute of Marine Sciences, University of California Santa Cruz, (2) SEA, Inc.Bearded seals have a circumpolar Arctic distribution and are closely associated with pack ice, spending nearly all of their lives in remote habitats; as a result, their biology and behavior remain largely unknown. With respect to sensory biology, bearded seals—like other marine mammals—rely on acoustic cues to support a range of behaviors including orientation, communication, and predator and prey detection. However, the ability of bearded seals to perceive sound has never been investigated. In this study, species-typical auditory profiles were obtained from two young bearded seals trained to cooperate in a go/no-go behavioral paradigm. Detection thresholds were measured for underwater tonal sounds from 0.10 - 61 kHz, in quiet conditions and in the presence of octave-band masking noise. The seals displayed sensitive underwater hearing, with peak sensitivity of 50 dB re 1 pPa and a broad range of best hearing from 0.350 - 45 kHz. Like other phocinae seals, they performed particularly well compared to other mammals when detecting target signals within background noise. Finally, one bearded seal completed additional testing to evaluate hearing before and immediately following voluntary exposure to impulsive noise from a seismic air gun. These psychoacoustic studies thoroughly describe the hearing capabilities of bearded seals. Combined with recently reported data for spotted and ringed seals, they inform regulatory guidelines regarding impulse noise exposures and best management practices for marine mammals in a rapidly changing Arctic environment.

***Photo, courtesy of Colleen Reichmuth***

### *BRAHSS: logistics, mitigation, field operations and safety*

**Noad, M.J.** (1), Dunlop, R.A. (1), McCauley, R.D. (2) and Cato, D.H. (3)

(1) Cetacean Ecology and Acoustic Lab., The University of Queensland, Gatton, Qld 4343 Australia. (2) Centre for Marine Science and Technology, Curtin University Australia. (3) School of Geosciences, University of Sydney and Defence Science &Technology Group, Australia.

The BRAHSS project involved four large field experiments. Each experiment consisted of a series of trials which involved a source vessel towing an air gun or array of air guns, up to 6 teams of land-based observers, 5 teams of boat-based observers, up to two tags deployed on whales, arrays of autonomous seafloor recorders, drifting recorders, and hydrophone buoys that could be monitored in real-time. During each trial, the operations of all teams and the source vessel were coordinated by a trial director. During active trials mitigation was conducted using a dynamic system that estimated cumulative acoustic dose of every whale in the study area in real-time. Up to 100 people were involved in the final experiment, with approximately half of these volunteers who were trained during an intensive period at the start of each experiment. Key to managing the project was a daily debrief that included all personnel. Associated operational and logistical challenges included feeding and accommodating all personnel, checking received levels of airgun sounds in an area of public use including in the surf zone and on a nearby dive site, and undertaking local public relations activities. Safety was of paramount concern and covered a diverse range of activities including operating airguns, diving, tagging whales, avoiding bomb-diving birds, and volunteers surfing. Safety was successfully managed through risk assessment of all activities prior to each field season and real-time management of risk during the field work using job safety analyses, tool box meetings and dedicated daily discussion.

### *Low Visibility Real-time Monitoring Techniques Review*

**Verfuss U. K.** (1) , Gillespie, D. (2), Gordon, J. (3), Marques, T. (4, 5), Miller, B. (1), Plunkett, R. (1), Theriault, J. (6), Tollit, D. (1), Zitterbart, D. P. (7, 8), Hubert, P. (9), & Thomas, L. (4).

(1) SMRU Consulting, (2) Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, (3) Marine Ecological Research, (4) Centre for Research into Ecological and Environmental Modelling, The Observatory, University of St Andrews, (5) Centro de Estalistica e AplicaOes, Faculdade de Ciéncias, Universidade de Lisboa, (6) Ocean Environmental Consulting, (7) Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, (8) Ocean Acoustics Lab, Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, (9) Prove Systems Ltd

