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Citation: Proc. Mtgs. Acoust. **27**, 040008 (2016); doi: 10.1121/2.0000299

View online: https://doi.org/10.1121/2.0000299

View Table of Contents: http://asa.scitation.org/toc/pma/27/1

Published by the Acoustical Society of America

Proceedings of Meetings on Acoustics

Volume 27 http://acousticalsociety.org/

Fourth International Conference on the Effects of Noise on Aquatic Life

Dublin, Ireland

10-16 July 2016

From physiology to policy: A review of physiological noise effects on marine fauna with implications for mitigation

Natacha Aguilar de Soto
CREEM. University of St. Andrews. St Andrews. Fife. Scotland.
BIOECOMAC. University of La Laguna, Tenerife, Canary Islands. naguilar@ull.es

Kalliopi Gkikopoulou, Sascha Hooker, Saana Isojunno, Mark Johnson, Patrick Miller, Peter Tyack, Paul Wensveen
Sea Mammal Research Unit, University of St. Andrews. St Andrews. Fife. Scotland.
kg366@st-andrews.ac.uk; sh43@st-andrews.ac.uk; si66@st-andrews.ac.uk; mj26@st-andrews.ac.uk; pm29@st-andrews.ac.uk; plt@st-andrews.ac.uk; pw234@st-andrews.ac.uk

Carl Donovan, Catriona M. Harris, Danielle Harris, Laura Marshall, Cornelia Oedekoven, Rocio Prieto, Len Thomas
CREEM. University of St. Andrews. St Andrews. Fife. Scotland.
crd2@st-andrews.ac.uk; cms11@st-andrews.ac.uk; dh17@st-andrews.ac.uk; lhm@st-andrews.ac.uk; cso2@st-andrews.ac.uk; rpg2@st-andrews.ac.uk; lt5@st-andrews.ac.uk

The development of guidelines for mitigating noise impacts on marine fauna requires data about the biological relevance of noise effects and about the practicality of mitigation options. Recent expansion of scientific knowledge has shown that noise effects vary among animals with different behavioral ecophysiology. Beaked whales exemplify that some sensitive species may experience negative effects of sound at kilometers from the source, due to behavioral reactions leading to indirect physiological damage. Moored hydrophone arrays have contributed substantially to our understanding of naval sonar effects on beaked whales and have been used to refine techniques for passive acoustic detection of cetaceans. Similarly, broadband Ocean Bottom Cables/Nodes could facilitate learning about effects of seismic sounds and cetaceans' distribution offshore. This information is essential to improve spatial mitigation in the planning-phase of activities. Also, passive acoustics can help real time mitigation, which requires early detection of vulnerable species and practical mitigation protocols triggered by detection. Detection could be aided by large-scale portable acoustic arrays, which are now technologically feasible. Pilot studies of technological applications for mitigation and cost-benefit modelling of potential mitigation scenarios will help to inform effective mitigation design. Mitigation reduces social conflict regarding noise effects, a win-win for all stakeholders.

Published by the Acoustical Society of America

 [DOI: 10.1121/2.0000299]

1. INTRODUCTION

Acoustic noise is considered a contaminant of emerging concern in the oceans (Weis, 2014). This is because we are still far from understanding how the ~200,000 known species of multi-cellular marine fauna use sound for different biological functions, and the mechanisms by which these species may be affected by noise (Wright *et al*., 2007; Kight and Swaddle, 2011). This scarcity of knowledge makes both the planning and management of noise-producing human activities at sea challenging. Documenting and measuring the effects of our activities are important first steps toward developing mitigation measures that reduce the impacts of anthropogenic noise on marine fauna. The second and necessary step is to apply research results to improve the environmental protocols of human activities at sea. Here we provide examples of observed physiological effects of noise on marine species to illustrate the need to apply an integrative approach to the assessment and management of noise-effects on marine fauna. This needs to consider both hearing and non-hearing related physiological damage, as well as damage caused directly by sound exposure or indirectly as a consequence of behavioral responses. Beaked whales demonstrate the latter (Jepson *et al*., 2003; Fernández *et al*. 2005; Cox *et al*. 2006) and pose an example of a family of vulnerable protected species for which it is challenging to develop mitigation strategies due to their low detectability at sea. Naval sonar has been related to mass strandings of beaked whales (D'Amico et al., 2009) and thus naval exercises elicit social concern about environmental protection.

Other activities producing intense noise at sea, such as seismic surveys, are sometimes confronted with negative public opinion also, due to concerns about effects of seismic pulses on the wellbeing of marine protected species (Castellote and Llorents, 2015) or on commercial fish catch (Engas *et al*., 1996). The fishing industry is a powerful lobby and governments need to make decisions balancing the countries´ interest on the extraction of two natural resources: fish and hydrocarbons. While reductions in fishing catch rates during seismic surveys have been observed for some species (Engas *et al*., 1996), no such effects have been recorded in other cases where the fishery used other techniques or targeted different commercial species (Parry *et al*. 2010). This apparent contradiction may just reflect the variety of natural behaviors and responses to sound of target species, and how these responses alter the effectiveness of the fishing techniques used. General conclusions are challenged by the scarcity of data available on effects of seismic sounds on marine fauna. The complexity of this issue can only be solved by gathering additional data and applying effective mitigation.

Technology plays a role in defining the practical limits on mitigation efforts. We outline examples of how existing technologies can be applied to fill knowledge gaps about animal responses and distribution, and to improve the effectiveness of mitigation efforts. Improving mitigation is not only a mandate of conservation law; demonstrating that all reasonable efforts are being invested to reduce impacts on protected species or on economic activities will undoubtedly reduce social conflicts that often challenge noisy activities. This will lead to a more positive public opinion about human tasks conducted in a responsible manner.

