Technical Note

Note: Technical notes are aimed at promoting discussion. The views expressed are not necessarily those of the editors or the Australian Acoustical Society. Contributions are not formally peer-reviewed.

UNDERWATER PASSIVE ACOUSTIC MONITORING & NOISE IMPACTS ON MARINE FAUNA—A WORKSHOP REPORT

Christine Erbe

Centre for Marine Science and Technology, Curtin University, GPO Box U1987, Perth 6845, Western Australia

Christine.erbe@curtin.edu.au

The marine ecosystem is being increasingly subjected to underwater noise from industrial operations. Our ability to monitor the marine soundscape using passive acoustic technology is important to determine the potential impacts of anthropogenic sound. The objectives of this workshop were to define our current capabilities with regard to passive acoustic monitoring (PAM); to define our current state of knowledge of the marine soundscape, and of underwater noise in particular, and of noise impacts; to identify the needs and concerns of the various stakeholders; and to determine future research and development needs. The workshop was held in Fremantle, Western Australia, on 21 November 2012, the day before the Australian Acoustical Society's annual conference. Three tutorial sessions were presented by leading researchers in the field on underwater acoustic terminology, metrics, the basics of sound propagation, noise modelling and prediction, the marine soundscape (physical ambient, anthropogenic and biological sources), sound recording technology and methods, noise impacts on marine fauna, mitigation and environmental management. Tutorials were followed by rapid-fire presentations of current research associated with the themes of passive acoustic monitoring and noise impact. Discussions pursued on the presented topics, with emphasis on stakeholder needs, prevailing problems, knowledge gaps, potential solutions and future initiatives. The workshop was attended by over 70 participants from within Australia and abroad, hosting a diverse range of expertise and representing the various stakeholders in the marine environment: the offshore oil and gas industry, consulting industry, fishing industry, defence, government (environmental officers, regulators, fisheries officers), environmental groups and academia. The outcomes of the workshop were:

- An appreciation of PAM for monitoring of marine fauna, for ecological studies, for measurements of anthropogenic noise, for studying noise impacts and for mitigation monitoring;
- A demonstration of the effectiveness of PAM for presence and abundance monitoring (with more acoustic detections than visual in certain circumstances);
- An understanding of the limitations of PAM (to vocalising animals) and the potential of combining PAM with visual observations and possibly active acoustic imaging to increase detection probability;
- An appreciation of the differences between regulatory approaches in different jurisdictions;
- The identification of the need to monitor (and address noise impacts on) entire ecosystems including less iconic (=non-mammalian) species;
- The identification of knowledge gaps with regards to unidentified sounds in marine soundscapes, natural variability in soundscapes with space and time necessitating long-term baseline recording, noise impacts on the vast majority of marine species, anthropogenic source signatures and sound transmission.

INTRODUCTION

The potential impacts of anthropogenic underwater noise (e.g. from seismic surveys, pile driving, dredging and defence operations) on marine fauna have grown in concern over the past few decades. An understanding of underwater sound emissions, sound propagation and bioacoustic impacts is necessary for sustainable development of marine resources. Passive acoustic monitoring of the marine soundscape, of anthropogenic operations and of—vocal—marine fauna is a non-invasive tool of rapidly growing application in bioacoustic environmental impact assessments (EIA). There are no standards, however, neither domestically within Australia, nor internationally, relating to the measurement, data analysis, and data reporting for such EIAs. As a result, the quality of many environmental impact assessments is poor, the results are not reliable, data are not comparable, errors (which are hardly ever assessed or reported) are huge, outcomes (e.g. impact zones, imposed mitigation requirements) are arbitrary and costs are as random as the lottery. The problem is particularly topical in Western Australia due to the amount of offshore development.

The annual conferences of the Australian Acoustical Society always attract a large number of underwater acousticians from within Australia and abroad. When Perth was announced as the site of the 2012 conference, the Centre for Marine Science and Technology (CMST) at Curtin University seized the opportunity to organise an underwater noise workshop in conjunction with the conference, as many experts would already be coming to Perth.