Regulators often require marine mammal monitoring before and/or during offshore industrial activities as part of mitigation to reduce potential acoustic impacts caused by the emitted sound. This IOGP funded project assessed and compared the relative strengths and weaknesses of low-visibility monitoring methods suitable for use as part of industrial seismic surveys and other E&P activities during periods when low-visibility would reduce the effectiveness of a visual Marine Mammal Observer (MMO). Passive (PAM), active (AAM) acoustic monitoring, RADAR and thermal infrared (IR) were identified as useful monitoring methods for the detection of animals used both in conjunction with MMOs and when visibility is poor. While thermal IR and RADAR (as is the case with visual MMOs) detect cues made at, or above the surface, acoustic methods (such as PAM and AAM) detect animals underwater. None of the detection methods, used alone, is likely to provide a sufficient detection probability for an in-time detection of all animals in all conditions during real-time monitoring in low-visibility. However, a combination of two or more complimentary methods will likely increase overall detection probability, noting effectiveness across methods often varies depending on each low visibility condition. We present the results of the project, identify both the technical (intrinsic) factors as well as the environmental and animal dependent (extrinsic) factors that influence the effectiveness of the monitoring methods and give recommendations on further research to assess and improve the effectiveness of real-time monitoring.

### *The 3-D-V Array: A volumetric, digital towed hydrophone array system capable of bearing and location estimation in 3-D space*

**Norris, T.**, D'Spain, G. and Gillespie, D.

Bio-waves Inc.

Real-time passive acoustic monitoring of marine mammals for mitigation requirements and boat-based surveys is typically conducted using a linear towed hydrophone array system. However, most linear towed array systems have limitations which preclude them from determining the vertical component of bearings (e.g. slant angles) to marine mammal sound sources. We are developing and testing a new, 3-D towed hydrophone array system (called the 3-D-V array) that will be capable of using both time-of-arrival-differences (TOAD) and beamforming methods to estimate bearings in three dimensions, for the ultimate goal of localizing marine mammals in three dimensional space. The main objectives of this project are to design, develop and test a fully digital, volumetric, towed hydrophone array system capable of real-time monitoring of marine mammals for mitigation purposes. This system uses beamforming, TOAD, angle-of-arrival, detection and localization algorithms that are fully integrated in PAMGuard as modules, for detecting and localizing bioacoustic signals from marine mammals. We overview hardware and software developments, and present results of preliminary bench and field test of this new system. Plans will be presented for testing in fall 2018 on the seismic vessel RN Langseth operated by Columbia University's Lamont-Doherty Earth Observatory.

***AVADECAF: Assessing the ViAbility of Density Estimation for Cetaceans from passive Acoustic Fixed sensors (DECAF) throughout the Life Cycle of an Offshore E&P Field Development***

**Booth, C.** (1), Oedekoven, c. (2), Gillespie, D. (3), MacAulay, J. (3), Marques, T. (2), Harris, D. (2), Marshall, L. (2), Plunkett, R. (1), Joy, R. (1), Wood, J. (1), Verfuss, U. (1), Tyack, P. (3), Johnson, M. (3) and Thomas, L. (2).

(1) SMRU Consulting (2) Centre for Research into Ecological and Environmental Modelling, University of St Andrews, (3) Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, UK.

We investigated how an array of fixed PAM systems could be used to estimate cetacean density/abundance across the life cycle and spatial extent of oil and gas fields. We reviewed the available knowledge on marine mammal species to determine their (current) suitability for employing PAM for density estimation. This included reviews of the current state of detection, classification and localization (DCL) capabilities and available PAM systems which have direct implications for employing DECAF methods. A crucial element of the project was the development of DECAF methods in a simulation tool (called `AVADECAF'). The development of this simulation tool represents the first time that each of the elements of DECAF have been integrated into a simulation setting. This tool allowed us to explore a set of power analyses and conduct a large sensitivity analysis to explore the feasibility and utility of implementing DECAF methods considering different PAM survey designs, species vocal characteristics, DCL capabilities, variable environments (and the role of error) using Marques et al (2009) as the foundation for this study. This analysis also considered the effect on the bias and precision of density/abundance estimates when integrating auxiliary data sources (such as DTAG data) into a DECAF analysis and we provide recommendations for further development to improve effectiveness and accuracy of estimating marine mammal abundance using PAM methods. The ability to explore the sensitivities of DECAF modelling and the value of different elements of a PAM programme will help in planning the monitoring for a wide range of cetacean species.