2. THE RELEVANCE OF BEHAVIORAL AND NON-HEARING PHYSIOLOGICAL EFFECTS

Southall *et al*. (2007) proposed that hearing damage is the most evident sign of noise-effects for marine mammals. However, Tougaard *et al*., (2015) challenged the view that safe exposure noise-limits can be defined by levels causing the onset of permanent or temporary hearing thresholds shifts (PTS/TTS). Also, Popper et al. (2014) provide a more holistic view of the hearing and non-hearing effects of noise on fish and turtles. The fact that noise effects may range from injury to behavioral responses is specifically considered in some national guidelines, e.g., the US Marine Mammal Protection Act distinguishes between type A (injury) and type B (behavioral) effects of noise. However, this classification does not capture that some behavioral responses may lead to physiological damage different from hearing threshold shifts. Recent guidelines for noise exposure developed by NOAA (2016) use the terms "safe exposure", "safe distance" and "effectively quiet" to define distances and received noise levels with low probability of causing hearing damage. While some of these terms are scientific nomenclature defined in the 1970's (Ward, in NOAA, 2016), it is important to note that these terms refer exclusively to hearing damage. There is, therefore, the potential for the terminology in NOAA (2016) to be cited out of context and misunderstood as referring generally to safe distances and exposure levels for animals.

NOAA (2016) represents a commendable effort to summarize current knowledge about hearing effects of noise exposure. A limitation to the results is that most studies on hearing damage in marine mammals have been performed with captive animals that may have been repeatedly exposed to experimental noise (e.g. Finneran *et al*., 2000; 2010). Recent studies on terrestrial mammals exposed to loud noise found delayed and non-recoverable neuro-auditory damage after the animals had recovered from TTS (Kujawa and Liberman, 2009). This raises doubts about how protective threshold criteria based on TTS really are. Also, results extracted from few repeatedly exposed individuals will probably not capture the range of effects that naive animals may experience in the wild. While experiments with mammals and fish in captivity have been valuable in forming the basis of our knowledge about hearing in marine fauna, captive studies cannot assess the ecological significance of even minor hearing loss for animals relying on sound detection for biological functions essential for survival and fitness, such as feeding, detecting predators or mating, as well as interacting or cumulative effects of exposure (Kunk et al., 2016).

Current scientific knowledge shows that non-hearing effects of noise on marine fauna may be as, or more, severe than hearing effects. Direct mortality can be caused by the shock wave of explosives producing barotrauma at short ranges from the source (von Benda-Beckmann *et al*., 2015). At larger ranges, indirect mortality can be caused in some cases by stress responses altering diving physiology and homeostasis (Fernández *et al*., 2005; Cox *et al*., 2006). Repetitive noise exposure may have potential population level consequences in some cases (Claridge 2013; Pirotta *et al*. 2015) but it is unknown if these effects may be related to hearing damage or to chronic non-hearing physiological stress.

A variety of physiological effects of intense sound sources in addition to hearing injury have been observed in marine fauna from invertebrates to mammals (e.g. Table 1). Some studies show no apparent effects of exposure to some noise sources on some species. However, others studies and other species show clear reactions and even death when animals are exposed to very high received levels, or when species or individuals are vulnerable to indirect effects of noise exposure (Cox *et al*., 2006). Variability in responses to noise is expected among the hundreds of thousands of marine species, as well as among different ontogenetic stages within the same species and different types of noise sources and receive levels. Quantifying dose-response and dose-severity probabilistic functions of noise effect (Miller et al., 2014) or lack of effect is essential to develop mitigation protocols that facilitate the coexistence of anthropogenic activities producing noise and the protection of marine fauna.

Table 1. Examples of physiological effects observed in marine fauna in addition to hearing injury.

	Barotrauma	Stress
 Mammals	*Danil & Leger, 2011*. Wild common dolphin deaths related to military underwater charges. *Ketten et al. 1993*. Humpback whales did not leave feeding area when explosions occurred and suffered barotrauma.	*Lyamin et al, 2015*. Cardiac responses in captive belugas. Individual variability. // *Rolland et al. 2012*. Higher stress hormones in right whales related to shipping noise. // *Jepson et al, 2003*. Beaked whales mass strandings related to flight response from naval sonar.
 Seabirds	*Danil & Leger, 2011 & // Gitschlag and Herczeg 1999*. Seabird deaths due to naval charges and platform removal.	*Wilson et al. 1991*. Startle responses of Adelie penguins to aircraft reduced birds in colony 15% and increased nest mortality 8%.
 Seaturtles	Klima *et al*. 1988 report signs of barotrauma in turtles related to explosive oil-platform removal.	*DeRuiter & Doukara, 2012*. Startle responses of wild loggerhead turtles to seismic airguns. Not in olive ridley turtles (*Weir 2007*)
 Fish	*Casper et al. 2012*. Barotrauma in stripped bass is recoverable in captivity. // *Gitschlag and Herczeg 1999* Thousands of fish deaths due to explosive platform removal.	*Fewtrell and McCauley, 2012*. Signs of anxiety in pink snapper and striped jack/trevally exposed to single shots of a seismic airgun. *Anderson et al., 2011*. Biochemical stress in captive seahorses.
 Invertebrates	*Guerra et al. 2004, 2011*. Giant squid mass strandings, where some squid showed barotrauma, coincided with seismic surveys in two occasions.	*Lagardere 1983*. Brown shrimp increased metabolism an reduced growth and reproductive output. // *Aguilar de Soto et al. 2013* observed delayed and abnormal development in scallop larvae.

Mitigation protocols will vary depending on their objective, e.g. from avoiding certain noise exposure on protected species to reducing interference with fishing activities. Some countries, e.g. Norway or Australia, apply planning phase mitigation to seismic surveys by consulting research bodies knowledgeable about temporal and spatial occurrence of fishing activities and spawning periods/locations of species of interest, or by active dialogue with stakeholders of the fishing industry. Several nations apply computational models linking spatial models of protected species distribution and models of underwater sound transmission to predict number of animals exposed to certain noise levels (e.g. SAKAMATA, Netherlands). In contrast to mitigation of effects of chemical pollution at sea, which is strongly regulated at national and international levels, mitigation targeting marine acoustic pollution is still in its infancy. A logical process when developing mitigation is focusing on the most vulnerable species. In the following we discuss the case of beaked whales (Ziphiidae), a family of 22 species of deep-diving cetaceans, because they have shown to be especially sensitive to noise (Cox *et al*., 2006).

