Position Paper 13

The effects of anthropogenic sound on marine mammals

A draft research strategy

June 2008
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- **Strategy:** Identifying and prioritising emergent disciplinary and interdisciplinary marine scientific issues of strategic European importance, initiating analysis and studies (where relevant, in close association with the European Commission) in order to develop a European strategy for marine research;
- **Synergy:** Fostering European added value to component national programmes, facilitating access and shared use of national marine research facilities, and promoting synergy with international programmes and organisations.
The effects of anthropogenic sound on marine mammals
A draft research strategy

This report is based on the activities and proceedings of an Expert Group on anthropogenic sound and marine mammals convened at the joint Marine Board-ESF and National Science Foundation (US) Workshop at Tubney House on October 4-8 2005 in Oxford, with logistical and financial support of the Marine Board-ESF.

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Foreword

The effect of anthropogenic sound on marine mammals has become a serious concern both for marine and maritime research and for economic activities. On one side, marine mammals rely largely on sound for their communication and organisation; on the other side, use of sound is an essential element of remote sensing methods in geophysics, sedimentology, oceanography and ecosystem studies. Furthermore, many human ocean-based activities such as oil exploitation, fisheries or defence activities, rely on emission of sounds of various frequencies and intensity. Marine mammals are a very important trophic and symbolic component of the marine biotope and because they are under threat, their protection has become an ecological issue. This concern has triggered a number of analyses of the issue of anthropogenic sounds and their impacts on marine mammals. Consequently, interaction between anthropogenic sound and marine mammals was identified as a key subject both by the Marine Board-ESF and the US National Science Foundation (NSF), which lead to a joint workshop on this topic. This workshop on “Marine Mammals and Acoustic Geo-Surveying Techniques”, hosted by the Marine Board in London on September 27th 2004, gathered 34 international experts, including science managers, engineers, geologists and biologists. Thirteen countries were represented, 11 participants being from North America (10 US and one Canadian) and 23 from Europe (Denmark, Germany, Ireland, Italy, Norway, The Netherlands and UK). A list of participants can be found in Annex II. The joint Marine Board and NSF workshop, co-chaired by Howard Roe (Director, National Oceanography Centre, Southampton, representing the Marine Board-ESF) and Mike Purdy (Director, Lamont Doherty Earth Observatory, Columbia University, representing NSF), addressed the impacts of acoustic geo-surveying techniques on marine mammals, including legal and practical implications for survey work.

The concept for this workshop was first proposed during the October 2003 Marine Board Plenary Meeting, and subsequently developed from discussions between the Marine Board and NSF. The timing was linked to the U.S. Marine Mammal Commission workshop in London 28th-30th September 2004, to facilitate participation at both (see Vos and Reeves [2006] for a full report of the U.S. Marine Mammal Commission workshop). The outcomes of these coupled workshops reach the same consensus: interaction between anthropogenic sound and marine mammals is a complex problem, as the effects of anthropogenic sound on marine mammals depend on many aspects, such as intensity and frequency of sounds, marine mammal species and their age, environmental conditions, etc. In addition, the physiological effects are not clearly understood. Thus, a scientific research strategy was clearly needed.

To follow up on recommendations of these workshops and to build on the momentum generated, it was agreed that a smaller joint Marine Board and NSF Expert Group would be convened to ultimately produce a Position Paper based partly on the workshop proceedings. This international Expert Group, chaired by Ian Boyd from the Sea Mammal Research Unit (SMRU – University of St...
Andrews) UK, further worked on establishing the outline of a much needed scientific research strategy. This would also allow the further elaboration of two of the key recommendations made by the 2004 Marine Board and NSF workshop participants, namely (i) establish some mechanism to allow better co-ordination of research between the US and Europe, ultimately leading to jointly funded research programmes between the two; and (ii) establish database(s) to enhance the sharing of data: US and European data must be made compatible.

The resulting Marine Board Expert Group was convened to meet at Tubney House on October 4-8 2005 in Oxford, with financial support of the Marine Board. The participants at the workshop are listed in Annex II. The report presented here describes an outline of a research strategy following the Expert Group’s efforts on the subject.

The main recommendation put forward in this report is to use a four-step analytical risk framework process adapted to the issue of marine mammals and anthropogenic sound to assess and identify priority research topics for reducing uncertainty. Such a risk framework includes: (i) hazard identification; (ii) characterizing exposure to the hazard; (iii) characterizing dose-response relationships; and (iv) risk characterization, typically feeding into a risk management step.

The risk assessment framework presented in this report is illustrated by focussing on the breakdown of three of the identified high-level research questions: (i) how can we reduce the risk posed by sonars to beaked whales; (ii) what are the effects of seismic surveys on individual marine mammals and populations; and (iii) what is the interaction between shipping traffic noise and baleen whales? The analysis has only expanded three of the key questions to illustrate the range of possible sub-questions that could form the basis of a research effort to undertake a formal risk assessment. Additional work is required to carry out the same process with the other important questions. To construct a full risk assessment, it is necessary to be able to make all the linkages between issues from sound production, through behaviour change, effects on life function, to impacts on vital rates and, by implication, the effects on populations. In particular, there is a need to improve knowledge of how effects on life function influence vital rates.

The Marine Board would like to thank the Expert Group Chair, Dr. Ian Boyd, and its expert participants, whose efforts resulted in this proposal for a research strategy in the field of interactions between anthropogenic sound and marine mammals.

Lars Horn and Niamh Connolly
Chairman and Executive Secretary, Marine Board-ESF
In some parts of the world the next two decades will probably see increasing levels of offshore industrial development and this will almost certainly lead to increased amounts of noise pollution in the oceans. Added to this, there is a great deal of speculation about whether current or future levels of anthropogenic sound are likely to be harmful to marine life. Some people advocate banning or curtailing some forms of activity and many of these people cite the potential sensitivity of marine mammals to anthropogenic sound as the reason for their concern. A few incidents involving the stranding of cetaceans in proximity to some sources of anthropogenic sound have brought this opinion into sharp relief. This position has been accompanied by some speculation about possible effects of anthropogenic sound on marine mammals that moves well beyond the knowledge available from current data and information.

Marine mammals could be one of the more sensitive groups of marine species because some species have a highly developed auditory system and use sound actively for feeding and for social communication. It is also known that some marine mammal populations are vulnerable to the effects of habitat loss or reduced survival and reproductive rate. Marine mammals have also become totems of environmental awareness and sustainability and this has resulted in a controversial stand-off between environmental groups and those who are responsible for producing sound in the oceans.

The problem faced by society is that many economically important activities are at risk because of a lack of information about the effects of anthropogenic sound on marine mammals. The Precautionary Principle has probably achieved customary status in international maritime legislation where the marine environment is involved, which means that the Precautionary Principle is likely to be applied even if it is not specifically stated. This also probably means that it is no longer satisfactory for users of the oceans to ask for evidence of the effects of some activities before they take action to mitigate these effects. Precautionary regulation is leading to considerable burdens being placed upon future development in some areas, but implementation is patchy. This patchy implementation is evident when one considers the different levels of regulation placed on the oil and gas industry compared with those imposed on the fishing industry. The report presented here brings forward a view from the marine mammal specialists within the scientific community about the research effort that is needed to assess the effects of anthropogenic sound upon marine mammals.

The test of a research strategy is whether funding organisations use it to provide an underpinning rationale for investing in research. Since the workshop that resulted in this report took place, two new research initiatives have been developed. Both initiatives involve multi-stakeholder collaborations because, as recognised in this report, the biological problems associated with investigating the effects of anthropogenic sound on marine life are so large that probably no single organisation is capable of funding the research effort. In one case, a consortium of oil and gas companies has built a fund of more than $25 million to investigate the effects of sound on marine life (see www.soundandmarinelife.org) and in the other case, the US Navy, assisted by other funders that also includes the oil and gas industry Sound and Marine Life Program, have sponsored a sound playback experiment on beaked whales. These initiatives reflect a serious intent on the part of organisations that actively emit sound into the oceans to address current environmental concerns. In both these cases, the research strategy in the report presented here has helped to focus their research effort on the principal research questions and approaches.

The report is a consensus of views from across the community of active researchers in the field of marine mammals. Where there are such controversial issues a consensus is often difficult to achieve. I am grateful to all those involved for entering into this initiative in a spirit of cooperation and for not allowing the debate to become polarised to such an extent that it undermined the outcome. I am also very grateful to the Marine Board of the European Science Foundation for sponsoring the workshop and for endorsing the emerging research strategy. I hope that others will find the research strategy presented here to be a useful reference for a long time into the future.
Marine mammals have always been a flagship group in awareness campaigns to protect the marine environment from the effects of human encroachment. This is because of their status as one of the most visible features of the marine fauna, their high public profile and their likely sensitivity to changes in the ecology of the oceans, including anthropogenic effects. Directed harvesting of marine mammals has declined but pollution and habitat loss are increasingly affecting marine mammals, often in ways that are difficult to observe directly. Marine mammals thus have a symbolic status as a bellwether of the extent to which marine ecosystems are being managed in a sustainable way.