In addition to underwater acoustic researchers, various stakeholders in the marine environment were invited. Expecting differing backgrounds in acoustics, the workshop commenced with tutorial sessions on underwater acoustics, marine soundscapes and noise impacts. These were followed by contributed rapid-fire presentations and whole-audience discussions. It was hoped that by establishing an understanding of the fundamentals of underwater acoustics, participants could gain more insight from current research presented in the rapid-fire sessions. The aim was to create a more equal platform for all stakeholders to discuss outcomes, research needs and recommendations. Marine bioacoustics is a multi-disciplinary field in terms of both research and application, and the strength of this workshop came from the participation of a diverse group of stakeholders, including researchers, industry representatives, defence representatives, environmental officers, consultants and regulators. The workshop was organised into two themes: passive acoustic monitoring and underwater noise impacts on marine fauna.

UNDERWATER PASSIVE ACOUSTIC MONITORING

The morning session began with two tutorials: 1) an introduction to underwater acoustics presented by Alec Duncan of Curtin University, and 2) an overview of the marine soundscape presented by Rob McCauley of Curtin University.

Tutorials

Sound is a small periodic (in time) perturbation of density and pressure from their hydrostatic means. Water particles move back and forth; the perturbation travels, but the water particles don't (instead they oscillate). Water is 1000 times as dense as air; the speed of sound in water is three times that in air; sound travels much better (over longer ranges) under water than in air. Sound levels are given in decibel (dB), which is a ratio, not a unit. The reference pressure (or intensity) must be listed, which is 1 μPa in air and 20 μPa underwater. Continuous sound is best described in terms of root-mean-squared pressure *SPLrms*. Impulsive sound is best described in terms of sound exposure level *SEL* and/or peak pressure level *SPLpk*.

Transmission loss is the ratio of received pressure (or intensity) to source pressure (or intensity), and is usually given in dB as well. It's largely due to the spreading of sound over a larger and larger area as the sound propagates away from its source, and due to absorption (conversion of acoustic energy to heat due to vibration of water molecules). Geometrical formulae accounting for spherical and cylindrical spreading are commonly used to estimate transmission loss, but are hardly ever applicable. Sound can be ducted into a surface channel when the speed of sound increases with depth. Sound can be ducted into the deep-ocean sound channel and traverse entire ocean basins. More sophisticated and environment-specific sound propagation models are available[1] and should be used, yet require significant expertise for correct implementation and application. Specifically, Australia's limestone seabeds are a challenge for sound propagation modelling [1].

Humans' air-filled ears hear poorly underwater, creating the misconception of a "quiet ocean". The ocean is indeed naturally noisy with contributions from wind, rain, ice, and—of course—animals (both vocalisations and activities such as breaching). The marine soundscape is very site-specific, not just because of different sources, but also because of different sound transmission regimes. Sites along the edge of the continental shelf usually have significant contributions (at frequencies < 100 Hz) from the deep ocean (e.g. wind and distant shipping). These sounds do not travel into shallow water and are not picked up on the continental shelf.

Biological and physical sea noise is believed to play a critical role in the life functions of marine animals. The ocean is naturally noisy and provides acoustic environmental cues to marine fauna. Fish choruses vary with season and moon phase [2]. Whale calls and song change over the years. The number of calling animals can sometimes be determined by counting overlapping calls. Migration routes of great whales can be pieced together from CMST noise logger data spanning 20 years and > 80 locations along the southern and western Australian coasts.

Ship noise is a continuous and chronic source, with a small number of very noisy ships contributing the majority of noise energy. Seismic surveying contributes significantly in certain areas and sound transmission environments. Airgun sound travels poorly in shallow water over limestone seafloors; yet surveys along the continental slope off southern WA were recorded at 2000 km range across the entire Great Australian Bight on noise loggers on the opposite continental slope. The same noise loggers also recorded colliding and calving icebergs in Antarctica 3000 km away.

Noise artefacts are often seen in EIA reports yet were not identified as such. Sources for artefacts are: hydrophone movement through the water, turbulent flow, cable strum, electronic noise, mooring noise, waves splashing against the deployment boat etc. Also, underwater moorings attract animals, and the sound recorded is no longer typical of the location in the absence of the mooring, e.g. crustaceans settle, fish move in, animals scratch and chew on the hydrophone and cables. Removing artefacts is particularly important when computing source levels of anthropogenic operations from levels received at some range; a common mistake is the inclusion and hence amplification of ambient noise, which should have been removed from the recording.

