Mitigating, monitoring and assessing the effects of anthropogenic sound on beaked whales

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ABSTRACT

Certain anthropogenic sounds are widely believed to cause strandings of beaked whales, but their impacts on beaked whale populations are not known and methods for mitigating their effects are largely untested. The sound sources that have been coincident with beaked whale strandings are military, mid-frequency sonar (2-10kHz) and airgun arrays, both of which are used widely throughout the world for defence and geophysical exploration, respectively and for which alternative technologies are not readily available. Avoidance of beaked whale habitats is superficially a straightforward means of reducing the potential effects, but beaked whales are widely distributed and can be found in virtually all deep-water marine habitats that are free of ice. Some areas of high beaked whale abundance have been identified, but the geographic distribution is poorly known for most species. Beaked whales are both visually and acoustically difficult to detect. Commonly used mitigation measures (e.g. 'ramp-up' and 'detection-modification-avoidance') have not been assessed for their effectiveness. Surveys to detect population-level impacts would likely require many years of regular monitoring and for most areas where beaked whale strandings have occurred, there are no pre-exposure estimates of population sizes. Risk assessment models can be used to estimate the sound levels to which beaked whales might be exposed under a variety of scenarios, however, the lack of information on the causal mechanism for sound-related beaked whale strandings makes it difficult to identify exposure levels that would warrant mitigative actions. Controlled exposure experiments, which measure the behavioural responses of animals to fully characterised sound sources, may hold the greatest potential for understanding the behavioural responses of beaked whales to sound and for designing mitigation methods to avoid future impacts.

KEYWORDS: MONITORING; POPULATION ASSESSMENT; BEAKED WHALE; ACOUSTICS; NOISE; STRANDINGS; SURVEY-AERIAL; SURVEY-ACOUSTIC; SURVEY-VESSEL

INTRODUCTION

Recent observations of beaked whale strandings coincident with loud, anthropogenic sounds (e.g. Frantzis, 1998; Anon., 2001; Jepson *et al.*, 2003; Peterson, 2003) have focused attention on the potential impact of such sounds on beaked whale individuals and populations. This paper provides a brief overview of the technologies and methods available for monitoring and mitigating the effects of man-made sound on beaked whales. Four subject areas are covered: (1) methods to detect beaked whales; (2) methods to mitigate the potential impact of anthropogenic sound on beaked whales; (3) methods to monitor the impact of sound on beaked whale individuals and populations; and (4) methods of risk assessment. The efficacy of measures currently taken to mitigate the impacts of anthropogenic sounds on marine mammals are reviewed, focusing on two common sources of loud anthropogenic sound: military, mid-frequency sonar and airgun arrays used for seismic surveys.

BEAKED WHALE DETECTION METHODS

Some acoustic mitigation strategies are based on detecting marine mammals before they are exposed to potentially dangerous sound levels and either avoiding the mammals or modifying the sound sources. Current detection methods and some new technologies that may assist in detecting beaked whales in the future are reviewed in the Section.

Visual detection

Visual surveys for beaked whales are typically conducted from ships or aircraft. Of all cetaceans, beaked whales are among the most difficult to detect and identify, posing problems for both types of survey (Barlow *et al.*, 2006). Beaked whales dive for long periods of time and are at or near the surface for very short periods. For Cuvier's beaked whales (*Ziphius cavirostris*), the median dive time is 29min and the median surface time is 2min; for *Mesoplodon* beaked whales the corresponding times are 20min and 2.5min (Barlow, 1999). The probability of detecting most beaked whales is thus low even in the best survey conditions and drops rapidly in sub-optimal survey conditions.

On ship line-transect surveys, two observers typically search using 7×50 handheld or 25×150 pedestal-mounted binoculars and one observer/data recorder searches by naked eye as the ship travels along specified tracklines at approximately 10kts (18.5km hr^{-1}). Observers scan forward of the ship from the highest stable deck, often the flying bridge deck or top of the pilothouse, though occasionally the bridge wings are used on larger ships. From ships, beaked whales are detected only when they surface to breathe. The effective search width for beaked whales is typically 1-2km for observers using 25× binoculars in excellent or good sighting conditions (Barlow *et al.*, 2006, table 2). Accounting for both submerged animals and animals that are otherwise missed by the observers in excellent survey conditions, only 23% of Cuvier's beaked whales and 45% of *Mesoplodon* beaked whales are estimated to be seen on ship surveys if they are located directly on the survey trackline (Barlow, 1999). The encounter rate of beaked whales decreases by more than an order of magnitude as survey conditions deteriorate from Beaufort 1 sea state to sea state 5 (Barlow *et al.*, 2006, table 1). Most estimates of beaked whale density from ship surveys are based only on search effort in excellent (Beaufort 0-2) or excellent to good (Beaufort 0-4) survey conditions (Barlow *et al.*, 2006, table 2). The beaked whale sighting rates of experienced observers are approximately twice those of inexperienced observers (Barlow *et al.*, 2006).

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On aerial line-transect surveys, teams of 2-3 observers typically search without binoculars from an altitude of 600-1,000ft (183-305m) and at a speed of approximately 100kts (185km hr^{-1}). 'Bubble' side windows are typically used to allow direct downward visibility, and ideally, a 'belly' window is also used to improve downward visibility. Aerial observers can see beaked whales only when the whales are at or near the sea-surface (typically within 5m of the surface). During aerial surveys, the ability to see submerged animals is adversely affected by sea state and cloud cover (e.g. Forney *et al.*, 1991). Most estimates of beaked whale density from aerial surveys are based only on search effort during survey conditions of Beaufort sea state 0-4 (Barlow *et al.*, 2006, table 2). Accounting for animals that are not detected because they are diving, approximately 7% of Cuvier's beaked whales and 11% of *Mesoplodon* beaked whales would be seen on aerial surveys if they are located directly on the survey trackline (Barlow *et al.*, 2006). The fraction that would be seen decreases rapidly with distance from the trackline; the effective search width is typically only 250-500m (on each side of the aircraft) for aerial observers searching by naked eye in good to excellent sighting conditions (Barlow *et al.*, 2006, table 2).

Passive acoustic detection

Passive acoustic detection refers to the detection of animals by listening for the sounds that they produce. There has been a rapid growth in the application of passive acoustic detection and monitoring of marine mammals in the last decade (e.g. Clark and Fristrup, 1997; Leaper *et al.*, 2000; Watkins *et al.*, 2000; Charif *et al.*, 2001; Clark and Gagnon, 2002; Mellinger *et al.*, 2004; Nieukirk *et al.*, 2004). Cetacean sounds can be detected with towed hydrophone arrays, stationary hydrophones monitored from ships or from land, autonomous-recording sea-floor hydrophones or drifting radio-linked sonobuoys deployed and monitored from ships, aircraft or land. Each monitoring system has distinct advantages and disadvantages, and the optimal choice depends on the frequency structures of the sounds of interest, the depth at which animals produce sounds and the logistics of mitigation (a stationary hydrophone might be inappropriate for a moving sound source, and a sea-floor recorder is not appropriate for real-time monitoring). Acoustic localisation of cetaceans typically requires more than one hydrophone. A Directional Fixing and Ranging (DIFAR) sonobuoy can give a compass bearing to a low-frequency sound source (<2.5kHz) and two such buoys can be used to localise that source (Greene *et al.*, 2003). Long towed arrays (1-5km) with 16 or more elements can determine the bearing and distance to a sound source, but typically cannot resolve whether the source is to the left or the right of the array. Short towed arrays with two or more elements can also provide a bearing angle (again with the left/right ambiguity) and a sound source can be localised by the convergence of a series of bearing angles measured from different locations as the array is towed behind a ship (Leaper *et al.*, 1992).

Most cetacean species produce sounds and one advantage of acoustic detection methods over visual methods is that these sounds can often be detected when animals are submerged or out of range for visual observations. One disadvantage is that sound production is voluntary and many cetaceans may be silent for long periods of time. At present there are no reports of the relative incidence of sound production by beaked whales.