Marine mammals are complex organisms embedded in complex ecosystems and environments. These factors mean that measurement and prediction of marine mammal responses to human presence in the marine environment is not a case of examining simple cause and effect scenarios. Instead, approaches using basic research need to be used to provide sufficient fundamental knowledge about distribution, abundance, behaviour, physiology and population dynamics to recognise the presence of likely anthropogenic impacts on these species. This will enable provision of timely advice about ways in which human impacts on marine mammals can be minimised.

Consequently, there is a need to pursue a vision of future management of marine resources where the expansion of human activities will be accompanied by a sound understanding of the risks and appropriate tools to mitigate those risks. Marine mammals are a particularly important feature of the marine environment to which this vision should be applied.
Why is sound an issue?

There is a high level of concern about the potential impacts of anthropogenic sound on marine fauna. Awareness of this issue has been heightened by a number of recent cetacean stranding events coincident with exposure to anthropogenic sound. Concern has centred upon marine mammals because they rely on sound as a major source of social communication and environmental information and for that reason have a very developed auditory receptor system. Consequently, anthropogenic sound may affect them in a number of different ways, and these effects may be felt at both the individual and population level.

In response to this, debates on the issues have led to numerous reports on how anthropogenic sound may affect marine mammals (NRC 2003 and 2005; Southall 2005 and see Annex I). Most of these debates and reports have acknowledged that the current level of scientific understanding is insufficient to allow construction of robust advice about the potential impacts of anthropogenic sound. Most reports have also drawn up high-level recommendations for research that is deemed necessary to address the question of where, when and what effects are occurring, and also how to mitigate any resulting impacts. However, most of these recommendations have emerged from discussions concerned principally with describing and managing the effects of anthropogenic sound. To date, there has been no structured analysis of the full research challenge that this presents.

The arguments about the issue of how and why anthropogenic sounds may affect marine mammals have become highly polarised. This has come about partly because of differing points of view about the level of precaution that needs to be adopted in the face of high scientific uncertainty\(^1\). Economic and social pressures responsible for the introduction of more anthropogenic sound into the marine environment are important underlying drivers of this process. Reduction in current production of anthropogenic sound could result in financial and opportunity costs to society, and this has created a need for new knowledge about the effects of anthropogenic sound on marine mammals.

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Objectives of this report

Our knowledge of the importance of anthropogenic sound to marine mammals has increased rapidly in recent years, mainly as a result of directed research emerging because of current concerns. This report provides a view of research that is most needed in future to address the issues concerning marine mammals and anthropogenic sound. The report starts from the position that there is a need to address all aspects of the importance of sound for marine mammals, and proceeds to develop a protocol for narrowing the focus to address specific issues. The reason for this approach is to ensure that scientific activities that may underlie all, or most, issues concerning the effects of anthropogenic sound on marine mammals, are flagged and prioritised appropriately.

Nevertheless, there is recognition in the structure of the research strategy presented here that investigations of fundamental scientific issues are open-ended in their scope and extent. The report attempts to balance the need to address these issues with the need to produce results that have greatest relevance to current information needs and knowledge gaps.

The report also attempts to reflect the complexity and scale of the scientific challenge. Implicit within the report is a need for a change in the approach taken towards the organisation, management and funding of research. Long-term investment will be needed in research, infrastructure and personnel, together with a focussed approach to creating inter-disciplinary, inter-institutional and international research teams.

The kinds of problems being addressed in the research strategy presented are complex because the observed, or inferred, effects of anthropogenic sound on marine mammals may result from many interacting causes. Therefore, marine mammals are themselves complex transducers of information received from their environment. A key message of this report is that it is unlikely that a small number of focussed experiments will provide the information necessary to solve most of the major concerns. Instead, one must rely upon an accumulation of evidence combined with a process of objective assessment of this evidence through periodic independent review. Recent efforts have focussed upon a review phase in this process (see Cox et al. 2006; Southall et al. 2007 and other literature cited in Annex I); there is now a need to achieve a rapid improvement in the state of knowledge by undertaking new research that is focussed on specific questions of high priority. This requires concerted, coordinated action across many expert groups within the scientific community.

Some of the stakeholders responsible for introducing sound into the marine environment have shown willingness to engage in addressing the uncertainty that surrounds current scientific understanding. This is particularly evident by their funding of research projects that address their specific needs. The research strategy presented in this report should help to connect the efforts and investments made by different groups working independently in this field.

To date, a major component missing from much of the debate surrounding the effects of anthropogenic sound on marine mammals is coordinated action from the scientific community, independent of the other stakeholders. Consequently, this report sets out to:

(i) Define a strategic framework for future research;
(ii) Provide guidance about prioritisation of research;
(iii) Suggest a process of implementation.

This report is also designed to advise stakeholders about the structure of the research effort that is required to address most of the major issues concerning the effects of anthropogenic sound on marine mammals. It does not specifically recognise the special interests of particular stakeholder groups; rather, it suggests ways that stakeholder groups may wish to contribute to the development of a research effort that could allow a range of stakeholders to benefit from the investments made by others.
Strategic approach

The authors start from the position that a focussed effort is required to define and reduce the risk presented to marine mammals by anthropogenic sound. In this case, risk can be defined by the probability of disturbance or injury that could affect the viability of individuals or populations.

So that prioritisation can be undertaken based upon a set of objective criteria, the approach adopted in this report has been to assess priorities under a risk assessment framework. This approach has not been adopted in the past by any of the groups considering where research effort should be directed. The risk framework adopted here includes:

(i) Hazard identification
(ii) Characterizing exposure to the hazard
(iii) Characterizing dose-response relationships
(iv) Risk characterization
(v) Risk management

The authors have assumed that some form of quantification is usually required in each of the steps (i) through to (iv) above, in order to establish appropriate measures to manage the risk, while also recognising that the risk assessment framework can be operated using qualitative information.

Research questions that emerged over the past few years have been assessed. A rationale is developed to help prioritise these questions and to develop a set of approaches that could be used to help answer these questions.
Sources of sound and hazards to marine mammals

Most human activities in the marine environment generate sound that has the potential to affect marine mammals. Many features of the marine environment are responsible for producing sound, including many natural factors such as wave action, rainfall and biological sources including fish, crustaceans and marine mammals themselves. Anthropogenic sources of sound include shipping, dredging, pile driving, seismic exploration, and a variety of sonars (both civil and military). The latter include fish-finders and depth profilers that are present in some form on a majority of vessels, as well as more specialized bottom profilers.

The assessment of what constitutes a hazard to marine mammals is to an extent subjective since, in most cases, there is still no direct evidence of an effect, let alone an effect that presents a significant risk to marine mammals. However, the list tabulated in Table 1 represents a set of sound sources that have been recognised as potentially important; all of these could be responsible for creation hazards to marine mammals. The listing is not exhaustive but these sources, which are all types of human activities, are found in most oceans and seas of the world. They are distributed in a very heterogeneous pattern, both in time and space and this alone can lead to a complex anthropogenic sound field.

Complexity is increased further because different components of anthropogenic sound attenuate at rates that depend upon the frequency involved and environmental conditions. This means that prediction of overall received sound levels, let alone those from a specific source, is surrounded by large uncertainty. This uncertainty has prompted the suggestion that it cannot be assumed that anthropogenic sound is benign, even if experimental evidence fails to show effects, because effects may only occur under special sets of circumstances that are difficult to replicate in experimental conditions. Relative to their frequency of use in the ma-
Marine environment, some sound sources may only have an effect on rare occasions. The important question is whether the magnitude of the effect, even if it only occurs rarely, is sufficient to be of concern.

There is also recognition that the effects of chronic and episodic (or acute) sound may differ. Sound received in short, infrequent pulses may have a different effect to sound at similar power levels received frequently or over long periods of time. However, the effects on marine mammals are generally poorly understood, but it means that a sound source can become a hazard depending upon how it is used, rather than on its operating power levels and signal characteristics.

Table 1. Types of anthropogenic sound sources that could affect marine mammals

<table>
<thead>
<tr>
<th>Source</th>
<th>Effects of greatest concern</th>
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<tbody>
<tr>
<td><strong>Vessels</strong></td>
<td>Masking, Habitat displacement</td>
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<tr>
<td><strong>Air guns</strong></td>
<td>Masking, Physical trauma, Hearing loss, Behavioural change, Habitat displacement, Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Intense low- or mid-frequency sonar</strong></td>
<td>Physical trauma, Hearing loss, Behavioural change, Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Pile driving</strong></td>
<td>Physical trauma, Hearing loss, Behavioural change, Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Other sonars (depth sounders, fish finders)</strong></td>
<td>Masking, Hearing loss, Behavioural change, Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Dredges</strong></td>
<td>Behavioural change, Behaviourally-mediated effects, Habitat displacement</td>
</tr>
<tr>
<td><strong>Drills</strong></td>
<td>Hearing loss, Behavioural change, Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Bottom towed fishing gear</strong></td>
<td>Behavioural change, Behaviourally-mediated effects, Habitat displacement</td>
</tr>
<tr>
<td><strong>Explosions</strong></td>
<td>Physical trauma, Hearing loss, Behavioural change, Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Recreational vessels</strong></td>
<td>Masking, Behavioural change, Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Acoustic deterrents</strong></td>
<td>Behaviourally-mediated effects</td>
</tr>
<tr>
<td><strong>Over flying aircraft (including sonic booms)</strong></td>
<td>Behaviourally-mediated effects</td>
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</table>
Sources of sound and hazards to marine mammals

Figure 6. Spectrograms of (a) man-made sound and (b) natural sound. The man-made sound is ship noise where the ship ran its engines intermittently. The natural sounds show two lightning strikes, heavy rainfall, thunder and the sounds of whales vocalizing.