3. BEAKED WHALES: AN EXAMPLE OF SPECIES THAT CHALLENGE MITIGATION OF NOISE EFFECTS

Toothed whales use sound to mediate biological functions including foraging and mating and are thus sensitive to effects of noise masking acoustic cues or eliciting negative behavioural or physiological impacts. Ziphiids seem to be particularly sensitive to naval sonar, as evidenced by the species composition of mass-stranding events related to sonar exercises (D'Amico *et al*., 2009). Ziphiids that have mass-stranded in coincidence with sonar exposure (e.g. Cuvier´s beaked whale, Figure 1) had evidence of fat/gas emboli leading to multi-organic hemorrhages (Jepson *et al*., 2003; Fernández *et al*., 2005). It has been shown that these pathologies could occur at sea before the whales stranded (Fernández *et al*., 2012, 2013), demonstrating that mortality is not necessarily related to the stranding itself but could be caused solely by the diving and stress response that followed noise exposure offshore. One of the most accepted explanations of the strandings was abnormal behaviour elicited by sonar exposure (Cox *et al*. 2006). Behavioural response studies on three species of beaked whales showed that all three species respond to sonar exposure at relatively low levels with avoidance and/or reduction of vocal activity (Tyack *et al*., 2011; DeRuiter *et al*., 2013; Miller *et al*., 2015). The received level of sonar exposure that elicits behavioural responses leading to physiological damage and to strandings of ziphiids is unknown, although it is likely to be considerably lower than levels causing hearing damage (Cox *et al*., 2006). However, responsiveness may also vary with individual and circumstances making it difficult to predict entirely safe levels. Thus, beaked whales exemplify that "safe exposure levels" defined for hearing damage (NOAA 2016) do not necessarily protect sensitive species from other physiological effects of noise that may have lethal consequences in some cases. This sensitivity may not be specific to navy sonar: several cases of mass strandings of beaked whales in coincidence with seismic surveys have been recorded (Castellote and Llorents, 2015) but lack of proper veterinary analysis makes it currently impossible to confirm or discount a cause-effect relationship.

Figure 1. Beaked whales are an example of sensitive species experiencing lethal indirect effects of noise exposure at received levels below hearing damage.

There has been much debate about the reasons behind the sensitivity of beaked whales to noise. Beaked whales have a highly specialized way of life, stretching their physiological capabilities to perform dives comparable to sperm whales but with a much smaller body size (Tyack *et al*., 2006; Hooker *et al*., 2011). This, and the poor social defenses of beaked whales from vocal predators such as killer whales, may explain why beaked whales are so sensitive to sound (Aguilar de Soto *et al*., 2012) and why they would risk such behavioral responses with severe physiological consequences (Cox *et al*., 2006). Population data of beaked whales are scarce offshore, but the US Navy has funded long-term monitoring in the Pacific and the Atlantic which shows that local populations are small (<100), have high site-fidelity and apparently low connectivity (Claridge, 2013; Reyes, 2016). These characteristics reduce resilience to potential population-level impacts. In this sense, it is relevant that observations of altered demographic parameters and lower density of beaked whales recorded in a naval training range suggest that repetitive exposure of beaked whales may have population-level consequences in this area (Claridge, 2013). The latter is just one observation of one population and more studies are needed to evaluate the hypothesis of population-level impacts of naval sonar.

Mitigation of noise effects for beaked whales is challenging, but not impossible. Spatio-temporal mitigation, i.e. avoiding areas and periods of known high concentration of sensitive species, is the most effective mitigation method. For example, after several events of mass-strandings that coincided with naval exercises off the Canary Islands, a moratorium on the use of naval sonar within 50 nm of the islands was established in 2004; since then, no atypical mass-strandings of beaked whales have been recorded in the archipelago (Fernández et al. 2013). This example illustrates the benefits of protecting known high concentration, or hot-spots, of vulnerable species (Williams et al., 2014). However, knowledge about the distribution and density of beaked whales is generally fragmentary and largely limited to near-shore areas that can be surveyed economically. The scarcity of data supporting animal density maps increases uncertainty about the expected number of animals to be affected by noise in a given area. Investment in surveys of potential sites at the planning phase is essential to reduce uncertainty and allow realistic estimates of the number of animals affected (Marques et al., 2013). Moreover, effective planning phase mitigation may reduce the effort required in real-time mitigation, which is inevitably more expensive because it may involve changes to the activity being carried out

Concentrating naval exercises in training ranges reduces sonar exposure of naive animals and enables long-term monitoring of potential population and habitat-wide effects. However, some exercises will be performed outside training areas, ranging from routine one-ship testing to large multi-nation exercises with several vessels operating tactical sonar. Beaked whales are difficult to detect visually, but some Ziphiidae species can be found in all oceans, meaning that any human activity producing intense sound in or near deep waters must consider beaked whales in the planning phase. Although the survey work required to inform spatial mitigation is time-consuming, recently developed acoustic monitoring technologies provide opportunities to improve distribution data and the effectiveness of spatial mitigation at relatively low cost.