Rapid-fire presentations

Following the tutorials were rapid-fire presentations by participants, covering PAM applications from both research and industry. A common commendation of PAM from

[1] see e.g. http://cmst.curtin.edu.au/products/actoolbox.cfm

ecologists was its ability to open up monitoring regions that are otherwise remote and difficult or expensive to survey. Tracey Rogers of the University of New South Wales presented results from visual surveys and PAM of leopard seals (*Hydrurga leptonyx*) in Antarctica. Visual surveys were biased towards females mostly occupying the sea ice and missed males mostly occupying the water, where they could only be detected by PAM. Furthermore, as PAM allowed differentiating juveniles from adults by their differing vocalisations, it was discovered that sparsely distributed adults occupied prime habitat, forcing juveniles into densely-populated areas [3]. Contrary to common belief, high-quality habitat is not necessarily heavily occupied, hence density is not always a predictor for prime habitat, and the importance of protecting sparsely-populated habitat is likely underestimated in EIAs.

The use of PAM as a viable tool for long-term monitoring in remote locations was further stressed by Craig McPherson of JASCO Applied Sciences, who presented a multi-year acoustic monitoring program in the Arctic. Baseline ambient conditions, industrial sounds and the spatio-temporal distribution of marine mammals were monitored in open-water summers as well as under-ice in winters.

Given the vast amount of PAM data collected these days, automatic tools are needed for efficiency, reliability, comparability and objectivity. While a plethora of tools from pattern recognition or voice recognition research is available, these have mostly been applied to specific cases, e.g. the detection of a limited number of calls of one or more species in a specific type of noise [4]. A higher-level characterisation into all sounds biological versus anthropogenic versus physical ambient is quite a challenge, and is currently being tackled by Shyam Madhusudhana of Curtin University. Such a characterisation would allow the computation of noise budgets, i.e. the contribution of underwater acoustic energy by source type, without having to identify the specific sources of sound. It could be used on large spatio-temporal scales to aid in quantifying the contribution of sound from marine industrial operators to the underwater soundscape, in determining trends over time and in characterising geographical variability.

Andrew Parker of SLR Consulting presented a case study of PAM in conjunction with visual surveying for mitigation monitoring during port construction. PAM proved to be a useful tool for the environmental assessment process. A good correlation was seen between PAM and visual data for great whales.

In conclusion, the PAM rapid-fire presentations applauded PAM as a highly useful tool to add to the suite of ecological research methods. Its applicability to short-term, real-time mitigation monitoring as well as long-term, large-scale monitoring was demonstrated.

Discussion

An open-audience discussion followed the rapid-fire presentations. In this discussion, the importance of sound to marine organisms, the usefulness of bioacoustics as an ecological research tool, and the diverse applicability of PAM as a research and monitoring tool were repeated. Additional case studies were mentioned, e.g. the passive acoustic detection of false killer whales (*Pseudorca crassidens*) predating on fish caught in fishing gear.

Monitoring the presence of marine animals with visual observers alone is limited to good light and weather conditions and to animals that spend a significant amount of time near the surface. Binoculars only offer a limited field of view (of a few degrees), and many observers are needed for full-circle monitoring. Passive acoustics works in poor visibility (at night time, high sea state or fog), can detect vocalising animals from all directions over much longer ranges and often in higher numbers than visual observation alone [6].

It is comparatively easy to determine relative abundance of cetaceans from PAM data, yet much more difficult to derive absolute abundance or triangulate the location and distance of specific cetaceans. Along migration routes, animals can potentially be counted quite successfully as any one animal only passes by once. In areas where animals mill, abundance estimation is much more difficult.

PAM, however, is not the golden bullet. PAM is often used as a complementary tool alongside other methods. It has more value in some circumstances (environments, species) than in others. Not all species vocalise, and only a subset of a population vocalises. Calling behaviour depends on age, gender, health and context (e.g. other non-acoustic behaviour). Small cetaceans often travel in large groups, and the chances of at least some of them vocalising at any one time and hence the group being detected are high. Large whales often travel in smaller groups and the chances of PAM detection are much lower. Finally, calls change over time, and tools developed based on specific calls may not work in future.