Figure 7. Spectrograms of (a) dolphin vocalizations including whistles that are audible to the human ear and higher frequency clicks and (b) typical clicks from a group of foraging Blainville’s beaked whales (*Mesoplodon densirostris*). The frequency of beaked whale clicks is above the threshold of the human ear but beaked whales can hear at frequencies similar to those of the dolphin whistles which are also within the frequency range of many man-made sounds.
A four-step analytic process is applied. A sound leaves a source (e.g., sonar transducer, seismic airgun array), moves through the water, and results in an exposure (marine mammals receiving sound). The exposure creates a dose in the exposed animals (the type and amount of the sound received by the animals, which may be expressed in any of several ways), and the magnitude, duration, timing, and other characteristics of the dose determine the extent to which there is an effect. This model is captured in the following analytic steps:

**Risk framework**

The impacts and mitigation of many types of environmental hazards may be considered within a risk framework. This applies to risk to human health as well as to wildlife. Risk frameworks help to rationalise the scientific research effort by focussing it into areas that are most likely to help reduce environmental impacts. The following descriptors for a risk framework applied to the effects of anthropogenic sound on marine mammals are a modification of generic frameworks used for other forms of pollution (NRC 1994b). Further definitions are provided in box 1.

The risk assessment framework as described in Box 1 and shown in Figure 8 is implemented in Table 2 in the context of the problems associated with marine mammals and anthropogenic sound. Not every risk assessment would necessarily encompass all four steps shown above. Risk assessment may sometimes consist only of a hazard assessment designed to evaluate the potential for anthropogenic sound to affect marine mammals. Applying this to the effects of anthropogenic sound on marine mammals will help to define the priority research topics necessary for reducing uncertainty.

The analytical steps described above are typically followed by a fifth step: Risk Management which involves the design and application of mitigation measures to reduce, eliminate, or rectify risks. Aside from identifying priority risks, the scientific community may contribute to risk management primarily by providing information and advice about effective mitigation techniques or strategies, which may be used by stakeholders to reduce these (priority) risks. Such information is also essential for the development of informed knowledge-based policy making.

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**Box 1. Risk Assessment Framework**

<table>
<thead>
<tr>
<th>Step 1:</th>
<th><strong>Step 2:</strong></th>
<th><strong>Step 3:</strong></th>
<th><strong>Step 4:</strong></th>
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<tr>
<td><strong>Hazard Identification:</strong> entails identification of the sound sources and the circumstances in which they are used that are suspected to pose hazards, quantification of the concentrations at which they are present in the environment, a description of the specific effects of the sound source, and an evaluation of the conditions under which these effects might be expressed in exposed marine mammals. Information for this step may be derived from environmental monitoring data and the direct correlation of effect with the presence of a hazard as well as other types of experimental work. This step is common to qualitative and quantitative risk assessment.</td>
<td><strong>Dose-Response Assessment:</strong> entails a further evaluation of the conditions under which the effects of sound might be manifest in exposed marine mammals, with particular emphasis on the quantitative relation between the dose and the response. This step may include an assessment of variations in response, for example, differences in susceptibility in relation to age, sex, reproductive status and time of year.</td>
<td><strong>Exposure Assessment:</strong> involves specifying the population that might be exposed to the hazard, identifying the routes through which exposure can occur, and estimating the characteristics (magnitude, duration, and timing) of the doses that marine mammals might receive as a result of their exposure.</td>
<td><strong>Risk Characterization:</strong> involves integration of information from the first three steps to develop a qualitative or quantitative estimate of the likelihood that any of the hazards associated with the sound source will be realized in exposed marine mammals. This is the step in which risk-assessment results are expressed. Risk characterization should also include a full discussion of the uncertainties associated with the estimates of risk.</td>
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Risk framework

Box 2. Risk Assessment Definitions

**Risk assessment approach:**

- **Risk:** “probability that something undesirable will happen” (Harwood 2000); the probability that a given hazard will cause harm (http://www.labour.gov.sk.ca/safety/repguide/basics2.htm)
  - “something undesirable”: e.g., disturbance or injury of marine mammals (individuals or populations)
  - hazard: any activity, situation or substance (energy) that can cause harm

- **Risk assessment**: methodology for quantifying uncertainties
  - **Step 1: Hazard Identification**: identification of causal factors/threats
  - **Step 2: Exposure Assessments and Exposure-Response Assessments**: determination of exposure to hazards and identification of range of possible responses
  - **Step 3: Risk Characterisation**: determination of the likelihood of undesirable outcomes of sound exposures

- **Risk management**: development and application of means to address risk

**Hazard Identification (what are the actual and potential threats?)**

- investigation of scenarios where there is suspicion of a relationship between sound and observations of deaths, injuries, and more subtle effects
- determine the causes of harm
- need for greater effort to identify baselines and to develop techniques to identify threats
- need for more detailed efforts to tease out the specific cause(s)

**Exposure Assessments (determine exposure to hazards)**

- marine mammal numbers and distributions
- sound characteristics and distributions
- overlap between marine mammals and sounds and moderated by species sensitivity

**Exposure-Response Assessments (determine range of possible responses)**

- marine mammal sensitivities at the species level: auditory effects, non-auditory physiological effects, behavioural effects, trophic and ecosystem effects, population-level effects
- dose-response relationship

**Risk Characterization**

- determine likelihood of undesirable outcomes of sound exposures

**Risk Management**

- development of mitigation
- will depend upon whether the risk of harm exceeds trigger levels set by legislation, societal views or because effects are deemed to be biologically significant.
Hazard identification

Exposure assessment
(number of animals involved, location and level of exposure)

Dose-response assessment
(toxicity and secondary effects)

Risk characterisation
(risk quotient)

Mitigation

Yes

Exceed trigger level for management?

No

Risk acceptable

* Trigger level defined by legislation, value judgement or biological significance

Figure 8. Illustration of the information flow and decision pathway for a risk assessment process. This shows a feedback process involving mitigation when the risk exceeds the trigger level for management action. This is an adaptive approach to managing risk.

Figure 9. Common dolphin kidney with gas embolism: normal (left) and abnormal (right) kidney lobes. This particular common dolphin stranded singly and it is not known if the dolphin was exposed to sonar (or other high-intensity man-made sound source). There are at least two hypothetical mechanisms for bubble formation in tissues: (i) a behavioural response to sonar exposure (e.g. rapid ascent followed by a series of shallow dives around 25-50m) that drives nitrogen tensions in body tissues to levels that might cause bubbles to form (most supported hypothesis by scientists); and (ii) a direct physical effect of acoustic sound energy on microscopic bubble precursors in tissues leading to instability of the micro-bubbles and a predisposition to grow to a larger size if the surrounding tissues are supersaturated with nitrogen gas (as occurs when a whale surfaces from a series of dives).
Table 2. The risk assessment framework as applied to the issue of marine mammals and anthropogenic sound with an assessment of prioritisation. Note that there is some overlap between the main research issues across the stages of risk assessment. For example, the distribution and abundance of anthropogenic sound sources is relevant to hazard identification, as well as exposure and dose-response assessments.

<table>
<thead>
<tr>
<th>Stage in risk assessment framework</th>
<th>Main research issues</th>
<th>Sub-issues</th>
<th>Degree of current uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1: Hazard Identification</td>
<td>Sources of sound in the marine environment</td>
<td>Characteristics of natural and anthropogenic sound sources</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distribution and abundance of sound sources</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Sound fields in the marine environment</td>
<td>Ambient noise fields</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sound fields of individual sources</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Auditory detection of sound</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-auditory sensitivity to sound</td>
<td>Moderate</td>
</tr>
<tr>
<td>Step 2 &amp; 3: Exposure Assessment and Dose-Response Assessments (both long- and short-term)</td>
<td>Marine mammals as receivers of sound</td>
<td>Distribution and abundance of marine mammals (including vertical)</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Auditory detection of sound</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-auditory sensitivity to sound</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distribution and abundance of sound sources</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Effects of sound on individuals</td>
<td>Physiological effects (e.g., TTS, PTS, stress)</td>
<td>Auditory Effects: Moderate Stress Effects: High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Masking (including potential chronic effects)</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Behavioural effects</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Life function effects (e.g., body condition, reproductive condition)</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Morbidity</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Issues related to beaked whale mass strandings (e.g., nitrogen bubble, tissue resonance, and haemorrhagic diathesis hypotheses)</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effects of sound on feeding through prey availability</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Effects on populations</td>
<td>Changes in vital rates (e.g., fecundity, survival)</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Cumulative and synergistic effects</td>
<td>Effects of multiple exposures to sound</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effects of sound in combination with other stressors</td>
<td>High</td>
</tr>
<tr>
<td>Step 4: Risk Characterisation</td>
<td>Risk of impact</td>
<td>Overlap of exposures and effects</td>
<td>High</td>
</tr>
<tr>
<td>Step 5: Risk Management</td>
<td>Methods to prevent or reduce risk</td>
<td>Mitigation tools and determining trigger levels for management action</td>
<td>High</td>
</tr>
</tbody>
</table>
Rationale for prioritisation of research and approaches

Individuals or populations?