Species identification from vocalisations is easier for some cetacean species than others. Baleen whales, in particular, appear to make stereotypical calls that can be used to distinguish species (Thomson and Richardson, 1995) and, in some cases, populations (Stafford *et al.*, 2001; Mellinger and Barlow, 2003). Dolphin whistles are more variable and species identification from whistles is difficult, with 30-50% error rates in species classification (see review by Oswald *et al.*, 2003). Echolocation clicks can be used to identify sperm whales (*Physeter macrocephalus*) with certainty and frequency can be used to distinguish clicks made by porpoises and *Cephalorhynchus* spp. from other odontocetes (Au, 1993; Cranford and Amundin, 2004; Nakamura and Akamatsu, 2004).

All beaked whales are believed to produce echolocation clicks and some or all may also produce whistles (Dawson *et al.*, 1998; MacLeod and D'Amico, 2006). The larger beaked whales (*Hyperoodon* and *Berardius* spp.) are very vocal and their vocalisations have been frequently recorded using surface hydrophones (Hobson and Martin, 1996; Dawson *et al.*, 1998; Hooker and Whitehead, 2002). In contrast, there have been many unsuccessful attempts to record sounds from Cuvier's and *Mesoplodon* beaked whales using surface hydrophones (Dawson *et al.*, 1998; Barlow and Rankin, unpubl. data) and relatively few successes (Frantzis *et al.*, 2002). Recent studies using acoustic recorders attached to individual animals (Johnson *et al.*, 2004) have shown that Cuvier's and Blainville's (*M. densirostris*) beaked whales frequently produce echolocation clicks when diving, but only when they are several hundred metres below the surface. The tendency for these smaller beaked whales to produce sounds primarily at great depth may explain the difficulty researchers have had in recording them. Past experience with other species has shown that the likelihood of acoustic detection improves tremendously if one knows what to listen for, so we anticipate improvements in passive acoustic monitoring as we learn more about beaked whale vocalisations. The echolocation clicks of beaked whales appear to be more narrow-banded than those of many other species in the same frequency range (Dawson *et al.*, 1998; Johnson *et al.*, 2004) and therefore, may be easier to distinguish using electronic filtering methods (as has been done for porpoise clicks, Chappell *et al.*, 1996).

Active acoustic detection – sonar

Commercially available sonar has been used to monitor the underwater movements of marine mammals for research purposes (Papastavrou *et al.*, 1989; Watkins *et al.*, 1993) and more recently, active sonar systems have been designed specifically to detect and track marine mammals under water (Miller, 2004; Stein, 2004). Active sonar has an advantage over passive acoustic or visual survey methods because it does not rely on the animal producing sound or being visible at the surface. In practice, effective mitigation will require a high probability of beaked whale detection. However, high detection rates can result in unacceptably high levels of false detections (mistaking entrained air bubbles, fish, other whales, or other phenomena for the object of interest). This trade-off between correct detections and false detections is referred to as the Receiver Operating Characteristics (ROC). At present there are no published ROC data for sonar systems used to detect marine mammals. Target (or species) identification is also a potential problem for active sonar. Although signal processing can improve data interpretation, the return signal varies with the animal's orientation, volume of respiratory air spaces (which change with depth) and other factors. False detections may be too common to allow active sonar to be a practical mitigation tool.

The ability to detect and identify beaked whales is not the only parameter for assessing the use of active sonar. Since active sonar releases acoustic energy into the environment, it must also be assessed for possible adverse effects. The operating frequencies of sonar for detection of marine mammals will likely fall within the hearing range of many species of small cetaceans, pinnipeds and fish. If animals can hear the sound source, they may react to it and that reaction may be beneficial if the animals move away from a potentially harmful sound. However, any sound within an animal's hearing range has the potential for causing auditory damage if received levels are too high. The use of active sonar for whale detection has been strongly opposed by some environmental groups and has resulted in threatened or actual litigation in the US.

New detection technologies

A variety of technologies (radar, infrared and hyper-spectral imagery, satellite imagery, and Light Detection and Ranging (LIDAR)) may hold promise for detecting beaked whales. LIDAR is a raster-scanned laser light source and receiver used from aircraft to 'see' subsurface objects up to depths of 30m or more and can reveal objects that would not be visible in ambient sunlight. Recent tests of radar systems showed that humpback whales (*Megaptera novaeangliae*) could be detected at distances that were equal to or greater than the distance at which these whales can be seen. Given the difficulty in detecting beaked whales using visual and passive acoustic methods, these new technologies should be evaluated. However, these methods only detect whales that are at or near the sea-surface, so the long, deep dives and short surface times of beaked whales will pose similar problems as those associated with visual survey. None of these technologies have been evaluated for detection of beaked whales.

Probabilities of visually detecting beaked whales for typical mitigation/monitoring efforts

The probabilities of detecting beaked whales have not been previously estimated for typical mitigation monitoring. For Cuvier's and *Mesoplodon* beaked whale species, detection probabilities have been estimated for research surveys utilising three observers and two 25× binoculars in excellent conditions (Beaufort 0-2 during daylight hours). These estimated values from research surveys are compared to the expected detection probabilities for mitigation monitoring. Mitigation associated with seismic surveys (Appendices 1 and 2) was chosen because the monitoring protocols for this type of survey are well defined. The average detection probabilities for mitigation efforts on seismic surveys would be less than on research surveys since: (1) seismic surveys are also conducted at night; (2) seismic surveys are not limited to calm sea conditions; (3) mitigation observers are primarily searching with unaided eyes and 7× binoculars; and (4) typically only one or possibly two observers are searching.

A crude estimate of the detection probabilities for beaked whales for typical mitigation monitoring can be made by reducing the probability estimates for research surveys (0.23 to 0.45 respectively for Cuvier's and *Mesoplodon* beaked whales, Barlow, 1999) by several independent factors to account for the differences in survey efficiency. These factors include a roughly two-fold reduction in efficiency because beaked whales cannot be seen at night, a two- to four-fold reduction to account for searches in rougher sea states (detection probabilities decrease by a factor of two for every increment in Beaufort sea state – Barlow *et al.*, 2006), a three-fold reduction to account for the image size difference in 7× vs 25× binoculars and a two-fold reduction to account for the lower number of observers used in mitigation surveys. Therefore, the overall probability of detecting beaked whales is likely to be 24 to 48 times lower for mitigation monitoring than for research vessel surveys. Based on this, mitigation monitoring detects fewer than 2% of beaked whales if the animals are directly in the path of the ship. This approach does not include factors to account for training or experience in identifying beaked whales, but Barlow *et al.* (2006) showed that experience can account for a two-fold difference in the likelihood of detecting beaked whales. The probability of detecting a beaked whale with 7× binoculars drops to zero approximately 1km from a ship.

MITIGATION METHODS

Removal or modification of the sound source

The simplest mitigation method would be to discontinue use of sound sources that pose a potential risk to beaked whales; however, this approach is not feasible. Mid-frequency sonar is widely used by the navies of the world as a critical part of their anti-submarine defence and it is unlikely that any would willingly abandon sonar use. Airguns are widely used in seismic surveys by the marine geophysical exploration industry to locate potential offshore deposits of oil and natural gas. Airguns are also used in a variety of research applications, including the detection and mapping of offshore fault zones. It is unrealistic to think that industrial and research use of airguns will stop in the near future.

While complete cessation of sonar operations might pose unacceptable risks to naval personnel and vessels, restricted or modified use may be acceptable in some circumstances. Sonar is used mostly during training and equipment testing, rather than in combat. One option might be the regional or seasonal closures of areas with high beaked whale population densities for all training and test exercises (see below). Another option might be to increase the use of simulations for sonar training in place of ship-based training. However, *in situ* training is considered critical to maintaining a combat-ready fleet, so it is unlikely that all training will ever be shifted to simulators.

Other acceptable modifications might include changes in the frequency or amplitude characteristics of the sonar signals. If adverse effects seen in beaked whales are caused by a narrow range of frequencies or by a particular waveform, other signal types might work just as well for locating submarines. Improvements in the processing of the received signals might enable sonar to achieve current performance standards, with reduced source levels. However, advances in signal processing would not necessarily lead to reduced source levels because there would still be an advantage in using both improved signal processing and the maximum achievable source levels.