Planning-phase mitigation, although essential and effective (e.g. Fernández *et al*. 2012, 2013) cannot eliminate the possibility of encountering and affecting beaked whales. For this reason, in addition to planning-phase mitigation, real-time mitigation protocols should be tested for their likely effectiveness in reducing risk of physiological damage for whales. An integrated approach to mitigation involves combining both planning phase and real-time strategies, each informed by relevant data of target species collected at each stage over appropriate time scales (Figure 2). For example, long-term surveys to establish reliable density estimates and distribution maps of a target species would be required at the planning phase, whereas animal presence would need to be established on shorter timescales during real-time monitoring. In addition, short surveys performed before an activity can be used to make choices among different potential locations of the activity. A large number of trade-offs must be resolved in the design of such an integrated strategy, for example: the cost of each mitigation action versus the risk of impacting species; the cost of acquiring information about the target species versus the reliability of this information; the cost of missing animal detections versus the cost of false alarms (particularly during real-time mitigation); and the relative cost of detection and mitigation in the planning phase versus during the activity. To establish an optimal strategy, these trade-offs have to be allocated costs and benefits in a robust statistical framework allowing different strategies to be evaluated by simulation. The process of allocating costs and assessing the risks of each activity and mitigation action requires broad stakeholder involvement. A critical enabling component of any mitigation program is a means to detect the presence of animals, either for real-time mitigation, or for planning phase monitoring to estimate animal density and distribution. The effectiveness of real-time mitigation methods increases significantly with the probability of detecting the target species (Marshall, 2012; Wensveen, 2016). For many toothed cetaceans passive acoustic monitoring (PAM) has higher probability of detection than visual monitoring and this is particularly true for beaked whales (Barlow *et al.*, 2013). The stereotyped inter-click interval patterns of beaked whales and their characteristic frequency-modulated clicks, at least when observed in front of the animal within their focused acoustic beam, facilitate the correct identification of Ziphiid clicks. The broad applicability of PAM to study beaked whales and other cetaceans can be exploited to increase the effectiveness of both planning phase and real-time mitigation, and some examples of this are given in the next section.

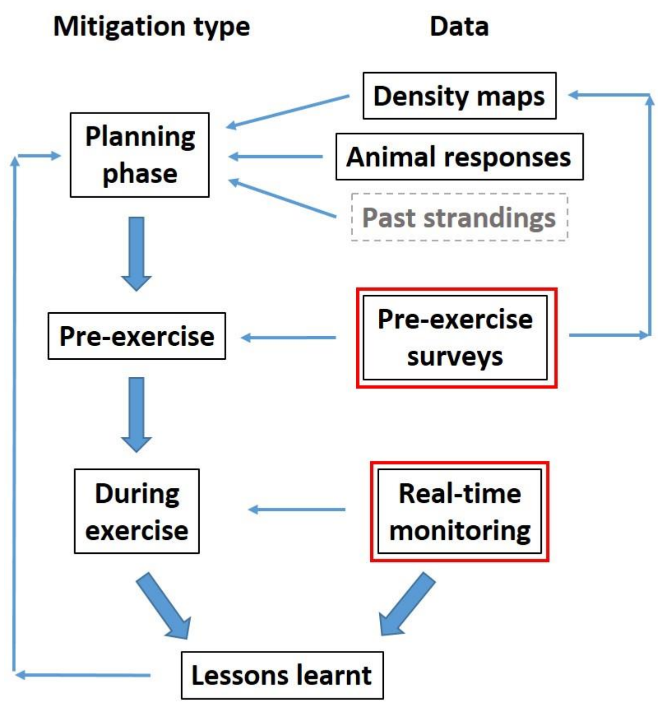

Figure 2. Conceptual model for an integrated mitigation process. Red squares indicate tasks in which new data are acquired each time an activity is undertaken to improve mitigation of the current activity, as well as future activities. The location of past mass strandings of beaked whales is an indicator of risk areas.

4. TECHNOLOGIES TO FILL DATA GAPS AND IMPROVE MITIGATION EFFECTIVENESS

a) Ocean Bottom Systems

Ocean Bottom (OB) hydrophone arrays in US naval training ranges have played a key role in the recent expansion of scientific knowledge about behavioral responses of whales to naval sonar and developing of methods of passive acoustic monitoring of these species including density estimation (e.g. Marques et al., 2009; Moretti *et al*., 2010, 2014; Tyack *et al*., 2011). These arrays can detect animals and track their movements over areas of hundreds of km^2 providing a powerful synoptic source of information for both planning phase and real-time mitigation as well as evaluating the effectiveness of mitigation procedures applied once animals are detected. The cost of installing and maintaining such arrays may be too high to be feasible for many activities occurring outside of such special facilities. However, the increasing use of OB Cables and Nodes in the routine activities of seismic operators (Figure 3) offers a new opportunity both to study effects of seismic sound on marine fauna and to inform mitigation protocols. While seismic surveys occur frequently in many parts of the world and seismic pulses are a persistent component of background noise in some ocean basins (Nieukirk *et al*., 2004), there is still surprisingly little knowledge about seismic noise effects on marine fauna. Seismic OB systems offer the opportunity to solve this data gap. Seismic OB systems typically have a low bandwidth matched to the frequencies of geophysical interest but these systems could presumably be equipped with high frequency hydrophones to study responses of beaked whales and other cetaceans at relatively low cost. Deployment of wide-band OB systems would enable a powerful experimental protocol in which data are collected before, during and after the activity. Results could provide information on the temporal and spatial footprint of effects of seismic surveys on protected vocal species. These results may reduce concerns of stakeholders if the footprint of effects is shown to be short-term or small-scale. The results may offer insights about potential patterns of occurrence and in the sensitivity of different species, and how these are influenced by seasonality, life cycle status, etc. Learning about these factors will improve the power of the seismic industry to plan surveys in a manner that reduces their potential impact on marine fauna and this would help to enhance public support for underwater exploration.