In order to determine whether the effects of anthropogenic sound on marine mammals result in changes in species viability, we must understand how the responses of individuals to sound change their behaviour and physiology in ways that affect their vital rates\(^1\). Without such an understanding, linkages between sound exposure and population changes can never be achieved. Although many marine mammal populations have experienced significant declines in the past few decades, the causal factors are difficult to ascertain post hoc.

Marine mammals use sound and respond to conspecific, natural, and anthropogenic sound in a variety of ways. Most of the responses are adaptive, which means that behaviour and physiology may change, but they do so in a manner that does not negatively affect the vital rates of the species involved. The question that is difficult to answer is: when do these adaptive responses to an environmental stress, which are within the norms of an animal’s capacity to respond, lead to reduced probabilities of surviving or reproducing? In extreme cases this may lead to anthropogenic sound having significant negative consequences for vital rates and populations. This was the subject of a recent US National Research Council report (NRC 1994a, 2000, 2003 and 2005).

The PCAD (Population Consequences of Acoustic Disturbance model, see Figure 11) presented in the US National Research Council report provides a rationale for prioritisation of research. It is represented by a flow diagram showing research topics in areas ranging from sound production, through behaviour change, effects on life function, to impacts on vital rates and, by implication, the effects on populations. To construct a full risk assessment, it is necessary to be able to make the linkages (labelled as 1-4 in Figure 11) between each subject. Analysis of this structure, in particular reveals the need to improve knowledge of how effects on life function influence vital rates. This is an area of research that requires a high level of effort, illustrated by the scores given to each transfer in the diagram of Figure 11. Understanding the mechanisms and linkages are fundamental to designing more effective mitigation strategies.

Long-term versus short-term research objectives

The areas most in need of research activities require consolidated long-term effort and funding. Questions focused at the level of populations cannot be easily addressed using conventional competitive funding streams that normally provide funds over comparatively short periods of time (1-4 years). A significant feature of the strategic approach being proposed here is the recognition that many funding agencies/organisations are not currently able to commit to long-term funding. The prioritisation of research therefore should provide a route by which coordination amongst short-term research projects leads to answers that could only be achieved otherwise through long-term strategic research.

\(^1\) "Vital rates" are the factors that determine the rate of growth of a population, such as the reproductive, survival and immigration and emigration rates.
Assessment of approaches

There is usually a limited range of methods that can be used to study marine mammals but, where there is a choice, criteria can be selected and used to focus attention on a narrow range of methods.

Each research approach was assessed with respect to the following evaluation criteria:

(i) Biological significance – an assessment of the contribution made to understanding the biological processes involved in the response to anthropogenic sound;
(ii) Financial cost – an assessment of the absolute financial costs of carrying out a particular approach;
(iii) Cost to animal – an assessment of the impact that a procedure will have on an individual;
(iv) Effectiveness – an assessment of the extent to which the approach will advance knowledge towards the goal of answering the question;
(v) Feasibility – an assessment of the constraints that may reduce the practical implementation of the approach, such as permitting, access to animals and availability of technology.

Costs and benefits of different approaches

This research strategy has not carried out an explicit cost-benefit analysis of different approaches. However, a cost-benefit analysis will be a necessary component of any research activity. The analysis presented in this report provides a structure for the assessment of costs and benefits in the future.
High-level research questions

Since natural sound is an important feature of the marine environment, the central issue concerning the effects of anthropogenic sound on marine mammals involves sources that produce sound above the natural background level, thereby producing localisable effects or adding to ambient noise budgets. The central questions to be answered are:

(i) How do marine mammals respond to sound levels that are above the natural background level?
(ii) What are the consequences of these responses?

These questions can be further expressed as a set of high-level operational research questions in the context of the risk assessment framework:

(i) What are the anthropogenic sound source characteristics and resulting sound fields?
(ii) What level of exposure do marine mammals experience?
(iii) What are the immediate physiological, pathological and behavioural effects of anthropogenic sound exposure?
(iv) What are the long-term effects of anthropogenic sound exposure at the level of both individuals and populations?
(v) How can we mitigate against any effects if they are found to be significant?
Specific research questions and approaches

Specific thematic questions are given in Table 3. These can be expanded into a set of more detailed questions. Three of these questions (the first three mentioned in Table 3) are considered in more detail to provide examples of this process.

(i) How can we reduce the risk of tactical mid-frequency sonars to beaked whales?
(ii) What are the effects of seismic surveys on individuals and populations of marine mammals?
(iii) What is the effect of shipping noise on marine mammals?

Tables 4, 5 and 6 show a set of sub-questions relating to these questions. The evaluation criteria detailed above were used to assess the general feasibility of each of the approaches that could be taken to investigate each sub-question. These have been arranged in the tables in Annex III to address different parts of the risk assessment process.

The research approaches are not fully exclusive and there is inevitably some overlap and therefore duplication in the assessments (e.g. cost to animal and difficulty in obtaining a permit for the work). Nevertheless, some possible approaches stand out as being better than others at addressing the question being asked. For the purpose of this report, it is better to look at the overall pattern of the assessment, rather than the precise details. The details are available for consultation at http://www.smru.st-and.ac.uk/. The approaches attracting most stars under the titles of biological significance, effectiveness and feasibility, and the fewest stars under financial cost and cost to animal are likely to yield the greatest value as a research investment.

Table 3. High-level research questions that relate to particular hazards

<table>
<thead>
<tr>
<th>Research Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>How can we reduce the risk of tactical mid-frequency sonars to beaked whales? (See Table 3)</td>
</tr>
<tr>
<td>What are the individual and population consequences of seismic surveys? (See Table 4)</td>
</tr>
<tr>
<td>What is the effect of shipping noise on marine mammals? (See Table 5)</td>
</tr>
<tr>
<td>What is the effect of commercial sonars such as depth sounders and fish-finders?</td>
</tr>
<tr>
<td>What risks do sonars present to marine mammals other than beaked whales?</td>
</tr>
<tr>
<td>What are the impacts, if any, of new low frequency sonar technologies?</td>
</tr>
<tr>
<td>What is the effect of acoustic oceanography on marine mammals?</td>
</tr>
<tr>
<td>What are the effects of acoustic deterrent devices that target marine mammals?</td>
</tr>
<tr>
<td>How do outboard motors affect marine mammals in the inshore area?</td>
</tr>
<tr>
<td>What are the population consequences of chronic exposure to all sound sources?</td>
</tr>
<tr>
<td>What are the consequences of chronic exposure to continuous low level sound sources?</td>
</tr>
<tr>
<td>How does pile-driving affect marine mammals?</td>
</tr>
<tr>
<td>What are the effects of sounds originating from vessels that follow marine mammals?</td>
</tr>
</tbody>
</table>
Tables 4, 5 and 6 each show an analysis of the dependencies between different sub-questions. This is shown using arrows between sub-questions. The direction of the arrows shows the inter-dependencies of the sub-questions.

As expected, the analyses show a general flow of dependencies from top to bottom of the risk assessment framework. The characterization of the dose-response relationship has a large number of dependencies within the section on exposure characterization. This pattern is similar for the investigation of the effects of sonars on beaked whales (Table 4), the effect of seismsics (Table 5) and shipping noise (Table 6) on marine mammals.

Using these tables, it is possible to define critical paths through the research field to help prioritise research. For example, a common concern refers to the probability of an adverse impact of an activity on a marine mammal population. This is expressed as a question under the risk characterization section of Tables 4, 5 and 6. The critical path for research to address this question is defined by dependencies on outputs from a cascade of other questions that leads back to questions about received sound levels and physiological and behavioural responses to these sound levels.

The analyses in Table 4, 5 and 6 suggests that being able to measure the sound received by a cetacean should be a major focus of research, because many other research questions rely upon this capability. This would point to renewed efforts to develop appropriate instrumentation and attachment methods together with efforts to provide fine-scale measurements of the sound field.
Table 4. Research sub-questions addressing the higher-level question “how can we reduce the risk of sonars to beaked whales?” Arrows between sub-questions indicate the result of the analysis of the dependencies between the different sub-questions.

<table>
<thead>
<tr>
<th>Hazard identification</th>
<th>Characterising exposure</th>
<th>Characterising dose-response relationship</th>
<th>Risk management</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the range of frequencies, intensities and duration of exposure (that causes risk)?</td>
<td>Where are the sound sources?</td>
<td>How close are beaked whales to their physiological limits while diving?</td>
<td>What is the effect of changing the acoustic source, operational characteristics and location of the source?</td>
</tr>
<tr>
<td>What is the effect of propagation conditions?</td>
<td>What is the overlap of beaked whale distribution with sound sources?</td>
<td>What is the pathological/physiological response?</td>
<td>How can beaked whales be detected within the operational zone in real time?</td>
</tr>
<tr>
<td>Are there unique habitat characteristics that create a hazard?</td>
<td>How do behavioural changes modulate exposure?</td>
<td>Is the response a direct physical effect?</td>
<td>How can overlap between beaked whales and sonar be reduced?</td>
</tr>
<tr>
<td>Have stranding rates changed?</td>
<td>What are the received sound characteristics at the whale?</td>
<td>What is the behavioural response?</td>
<td></td>
</tr>
<tr>
<td>Where are the sound sources?</td>
<td></td>
<td>How are behavioural and physiological responses related?</td>
<td></td>
</tr>
<tr>
<td>Where are the beaked whales?</td>
<td></td>
<td>Is there habitat displacement and over what temporal and spatial scales?</td>
<td></td>
</tr>
<tr>
<td>What is the overlap of beaked whale distribution with sound sources?</td>
<td></td>
<td>What proportion of the exposed animals is affected?</td>
<td></td>
</tr>
<tr>
<td>How do behavioural changes modulate exposure?</td>
<td></td>
<td>Does sensitivity vary between individuals?</td>
<td></td>
</tr>
<tr>
<td>What are the received sound characteristics at the whale?</td>
<td></td>
<td>How are populations and their vital rates affected?</td>
<td></td>
</tr>
<tr>
<td>How close are beaked whales to their physiological limits while diving?</td>
<td></td>
<td>What is the probability of impacts on individuals?</td>
<td></td>
</tr>
<tr>
<td>What is the pathological/physiological response?</td>
<td></td>
<td>What is the probability of adverse population impacts?</td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Research sub-questions addressing the higher-level question “what are the effects of seismics on individuals and populations?” Arrows between sub-questions indicate the result of the analysis of the dependencies between the different sub-questions.