Low Frequency Active (LFA) sonar (operating below 2kHz) is being developed by several nations to address the need to increase the range at which sonar can detect modern, quiet, diesel-fuelled submarines. There have been no reported beaked whale strandings associated with LFA sonar alone; however, the beaked whale stranding in Greece in 1996 occurred in conjunction with testing of a sonar possessing both low frequency (300Hz, 228dB re:1μPa) and typical mid-frequency (3kHz, 226dB re:1μPa) sound sources (D'Amico and Verboom, 1998). LFA sonar has been the subject of considerable attention because its low frequency sounds travel greater distances than sounds from mid-frequency sonar, but the potential of LFA sonar to cause strandings or produce other adverse effects on beaked whales is still uncertain. If the impact on beaked whales is frequency-specific, LFA sonar might have fewer adverse effects than mid-range sonar.

Another anthropogenic sound of potential concern for beaked whales is produced by airguns used for seismic exploration. The inferred association between airgun use and beaked whale strandings (Peterson, 2003) is based largely on one stranding of two Cuvier's beaked whales in the Gulf of California. In that instance, the ship that was towing the airgun array was also using two active sonar systems, including a sub-bottom profiler with a frequency (3.5kHz) similar to military mid-frequency sonar but with a 20dB lower source level (204dB re:1μPa) and a much shorter ping duration (1-4msec) (Federal Register, 2003). Regardless of what caused that particular stranding event, airguns produce some of the loudest manmade sounds in the ocean, with source levels of up to 259dB re:1μPa (Richardson *et al.*, 1995) and the potential for causing harm to marine mammals has long been recognised. Alternative sources of acoustic or vibrational energy for imaging geological structures have been substituted for airguns in some cases, but are not widely used. Again, improved signal processing methods may allow for use of lower source levels for airguns without loss of performance.

Avoiding beaked whale habitat

Another mitigation option is simply to avoid beaked whale habitat. Beaked whales occur in virtually all deep-water habitats that are not ice-covered (MacLeod *et al.*, 2006). Previous studies of sightings and strandings (Waring *et al.*, 2001; D'Amico *et al.*, 2003; MacLeod, 2004) identified continental slopes, canyons and seamounts as areas of particularly high beaked whale abundance. MacLeod (2004) presented lists of known 'hot spots' or areas with high densities of beaked whales. Ferguson *et al.* (2006) show that the habitat preferences of beaked whales in the Northeast Atlantic Ocean and Mediterranean Sea appear to differ from those in the eastern tropical Pacific, where beaked whales are found in more pelagic waters, far from continental slopes. While there is little doubt that 'hot spots' of high beaked whale density do occur, the areas identified to date are based on limited data and caution is recommended in extrapolating habitat preferences to unsurveyed areas (Ferguson *et al.*, 2006). Consideration should also be given to the potential sound impacts on other marine animals if sound production is shifted away from beaked whale habitat; for example, the densities of dolphins and baleen whales are often much higher in shelf waters where beaked whale densities are low.

Ramp-up procedures

Perhaps the most widely used mitigation method is 'ramp-up' or 'soft start'; the stepwise increase of the sound-level over a period of several minutes or hours, to enable animals to detect the sounds at low levels and presumably, move away before harmful effects occur. This is practical in some cases (for example, air gun arrays, see Appendices 1 and 2), but not in others (such as tactical use of sonar in anti-submarine combat). Ramp-up mitigation is based on the assumption that animals will locate the source of the low-level sound and will react appropriately to avoid exposure. However, the effectiveness of this mitigation method has not yet been tested (Stone, 2003). The potential remains that ramp-up may not have the desired effect, and may even create greater risk by causing animals to approach the sound-source. Another premise of ramp-up mitigation is that when a sound-source is at its maximum amplitude, animals that are newly exposed to the sound by relocation of the sound source will experience a gradual ramp-up as it approaches. Although the theory seems sensible, the sound-related beaked whale strandings in the Bahamas (Anon., 2001) occurred with moving sound sources that had been active for some time.

Detection of beaked whales and modification of sound-producing activities

Many mitigation plans include a strategy for detecting marine mammals (visually or acoustically) and modifying activities to avoid the detected animals, decrease amplitude, or turn off the sound source if the animals are within a critical distance. These methods depend on the detection of animals before they are exposed to potentially dangerous levels of sound.

Mitigation plans for seismic surveys or experimental sound sources usually require searching by ship-based marine mammal observers during daylight hours and in some cases, at night using nightvision devices (Appendix 1). Typically, mitigation observers search using the naked eye and 7× binoculars during daylight hours. Mitigation plans often provide no guidelines for 'acceptable' survey conditions and in some cases, searching may continue in Beaufort sea states of 7 or 8 (Appendix 1). In some mitigation plans, such as those for the ship-shock trials of the destroyer USS *John Paul Jones* in the Pacific Ocean, aerial observations made in front of a moving vessel may augment visual surveys from a ship (Department of the Navy, 1994). Given the difficulty in detecting and identifying beaked whales using even experienced observers in optimal conditions (see above), mitigation observers from either ships or aircraft will likely detect only a small fraction of the animals that are within their range of vision.

Passive acoustic detection has been used in some mitigation plans. Sonobuoys dropped from aircraft were used to detect whales during the *John Paul Jones* ship-shock trials in the Pacific Ocean and resulted in several detections of baleen whales. A towed hydrophone array was used experimentally in a recent seismic test (Appendix 1), but no marine mammals were acoustically detected during this short experiment.

Active sonar has been used to detect marine mammals as part of the mitigation plan for the Surveillance Towed Array Sensor System (SURTASS) LFA sonar, and active sonar could potentially be used in other mitigation contexts to detect marine mammals. The Environmental Impact Statement for SURTASS LFA (Department of the Navy, 2001) and Johnson (2004) describe the design, tested effectiveness and usage of active sonar in mitigation.

Currently, none of the available detection methods (visual search and passive acoustic monitoring) has a high probability of detecting and identifying beaked whales. Improvements in passive acoustic detection methods are anticipated, but the tendency for smaller beaked whales to only make sounds at depth may limit the degree to which detection distances can be improved, at least with surface hydrophones.

Sound screening procedures

Mitigation measures for stationary sound sources such as pile-driving or explosives include the use of bubble screens or material screens that impede sound propagation from its source (Vagle, 2003). For typically mobile sources, such as ship sonars and airgun arrays, this form of mitigation is unlikely to be an option.

Alerting stimuli and alarms

Alarm signals have been proposed as a means of moving animals away from a potentially dangerous situation. Acoustic Deterrent Devices (ADDs or 'pingers') are low-amplitude sound sources (<150dB re:1μP) that are commonly used on gillnets to reduce cetacean bycatch. Acoustic Harassment Devices (AHDs) are higher amplitude sound sources (>180dB re:1μP) typically used to keep seals and sea lions away from aquaculture pens, fish ladders and other locations where they could cause damage to resources or property. ADDs have been shown to be effective at reducing gillnet bycatch of harbour porpoises (*Phocoena phocoena*) (Kraus *et al.*, 1997; Gearin *et al.*, 2000) and other cetaceans species (Barlow and Cameron, 2003); however, the mechanism by which they work is not clear (Kraus *et al.*, 1997). The sound from ADDs appears to be aversive to many cetaceans (Anderson *et al.*, 2001), thus the difference between 'deterrent' and 'harassment' devices may be artificial. Since California-based drift gillnet vessels began to use pingers in 1996 no beaked whales have been observed entangled in nets with pingers (Carretta *et al.*, 2005), whereas, 26 beaked whales were observed caught in nets from 1991-95 (Julian and Beeson, 1998).

To evaluate the effectiveness of an alarm signal, it will be necessary to assess the type of alarm response elicited and its likelihood of reducing risk. Some responses to alarms may not reduce the risk of harm, as Nowacek *et al.* (2004) showed, when the behavioural response of right whales (*Eubalaena* spp.) to an alarm signal (reduced diving and increased surface time) probably increased their vulnerability to vessel collisions. It should be noted that the risks associated with vessel collisions may be completely different to those associated with sonar.