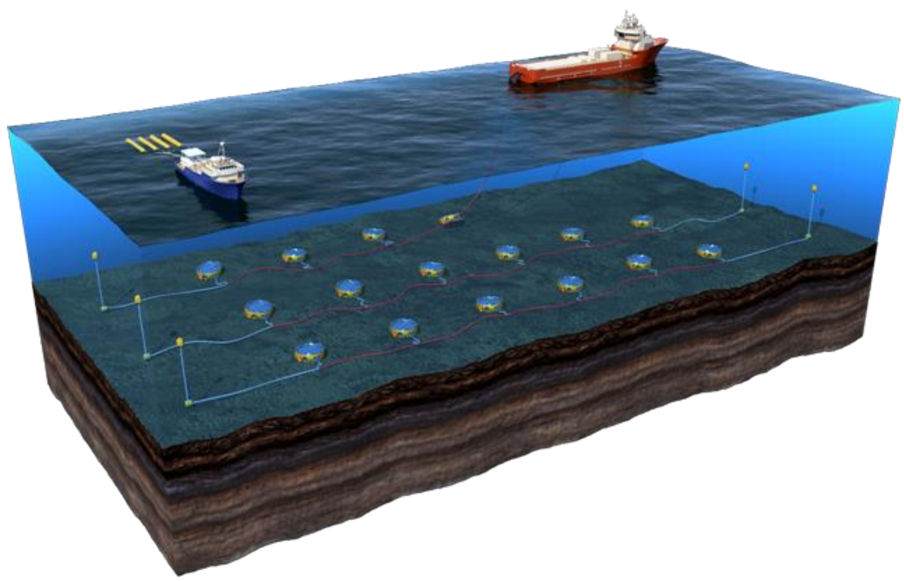

Figure 3. Ocean Bottom Cables/Nodes equipped with additional sensors could play a key role in understanding the temporal and spatial footprint of effects of seismic surveys on marine fauna, such as vulnerable beaked whales. Results can be used to inform environmental impact assessment and effective mitigation. Image © Geoserve.

b) Portable Passive Acoustic Monitoring Arrays (PORT-PAM)

When moored arrays of hydrophones are not feasible in the target location of an activity, portable passive acoustic monitoring arrays could be used to detect beaked whales and other vulnerable sound-producing cetacean species over the potentially large impact zones of high intensity sound sources. This could be achieved by scaling up existing technologies such as drifting hydrophones, sonobuoys and gliders (e.g., Haun *et al*., 2008, Baumgartner et al. 2013; Miller et al., 2015) to create relatively low cost and rapid-deployable arrays. Examples of technology available for portable passive acoustic monitoring (PORT-PAM) are:

i. PAM from vessels. Acoustic data from towed hydrophone arrays or hull-hydrophones could be streamed to an independent computer with classifiers for cetacean vocalizations, building on on-going efforts, e.g., PAMGuard.

ii. Deployment of a network of radio-linked drifting sonobuoys or acoustic detectors: these could comprise low-cost recorders capable of radio-transmitting raw acoustic data and/or detections from programmed classifiers (Figure 4). Equipping the buoys with GPS trackers or AIS transmitters would facilitate their recovery. This will require protocols to guarantee operational efficiency.

iii. Underwater vehicles similarly equipped with recorders and detectors, sending information via radio to collecting nodes at programmable times when at the surface.

Although in *situ* detectors and classifiers for cetacean vocalizations are constantly being improved, these will never be perfect. A large but known proportion of false alarms is tolerable in statistical estimation of animal density, but false alarms could be extremely costly during real-time mitigation. Thus, in a real-time scenario, potential detections would need to be subject to an additional level of scrutiny, best performed by trained bioacousticians. To facilitate this, the distributed array of sound detectors would need to send short audio segments for each detection to a central command point for further refined classification. This functionality is already implemented in some systems (e.g. PAMGuard).

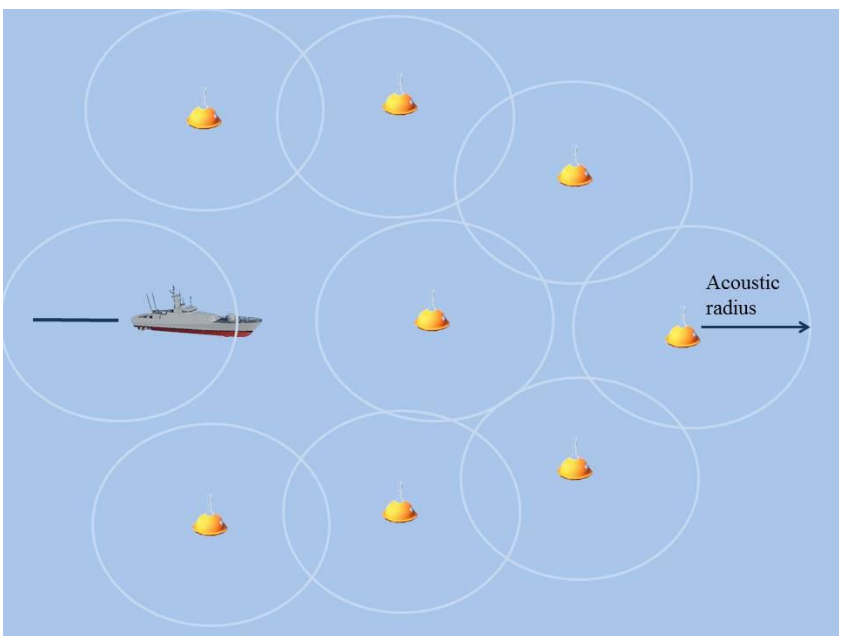

Figure 4. Schema of a large-scale Portable Passive Acoustic Monitoring Array (PORT-PAM): in this case a network of radio-linked drifting hydrophones, e.g., deployed by aircraft ahead of the noise source in a real-time mitigation scenario.

5. CONCLUSIONS

Management and mitigation of marine pollutants is a slow process, requiring scientific assessment of effects and the development of technologies and guidelines for reducing these effects. In the case of underwater noise pollution increasing scientific knowledge has expanded the concern about noise effects from just hearing damage to other types of physiological damage and also behavioral responses, which may have greater consequences than hearing loss in some cases. These individual responses can furthermore lead to population level and thus ecosystem effects. For some species, the development of marine sound detection technology means it is now possible to apply large-scale detection systems for vulnerable vocal species at relatively low cost to improve both planning phase and real-time mitigation. Modelling of mitigation scenarios is essential to inform the design of practical and effective actions. A range of mitigation options needs to be considered, targeted to vulnerable species in the area of interest.