<table>
<thead>
<tr>
<th>Hazard Identification</th>
<th>Characterising Exposure</th>
<th>Characterising Impact &amp; Response</th>
<th>Risk Characterisation</th>
<th>Risk Management</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>What is the range of frequencies, intensities and durations of exposure (that causes risk)?</td>
<td>Have stranding rates changed?</td>
<td>What is the effect of propagation conditions?</td>
<td>What are the sources?</td>
</tr>
<tr>
<td></td>
<td>What is the effect of propagation conditions?</td>
<td>Has seismic activity affected the distribution and abundance of any marine mammal?</td>
<td>Where are the marine mammals?</td>
<td>Where are the marine mammals?</td>
</tr>
<tr>
<td></td>
<td>Have stranding rates changed?</td>
<td>Does seismic survey activity affect prey availability for marine mammals?</td>
<td>What are the received sound characteristics?</td>
<td>What is the overlap of marine mammal distribution with sound sources?</td>
</tr>
<tr>
<td></td>
<td>Has seismic activity affected the distribution and abundance of any marine mammal?</td>
<td>Where are the marine mammals?</td>
<td>What are the received sound characteristics?</td>
<td>How do behavioural changes modulate exposure?</td>
</tr>
<tr>
<td></td>
<td>Does seismic survey activity affect prey availability for marine mammals?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td></td>
<td>What are the sources?</td>
<td>What is the overlap of marine mammal distribution with sound sources?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>Are there physiological responses?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What is the overlap of marine mammal distribution with sound sources?</td>
</tr>
<tr>
<td>Do airguns have a direct physical effect?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>Is there habitat displacement and over what temporal and spatial scales?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>Does sensitivity vary between individuals?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>How are populations and their vital rates affected?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>What is the probability of impacts on individuals?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>What is the probability of adverse population impacts?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>What is the effect of changing the acoustic source, operational characteristics and location of the source?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>Is ramp-up an effective mitigation measure?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>How can marine mammals be detected within the operational zone in real time?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>How to reduce risk of overlap between marine mammals and seismic surveys?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>How to design Marine Protected Areas to minimize risk to animals in areas where seismic exploration is likely?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
<tr>
<td>What acoustic buffer zones are required to reduce risk to animals within marine protected areas consistent with goals of the protection?</td>
<td>What are the received sound characteristics?</td>
<td>How do we assess the significance of observed habitat shifts?</td>
<td>What are the received sound characteristics?</td>
<td>What are the received sound characteristics?</td>
</tr>
</tbody>
</table>
### Analyses of dependencies and critical paths

Table 6. Research sub-questions addressing the higher-level question “what is the interaction of shipping traffic noise with baleen whales?” Arrows between sub-questions indicate the result of the analysis of the dependencies between the different sub-questions.

<table>
<thead>
<tr>
<th>Hazard Identification</th>
<th>Characterising dose-response relationship</th>
<th>Risk Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is the range of frequencies, intensities and duration of exposure (that causes risk)?</td>
<td>How has vessel noise and traffic noise changed as a component of ambient sound across space and time?</td>
<td>What is the effect of changing the acoustic source, operational characteristics and location of the source?</td>
</tr>
<tr>
<td>How has vessel noise and traffic noise changed as a component of ambient sound across space and time?</td>
<td>What is the effect of propagation conditions?</td>
<td>How can baleen whales be detected in real time in order to reduce vessel collisions?</td>
</tr>
<tr>
<td>What is the effect of propagation conditions?</td>
<td>Are there unique habitat characteristics that create a hazard?</td>
<td>How can the overlap between baleen whales and vessel noise be reduced?</td>
</tr>
<tr>
<td>Are there unique habitat characteristics that create a hazard?</td>
<td>Does vessel traffic noise affect risk of collision?</td>
<td></td>
</tr>
<tr>
<td>Where are the sources?</td>
<td>Where are the baleen whales?</td>
<td></td>
</tr>
<tr>
<td>Where are the baleen whales?</td>
<td>What is the overlap of marine mammal distribution with sound sources?</td>
<td></td>
</tr>
<tr>
<td>What is the overlap of marine mammal distribution with sound sources?</td>
<td>How do behavioural changes modulate exposure?</td>
<td></td>
</tr>
<tr>
<td>How do behavioural changes modulate exposure?</td>
<td>What are the received sound characteristics?</td>
<td></td>
</tr>
<tr>
<td>What are the received sound characteristics?</td>
<td>Do baleen whales respond to compensate for increased vessel noise?</td>
<td></td>
</tr>
<tr>
<td>Do baleen whales respond to compensate for increased vessel noise?</td>
<td>What are the functions of sound produced by baleen whales?</td>
<td></td>
</tr>
<tr>
<td>What are the functions of sound produced by baleen whales?</td>
<td>Do whales utilize sounds from other sources (e.g. predator calls, ambient noise) and over what ranges are these effective?</td>
<td></td>
</tr>
<tr>
<td>Do whales utilize sounds from other sources (e.g. predator calls, ambient noise) and over what ranges are these effective?</td>
<td>Do whales use multi-path and echoes of their own calls?</td>
<td></td>
</tr>
<tr>
<td>Do whales use multi-path and echoes of their own calls?</td>
<td>Is masking occurring from point sources or traffic/ambient noise?</td>
<td></td>
</tr>
<tr>
<td>Is masking occurring from point sources or traffic/ambient noise?</td>
<td>What is the behavioural response to a communication signal in varying noise?</td>
<td></td>
</tr>
<tr>
<td>What is the behavioural response to a communication signal in varying noise?</td>
<td>Can chronic vessel noise cause threshold shifts?</td>
<td></td>
</tr>
<tr>
<td>Can chronic vessel noise cause threshold shifts?</td>
<td>Are there indicators of stress related to noise exposure?</td>
<td></td>
</tr>
<tr>
<td>Are there indicators of stress related to noise exposure?</td>
<td>Is there habitat displacement and over what temporal and spatial scales?</td>
<td></td>
</tr>
<tr>
<td>Is there habitat displacement and over what temporal and spatial scales?</td>
<td>Does sensitivity vary between individuals?</td>
<td></td>
</tr>
<tr>
<td>Does sensitivity vary between individuals?</td>
<td>How are populations and their vital rates affected?</td>
<td></td>
</tr>
<tr>
<td>How are populations and their vital rates affected?</td>
<td>How is masking related to changes in individual life functions?</td>
<td></td>
</tr>
</tbody>
</table>
Setting priorities

The foregoing analysis for the example questions used provides a framework within which research priorities can be established. Additional types of analyses need to be carried out for the remaining research questions but the fundamental messages are likely to differ little from the examples used here. Based upon Tables 4, 5 and 6, questions addressing the characterization of exposure appear to be a high priority. Although these questions depend upon the nature of the hazard, in general, the difficulty associated with researching the hazards is lower than that with characterizing exposure. However, because of the direction of flow in the dependencies in Tables 4, 5 and 6, addressing questions in the later parts of the risk assessment process (towards the lower end of these tables) will be increasingly difficult.

Controlled exposure experiments have been suggested as a high research priority. The analyses suggest that characterising the dose response relationship is an important pre-cursor to assessing the impacts on either individuals or populations. It further shows that opportunistic experiments are unlikely to be valuable unless there is an appropriate measure of the received sound at the level of the individual marine mammal.

It is recommended to develop the research agenda across a broad front and to use the risk framework, and the questions defined in Tables 4, 5 and 6, as ways of assessing where research fits appropriately into the required effort. At some point in the future, it may be appropriate to use this framework to assess progress and to identify critical gaps in knowledge.
Implementation

Methodologies and approaches
Each of the questions defined in Tables 4, 5 and 6 can be addressed using a set of methodologies and approaches. These Tables are expanded further in Annex III to show the methods and approaches that could be used in each case, together with assessments of their biological significance, estimated financial costs, effectiveness and the possible impacts on the animals involved.

Strategic considerations
This analysis has only expanded three of the questions in Table 3 to show the range of possible sub-questions that could form the basis of a research effort to undertake a formal risk assessment. Additional work is required to carry out the same process with the other important questions. Moreover, the present analysis is a first step towards defining a research strategy and will need further review and modification as additional intellectual effort is applied to this field. This research strategy must be subjected to a peer-review process to ensure that it reflects the broad range of experience within the research community and to ensure that it provides coherent strategic guidance.