MONITORING THE IMPACT OF SOUND ON BEAKED WHALES

In general, monitoring for impacts of sound on beaked whales has received less emphasis than mitigation measures to prevent impacts. Although it is clearly better to prevent impacts, the efficacy of all current mitigation methods remains untested. It is therefore important to develop monitoring tools to directly evaluate impacts when they occur.

Surveys for dead or injured whales

The most direct method of monitoring beaked whale injury or death is to conduct surveys to detect dead or injured whales during and after exposure to a sound source. To date, all beaked whale strandings associated with anthropogenic sound have been detected by chance, without dedicated search efforts. Instead of relying on accidental detections, ship or aerial surveys could be used to detect dead or injured whales at sea and aerial or ground-based surveys could be used to detect stranded whales onshore. Whales are likely to be identified as injured only if their surface behaviour is grossly changed, so there are some limitations to the effectiveness of this approach, but those limitations may be minor relative to the advantages of prompt detection. Such surveys have been used before, for example in the *John Paul Jones* ship shock trials (Department of the Navy, 1994). The merit of directed survey for dead or injured animals would depend on the probabilities of mortality or injury occurring and being detected, the survey effort needed to effectively cover an area of concern and its cost. Direct impact assessment by detecting dead and injured whales is best for measuring the impact on individuals, but cannot easily be used to infer population-level impacts, unless the population sizes and structures are already well known. Implementation of such surveys may require a public education component, since several recent proposals to monitor for mortality and injury have been construed as anticipation that mortality would certainly occur, leading to public opposition and cancellation of the activities that had otherwise been deemed low risk.

Uncertainties in directly monitoring impacts include the probability that a dead whale will float and if it does, the probability that it will strand on a beach. The probability that a dead beaked whale will float is at least partially dependent on the depth at which it dies. Experiments with freshly stranded beaked whales and buoyancy modelling may help resolve these uncertainties.

Special methods for the collection, preservation and analysis of specimen materials are required for stranded dead and injured beaked whales associated with anthropogenic sounds (Jepson *et al.*, 2003). As hypotheses are developed about the possible causal mechanisms of the observed physiological effects, new collection and analytical methods may be needed when stranded beaked whales are detected. At present, few investigators are sufficiently trained to perform these and such response personnel are needed to mount effective stranding responses.

Surveys to detect changes in abundance

Ship or aerial surveys can be used to estimate the abundance of beaked whales (Barlow *et al.*, 2006) and such estimates, if repeated over time, can be used to estimate changes in beaked whale abundance. A significant, population-wide decline in abundance may indicate anthropogenic impacts from sound or other factors (such as bycatch). This approach does not hold much promise in the short term due to the lack of precision in estimates of beaked whale population sizes. Taylor and Gerrodette (1993) discussed the problems associated with detecting changes in population size for rarely seen species and showed that they could become extinct before a statistically significant decline is detected. The coefficients of variations in beaked whale abundance estimates from a single survey are typically high (40-100%, Barlow *et al.*, 2006, table 2). This lack of precision means that many years of annual surveys would be required to detect any change. The lack of any baseline abundance information for the vast majority of the world's oceans adds further to the problem of detecting changes.

Individual identification and mark-recapture studies

Many species of beaked whale are well marked with scars on their bodies or nicks in their dorsal and caudal fins and individuals can be recognised from those marks. Most individual identification studies are based on photographs; however, individuals can also be identified genetically. Individual identification studies have proven to be a valuable tool for the study of many cetacean populations (e.g. Hammond *et al.*, 1990; Calambokidis and Barlow, 2004) and can be used to determine residency patterns, population size, mortality rates and reproductive parameters. Individual identification studies benefit most from a continuous series of observations over many years. However, valuable information can be gathered over shorter time periods and abundance estimates can often be made with two seasons of fieldwork (typically separated by a year to allow random mixing of the marked animals within the population).

The only long-term, photo-identification study of Cuvier's and *Mesoplodon* beaked whales is based on Abaco Island in the area of the Bahamas where a beaked whale mass-stranding coincided with a Navy sonar exercise in March 2000 (Anon., 2001). This study began prior to the strandings and has since continued (Claridge and Balcomb, 1993; 1995; Claridge *et al.*, 2001). A complete analysis of the data from this study may provide a more precise estimate of the population size than would line-transect surveys. Continued studies in the area might provide a unique insight into the long-term effects of sound on marine mammals. A similar long-term study of northern bottlenose whales, *H. ampullatus* (Whitehead *et al.*, 1997; Gowans *et al.*, 2000) also provides behavioural and ecological information that is relevant to monitoring sound impacts on beaked whales. Additional opportunities for long-term photo-identification studies exist in other locations and should be explored.

Controlled exposure experiments

One way to monitor the effect of sound on beaked whales would be to deliberately expose whales to a known sound source while studying their behaviour. Such controlled exposure experiments (CEEs) are amongst the most powerful tools for monitoring the responses of animals to sound (Tyack *et al.*, 2004). Changes in behaviour in response to a sound are difficult to detect from opportunistic observations because uncontrolled variables often mask any response. However, CEEs may put some animals at risk and individuals and organisations have previously objected to and attempted to block such experiments and objections are likely to be again voiced in the future.

The behavioural responses of beaked whales to sound are difficult to directly observe because of their long dive times. Recently, acoustic data-logging tags (Burgess *et al.*, 1998; Johnson and Tyack, 2003) have been developed that allow measurement of the sound levels received by individual animals. Depth and detailed behaviour (orientation, roll, pitch, acceleration, fluke stroke-rate, sound production, etc.) can also be recorded. The deployment of such tags on beaked whales is a critical first step in measuring underwater behavioural responses and hence enabling CEEs with beaked whales. CEEs without data-logging tags are already possible, but provide much less information. The logistical problems of reliably finding and tagging beaked whales with appropriate instruments need to be resolved. Recently, researchers have succeeded in tagging Cuvier's and *Mesoplodon* beaked whales (Baird *et al.*, 2004; Johnson *et al.*, 2004) and as expertise is gained in using acoustic data-logging tags, direct CEE assessment of beaked whale response to sound may become possible.

RISK ASSESSMENT MODELS

Risk assessment is a powerful but under-used tool in conservation biology (Harwood, 2000). Risk assessment models can be used to evaluate the possible exposure of marine mammals to specific sound sources, given different sound production scenarios and sound propagation conditions. The number of marine mammals exposed to any anthropogenic sound source and their levels of exposure will depend on the characteristics of the source, the local abundance of marine mammals, their diving behaviour, their distance from the source and the local sound propagation characteristics. Simple risk models assume a cylindrical or spherical sound propagation and assume that all individuals are at the depth of highest sound levels. More complicated models use simulations to reduce the number of simplifying assumptions. At least two such models have been developed and used to model risks from underwater sound. The first is the Acoustic Integration Model (AIM) developed by Marine Acoustics Inc. and now marketed in a variety of versions (Ellison *et al.*, 1999). The second is the Effects of Sound on the Marine Environment (ESME) programme, sponsored by the US Office of Naval Research, which is attempting to bring together state-of-the-art science in all the relevant fields of information to create an integrated mathematical model of risk. The ESME model accounts for uncertainty within its components and thus allows sensitivity analyses for any of the parameters.

Risk assessment models are, themselves, valuable tools in assessing research/data needs. For example, one might be faced with the choice of investing a million dollars and three years in improving the accuracy of the sound field prediction in reverberant environments only to find that it only alters the outcome by 1%, whereas a much smaller investment in improved beaked whale density estimates for the same site might produce a much larger difference in the estimated outcome of the model. Model sensitivity therefore becomes a good guide in how to best allocate limited resources to achieve the greatest gains in certainty.

Understanding the sound exposure experienced by a diving animal is critical to risk assessment. However, until we have improved population data and improved understanding of the physical, physiological, and/or behavioural mechanisms by which sound is adversely affecting beaked whales, we will not be able to confidently assess risk.

CONCLUSIONS

We have briefly reviewed a range of options for mitigating, monitoring and assessing the potential impacts of human acoustic activities on beaked whales. Clearly, this is extremely complex. Beaked whales are difficult to detect by any available method and given their wide distribution, are difficult to avoid. The effectiveness of all mitigation methods that are currently in use has not been established for beaked whales. The number of animals exposed and the sound exposure levels can be estimated with risk assessment models, but actual risk to populations or individuals cannot be confidently estimated without knowing the causal relationship between anthropogenic sounds and beaked whale strandings. We hope that by focusing attention on the problems associated with mitigating and monitoring the effects of sound on beaked whales, research will be directed to solve these problems.