Alternative methods, such as active acoustic (sonar) detection were discussed and can be useful for non-vocal species or in noisy environments where animal calls might be masked.

PAM is not only a tool for monitoring marine fauna, but also for monitoring anthropogenic development and marine soundscapes in general. A common step in the EIA process is the modelling and prediction of noise footprints of specific anthropogenic operations. At a later stage, model results can be validated in the field using passive acoustic techniques, in order to verify predictions of the EIA and in order to improve models.

Australia's neighbouring countries (Indonesia, Papua New Guinea and Singapore) are archipelagic nations. Indonesia is the largest archipelago on Earth with over 17,000 islands. These marine labyrinths are often characterised by the lack of a continental shelf (e.g., East Indonesia, PNG, SI), yet they are not open ocean either. These “deep-sea yet near-shore” habitats are often highly bio-diverse. The corresponding soundscapes are expected to be complex yet have hardly been studied at all. Both sound shielding and noise ducting likely play a significant role. These specific marine soundscape characteristics may have ramifications for effective management of anthropogenic underwater noise. One workshop participant voiced concern about sounds from seismic surveys in deep inter-island passages "driving" or "acoustically flushing out" marine life as the intense sound reverberates through such passages. This question is especially relevant for Indo-Pacific migration corridors and other critical habitats for oceanic cetaceans and other marine life.

The value of long-term data sets on marine soundscapes was stressed several times. This data is useful to biologists and ecologists studying marine fauna. It is useful to oceanographers for the study of ambient noise, geographic variability and trends in time. It is useful to environmental scientists for studying human impacts. This data provides a record of the marine soundscape with future uses potentially not yet identified. For example, as the sources of currently unidentified sounds become known (e.g. if whale calls are identified through combined visual and acoustic surveys), we can go back in time picking these calls in old recordings in order to determine this species' whereabouts, migration and abundance.

The Australian Integrated Marine Observation System (IMOS) includes autonomous underwater acoustic recorders deployed and maintained by CMST, Curtin University, in four locations: off Sydney (New South Wales), off Portland (Victoria), off Perth (Western Australia) and off Scott Reef (Western Australia). Data from as early as 2008 is available online for free at http://www.imos.org.au/. A graphical user interface allows the display of sound spectrograms and the listening to sounds online. Sections can be selected for immediate download. Alternatively, entire recordings can be requested through the University of Tasmania. The more people use this free data set and tool, the more funding will likely be made available for the continuation of the IMOS program.

The benefits of data sharing were highlighted. CMST has collected soundscape data around Australia for over 20 years, on behalf of the offshore oil and gas industry, defence and government. The respective clients own individual data sets. Data sharing would allow a synthesis of soundscape data to determine geographical commonalities, trends over time, noise budgets, migration routes of great whales, habitat usage patterns etc. Under the oil and gas industry's Collaborative Environmental Research Initiative (CERI) some of this data is being shared for very specific syntheses such as migration patterns.

Future needs

During the presentations and discussion, a number of points were raised that should be addressed in the near future.

- The deployment of more PAM buoys was urged; ideally through public initiatives such as IMOS.
- The deployment of localisation arrays or time-synchronised autonomous recorders that can be used for localisation and tracking was encouraged—again ideally through programs like IMOS.
- The sharing of the data between stakeholders (academia, industry, government and public) was encouraged.
- The publication of raw data was desired.
- The timely publication of results was urged.
- Standards or guidelines for noise measurement, analysis and reporting are needed.
- Standards or guidelines for the usage of PAM in mitigation monitoring would be helpful (e.g. what a priori info on species present, calling behaviour and context is needed and where to find it; equipment and deployment guidelines; operational protocols).

IMPACTS OF UNDERWATER NOISE

The afternoon session began with a tutorial on bioacoustic impacts by Christine Erbe.

Tutorial

Similar types of impact have been described for marine mammals and fish. At long ranges, a sound source might merely be audible. With decreasing range, noise can cause a behavioural response, masking of communication or environmental cues, temporary hearing loss and potentially injury.