The process of further development and implementation of this research strategy would be strengthened if the strategy were adopted by organisations with an interest in funding independently peer-reviewed science. There is a strong case for establishing a process of independent peer review of all science proposals and outputs on this topic that are funded by stakeholders.

A key element in this process is that there is some form of oversight of the implementation of this research strategy through regular independent review of ongoing funded research, in terms of how it helps to answer the high-level strategic research questions defined here. This will provide a point of reference for researchers, managers and policy-makers to identify gaps that need additional work.

Preferred funding and overview scenario
There has been considerable controversy surrounding some of the research on impacts of anthropogenic sound on marine mammals. For such research to be effective it must not only be based upon robust scientific principles, but it must also be seen as widely credible and unaffected by conflicts of interest. Such impartiality can only be achieved by using a transparent funding structure, independent from both sides of a polarised conservation debate. Therefore, it is critical that as much as possible of this research be funded in a way that insulates the scientists from conflicts of interest, perceived or otherwise.

If possible, an independent body should have responsibility for the apportionment of funds and monitoring and delivery of outputs of research on the effects of anthropogenic sound on marine mammals.

Such an independent body would clearly have to satisfy stakeholders and funding agencies that (i) a transparent process of peer review is used to select the best science performers and approaches; (ii) their funding would be properly audited; (iii) their funding would be distributed to an area of science defined by the interests of the funder; (iv) there would be appropriate overview of project management so that delivery could be guaranteed; and (v) this process would deliver value for money.
Conclusions

There is a high level of concern about the potential impacts of anthropogenic sound on marine fauna in general, and towards marine mammals in particular, since they rely on sound as a major source of social and environmental information. In spite of this concern, the current level of scientific understanding is insufficient to produce robust advice about the potential impacts of anthropogenic sound on marine mammals. To date, there has been no structured analysis of the full research challenge that this presents. In order to do so, there is a need to develop a protocol for narrowing the research focus to address specific issues and to prioritise research activities appropriately.

The ultimate goal of a research strategy should be to define and reduce the risk (probability of disturbance or injury that could affect viability) presented to marine mammals by anthropogenic sound. Therefore, priorities should be assessed under a risk assessment framework.

The main recommendation put forward in this report is to use a four-step analytical risk framework process adapted to the issue of marine mammals and anthropogenic sound to assess and identify priority research topics for reducing uncertainty. Such a risk framework includes: (i) hazard identification; (ii) characterizing exposure to the hazard; (iii) characterizing dose-response relationships; and (iv) risk characterization, typically feeding into a risk management step.

Risk frameworks help to rationalise the research effort by focussing it into areas that are most likely to help reduce environmental impacts. Such frameworks allow for prioritising research questions and identifying appropriate research methods by breaking down high-level research questions into sub-questions with cascades of interdependencies. In addition, as many funding agencies are not currently able to commit to long-term funding, risk frameworks should also provide a route through which coordination amongst short-term research projects leads to answers that could only otherwise be achieved through long-term strategic research.

The risk assessment framework presented in this report is illustrated by focussing on the breakdown of three of the identified high-level research questions: (i) how can we reduce the risk posed by sonars to beaked whales; (ii) what are the effects of seisms on individuals marine mammals and populations; and (iii) what is the interaction of shipping traffic noise with baleen whales? The analysis has only expanded three of the key questions to illustrate the range of possible sub-questions that could form the basis of a research effort to undertake a formal risk assessment. Additional work is required to carry out the same process with the other important questions. To construct a full risk assessment, it is necessary to be able to make all the linkages between issues from sound production, through behaviour change, effects on life function, to impacts on vital rates and, by implication, the effects on populations. In particular, there is a need to improve knowledge of how effects on life function influence vital rates.

The present analysis is a first step towards defining a research strategy and will need further review and modification as additional intellectual effort is applied to this field, to ensure that it reflects the broad range of experience within the science community and that it provides coherent strategic guidance. At some point in the future, it would be appropriate to use this framework to assess progress and to identify critical gaps in knowledge.

Another challenge to overcome relates to the polarisation of the debate and arguments about how and why anthropogenic sound may affect marine mammals. The level of polarisation has come about partly because of differing points of view about the level of precaution that needs to be adopted in the face of high scientific uncertainty. As a result of this polarisation, there has been considerable controversy surrounding some of the research. For the research to be effective it must not only be based upon sound scientific principles but it must also be seen as widely credible and unaffected by conflicts of interest. This impartiality can only be achieved using a transparent funding structure, independent from both sides of a polarised conservation debate. Therefore, it is critical that as much as possible of this research be funded in a way that insulates the scientists from conflicts of interest, perceived or otherwise. If possible, an independent body should have responsibility for the dispersal of funds and monitoring and delivery of outputs of research on the effects of anthropogenic sound on marine mammals. Such a body would clearly have to satisfy stakeholders and funders that (i) a transparent process of peer review is used to select the best science performers and approaches; (ii) their funding would be properly audited; (iii) their funding would be distributed to an area of science defined by the interests of the funder; (iv) there would be appropriate oversight of project management and (v) this process would deliver value for money.
Key recommendations

1. Establishing/implementing the proposed scientific research strategy. This would also allow the further elaboration of two of the key recommendations made by the 2004 Marine Board and NSF workshop participants, namely (i) establish some mechanism to allow better co-ordination of research between the US and Europe, ultimately leading to jointly funded research programmes between the two; and (ii) establish database(s) to enhance the sharing of data: US and European data must be made compatible.

2. A key message of this report is that a risk assessment framework needs to be used to define where the research effort can be applied with greatest effect. At some point in the future, it may be appropriate to use this framework to assess progress and to identify continuing critical gaps in knowledge.

3. There is a need to achieve a rapid improvement in the state of knowledge by undertaking new research that is focussed on specific questions of high priority. This requires concerted, coordinated action across many expert groups within the scientific community.

4. Focussed experiments should be conducted within a broader strategic framework so that, when combined together, their results are more likely to address larger and more complex questions with particular relevance to policy.

5. Controlled exposure experiments are recommended as a high research priority. The analyses suggest that characterising the dose-response relationship is an important pre-cursor to assessing the impacts on either individuals or populations. It further shows that opportunistic experiments are unlikely to be valuable unless there is an appropriate measure of the received sound at the level of the individual marine mammal.

6. The responsibility for the apportionment of funds and monitoring and delivery of outputs of research on the effects of anthropogenic sound on marine mammals should be within the remit of an independent body (e.g. NSF and/or ESF) that would be responsible to stakeholders and funders for (i) a transparent process of peer review to select the best science performers and approaches within the context of this strategy; (ii) auditing the use of funds provided by stakeholders; (iii) distributing funding to an area of science defined by the interests of the funder but within the context of this strategy; (iv) applying appropriate oversight of project management and (v) ensuring this process would deliver value for money.
References


Additional sources of previous research recommendations on sound and marine mammals


### Annex II

#### A. List of attendees at the Marine Board–ESF and NSF workshop

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
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</thead>
<tbody>
<tr>
<td>Arne Bjørge</td>
<td>Institute of Marine Research</td>
<td>Norway</td>
</tr>
<tr>
<td>Olaf Boebel</td>
<td>Alfred Wegener Institute for Polar and Marine Research</td>
<td>Germany</td>
</tr>
<tr>
<td>Ian Boyd</td>
<td>University of St Andrews - Sea Mammal Research Unit</td>
<td>UK</td>
</tr>
<tr>
<td>John Breslin</td>
<td>Marine Institute</td>
<td>Ireland</td>
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<tr>
<td>Elke Burkhardt</td>
<td>Alfred Wegener Institute for Polar and Marine Research</td>
<td>Germany</td>
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<tr>
<td>Claire Burt</td>
<td>Naval Systems</td>
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<tr>
<td>Michael Carron</td>
<td>NATO Undersea Research Center</td>
<td>Italy</td>
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<tr>
<td>Roger Gentry</td>
<td>NOAA</td>
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<tr>
<td>Mick Geoghegan</td>
<td>Geological Survey of Ireland</td>
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<td>Jonathan Gordon</td>
<td>University of St Andrews - Sea Mammal Research Unit</td>
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<tr>
<td>Trevor Guymer</td>
<td>Secretary, IAMST - Southampton Oceanography Centre</td>
<td>UK</td>
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<tr>
<td>Mardi Hastings</td>
<td>ONR</td>
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<tr>
<td>John Hildebrand</td>
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<td>Simon Ingram</td>
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<td>Paul D. Jepson</td>
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<td>Ron Kastelein</td>
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<td>Darlene Ketten</td>
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<tr>
<td>Paul Lepper</td>
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<tr>
<td>Klaus Lucke</td>
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<td>Mick Mackey</td>
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<tr>
<td>Agnes McLaverty</td>
<td>Shell Oil Ireland</td>
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<tr>
<td>Lee A. Miller</td>
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<td>Ole Misund</td>
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<tr>
<td>Paul Nachtigal</td>
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<td>Gianni Pavan</td>
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<td>Mike Purdy</td>
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<tr>
<td>W. John Richardson</td>
<td>LGL Ltd</td>
<td>Canada</td>
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<tr>
<td>Howard Roe</td>
<td>Southampton Oceanography Centre/EMB</td>
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<tr>
<td>Roland Rogers</td>
<td>QinetiQ</td>
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<tr>
<td>Maya Tolstoy</td>
<td>Lamont</td>
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<tr>
<td>Peter Tyack</td>
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<tr>
<td>Douglas Wartzok</td>
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<td>US</td>
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<tr>
<td>Geraint West</td>
<td>Southampton Oceanography Centre</td>
<td>UK</td>
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<tr>
<td>Peter Worchester</td>
<td>Scripps Institution of Oceanography</td>
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</table>