***Evaluation of DECAF Methods Using an Existing Eight-Year Fixed Acoustic Monitoring and Localization Dataset, Deployed During E&P Activities Along the Arctic Continental Shelf***

Kim, K. (1), Blackwell, S. (1), Conrad, A. (1), Thode, A. (2), Marques, T. (3), Danielle Harris, D. (3), Oedekoven, C. (3) and **Thomas, L.** (3)

(1) Greeneridge Sciences Inc, (2) Scripps Institution of Oceanography, (3) Centre for Research into Ecological and

We used 8 years of data from 5 static passive acoustic arrays in the Beaufort Sea to compare and evaluate multiple methods for estimating call density of migrating bowhead whales. Each array comprised between 3 and 13 direction-sensing recorders (Directional Autonomous Seafloor Acoustic Recorders – DASARs), typically separated by 7km and located in shallow water (20-55m) off the north coast of Alaska. Bowhead calls were detected and classified by two methods: manually by observers screening the spectrograms of the recordings and using an automated algorithm; calls on two or more DASARs could be localized (in 2D). We compared three methods of density estimation separately on manual and automated data: (1) direct census (where calls within a fixed radius of each sensor are assumed to be detected with certainty, and those outside that radius are discarded); (2) distance sampling (where range-specific detection probability of calls is estimated from the distribution of detection distances); and (3) spatially-explicit capture recapture (SECR, where range-specific detection probability is estimated from the pattern of detections across sensors). Direct census and distance sampling methods produced similar results; SECR was problematic for automated data due to a large number of detections on single sensors (probably mostly false positives) and for manual data due to non-independence between sensors. We discuss the pros and cons of each method.


***Photo Courtesy of the IAGC***

### *Broadband airgun-source characterisation: the Svein Vaage dataset.*

**Prior, M. K.** (1), Ainslie, M. A. (2), Halvorsen, M. B. (3), Hartstra, I. (1), Laws, R. M (4), MacGillivray, A. (5), Mller, R. (1), Robinson, S. (6) and Wang, L. (6)

(1) TNO, (2) JASCO, (3) CSA Ocean Sci., Inc., (4) Cambridge, UK; (5) JASCO Canada; (6) NPL

Signals produced by single marine-seismic airguns are distributed with frequency and angle in a manner determined primarily by operating depth, charging air pressure and chamber volume. Design details also mean that signals transmitted in identical conditions may vary between airguns of different make and model. While airguns are typically deployed in arrays, prediction of array performance requires a thorough understanding of the acoustic output of constituent airguns.

Metrics such as zero-to-peak sound pressure, primary/bubble amplitude and bubble period describe signals received at distance from airguns over the bandwidth used for imaging and are used to estimate the quality of images that may be obtained. Regulators also require metrics to describe the risk of adverse impact of sound on marine life. Some of these will be driven by animal physiology and differ from imaging metrics. Generally, a larger bandwidth is needed. Prediction of metrics requires accurate descriptions of airgun sources and this is normally achieved by computational models, constrained by high-quality measurements.

Between 2007 and 2010, the E&P Sound and Marine Life Joint Industry Prgramme sponsored a series of measurements of sound transmissions from airgun sources under controlled conditions. The resulting dataset comprises signals measured at various depths and horizontal offsets from airguns.

The paper describes quality checks carried out on the 2007-2010 measurements and subsequent processing implemented to produce metrics relevant to both seismic imaging and environmental impact of sound on marine life. Further processing necessary to produce source descriptions is also described and preliminary results are presented.

### *3-dimensional seismic source characterization study*

**Sidorovskaia, N. (**1), Li, K. (1), Jenkerson, M. (2), Summerfield, P. (2)

(1) Department of Physics, University of Louisiana at Lafayette, (2) ExxonMobil Exploration Co.