Behavioural and auditory evoked potential (AEP) audiograms have only been measured for few individuals of about 20 marine mammal species. There are no audiograms for polar bears under water, sea otters, sperm whales or baleen whales. In the absence of direct measurements, anatomical evidence for hearing sensitivity can be derived from structural properties of the ear [7,8].

Behavioural responses can sometimes be seen at very long ranges approaching the limit of audibility. Measurement indicators include changes in swim speed and direction, dive and surfacing duration and interval, respiration rate, and changes in contextual and acoustic behaviour. Behavioural responses can depend on prior exposure (habituation versus sensitisation), age, gender, health and current behavioural state. Case studies of behavioural responses were presented, including controlled exposure experiments of humpback whales (*Megaptera novaeangliae*) to a 2700 cui seismic array, undertaken by the Centre for Whale Research and Rob McCauley in 1996. Localised avoidance at 3 km range, without large-scale migratory changes were seen; cow-calf pairs were more responsive (at received levels of 129 dB re 1 $\mu Pa^2 s$) than males, who approached the air gun in 9 out of 16 trials [9]. The multi-year Behavioural Response of Australian Humpback whales to Seismic Surveys (BRAHSS) experiment exposed humpbacks to a single airgun and ramped-up signals in 2010 and 2011; data analysis is ongoing; the experiment will continue in 2013 and 2014 leading up to a full commercial array [10].

Noise can mask communication, echolocation and the sounds of predators, prey and the environment. Masking depends on the spectral and temporal characteristics of signal and noise. Masking is more complex than a mere energy comparison within frequency bands. Directional hearing, frequency and time discrimination capabilities, co-modulation masking release, and anti-masking strategies (increasing call level, frequency shifting, building in redundancy) help reduce the masking effect [11,12].

Noise exposure can cause hearing loss [13]. Klaus Lucke measured the onset of a Temporary Threshold Shift (TTS) in harbour porpoises (*Phocoena phocoena*) at a SEL of 164 dB re 1 $\mu Pa^2 s$ and at a peak-to-peak sound pressure level (*SPLpkpk*) of 200 dB re 1 μPa [14]. Behavioural responses were documented at SEL = 145 dB re 1 $\mu Pa^2 s$ and $SPLpkpk$ = 174 dB re 1 μPa. This data (plus a "buffer" of a few dB) became Germany's official regulation thresholds for porpoises: SEL < 160 dB re 1 $\mu Pa^2 s$, $SPLpkpk$ < 190 dB re 1 μPa. Mitigation methods (e.g. bubble curtains) have to be used around pile driving to keep levels low and animals out of this risk zone.

Jane Fewtrell and Rob McCauley exposed caged fish, turtles and squid to a 20 cui airgun in 1996. Fish swam faster, in tighter circles and deeper as the airgun approached. Hair cells in the inner ear were damaged at a cumulative *SEL* of 187 dB re 1 μPa^{2}s, and recovered over the duration of > 1 month [15]. In 2007, caged tropical fish exposed to a 2055 cui array at 45 m range showed no pathological damage, and only mild and insignificant TTS. Free fish dropped to the seafloor, and more fish were seen on echosounders > 500 m from the seismic transect. Zooplankton also showed signs of dispersing near the transect.

Noise—in certain circumstances—can also affect the vestibular system, reproductive system, nervous system and other tissues and organs. Stress is a physiological response to a stressor aimed at surviving the immediate threat, yet can cause health problems if it becomes chronic.

The biological significance of acoustic impacts is still poorly understood. What levels and impacts can threaten the survival of a population? Stressors can be additive and cumulative, with noise impacts "adding" to other impacts (chemical pollution, food depletion etc.).

Rapid-fire presentations

Bethan Parnum of Environmental Resources Management began the session with an overview of the environmental impact assessment process, which involves the following steps: baseline monitoring of the marine soundscape (PAM) and animal surveys, literature and database searches for anthropogenic source signatures, sound propagation modelling, literature searches for noise impacts on species present, comparison of modelled received levels to known impact (threshold) levels, and finally the design of situation-specific mitigation and management measures.