#### Marine Board Secretariat

<table>
<thead>
<tr>
<th>Name</th>
<th>ESF Marine Board – Head of Unit</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niamh Connolly</td>
<td>ESF Marine Board – Head of Unit</td>
<td>France</td>
</tr>
<tr>
<td>Nicolas Walter</td>
<td>ESF Marine Board – Science Officer</td>
<td>France</td>
</tr>
</tbody>
</table>
# B. List of Attendees at Expert Group Meeting – Tubney House, Oxford, from 5-9 October 2005

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Country</th>
</tr>
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<tbody>
<tr>
<td>Ian Boyd</td>
<td>Sea Mammal Research Unit, University of St Andrews</td>
<td>UK</td>
</tr>
<tr>
<td>Bob Brownell</td>
<td>National Marine Fisheries Service, Pacific Grove</td>
<td>USA</td>
</tr>
<tr>
<td>Doug Cato</td>
<td>Defence Science and Technology Organisation</td>
<td>Australia</td>
</tr>
<tr>
<td>Chris Clarke</td>
<td>Cornell University, New York</td>
<td>USA</td>
</tr>
<tr>
<td>Dan Costa</td>
<td>University of California, Santa Cruz</td>
<td>USA</td>
</tr>
<tr>
<td>Peter Evans</td>
<td>Seawatch Foundation, Oxford</td>
<td>UK</td>
</tr>
<tr>
<td>Jason Gedanke</td>
<td>Australian Antarctic Division, Hobart</td>
<td>Australia</td>
</tr>
<tr>
<td>Roger Gentry</td>
<td>Washington DC</td>
<td>USA</td>
</tr>
<tr>
<td>Bob Gisiner</td>
<td>Office of Naval Research, Washington DC</td>
<td>USA</td>
</tr>
<tr>
<td>Jonathan Gordon</td>
<td>Sea Mammal Research Unit, University of St Andrews</td>
<td>UK</td>
</tr>
<tr>
<td>Paul Jepson</td>
<td>Institute of Zoology, London</td>
<td>UK</td>
</tr>
<tr>
<td>Patrick Miller</td>
<td>Sea Mammal Research Unit, University of St Andrews</td>
<td>UK</td>
</tr>
<tr>
<td>Luke Rendell</td>
<td>Sea Mammal Research Unit, University of St Andrews</td>
<td>UK</td>
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<tr>
<td>Mark Tasker</td>
<td>Joint Nature Conservation Committee, Aberdeen</td>
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<tr>
<td>Peter Tyack</td>
<td>Woods Hole Institution of Oceanography, Woods Hole</td>
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<tr>
<td>Erin Vos</td>
<td>Marine Mammal Commission, Washington DC</td>
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<tr>
<td>Hal Whitehead</td>
<td>Dalhousie University, Halifax</td>
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<tr>
<td>Doug Wartzok</td>
<td>Florida International University</td>
<td>USA</td>
</tr>
<tr>
<td>Walter Zimmer</td>
<td>NATO Undersea Research Centre</td>
<td>Italy</td>
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</table>
Research approaches

This annex expands the research questions listed in Tables 4, 5 and 6 of the main document by listing under each question the approaches that can be adopted. In addition, it makes an assessment of the relative utility of each approach using the following criteria:

### Financial cost

Total cost of the project, not including aspects such as essential help in kind (e.g. use of naval sonar source)

- **Low:** < $US 50,000
- **Medium:** $US 50-500,000
- **High:** > $US 500000

Note that it is difficult to assess the total cost of research projects that included considerable “in kind” support. For example, since naval sonars are not readily available for hire they are likely to be provided by the navy and not by the researcher. In other cases it will be necessary to include the cost of the source as part of the research program.

### Cost to animal

- **Low:** No impact whatsoever
- **Medium:** No lethality, behavioural, minor invasive procedures
- **High:** Potential lethality, major invasive, effects on vital rates, behavioural effects over large area or time scales

Note that the benefit to the population of marine mammals as a whole that would derive from successful completion of the work, followed by action to reduce any overall risk, was not evaluated. The cost to an individual was also not weighed against the benefit to the population. In addition, the cost associated with delaying action because of the time taken to implement and carry out research was included: Low <1 year; High >5 years.

### Effectiveness

Assessed based upon:

- (i) Likely change in scientific understanding
- (ii) Consequences to risk management
- (iii) Statistical power
- (iv) Significance to other elements of the programme
- (v) Enables other elements of the programme

### Feasibility

Assessed based upon:

- (i) Availability of qualified personnel
- (ii) Availability of appropriate research tools
- (iii) Dependency on other projects
- (iv) Permits and authorisation
- (v) Likelihood of success
| Table 1. Research questions and approaches addressing the higher-level question “how can we reduce the risk of sonars to beaked whales?” Under each category, an approach has been scored as “high” (three dots), “medium” (two dots) and “low” (one dot). “dep” signifies that the score depends on the species or circumstances. |
|-----------------|-----------------|-----------------|-----------------|
| What is the range of frequencies, intensities and duration of exposure (that causes risk)? | Investigation of naval sonar usage patterns | ** | ** | ** |
| | Responses of an instrumented animal in context of sonar and alternative stimuli | ** | | ** |
| | Modelling of received sound pressures (acoustic) | ** | ** | ** |
| | ** | ** | ** |
| What is the effect of propagation conditions? | Survey of historical data sets in presence/absence of naval exercises | ** | ** | ** |
| | Responses of an instrumented animal in context of sonar in absent propagation conditions | ** | ** | ** |
| Are there unique habitat characteristics that create a hazard? | Survey of historical data sets with varying coastal characteristics and ship tracks | ** | ** | ** |
| | Responses of an instrumented animal to varying coastal characteristics and ship tracks | ** | ** | ** |
| | Modelling and measurement of sound fields in varying coastal characteristics and ship tracks | ** | ** | ** |
| How are stranding rates changed? | Epidemiological analysis of historical data on strandings and sonar usage | ** | ** | ** |
| Where are the sound sources? | Ask the navies | ** | ** | ** |
| | Ocean observing systems | ** | ** | ** |
| Where are the beaked whales? | Surveys (acoustic or visual) throughout year and all oceans | *** | *** | *** |
| | Recording diving behaviour (instrumented animals, remote observation incl. acoustics) | *** | *** | *** |
| | Recording movement data (long-term telemetry, photo id, focal follow) | *** | *** | *** |
| | Habitat utilisation models (based on data from surveys; telemetry; past catch data) | *** | *** | *** |
| | Stranding data | *** | *** | *** |
| How is the overlap of beaked whale distribution with sound sources? | Combines above three approaches using geographical and temporal model | *** | *** | *** |
| How do behavioural changes modulate exposure? | ** | ** | ** |
| | Instrumented animals | ** | ** | ** |
| | Acoustic tracking in three dimensions | ** | ** | ** |
| | Behavioural models | ** | ** | ** |
| | Measurements of behavioural states and relative to observed response to exposure | ** | ** | ** |
| | Visual behaviour observation | ** | ** | ** |
| What are the received sound characteristics at the whale? | ** | ** | ** |
| | Acoustic behaviour | ** | ** | ** |
| | Model | ** | ** | ** |
| How close are beaked whales to their physiological limits while diving? | ** | ** | ** |
| | Dive behaviour in detail using instrumented animals | ** | ** | ** |
| | Baseline physiological measurements coupled with physiological models | ** | ** | ** |
| | Experiments with captive and surrogate animals | ** | ** | ** |
| | Necropsy/Pathology of stranded animals | ** | ** | ** |
| What is the pathophysiological response? | Necropsy/Pathology/Behaviour of stranded/newly dead/injured/live animals (compare presence/absence of sonar) | dep | ** | ** |
| | Incubate/Examine new born with and without/before and after exposure | dep | ** | ** |
| | Physiological tests (e.g. nitrogen saturation) | dep | ** | ** |
| | Measure nitrogen saturation | dep | ** | ** |
| If the response is a direct physical effect? | ** | ** | ** |
| | Determine mechanisms of micro-bubble formation and stabilisation | ** | ** | ** |
| | Determine threshold of direct acoustic trauma | ** | ** | ** |
| | Model threshold of direct acoustic trauma | ** | ** | ** |
| | Measure and model tissue and bone response | ** | ** | ** |
| | Experiments and modelling with captive animals | ** | ** | ** |
| What is the behavioural response? | ** | ** | ** |
| | Measure changes in behaviour in presence/absence of sonar with tags, visual observation acoustic means | ** | ** | ** |
| | ALQs | ** | ** | ** |
| | Experiments and modelling with captive animals | ** | ** | ** |
| How are behavioural and physiological responses related? | ** | ** | ** |
| | Combines/Integrates above approaches | ** | ** | ** |
| | Modelling | ** | ** | ** |
| Are there differences in strandings related to what is temporally and spatially scales? | ** | ** | ** |
| | Photos (ID) | ** | ** | ** |
| | Satellite tags | ** | ** | ** |
| | Survey and monitoring (visual and acoustic) | ** | ** | ** |
| | Genetics | ** | ** | ** |
| | Voices of animals (dialects) | ** | ** | ** |
| | Diet assessment/paradigm fauna | ** | ** | ** |
| What proportion of the exposed animals is affected? | ** | ** | ** |
| | Abundance surveys and monitoring | ** | ** | ** |
| | Modelling | ** | ** | ** |
| | Long-term photo-id and/or genetics across study period | ** | ** | ** |
| What is the potential for very long-term individuals? | ** | ** | ** |
| | Measure responses of long-term individuals | ** | ** | ** |
| | Compare stranded “population structure” with at sea “population structure” including mass versus single strandings | ** | ** | ** |
| How are populations and their affairs affected? | ** | ** | ** |
| | Long-term studies of identified individual(s) (multiple techniques) | ** | ** | ** |
| | Studies of population and social structure with and without/before and after exposure | ** | ** | ** |
| What is the probability of impacts on individuals? | ** | ** | ** |
| | Models that integrate exposure and response of individuals | ** | ** | ** |
| What is the probability of adverse population impacts? | ** | ** | ** |
| | Define extent of population | ** | ** | ** |
| | Extrapolate individual models to populations | ** | ** | ** |
| | Models that integrate exposure and changes of population parameters | ** | ** | ** |
| What is the effect of changing the acoustic source, operational characteristics and location of the source? | ** | ** | ** |
| | Differences in sound source based on understanding of causes (physical and biological) of adverse effect and whale biology and test results of these changes | ** | ** | ** |
| | Modelling informed by the above | ** | ** | ** |
| | Experimental variation in source acoustics/source/operation/characteristics | ** | ** | ** |
| | Monitoring effects of (non-experimental) variation in sources/operation/characteristics | ** | ** | ** |
| How can we reduce the risk of beaked whales being detected within the operational zone in real-time? | ** | ** | ** |
| | ALQs | ** | ** | ** |
| | Test effectiveness of active acoustic | ** | ** | ** |
| | Test effectiveness of passive acoustic | ** | ** | ** |
| | Test effectiveness of visual observations | ** | ** | ** |
| | Test effectiveness of radar | ** | ** | ** |
| | Test effectiveness of lidar | ** | ** | ** |
| | Test effectiveness of infrared | ** | ** | ** |
| | Test effectiveness of aerial/camera imagery | ** | ** | ** |
| How can we reduce the risk of beaked whales and sonar being reduced? | ** | ** | ** |
| | Develop methods to find cold hot spots (time and space) | ** | ** | ** |
| | Develop repellents and modify live training in order to improve effectiveness of sonar operators (in order to reduce live use of sonar) | ** | ** | ** |