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REFERENCES

Anderson, R.C., Barlow, J. and Bowles, A.E. 2001. Pingers are acoustic harassment devices. Information document ICRAM/AHD/INFO 3 for the ICRAM Workshop on Interactions between Dolphins and

Fisheries in the Mediterranean: Evaluation of Mitigation Alternatives, 4-5 May 2001, Rome, Italy. [Available from: Jay Barlow, SWFSC, PO Box 271, La Jolla, CA 92038, USA].

Anon. 2001. Joint interim report on the Bahamas marine mammal stranding event of 15-16 March 2000 (December 2001). NOAA unpublished report. 59pp. [Available at *http://www.nmfs.noaa.gov/prot_res/overview/Interim_Bahamas_Report.pdf*].

Au, W.W.L. (ed.). 1993. *The Sonar of Dolphins*. Springer-Verlag, New York. 277pp.

Baird, R.W., McSweeney, D.J., Ligon, A.D. and Webster, D.L. 2004. Tagging feasibility and diving of Cuvier's beaked whales (*Ziphius cavirostirs*) and Blainville's beaked whales (*Mesoplodon densirostris*) in Hawaii. SWFSC Admin. Report prepared under Order No. AB133F-03-SE-0986 to the Hawaii Wildlife Fund, Volcano, HI. 15pp. [Available from: *swfsc.nmfs.noaa.gov*].

Barlow, J. 1999. Trackline detection probability for long-diving whales. pp. 209-21. *In:* G.W. Garner, S.C. Amstrup, J.L. Laake, B.F.J. Manly, L.L. McDonald and D.G. Robertson (eds.) *Marine Mammal Survey and Assessment Methods*. Balkema Press, Rotterdam, Netherlands. 287pp.

Barlow, J. and Cameron, G.A. 2003. Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. *Mar. Mammal Sci.* 19(2):265-83.

Barlow, J., Ferguson, M., Perrin, W.F., Ballance, L., Gerrodette, T., Joyce, G., MacLeod, C.D., Mullin, K., Palka, D.L. and Waring, G. 2006. Abundance and densities of beaked and bottlenose whales (family Ziphiidae). *J. Cetacean Res. Manage.* 7(3):This volume.

Burgess, W.C., Tyack, P.L., Le Boeuf, B.J. and Costa, D.P. 1998. A programmable acoustic recording tag and first results from free-ranging northern elephant seals. *Deep Sea Research* II(45):1327-51.

Calambokidis, J. and Barlow, J. 2004. Abundance of blue and humpback whales in the eastern North Pacific estimated by capture-recapture and line-transect methods. *Mar. Mammal Sci.* 20(1):63-85.

Carretta, J.V., Price, T., Petersen, D. and Read, R. 2005. Estimates of marine mammal, sea turtle, and seabird mortality in the California drift gillnet fishery for swordfish and thresher shark, 1996-2002. *Mar. Fish. Rev.* 66(2):21-30.

Chappell, O.P., Leaper, R. and Gordon, J. 1996. Development and performance of an automated harbour porpoise click detector. *Rep. int. Whal. Commn* 46:587-94.

Charif, R.A., Clapham, P.J. and Clark, C.W. 2001. Acoustic detections of singing humpback whales in deep waters off the British Isles. *Mar. Mammal Sci.* 17:751-68.

Claridge, D.E. and Balcomb, K.C. 1993. In search of marine mammals. *Bahamas Naturalist* 7(1):11-7.

Claridge, D.E. and Balcomb, K.C. 1995. Photo-identification of dense-beaked whales (*Mesoplodon densirostris*) in the north-eastern Bahamas. Abstracts of the 11th Biennial Conference on the Biology of Marine Mammals, Orlando, December 1995, p.23. [Available from *www.marinemammalogy.org*].

Claridge, D.E., Parsons, K.M., Durban, J.W., Ellifrit, D.K. and Balcomb, K.C. 2001. Harem society identified in dense-beaked whales (*Mesoplodon densirostris*) from the Bahamas. Abstracts of the 14th Biennial Conference on Marine Mammals, Vancouver, British Columbia. [Available from *www.marinemammalogy.org*].

Clark, C.W. and Fristrup, K.M. 1997. Whales '95: a combined visual and acoustic survey of blue and fin whales off southern California. *Rep. int. Whal. Commn* 47:583-600.

Clark, C.W. and Gagnon, G.C. 2002. Low-frequency vocal behaviours of baleen whales in the North Atlantic: insights from IUSS detections, locations, and tracking from 1992 to 1996. *Journal of Underwater Acoustics* 52(3).

Cranford, T.W. and Amundin, M. 2004. Biosonar pulse production in odontocetes: the state of our knowledge. pp. 27-35. *In:* J.A. Thomas, C.F. Moss and M. Vater (eds.) *Echolocation in Bats and Dolphins*. University of Chicago Press, Chicago, IL.

D'Amico, A. and Verboom, W. 1998. Summary record and report of the SACLANTCEN Bioacoustics Panel, La Spezia, Italy 15-17 June 1998. SACLANT Undersea Research Centre. 128pp. [Available at: *http://enterprise.spawar.navy.mil/nepa/whales/bioacoust.cfm*].

D'Amico, A., Bergamasco, A., Zanasca, P., Carniel, S., Nancini, E., Portunato, N., Teloni, V., Mori, C. and Barbanti, R. 2003. Qualitative correlation of marine mammals with physical and biological parameters in the Ligurian Sea. *IEEE J. Ocean. Engr.* 28(1):29-43.

Dawson, S., Barlow, J. and Ljungblad, D. 1998. Sounds recorded from Baird's beaked whale, *Berardius bairdii*. *Mar. Mammal Sci.* 14(2):335-44.

Department of the Navy. 1994. Marine mammal protection/mitigation and results summary for the shock trial of the USS *John Paul Jones* (DDG 53). Prepared by Commander, Naval Air Warfare Center, Weapons Division 521, 9th St., Point Magu, CA 93042-5001. Available from the Office of Protected Resources, National Marine Fisheries Service, 1335 East-West Highway, Silver Springs, MD 20910-3226. 26pp.

Department of the Navy. 2001. Final overseas environmental impact statement and environmental impact statement for surveillance towed array sensor system low frequency alive (SURTASS LFA) sonar (2 volumes). Chief of Naval Operations, Washington DC, January 2001. [Available at *http://www.surtass-lfa-eis.com/*].

Ellison, W.T., Weixel.K and Clark, C.W. 1999. An acoustic integration model (AIM) for assessing the impact of underwater noise on marine wildlife. *J. Acoust. Soc. Am.* 106(4 part 2):2250. [Invited paper, October 1999].

Federal Register. 2003. Taking marine mammals incidental to specified activities: oceanographic surveys at the Storegga Slide, Norwegian Sea. *Federal Register Notice* 68(177):53714-20. [September 12, 2003].

Ferguson, M.C., Barlow, J., Reilly, S.B. and Gerrodette, T. 2006. Predicting Cuvier's (*Ziphius cavirostris*) and *Mesoplodon* beaked whale population density from habitat characteristics in the eastern tropical Pacific Ocean. *J. Cetacean Res. Manage.* 7(3):This volume.

Forney, K.A., Hanan, D.A. and Barlow, J. 1991. Detecting trends in harbor porpoise abundance from aerial surveys using analysis of covariance. *Fish. Bull.* 89(3):367-77.

Frantzis, A. 1998. Does acoustic testing strand whales? *Nature* 392(6671):29.

Frantzis, A., Goold, J.C., Skarsoulis, E.K., Taroudakis, M.I. and Kandia, V. 2002. Clicks from Cuvier's beaked whales, *Ziphius cavirositris* (L.). *J. Acoust. Soc. Am.* 112(1):34-7.