Roberto Racca of JASCO Applied Sciences presented a multi-year monitoring and mitigation project to protect grey whales (*Eschrichtius robustus*) from impacts of seismic surveys off Sakhalin Island. Individual whales were tracked visually; received levels were estimated via pre-season modelling and *in-situ* real-time measurements; shut-downs were imposed if whales within the near-shore feeding zone received *SEL* > 156 dB re 1 μPa^{2}s per pulse. Whale behaviour was variable. One animal travelling somewhat parallel to the seismic transect received increasing *SEL*/pulse and deflected as the received *SEL*/pulse reached 150 dB re 1 μPa^{2}s. Another whale paralleled the seismic transect further offshore outside of the feeding zone at received levels of up to 163 dB re 1 μPa^{2}s without deflecting. Received level alone is not a successful indicator for behaviour; rather, multiple variables such as behavioural state, environmental conditions, prey availability and demographic parameters must be included [16].

Chandra Salgado-Kent of Curtin University presented results of the BRAHSS experiment based on visual observations from the source vessel during control, ramp-up and active airgun trials. She showed that different groups of animals responded differently, with mother-calf pairs keeping a distance from the source, yet males occasionally approaching. Whether this puts them at higher risk for bioacoustic impact needs to be investigated. She highlighted the need for solid statistical and spatial models to support data analysis.

Klaus Lucke of IMARES presented data from visual and acoustic observations of harbour porpoises around pile driving showing avoidance within 20 km range and increased detections at 25 – 50 km range. The effect was the stronger, the longer the pile driving duration.

Justin McDonald of Western Australian Fisheries and Marine Research Laboratories showed the "opposite" response: crustaceans, molluscs and ascidians were attracted to low-frequency noise and settled on ship hulls (biofouling). In a controlled experiment, *Ciona intestinalis* had a greater survival rate, faster settlement rate, and a faster rate of metamorphosis when exposed to vessel noise. As raised during the discussion, apart from noise, hydrodynamic flow might also affect settlement, as some whales have barnacles at different locations on their heads and bodies.

In contrast, Geoff McPherson of James Cook University showed how sound could intentionally be used to modify the behaviour of marine mammals around fishing gear. A specific case of mammal depredation around oceanic longline gear was presented. Passive acoustic sonar reflectors and active acoustic depredation mitigation pingers were shown to significantly mitigate depredation in Indo-Pacific longline fisheries by acoustically interfering with the terminal stages of depredation behaviour. Long-range acoustic detection of depredation behaviour is an option to modify fishing behaviour to minimise the need to expose mammals to behaviour modification techniques. Geoff argued that it was worth making short-range modifications to toothed whale behaviour to prevent mortality associated with fishing gear.

In conclusion, there was a great diversity in results presented, such as the ability of underwater sound to affect animal behaviour both negatively (source avoidance) and positively (biofouling settlement), both unintentionally (byproduct of acoustic surveying) and intentionally (active deterrence). Sound clearly has the potential to influence the ecology of marine organisms to various degrees.

Discussion

There was some discussion of metrics for impact assessment. We use decibels instead of linear units in order to handle the large dynamic range of sound levels underwater. Different types of impact relate to different quantities. For impulsive sound, the duration of the sound or the duty cycle seem to matter, which is why quantities such as *SEL* and cumulative *SEL* are useful. Also, peak pressure, pressure change and rise time have been related to impacts of impulsive sound, specifically effects other than auditory. Mammalian ears respond to intensity; other species' ears respond to pressure. Vibration of the seafloor is potentially critical for benthic organisms; CMST in collaboration with the University of Tasmania is currently investigating the impacts of seismics on benthic scallops and lobsters.

As sound propagates away from its source, the quantities that "matter" change. Close to an airgun, peak pressure might be critical, however, at longer ranges, pulses spread out, peak pressure drops and intensity and *SEL* become more critical. In addition, it is difficult to assign acoustic source signatures even within one source type. For example, in the case of blasting, and specifically home-made bombs used by fishermen in Asia, the source signatures vary from case to case.

Dynamite fishing also happens in Australia with blast sounds recorded by CMST off Scott Reef and with two arrests of Indonesian fishing vessels illegally carrying dynamite in 2012. Blast effects in marine animals seem to correlate inversely with body mass; while sea turtles seem somewhat resistant to blast trauma. Multiple blasts in tight succession are worse than single blasts, with impact inversely correlated to the interblast interval.