The Littoral Acoustic Demonstration Center conducted a Source Characterization Study to fully describe the 3-D acoustic field of a standard seismic array deployed in the Gulf of Mexico. Three vertical moorings with paired sensitive and desensitized hydrophones at different depths were deployed to measure the full dynamic range and bandwidth of the acoustic field emitted by the array, while a designated seismic source vessel shot a specified set of seismic lines to provide broad coverage of arrival angles, takeoff angles and ranges. The array positions were measured using standard techniques in real-time. Autonomous positioning systems were deployed to estimate the vertical mooring profiles. 3D acoustic positions were estimated using Ultra Short Baseline (USBL) acoustics during the source vessel line changes to minimize unnecessary acoustic interference. The Environmental Acoustic Recording System (EARS) was fully calibrated and allowed absolute values of peak pressures, RMS sound pressure levels (SPL), sound exposure levels, energy spectra, and one-third octave band energy distribution to be estimated to characterize the 3D acoustic field. Up-to-date results, statistical analysis of range-angle binned data, and analysis methods are presented and discussed

### *Terminology, measurement, processing and reporting standards for assessing effects of underwater sound on aquatic life*

**Ainslie, M. A.** (1), de Jong, C A. F. (2), Halvorsen, M. B. (3) and Morfey, C. L. (4)

(1) JASCO, Germany; (2) TNO; (3) CSA Ocean Sci., Inc., (4) University of Southampton.

The analysis of the effects of sound on aquatic animals requires an understanding of the generation and reception of sound by these animals, and of the possible detrimental effects of underwater noise. In the past, scientists and engineers from different disciplines have developed their own distinct jargons, making it difficult to communicate between disciplines without misunderstandings. A combination of regulation and ethical concern for aquatic animals has generated both the need and the will for scientists from these different disciplines to communicate with one another. We describe a tool that facilitates effective communication by defining a common language for all: the international standard ISO 18405:2017 Underwater Acoustics — Terminology. Standardization of acoustical terminology in air began in the 1940s, and today the jargon of airborne acoustics is widely accepted for noise impact assessments, as consolidated in national and international standards. By comparison, underwater acoustical terminology lags 60 years behind. ISO 18405 provides for the first time a set of internationally accepted definitions for terms in widespread use such as sound pressure level, sound exposure level, source level, transmission loss, propagation loss, echolocation click, hearing threshold, temporary and permanent hearing threshold shifts, frequency weighting function, detection threshold, ambient sound, ambient noise and many more. The definitions are distinct, unambiguous and applicable to all marine fauna, including marine mammals, fish, turtles and invertebrates. ISO 18405 and the process that led to the published definitions are summarized. The benefits of the standard are described in the context of specific examples of its use.

### *Acoustic Impacts on Marine Fauna from Marine Vibroseis Technologies*

Matthews, M.-N.R. (1), Ireland, D. (2), Brune, R. (3), **Zeddies, D.G.** (4), Christian, J. (5), Warner, G. (1), Deveau, T.J. (1), Frouin-Mouy, H. (1), Denes, S. (4), Pye, C. (4), Moulton, V.D. (2), and Hannay, D.E. (1)

(1) JASCO Applied Sciences (Canada) Ldt., (2) LGL Ecological Research Associates, Inc. (3) Robert Brune LLC (4) JASCO Applied Sciences (USA) Inc. (5) LGL Limited

Concerns about the potential impacts of seismic airgun sources on marine fauna have prompted research and development of alternate geophysical source technologies like marine vibroseis (MV). Sounds from MV are expected to have less effect on marine fauna than airgun-type sources, but few studies have quantitatively evaluated their potential effects. This Joint Industry Program (JIP) sponsored study used source and acoustic propagation models to calculate and compare the sounds produced by MV and airgun sources in three depth environments. Agent-based (animat) models were used to predict exposures to evaluate possible injurious and behavioral effects. The MV sources operate in a more non-impulsive manner, with minimum quiet inter-pulse periods that produce lower acoustic pressures with spectral content limited to lower frequencies than airgun arrays. The number of marine mammals predicted to receive injurious sound levels was smaller for MV sources than airgun arrays. The number of animals potentially displaying behavioral response was strongly dependent on the effects metrics and selected thresholds. A higher number of animals was predicted for MV sources with a single-step 120 dB re pPa threshold than for airgun arrays assessed with a single-step 160 dB re pPa threshold, although numbers were very low for both sources. Conversely, MV sources were predicted to affect fewer animals than airguns when assessed using a frequency-weighted multiple-step probabilistic effects threshold function. Distances from the sources where masking may occur were 2-5 times shorter for the MV sources. However, the duration of the masking lasted 5-9 times longer.

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