The development of mitigation protocols is particularly relevant for beaked whales given their sensitivity to human noise sources. Real-time mitigation protocols are more effective when target species for mitigation can be readily detectable (Marshall 2012; Wensveen, 2016). The low availability for visual detection of beaked whales means that surveys and mitigation actions based on visual detection of these species are not effective. However, beaked whales are vocally active for two or three times as long as they are visually detectable (Aguilar de Soto *et al*., 2012), meaning that PAM may be the best way forward for beaked whale mitigation. Recent research has allowed the characterization of beaked whale clicks (Johnson *et al*., 2004; Zimmer *et al*., 2003; Gillespie *et al*. 2010; Bauman Pickering et al., 2013) and a substantial advance of automated classification methods. This means current scientific knowledge and detector technology is ready to be applied in a serious investigation about how to create an effective PAM-based mitigation system and what its characteristics would be.

6. ACKNOWLEDGEMENTS

NAS was supported for this work by project ECOSOUND, a Marie Slodowska Curie fellowship funded by the EU program Horizon 2020 (project 621081).

REFERENCES

Aguilar de Soto, N., Delorme, N., Atkins, J., Howard, S., Williams, J. and Johnson, M. (2013). “Anthropogenic noise causes body malformations and delays development in marine larvae.” Scientific Reports **3**, 2831.

Aguilar de Soto N., Kight C. (2016). “Physiological effects of noise on aquatic animals.” In *Stressors in the Marine Environment* (Oxford University Press) pp. 135–158.

Aguilar de Soto, N., Johnson., M., Tyack, P., Arranz, P., Revelli, E., Marrero, J., Fais, A. and Madsen, P. (2012). “No shallow talk: cryptic strategy in the vocal communication of Blainville´s beaked whales.” Marine Mammal Science **28(2),** E75–E92. DOI:10.1111/j.1748–7692.2011.00495.x

Anderson, P.A., Berzins, I.K., Fogarty, F., Hamlin, H.J. and Guillette, L.J. (2011). “Sound, stress and seahorses: the consequences of a noisy environment to animal health.” Aquaculture **311**(1–4), 129–138.

Barlow J., Tyack PL., Johnson MP., Baird RW., Schorr GS., Andrews RD., Aguilar de Soto, N. (2013). “Trackline and point detection probabilities for acoustic surveys of Cuvier’s and Blainville’s beaked whales.” The Journal of the Acoustical Society of America **134**, 2486–2496. DOI: 10.1121/1.4816573.

Baumgartner. M., Fratantoni, D., Hurst, T., Brown, M., Cole, T., Van Parijs, S. and Johnson, M. (2013). “Real-time reporting of baleen whale passive acoustic detections from ocean gliders.” The Journal of the Acoustical Society of America 134:1814–1823.

Baumann-Pickering. S., McDonald. M., Simonis, A., Berga, A., Merkens, K., Oleson, E., Roch, M., Wiggins, S., Rankin, S., Yack, T. and Hildebrant, J. (2013). “Species-specific beaked whale echolocation signals.” The Journal of the Acoustical Society of America 134:2293.

Casper, B.M., Halvorsen, M.B., Matthews, F., Carlson, T.J. and Popper, A.N. (2013) "Recovery of barotrauma injuries resulting from exposure to pile driving sound in two sizes of hybrid striped bass." PLoS ONE **8(9)**:e73844.

Castellote, M. and Llorents, C. (2015). "Review of the effects of offshore seismic surveys in cetaceans: are mass strandings a possibility?" Effects of Noise on Aquatic Life II. Popper, A.N., Hawkins, A. (Eds.). Springer New York, New York.

Claridge, D. (2013). "Population ecology of Blainville's beaked whales (*Mesoplodon densirostris*)." PhD University of St Andrews. 312 pp

Cox, T.M., Ragen, T.J., Read, A.J., Vos, E., Baird, R.W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'amico, A., D'spain G., Fernández, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houserp, D., Hullar, T., Jepson, P.D., Ketten, D., Macleod, C.D., Miller, P., Moore, S., Mountain, D.C., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Meads, J. and Benner, L. (2006). "Understanding the impacts of anthropogenic sound on beaked whales." Journal of Cetacean Research and Management **7(3)**, 177–187.

D'Amico A., Gisiner RC., Ketten DR., Hammock JA., Johnson C., Tyack PL., Mead J. (2009). "Beaked whale strandings and naval exercises." Aquatic Mammals **35**, 452–472. DOI: 10.1578/AM.35.4.2009.452.

Danil, K. and Leger, J.A. (2011)." Seabird and dolphin mortality associated with underwater detonation exercises." Marine Technology Society Journal **45(6)**, 89–95.

DeRuiter, S. and Larbi Doukara, K. (2012). "Loggerhead turtles dive in response to airgun sound exposure." Endangered Species Research **16**, 55–63.

DeRuiter, S.L., Southall, B.L., Calambokidis, J., Zimmer, W.M.X., Sadykova, D., Falcone, E.A., Friedlaender, A.S., Joseph, J.E., Moretti, D., Schorr, G.S., Thomas, L. and Tyack, P.L. (2013). "First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar." Biology Letters **9**, 20130223. doi:10.1098/rsbl.2013.0223

Engas, A., Lokkeborg, S., Ona, E., Soldal, A. « Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*)." Canadian Journal of Fisheries and Aquatic. Sciences **53,** 2238-2249 (1996).

Fernández, A., Edwards, J.F., Rodríguez F, Espinosa de los Monteros, A., Herráez, P., Castro, P. and Arbelo, M. (2005). "Gas and fat embolic syndrome involving a mass stranding of beaked whales (family Ziphiidae) exposed to anthropogenic sonar signals." Veterinary Pathology **42**,446–457.

Fernández, A., Sierra, E., Martín, V., Méndez, M., Sacchinni, S., Bernaldo de Quirós, Y., Andrada, M., Rivero, M., Quesada, O., Tejedor, M. and Arbelo, M. (2012). "Last 'atypical' beaked whales mass stranding in the Canary Islands (July, 2004)." Journal of Marine Science: Research and Development **2**, 2. doi:10.4172/2155–9910.1000107

Fernández A., Arbelo M., Martín V. (2013). "Whales: No mass strandings since sonar ban." Nature 497:317–317. DOI: 10.1038/497317d.