This brought up a discussion of whether "one number" for a specific source and a specific species is "good enough" as a do-not-exceed threshold to adequately protect this species. Considering an airgun, the acoustic characteristics vastly differ close to the source compared to far from the source. Different quantities matter at different ranges. Also, would x dB from a single airgun have the same impact as x dB from an airgun array? What other factors and contexts need to be examined? This moved the discussion towards regulation.

Germany has regulations only for impulsive noise from pile driving. At 750 m from the source, *SEL* must be < 160 dB re 1 $\mu Pa^2 s$ and *SPLpkpk* must be < 190 dB re 1 μPa. Mitigation methods such as bubble curtains must be employed to keep below these levels. In the Netherlands, pile driving is prohibited during the first six months of the year to protect fish larvae, and permitted without mitigation during the second six months of the year. Across the EU, impulsive noise and continuous noise are being monitored throughout the year to determine baselines and achievable thresholds [17], which will be set in the near future—likely individually by country.

In Australia, NOPSEMA came into existence on 1.1.2012 as the federal regulator for the offshore oil and gas industry operating in Commonwealth waters, handling all approvals for petroleum activities. NOPSEMA want to avoid having "one number" for all circumstances, and want to avoid that developers simply work towards "one number". Rather, developers are encouraged to engage with the research community to determine the best approach for local protection of the specific marine environment—under the ALARP (as low as reasonably practicable) principle. Proponents have to determine reasonable thresholds for the various operations and animal populations and demonstrate how they are going to meet these goals. The success of this process hinges on scientists publishing their results, and greatly benefits from the sharing of data and research outcomes.

Greater availability and accessibility of information on noise and impacts was repeatedly requested during the presentations and discussions. Workshops, such as this, were commended as they brought together multi-disciplinary scientists and stakeholders, and communicated results as well as knowledge gaps to a broad audience of people with different application requirements.

Future needs

- Science transfer: Results of research studies must be published and presented in order to guarantee uptake by industry and regulators and in order to guarantee best possible management of the marine environment.
- Environmental management would greatly benefit from the sharing of data.
- Underwater noise is an integral part of the soundscape and should be considered in fishery and environmental management plans as a factor (and potential pollutant) of water quality.
- Most of our knowledge relates to iconic (mammalian) species. With indications of anthropogenic impact on coral, crustacean and fish larvae and adults, it is clear that we must investigate impacts on all animals within an ecosystem, of which the better-studied, charismatic megafauna are only a small part.
- We know very little to nothing about noise impacts on most species and need to expand the database on basic hearing and hearing impacts, and non-auditory impacts.
- There is a place for experiments with captive animals and these should be supported; however, the translation of results from captive animals to wild animals has to be done with care, specifically if the experiments relate to behaviour.
- There should potentially be more 'real world' studies carried out in which the behaviour of animals and potential impacts on animals are studied in conjunction with a real activity such as a seismic survey. This would remove the significant issues of translating the results of 'artificial' studies using caged animals or an unrepresentative source into the 'real world'.
- We need to test a large number of individuals of a population in order to get statistically significant results and in order to assess variability within a population. E.g., young animals are often more susceptible than older animals, yet male adult humpback whales potentially expose themselves to higher sound levels.
- Individual impacts are likely not biologically significant; population effects are what we need to understand.

ACKNOWLEDGEMENTS

Sacha Guggenheimer drafted the first summary of PAM and noise impact presentations. John Hughes, Geoff McPherson, Chandra Salgado-Kent, Rob McCauley, Benjamin Kahn, and Craig McPherson provided constructive feedback on the workshop report and manuscript.