Gearin, P.J., Gosho, M.E., Laake, J., Cooke, L., Delong, R.L. and Hughes, K.M. 2000. Experimental testing of acoustic alarms (pingers) to reduce bycatch of harbour porpoise, *Phocoena phocoena*, in the state of Washington. *J. Cetacean Res. Manage.* 2(1):1-10.

Gowans, S., Whitehead, H., Arch, J.K. and Hooker, S.K. 2000. Population size and residency patterns of northern bottlenose whales (*Hyperoodon ampullatus*) using the Gully, Nova Scotia. *J. Cetacean Res. Manage.* 2(3):201-10.

Greene, C.R., Jr., McLennan, M.W., Norman, R.G., McDonald, T.L. and Richardson, J.W. 2003. Using DIFAR sensors to locate calling bowhead whales and monitor their migration. Abstract, 15th Biennial Conference on the Biology of Marine Mammals, Greensboro NC, 14 – 19 December, 2003. [Available from the Society for Marine Mammalogy at *www.marinemammalogy.org*].

Hammond, P.S., Mizroch, S.A. and Donovan, G.P. (eds.). 1990. *Report of the International Whaling Commission (Special Issue 12). Individual Recognition of Cetaceans: Use of Photo-Identification and Other Techniques to Estimate Population Parameters*. International Whaling Commission, Cambridge, UK. [vi]+440pp.

Harwood, J. 2000. Risk assessment and decision analysis in conservation. *Biol. Conserv.* 95:219-26.

Hobson, R.P. and Martin, A.R. 1996. Behaviour and dive times of Arnoux's beaked whales, *Berardius arnouxii*, at narrow leads in fast ice. *Can. J. Zool.* 74:388-93.

Hooker, S.K. and Whitehead, H. 2002. Click characteristics of northern bottlenose whales (*Hyperoodon ampullatus*). *Mar. Mammal Sci.* 18(1):69-80.

Jepson, P.D., Arbelo, M., Deaville, R., Patterson, I.A.P., Castro, P., Baker, J.R., Degollada, E., Ross, H.M., Herraez, P., Pocknell, A.M., Rodriguez, F., Howiell, F.E., Espinosa, A., Reid, R.J., Jaber, J.R., Martin, V., Cunningham, A.A. and Fernández, A. 2003. Gas-bubble lesions in stranded animals: Was sonar responsible for a spate of whale deaths after an Atlantic military exercise? *Nature* 425(6958):575-76.

Johnson, J.S. 2004. High frequency marine mammal monitoring active sonar system. *ECS Newsletter* 42(Special Issue):63-5. Proceedings of the Workshop on Active Sonar and Cetaceans held at the European Ceatcean Society's 17th Annual Conference, Auditorio Alfredo Kraus, Las Palmas, Gran Canaria, 8th March 2003.

Johnson, M. and Tyack, P.L. 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *IEEE J. Ocean. Engr.* 28:3-12.

Johnson, M., Madsen, P.T., Zimmer, W.M.X., Aguilar de Soto, N. and Tyack, P.L. 2004. Beaked whales echolocate on prey. *Proc. R. Soc. Lond. Ser. B.* Supplement 6(271(S6)):383-6.

Julian, F. and Beeson, M. 1998. Estimates of marine mammal, turtle, and seabird mortality for two California gillnet fisheries: 1990-1995. *Fish. Bull.* 96:271-84.

Kraus, S.D., Read, A.J., Solow, A., Baldwin, K., Spradlin, T., Anderson, E. and Williamson, J. 1997. Acoustic alarms reduce porpoise mortality. *Nature* 388:525.

Leaper, R., Chappell, O. and Gordon, J. 1992. The development of practical techniques for surveying sperm whale populations acoustically. *Rep. int. Whal. Commn* 42:549-60.

Leaper, R., Gillespie, D. and Papastavrou, V. 2000. Results of passive acoustic surveys for odontocetes in the Southern Ocean. *J. Cetacean Res. Manage.* 2(3):187-96.

MacLeod, C.D. 2004. Insights into the determination of beaked whale 'hotspots' through the development of a global database. *ECS Newsletter* 42(Special Issue):70-2. Proceedings of the Workshop on Active Sonar and Cetaceans held at the European Ceatcean Society's 17th Annual Conference, Auditorio Alfredo Kraus, Las Palmas, Gran Canaria, 8th March 2003.

MacLeod, C.D. and D'Amico, A. 2006. A review of beaked whale behaviour and ecology in relation to assessing and mitigating impacts of anthropogenic noise. *J. Cetacean Res. Manage.* 7(3):This volume.

MacLeod, C.D., Perrin, W.F., Pitman, R., Barlow, J., Ballance, L., D'Amico, A., Gerrodette, T., Joyce, G., Mullin, K.D., Palka, D.L. and Waring, G.T. 2006. Known and inferred distributions of beaked whale species (Cetacea: Ziphiidae). *J. Cetacean Res. Manage.* 7(3):This volume.

Mellinger, D.K. and Barlow, J. 2003. Future directions for acoustic marine mammal surveys: stock assessment and habitat use. NOAA OAR Special Report, NOAA/PMEL Contribution 2557. 37pp. [Available from NOAA Pacific Environmental Laboratory].

Mellinger, D.K., Stafford, K.M. and Fox, C.G. 2004. Seasonal occurrence of sperm whale (*Physeter macrocephalus*) sounds in the Gulf of Alaska, 1999-2001. *Mar. Mammal Sci.* 21(1):48-62.

Miller, J.W. 2004. Website information on FarSounder sonar. See *www.farsounder.com*.

Nakamura, K. and Akamatsu, T. 2004. Comparison of click characteristics among odontocete species. pp. 36-9. *In:* J.A. Thomas, C.F. Moss and M. Vater (eds.) *Echolocation in Bats and Dolphins*. University of Chicago Press, Chicago, IL.

Nieukirk, S.L., Stafford, K.M., Mellinger, D.K., Dziak, R.P. and Fox, C.G. 2004. Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic. *J. Acoust. Soc. Am.* 115(4):1832-43.

Nowacek, D.P., Johnson, M.P. and Tyak, P.L. 2004. North Atlantic right whales *Eubalaena glacialis* ignore ships but respond to alerting stimuli. *Proc. Royal Soc., Biol. Sci.* 271(1536):227-31.

Oswald, J.N., Barlow, J. and Norris, T.F. 2003. Acoustic identification of nine delphinid species in the eastern tropical Pacific Ocean. *Mar. Mammal Sci.* 19(1):20-37.

Papastavrou, V., Smith, S.C. and Whitehead, H. 1989. Diving behaviour of the sperm whale, *Physeter macrocephalus*, off the Galapogos Islands. *Can. J. Zool.* 67(4):839-46.

Peterson, G. 2003. Whales beach seismic research. *Geotimes* Jan 2003:8-9. [Available at *www.geotimes.org/jan03/NNwhales.html*].

Richardson, W.J., Greene Jr, C.R., Malme, C.I. and Thomson, D.H. 1995. *Marine Mammals and Noise*. Academic Press, San Diego. 576pp.

Stafford, K.M., Nieukirk, S.L. and Fox, C.G. 2001. Geographic and seasonal variation of blue whale calls in the North Pacific. *J. Cetacean Res. Manage.* 3(1):65-76.

Stein, P.J. 2004. Website information on HFM3 and IMATS sonars. See *www.scisol.com*.

Stone, C.J. 2003. The effects of seismic activity on marine mammals in UK waters, 1998-2000. JNC Report 323, Joint Nature Conservation Committee, Dunnet House, 7 Thistle Place, Aberdeen, Scotland. 77pp.

Taylor, B.L. and Gerrodette, T. 1993. The uses of statistical power in conservation biology: the vaquita and northern spotted owl. *Conserv. Biol.* 7(3):489-500.

Thomson, T.J. and Richardson, W.J. 1995. Marine mammal sounds. p. 576. *In:* W.J. Richardson, C.R. Greene, C.I. Malme and D.H. Thomson (eds.) *Marine Mammals and Noise*. Academic Press, San Diego. 587pp.

Tyack, P., Gordon, J. and Thompson, D. 2004. Controlled exposure experiments to determine the effects of noise on large marine mammals. *Mar. Technol. Soc. J.* 37(4):41-53.