Fewtrell, J.L. and McCauley, R.D. (2012). "Impact of air gun noise on the behaviour of marine fish and squid." Marine Pollution Bulletin **64(5)**, 984–993.

Finneran, J.J., Schlundt, C.E., Carder, D.A., Clark, J.A., Young, J.A., Gaspin, J.B. and Ridgway, S.H. (2000). "Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions." The Journal of the Acoustical Society of America **108(1)**, 417–431.

Finneran JJ., Carder DA., Schlundt CE., Dear RL. (2010). "Temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) exposed to intermittent tones." The Journal of the Acoustical Society of America **127,** 3267. DOI: 10.1121/1.3377052.

Gillespie, D., Dunn, C., Gordon, J., Claridge, D., Embling, C., and Boyd, I. (2009). "Field recordings of Gervais' beaked whales *Mesoplodon europaeus* from the Bahamas." The Journal of the Acoustical Society of America **125**, 3428–3433.

Gitschlag, G. and Herczeg, B.A. (1994). "Sea turtle observations at explosive removals of energy structures." Marine Fisheries Review **56 (2)**, 1–8.

Guerra, Á., González, Á.F., Pascual, S. and Dawe, E.G. (2011). "The giant squid Architeuthis: An emblematic invertebrate that can represent concern for the conservation of marine biodiversity." Biological Conservation **144 (7)**, 1989–1997.

Guerra, Á., González, Á.F., Rocha, F. (2004). "A review of records of giant squid in the northeastern Atlantic and severe injuries in *Architeuthis dux* stranded after acoustic exploration." ICES **29**, 1–17

Haun, J., Ryan, K., Portunato, N. (2008). "Marine Mammal Risk Mitigation using passive acoustic technologies." In: *New Trends for Environmental Monitoring Using Passive Systems, 2008*. IEEE, 1–5.

Hooker, S.K., Fahlman, A., Moore, M.J., Soto, N.A. de, Quirós, Y.B. de, Brubakk, A.O., Costa, D.P., Costidis, A.M., Dennison, S., Falke, K.J., Fernandez, A., Ferrigno, M., Fitz-Clarke, J.R., Garner, M.M., Houser, D.S., Jepson, P.D., Ketten, D.R., Kvadsheim, P.H., Madsen, P.T., Pollock, N.W., Rotstein, D.S., Rowles, T.K., Simmons, S.E., Bonn, W.V., Weathersby, P.K., Weise, M.J., Williams, T.M., Tyack, P.L. (2011). "Deadly diving? Physiological and behavioural management of decompression stress in diving mammals." Proceedings of the Royal Society B: Biological Sciences **279(1731)**, 1041–1050. doi:10.1098/rspb.2011.2088

Isojunno S. (2015). "Influence of natural factors and anthropogenic stressors on sperm whale foraging effort and success at high latitudes." PhD Thesis. University of St Andrews.

Jepson, P.D., Arbelo, M., Deaville, R., Patterson, I.A.P., Castro, P., Baker, J.R., Degollada, E., Ross, H.M., Herráez, P., Pocknell, A.M., Rodriguez, F., Howie, F.E., Espinosa, A., Reid, R.J., Jaber, J.R., Martin, V., Cunningham, A.A. and Fernández, A. (2003). "Gas-bubble lesions in stranded cetaceans. Was sonar responsible for a spate of whale deaths after an Atlantic military exercise?" Nature **425(6958)**, 575–576.

Ketten, D.R., Lien, J. and Todd, S. (1993). "Blast injury in humpback whale ears: evidence and implications." The Journal of the Acoustical Society of America **94(3)**, 1849–1850.

Kight, C.R. and Swaddle, J.P. (2011). "How and why environmental noise impacts animals: an integrative, mechanistic review." Ecology Letters **14(10)**, 1052–1061.

Klima, E., Gitschlag, G. and Renaud, M. (1988). "Impacts of the explosive removal of offshore petroleum platforms on sea turtles and dolphins." Marine Fisheries Review **50(3)**, 33–42.

Kujawa, S.G. and Liberman, M.C. (2009). "Adding insult to injury: cochlear nerve degeneration after «temporary» noise-induced hearing loss." Journal of Neuroscience **29(45)**,14077.

Kunc, H., McLaughlin, K. and Schmidt, R. (2016). "Aquatic noise pollution: implications for individuals, populations, and ecosystems." Proceedings of the Royal Society B: Biological Sciences **283**:20160839. DOI: 10.1098/rspb.2016.0839.

Lagardere, J.P. (1982). "Effects of noise on growth and reproduction of *Crangon crangon* in rearing tanks." Marine Biology **71**,177–185.

Lyamin, O., Rozhnov, V. and Mukhametov, L. (2015). "Cardiorespiratory responses to acoustic noise in belugas." Effects of Noise on Aquatic Life II. Popper, A.N., Hawkins, A. (Eds.). Springer New York, New York.

Lyamin, O., Korneva, S., Rozhnov, V. and Mukhametov, L. (2011). "Cardiorespiratory changes in beluga in response to acoustic noise." Doklady Biological Sciences **440(1)**, 275–278.

Marques, T.A, Thomas, L., Martin, S., Mellinger, D., Ward, J., Moretti, D., Harris, D., and Tyack, P. (2013). "Estimating animal population density using passive acoustics." Biological Reviews 88: 287-309.

Marshall L. 2012. *Statistical developments for understanding anthropogenic impacts on marine ecosystems*. PhDs Thesis. University of St Andrews.

Miller, B., Barlow, J., Calderan, S., Collins, K., Leaper, R., Olson, P., Ensor, P., Peel, D., Donnelly, D., Andrews-Goff, V., Olavarria, C., Owen, K., Rekdahl, M., Schmitt, N., Wadley, V., Gedamke, J., Gales, N. and Double, M. (2015). "Validating the reliability of passive acoustic localisation: a novel method for encountering rare and remote Antarctic blue whales." Endangered Species Research **26**:257–269. DOI: 10.3354/esr00642.