REFERENCES

[1] A.J. Duncan and A. Gavrilov, "Low-frequency acoustic propagation over calcarenite seabeds with thin, hard caps", *Proceedings of Acoustics 2012 Fremantle*, Western Australia, 21-23 November 2012

[2] R.D. McCauley, "Fish choruses from the Kimberley, seasonal and lunar links as determined by long term sea noise monitoring", *Proceedings of Acoustics 2012 Fremantle, Western Australia*, 21-23 November 2012

[3] T. Rogers, M. Ciaglia, H. Klinck and C. Southwell, "Can singing be used to predict critical habitats? ", *Proceedings of Acoustics 2012 Fremantle*, Western Australia, 21-23 November 2012

[4] C. Erbe and A.R. King, "Automatic detection of marine mammals using information entropy", *Journal of the Acoustical Society of America* **124**(5), 2833-2840 (2008)

[5] J. Barlow and B.L. Taylor, "Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey", *Marine Mammal Science* **21**(3), 429-445 (2005)

[6] S. Rankin, T.F. Norris, M.A. Smultea, C. Oedekoven, A.M. Zoidis, E. Silva and J. Rivers, "A visual sighting and acoustic detections of Minke whales, Balaenoptera acutoroshata (Cetacea: Balaenopteridae), in nearshore Hawaiian waters", *Pacific Science* **61**(3), 395-398 (2007)

[7] A. Tubelli, A.L. Zosuls, D. Ketten, M. Yamato and D. Mountain, "A prediction of the minke whale (Balaenoptera acutorostrata) middle-ear transfer function", *Journal of the Acoustic Society of America* **132**(5), 3263-3272 (2012)

[8] D.R. Ketten, "Cetacean Ears", in: W.L. Au, R.R. Fay, A.N. Popper (Eds.), *Hearing by whales and dolphins (SHAR Series for Auditory Research)*, Springer-Verlag, New York, 2000, pp. 43-108

[9] R.D. McCauley, J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I. T. Prince, A. Adhitya, J. Murdoch and K. McCabe, "Marine seismic surveys: a study of environmental implications", *Australian Petroleum Production Exploration Association (APPEA) Journal* **40**, 692-708 (2000)

[10] D.H. Cato, M.J. Noad, R.A. Dunlop, R.D. McCauley, N.J. Gales, C.P. Salgado-Kent, H. Kniest, D. Paton, C. Jenner, J. Noad, A.L. Maggi, I.M. Parnum and A.J. Duncan, "Project BRAHSS: Behavioural response of Australian humpback whales to seismic surveys", *Proceedings of Acoustics 2012 Fremantle*, Western Australia, 21-23 November 2012

[11] C. Erbe, "Critical ratios of beluga whales (Delphinapterus leucas) and masked signal duration", *Journal of the Acoustical Society of America* **124**(4), 2216-2223 (2008)

[12] C. Erbe and D.M. Farmer, "Masked hearing thresholds of a beluga whale (*Delphinapterus leucas*) in icebreaker noise", *Deep-Sea Research Part II* **45**(7), 1373-1388 (1998)

[13] D. Ketten, Marine mammal auditory system noise impacts: Evidence and incidence," in: A.N. Popper, A.D. Hawkins (Eds.), *The Effects of Noise on Aquatic Life. Advances in Experimental Medicine and Biology 730*, Springer Verlag, New York, 2012, pp. 207-212

[14] K. Lucke, U. Siebert, P.A. Lepper and M.-A. Blanchet, "Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli", *Journal of the Acoustical Society of America* **125**(6), 4060-4070 (2009)

[15] R.D. McCauley, J. Fewtrell and A.N. Popper, "High intensity anthropogenic sound damages fish ears", *Journal of the Acoustical Society of America* **113**, 638-642 (2003)

[16] R. Racca, A. Rutenko, K. Broker and G. Gailey, "Model based sound level estimation and in-field adjustment for real-time mitigation of behavioural impacts from a seismic survey and post-event evaluation of sound exposure for individual whales", *Proceedings of Acoustics 2012 Fremantle*, Western Australia, 21-23 November 2012

[17] M.L. Tasker, M. Amundin, M. Andre, A.D. Hawkins, W. Lang, T. Merck, A. Scholik-Schlomer, J. Teilman, F. Thomsen, S. Werner and M. Zakharia, *Marine Strategy Framework Directive: Task Group 11 Report: Underwater noise and other forms of energy*, JRC Scientific and Technical Report No. EUR 24341 EN - 2010, European Commission and International Council for the Exploration of the Sea, Luxembourg, 2010