Vagle, S. 2003. On the impact of underwater pile-driving noise on marine life. Report prepared for the Canadian Coast Guard, Department of Fisheries and Oceans, Canada (unpublished). 41pp. [Available from *www.dfo-mpo.gc.ca*].

Waring, G.T., Hamazaki, T., Sheenan, D., Wood, G. and Baker, S. 2001. Characterization of beaked whale (Ziphiidae) and sperm whale (*Physeter macrocephalus*) summer habitat in shelf-edge and deeper waters off the northeast US. *Mar. Mammal Sci.* 17(4):703-17.

Watkins, W.A., Dahler, M.A., Fristrup, K.M., Howald, T.J. and Notarbartolo-di-Sciara, G. 1993. Sperm whales tagged with transponders and tracked underwater by sonar. *Mar. Mammal Sci.* 9(1):55-67.

Watkins, W.A., Daher, M.A., Reppucci, G.M., George, J.E., Martin, D.L., DiMarzio, N.A. and Gannon, D.P. 2000. Seasonality and distribution of whale calls in the North Pacific. *Oceanography* 13:62-7.

Whitehead, H., Faucher, A., Gowans, S. and McCarrey, S. 1997. Status of the northern bottlenose whale, *Hyperoodon ampullatus*, in the Gully, Nova Scotia. *Can. Field-Nat.* 111:287-92.

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Appendix 1

SEISMIC MITIGATION AND MONITORING ON ACADEMIC RESEARCH SURVEYS

Airguns produce some of the loudest sounds made by humans (Richardson *et al*., 1995) and some of the most powerful airgun arrays are used in geophysical research on the structure of the earth's crust. Marine mammal monitoring and mitigation reports are available for four seismic surveys and tests conducted in 2003 by the Lamont-Doherty Earth Observatory on the research vessel *Maurice Ewing* (LGL, 2003; Smultea and Holst, 2003; MacLean and Haley, 2004 and Holst, 2004). The monitoring and mitigation methods used on these four projects and the results of their monitoring efforts are briefly reviewed below.

All the mitigation and monitoring described here were associated with the use of airgun arrays configured with 2-20 airguns. Following guidance from the US National Marine Fisheries Service (NMFS), it was assumed that some marine mammals could be 'taken by harassment' (disturbed) if exposed to a received sound level of greater than 160dB re:1μPa. The potential for injury occurs at a higher sound level; the NMFS standard at that time was that cetaceans and pinnipeds should not be exposed to pulsed sounds at received levels greater than 180dB and 190dB, respectively. For the projects described here, 'precautionary safety radii' were defined as 1.5× times the distance at which sounds were predicted to diminish to 180dB for cetaceans and 190dB for pinnipeds. The factor of 1.5× was introduced to account for uncertainty in estimating safe distances via a propagation model that was, at the time, not yet validated by empirical measurements. The safety radius used for cetaceans (1.5× the predicted 180dB radii) varied from as low as 75m (with two airguns) to as high as 1,350m (with 20 airguns).

The mitigation plan for each survey included: (1) changing vessel heading and speed, when feasible, to avoid marine mammals ahead of the ship; (2) 'ramp-ups' whenever arrays with more than two guns started firing after a period without operation; and (3) 'power-downs' (turning off the array) whenever marine mammals were detected within, or about to enter the applicable safety radius. In general, if all airguns were shut down for an extended period at night, airgun operations did not resume until daylight. Marine mammal monitoring was also part of the mitigation plan and was critical to mitigation strategies (1) and (3) above.

Monitoring was normally the responsibility of three biological observers, who were trained to identify marine mammals and sea turtles. Typically, when the array was active during daylight hours, two observers searched with 7×50 binoculars and with naked eyes, while the third observer rested. Given the limited ability to sight marine mammals at night even when night vision devices (NVDs) were used, observers did not search at night except prior to and during ramp-ups; at those times, they searched with 3rd generation, 3× NVDs. Tests on one cruise (Holst, 2004) indicated that three white milk jugs tied together were generally visible out to 50-65m, but were only visible to one of three observers at 150m (on a bright night in Beaufort 4 conditions). During night periods when the airguns were active, bridge crew watched for marine mammals and sea turtles near the vessel as part of their normal watch duties. One marine mammal observer was on-call incase the bridge crew saw a marine mammal at night. One project (LGL, 2003) had eight observers (extras were aboard for another project) and two 25×150 *Big-Eye* binoculars. On that project, daytime monitoring was done by four observers, two searching with 25× binoculars and two searching with 7×50 binoculars and naked eyes and there were no night time airgun activities.

Table A1 gives the hours of monitoring effort when the airgun arrays were active (including power-up time), stratified by Beaufort sea state. Marine mammal sightings when the arrays were active are summarised in Table A2. The mitigation and monitoring reports also detail the monitoring effort and marine mammal sightings during transit to the study area and at other times that the array was not active. During night time operations, no marine mammals were seen by the observers or reported to the observers by bridge crew.

Passive acoustic monitoring was attempted in the Gulf of Mexico project (LGL, 2003). The Seamap Cetacean Monitoring System (Seamap, 2002) consisted of a towed hydrophone array capable of detecting signals between 8Hz and 24kHz. One person aurally monitored signals and visually monitored spectrographs. Monitoring occurred for 32hrs, mostly when the array was not firing. Three visual sightings were made during periods of acoustic monitoring, but no marine mammals were detected acoustically.

Table A1

Hours of monitoring effort by marine mammal observers when airgun arrays were active (including ramp-up periods) stratified by Beaufort sea state. Average Beaufort is a time-weighted average.

Project area	Beaufort sea state 0	1	2	3	4	5	6	7	8	Average Beaufort	Reference	Total hours
Northern Gulf of Mexico	0.0	0.0	8.8	7.8	0.8	0.0	0.0	0.0	0.0	2.5	LGL (2003)	17.4
Hess Deep/eastern tropical Pacific	0.5	0.0	0.0	13.3	38.0	38.8	8.4	0.0	0.0	4.4	Smultea and Holst (2003)	99.1
Storegga Slide/Norway	0.5	8.7	25.2	33.2	56.7	59.6	61.8	18.3	1.9	4.5	MacLean and Haley (2004)	265.9
Mid-Atlantic Ridge	0.0	0.0	0.0	1.3	6.0	7.2	7.7	0.1	0.0	5.0	Holst (2004)	22.4

Table A2

Total monitoring effort and marine mammal sightings made when airguns were active (including ramp-up periods). Animal actions are relative to the vessel, but are not necessarily reactions to the vessel or airgun array. Airguns were powered down in response to marine mammal sightings in five instances. Beaufort sea state for sightings off Norway from LGL (B. Hayley, pers. comm.).

Project area	Monitoring (hrs)	Species	Group size	Date (dd/mm)	Distance (m)	Beaufort sea-state	Animal action	Array power down?
Northern Gulf of Mexico	17.4	Dwarf sperm whale	2	30/05	5,000	2	Dive	No
		Bottlenose dolphin	8	02/06	1,125	3	Swim away	No
Hess Deep/eastern tropical Pacific	99.1	Unidentified beaked whale (probable)	1	17/07	1,000	4	Breaching	Yes
Storegga Slide/Norway	265.9	Fin whale	1	01/09	3,306	3	Swim away	No
		Unidentified whale	3	01/09	2,074	3	Swim away	No
		Unidentified whale	2	01/09	3,306	3	Swim away	No
		Minke whale	2	01/09	3,306	3	Swim away	No
		Minke whale	2	01/09	3,306	3	Swim away	No
		Unidentified beaked whale	2	01/09	2,074	3	Swim away	No
		Unidentified dolphin	10	01/09	1,519	3	Milling	No
		Minke whale	1	04/09	533	4	Swim toward	No
		Minke whale	1	05/09	847	5	Swim parallel	No
		Minke whale	1	05/09	200	5	Swim toward	Yes
		Unidentified whale	1	05/09	2,074	5	Swim away	No
		Long-finned pilot whale	7	06/09	200	6	Swim toward	Yes
		Long-finned pilot whale	25	06/09	277	5	Swim parallel	Yes
		Long-finned pilot whale	15	06/09	4,500	6	Swim toward	No
		Unidentified whale	1	07/09	4,813	4	Swim parallel	No
		Unidentified whale	3	07/09	847	4	Swim toward	Yes
		Unidentified whale	1	11/09	654	2	Swim away	No
Mid-Atlantic Ridge	22.4	None	n/a	n/a	n/a	n/a	n/a	n/a

REFERENCES

Holst, M. 2004. Marine mammal monitoring during Lamont-Doherty Earth Observatory's TAG seismic study in the mid-Atlantic Ocean, October-November 2003. LGL Report TA2822-21 from LGL Ltd., King City, Ontario, for Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, and National Marine Fishery Service, Solvery Spring, MD. 42pp.