Miller, P.J.O., Kvadsheim, P.H., Lam, F.P.A., Tyack, P.L., Cure, C., DeRuiter, S.L., Kleivane, L., Sivle, L.D., van Ijsselmuide, S.P., Visser, F., Wensveen, P.J., von Benda-Beckmann, A.M., Martin Lopez, L.M., Narazaki, T., Hooker, S.K. (2015). "First indications that northern bottlenose whales are sensitive to behavioural disturbance from anthropogenic noise." Royal Society Open Science **2,** 140484–140484.

Miller PJO., Antunes RN., Wensveen PJ., Samarra FIP., Catarina Alves A., Tyack PL., Kvadsheim PH., Kleivane L., Lam F-PA., Ainslie MA., Thomas L. (2014). "Dose-response relationships for the onset of avoidance of sonar by free-ranging killer whales." The Journal of the Acoustical Society of America **135**:975–993.

Moretti D., Marques TA., Thomas L., DiMarzio N., Dilley A., Morrissey R., McCarthy E., Ward J., Jarvis S. (2010). "A dive counting density estimation method for Blainville's beaked whale (*Mesoplodon densirostris*) using a bottom-mounted hydrophone field as applied to a Mid-Frequency Active (MFA) sonar operation." Applied Acoustics **71**, 1036–1042. DOI: 10.1016/j.apacoust.2010.04.011.

Nieukirk SL., Mellinger DK., Moore SE., Klinck K., Dziak RP., Goslin J. (2012). "Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2009." The Journal of the Acoustical Society of America **131,** 1102–1112. DOI: 10.1121/1.3672648.

Parry, G.D., Gason, A. (2006). "The effect of seismic surveys on catch rates of rock lobsters in western Victoria, Australia." Fisheries Research **79**, 272–284.

Pirotta, E., Harwood, J., Thompson, P., New, L., Cheney, B., Arso, M., Hammond, P., Donovan, C. and Lusseau, D. (2015). "Predicting the effects of human developments on individual dolphins to understand potential long-term population consequences." Proceedings of the Royal Society B: Biological Sciences **282**:20152109. DOI: 10.1098/rspb.2015.2109.

Popper, A.N., Hawkins, A.D., Fay, R.R., Mann, D.A., Bartol, S., Carlson, T.J., Coombs, S., Ellison, W.T., Gentry, R.L., Halvorsen, M.B., Løkkeborg, S., Rogers, P.H., Southall, B.L., Zeddies, D.G., Tavolga, W.N. (2014). "Sound Exposure Guidelines". ASA S3/SC14 TR-2014 *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1*. pp. 33–51. Springer International Publishing. http://link.springer.com/10.1007/978–973–319–06659–2_7

National Marine Fisheries Service. (2016). *Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing. Underwater acoustic thresholds for onset of permanent and temporary threshold shifts.* U.S. Dept. of Commer., NOAA.

Reyes, C., (2016). "Population abundance of Blainville's and Cuvier´s beaked whales (*Mesoplodon densirostris* and *Ziphius cavirostris*) at El Hierro (Canary Islands)". Master thesis University of St Andrews (to be submitted in November 2016).

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., Wasser, S.K., Kraus, S.D. (2012). "Evidence that ship noise increases stress in right whales." Proceedings of the Royal Society B: Biological Sciences **279(1737)**, 2363–2368.

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W., Thomas, J., Tyack, P. (2007). "Exposure criteria to noise for marine mammals." Aquatic Mammals **33(4)**, 411–414.

Tougaard, J., Wright, A.J. and Madsen, P.T. (2015). "Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises." Marine Pollution Bulletin **90**, 196–208. doi:10.1016/j.marpolbul.2014.10.051

Tyack, P.L., Johnson, M., Aguilar de Soto, N., Sturlese, A. and Madsen, P.T.M. (2006) "Extreme diving of beaked whales." Journal of Experimental Biology **209**, 4238–4253.

Tyack, P.L., Zimmer, W.M.X., Moretti, D., Southall, B.L., Claridge, D.E., Durban, J.W., Clark, C.W., D'Amico, A., DiMarzio, N., Jarvis, S., McCarthy, E., Morrissey, R., Ward, J., Boyd, I.L. (2011). "Beaked whales respond to simulated and actual navy sonar." PLoS ONE **6**, e17009. doi:10.1371/journal.pone.0017009

von Benda-Beckmann, A.M., Aarts, G., Sertlek, O.H., Lucke, K., Verboom, W.C., Kastelein, R.A., Ketten, D.R., van Bemmelen, R., Lam, F.-P.A., Kirkwood, R.J., Ainslie, M.A., 2015. "Assessing the impact of underwater clearance of historical explosives on harbour porpoises (*Phocoena phocoena*) in the southern North Sea." Aquatic Mammals **41**, 503–523. doi:10.1578/AM.41.4.2015.503

Wensveen, P.J. (2016). "Detecting, assessing, and mitigating the effects of naval sonar on cetaceans." PhD thesis, School of Biology, University of St Andrews, UK

Weir, C.R. (2007). "Observations of marine turtles in relation to seismic airgun sound off Angola." Marine Turtle Newsletter **116**, 17−20.

Weis, J.S. (2014). "*Physiological, Developmental and Behavioral Effects of Marine Pollution*." Springer Netherlands. 452 pp.

Wilson, R. P., Culik, B., Danfeld, R., and Adelung, D. (1991). "People in Antarctica, how much do Adelie penguins, *Pygoscelis adeliae*, care?" Polar Biology **11**:363–370.

Wright, A.J., Aguilar de Soto, N., Baldwin, A.L., Bateson, M., Beale, C.M., Clark, C., Deak, T., Edwards, E.F., Fernández, A., Godinho, A., Hatch, L.T., Kakuschke, A., Lusseau, D., Martineau, D., Romero, M.L., Weilgart, L.S., Wintle, B.A., Notarbartolo-di-Sciara, G., Martin, V. (2007). "Are marine mammals stressed by anthropogenic noise?" International Journal of Comparative Psychology **20**, 274–316.

Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and Tyack, P. L. (2005). "Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*)." Journal of the Acoustic Society of America **117,** 3919–3927.