LGL. 2003. Marine mammal monitoring during Lamont-Doherty Earth Observatory's acoustic calibration study in the northern Gulf of Mexico, 2003. LGL Report TA2822-12 from LGL Ltd., King City, Ontario, for Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, and National Marine Fishery Service, Solvery Spring, MD. 76pp.

MacLean, S.A. and Haley, B. 2004. Marine mammal monitoring during Lamont-Doherty Earth Observatory's seismic study in the Storegga Slide area of the Norwegian Sea, August-September, 2003. LGL Report TA2822-20 from LGL Ltd., King City, Ontario, for Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, and National Marine Fishery Service, Solvery Spring, MD. 59pp.

Richardson, W.J., Greene Jr, C.R., Malme, C.I. and Thomson, D.H. 1995. *Marine Mammals and Noise*. Academic Press, San Diego. 576pp.

Seamap 2002. Cetacean monitoring system. Technical overview. Revision 1.0. CMS 420. Doc. #10-32-0010. Prepared by Seamap Pte, Ltd., Singapore.

Smultea, M.A. and Holst, M. 2003. Marine mammal monitoring during Lamon-Doherty Earyh Observatory's seismic study in the Hess Deep area of the eastern equatorial tropical Pacific, July 2003. LGL Report TA2822-16 from LGL Ltd., King City, Ontario, for Lamony-Doherty Earth Observatory, Columbia University, Palisades, NY, and National Marine Fisheries Service, Silver Spring, MD. 68pp.

Appendix 2

SEISMIC MITIGATION AND MONITORING FOR OIL AND GAS EXPLORATION

Airguns are in common use worldwide for oil and natural gas exploration. Most commercial users of airguns have instituted some form of mitigation to reduce the potential for marine mammal injury. Pierson *et al*. (1998) and Stone (2003) have summarised the mitigation methods used by the seismic exploration industry and a very brief synopsis of these methods based on those papers is detailed below.

Mitigation measures for seismic surveys are not required by any international agreement, but are required by national laws in the waters of many countries (Pierson *et al.*, 1998). Commonly, mitigation measures required under national laws include closures of certain regions, or a combination of regional and seasonal closures to protect areas of known high density of marine mammals, or to protect migrating marine mammals. Examples include seasonal limitations to protect migrating gray whales in US waters off California, a temporary moratorium on seismic exploration in the 'Gully' off eastern Canada, a closure of nearshore waters to night time seismic surveys in Italy and many others. Even where no national closed areas are established, permit applications are often reviewed on a case-by-case basis and season/area limitations are sometimes applied. Countries requiring permits for seismic exploration include the US, Canada, the UK, Italy, Norway and Brazil.

Other commonly applied mitigation measures include 'ramp-up' (also known as 'soft start' in the UK and elsewhere) and the use of safety zones in conjunction with real-time monitoring. 'Ramp-up' criteria may be based on the rate at which output is increased (such as 6dB $\min^{-1}$ above 160dB in the US), or may be based on absolute time duration (a slow build-up over 20 minutes in the UK). A safety zone is defined as a region where there is at least some potential for temporary auditory damage in marine mammals and may range 100-1,000m from an airgun array, depending on the source levels and propagation conditions. This safety zone may be monitored prior to and during ramp-up, or may be monitored during any seismic operation. In their guidelines for minimising disturbance to marine mammals, the UK Joint Nature Conservation Committee sets this safety zone at 500m and recommends surveys beginning at least 30mins before the use of seismic sources and during ramp-up (Stone, 2003). In some cases an airgun array is powered down if a marine mammal is seen within the safety zone, but an exception is sometimes made for marine mammals, especially pinnipeds, that appear to voluntarily approach the source. The application of safety zones requires some form of real-time monitoring, typically visual shipboard monitoring. Observers generally search by naked eye or 7×50 binoculars. If monitoring occurs only during and prior to ramp-up, one observer may be required, but for longer periods, two or three observers alternate to avoid fatigue. Many of the companies operating seismic survey vessels have instituted voluntary standards for ramp-up, safety zones and visual monitoring in countries where mitigation is not required.

Stone (2003) conducted the largest study to date on the results of marine mammal monitoring efforts in conjunction with seismic surveys in UK and adjacent waters. Her analysis included almost 45,000 hours of visual monitoring in 1998-2000 and the detection of 1,652 groups of marine mammals. She found that the effect of airguns varied between species. Sighting rates were generally lower and detection distances greater for small odontocetes when the airguns were firing, compared to period when they were silent and small cetaceans showed the most conspicuous avoidance response. Killer whales (*Orcinus orca*) were seen further from the airguns when they were firing and pilot whales (*Globicephala*, spp.) oriented away from the survey vessel. Sperm whales showed no apparent changes. Baleen whales showed fewer responses to airguns than small cetaceans, but were found at greater distances when airguns were firing compared to control periods when airguns were silent. Only three of the 1,652 sightings included beaked whales (two with northern bottlenose whales and one with a Sowerby's beaked whale (*M.bidens*)) and consequently no analyses were presented for beaked whale. Thirty-minute, pre-shot surveys were completed in approximately 80% of the 5,343 recorded startups, with much higher compliance when a dedicated marine mammal observer was aboard (Stone, 2003, table 17). Marine mammals were detected in the safety zone during 27 of these pre-shot surveys, and start-up was delayed only 14 times (and only when a dedicated marine mammal observer was aboard) (Stone, 2003, table 17).

REFERENCES

Pierson, M.O., Wagner, J.P., Langford, V., Birnie, P. and Tasker, M.L. 1998. Protection from, and mitigation of, the potential effects of seismic exploration on marine mammals. Presented to the Seismic and Marine Mammals Workshop, London, 23-25 June 1998. [Available at *smub-st-and.ac.uk/seismic/docs/7.doc*].

Stone, C.J. 2003. The effects of seismic activity on marine mammals in UK waters, 1998-2000. JNC Report 323, Joint Nature Conservation Committee, Dunnet House, 7 Thistle Place, Aberdeen, Scotland. 77pp.

Appendix 3

MITIGATION AND MONITORING FOR NAVY OPERATIONS

All US Naval operations and exercises are planned using available data on beaked whale sightings and strandings, as well as the most recent predictive habitat correlative studies. Single-ship sonar exercises use dedicated observers to search for marine mammals from the ship's bridge. Watchstanders receive special training, including methods for detecting, identifying and reporting marine mammals. All vessels are equipped with 7× handheld binoculars and 20× *BigEye* binoculars, although the 20× binoculars are not usually used on bridge watches due to the narrow field of view of these higher power binoculars. All ships have standardised marine mammal and sea turtle reporting forms and observers are strongly encouraged to complete forms for all sightings. If marine mammals are sighted prior to planned sonar use, sonar usage is deferred until the area is determined to be clear of marine mammals. For multi-ship exercises, aerial and shipboard surveys are conducted in the area prior to the exercise. The commander of the exercise must determine that the area is 'clear' prior to initiating sonar usage. If marine mammals or sea turtles are detected in the area during the exercise, the sonar is shut down and not resumed until the area is determined to be clear. Use of active sonar requires prior deployment and checking of the passive receiving array. During that time, a minimum of 2 mins, the sonar operator monitors the passive listening arrays for marine mammal sounds. Training of Navy sonar operators has traditionally included the identification of marine mammal sounds and other 'biologics'. Current training is providing a greater emphasis on the understanding of marine mammal sounds and their significance. Active sonar is not turned on if marine mammal sounds are detected on the passive arrays prior to active sonar operations.