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<table>
<thead>
<tr>
<th>Research question</th>
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<th>Characterizing dose-response relationship</th>
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<td>What is the effect of propagation conditions?</td>
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<td>Models of and measurement of sound fields under varying propagation conditions (surface duct, reverberation, others)</td>
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<tr>
<td>Have stranding rates changed?</td>
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<td>Epidemiological analyses of historical data on seismic survey activity</td>
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<td>Has seismic activity affected the distribution and abundance of any marine mammal?</td>
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<td>Analysis of historical distribution data and seismic activity</td>
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<td>Where are the marine mammals?</td>
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<td>Survey (acoustic or visual) throughout year and all oceans including principal haulouts</td>
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<td>Target effort at existing and prospective seismic survey sites</td>
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<td>Recording diving behaviour (instrumented animals, remote observation incl. acoustics)</td>
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<td>Recording movement data (long-term telemetry, photo id, focal follow)</td>
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<td>Habitat utilisation models (based on data from surveys; telemetry; past catch data)</td>
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<td>Stranding and haulout data</td>
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<td>What is the overlap of marine mammal distribution with sound sources?</td>
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<td>Combine output above two approaches using geospatial and temporal modeling</td>
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<td>How do behavioral changes modulate exposure?</td>
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<td>Instrumented animals</td>
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<td>Acoustic tracking in three dimensions</td>
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<td>Visual behavioral observation</td>
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<td>What are the received sound characteristics?</td>
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<td>Instrumented animal</td>
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<td>Hydrophone()</td>
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<td>Modeling received sound characteristics</td>
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<td>Are there physiological responses?</td>
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<td>Molecular and physiological indices of stress in exposed and unexposed animals</td>
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<td>Physiological tags (e.g. samples at short intervals)</td>
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<td>Are sampling attended or try-cought animals for evidence of chronic stress in areas of seismic activity and non-activity</td>
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<td>Do airguns have a direct physical effect?</td>
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<td>Determine threshold of direct acoustic trauma</td>
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<td>Model threshold of direct acoustic trauma</td>
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<tr>
<td>Experiments and modeling with surrogate species</td>
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<tr>
<td>Experiments to determine onset of TTS (and PTS?) from varying number of airgun pulses at varying levels</td>
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<td>Determine hearing function (using ABF in individuals that have probably had a high vs to exposure to seismic)</td>
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<td>What is the behavioral response?</td>
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<td>Measure changes in behaviour in presence/absence of seismic tags, visual observation acoustic means</td>
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<tr>
<td>Experiments and observations with model species selected as vulnerable and use of surrogate species where endangered species are concerned</td>
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<tr>
<td>How do habitat displacement and over what temporal and spatial scales?</td>
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<td>Photos ID</td>
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<td>Satellite tags</td>
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<td>Survey and monitoring (visual and acoustic)</td>
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<td>Genetics</td>
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<td>Voices of animals (skunks)</td>
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<td>Dietary assessment/parasite fauna</td>
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<td>How were the survival and survival rates affected?</td>
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<td>Long-term studies of identified individuals (multiple techniques)</td>
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<td>Studies of population and social structure with and without/before and after exposure</td>
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<td>What is the probability of impacts on individuals?</td>
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<td>Models that integrate exposure and response of individuals</td>
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<td>Models that integrate exposure and response of prey species</td>
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<td>Are sensitivity vary between individuals?</td>
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<td>Measure responses of known individuals</td>
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<td>Compare pre- and post-exposure species distributions</td>
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<td>How are populations and their vital rates affected?</td>
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<td>Long-term studies of identified individuals (multiple techniques)</td>
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<td>Studies of population and social structure with and without/before and after exposure</td>
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<td>What is the probability of adverse population impacts?</td>
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<td>Define extent of population</td>
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<td>Extrapolate individual models to populations</td>
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<td>Models that integrate exposure and changes of population parameters</td>
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<tr>
<td>What is the effect of changing the acoustic source, operational characteristics and location of the source?</td>
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<td>Re-engineer sound source based on understanding of causes (physical and biological) of adverse effect and whale biology and test results of these changes</td>
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<td>Modeling informed by the above</td>
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<td>Experimental variation in source acousticity/operation/location, monitor response</td>
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<tr>
<td>Monitoring effects of (non-experimental) variation in sources/operation/location</td>
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<td>In ramp-up an effective mitigation measure?</td>
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<td>Monitoring (visual or acoustic) of ranges of marine mammals with varying number of gun operating</td>
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<td>Experimental or observational acoustic studies of instrumented animals during ramp-up period</td>
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<td>Monitoring behaviour of animals (visual and acoustic) tracked during ramp-up</td>
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<td>How can marine mammals be detected within the operational zone at real time?</td>
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<td>Test effectiveness of active acoustic</td>
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<td>Test effectiveness of passive acoustic</td>
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<td>Test effectiveness of visual detection</td>
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<td>Test effectiveness of Radar</td>
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<td>Test effectiveness of lidar</td>
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<td>Test effectiveness of infra-red</td>
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<td>Test effectiveness of visual imaging</td>
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<td>How to reduce risk of overlap between marine mammals and seismic surveys?</td>
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<td>Within current prospective survey area, find season with lowest abundance and/or vulnerability</td>
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<td>To avoid unnecessary exposure, encourage/legislate sharing of seismic data</td>
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<td>How to design MPAs to minimize risk to animals in areas where seismic exploration is likely?</td>
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<td>Survey</td>
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<td>Movement patterns</td>
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<td>Studies of response/vulnerability as listed above</td>
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<td>Habitat characterization modeling</td>
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<td>Empirical buffer areas are required to reduce risk to animals within marine protected areas consistent with goals of the protection?</td>
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<td>Measure and model propagation from MPA boundary</td>
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<tr>
<td>Monitoring sound field within and at boundary of MPA during seismic activity</td>
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</table>
Table 3. Research questions and approaches addressing the higher-level question “what is the interaction of shipping traffic noise with baleen whales?” Under each category, an approach has been scored as “high” (three dots), “medium” (two dots) and “low” (one dot). “dep” signifies that the score depends on the species or circumstances.

<table>
<thead>
<tr>
<th>Biological significance</th>
<th>Financial cost</th>
<th>Cost to animal</th>
<th>Effectiveness</th>
<th>Feasibility</th>
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</thead>
</table>

**What is the range of frequencies, intensities and duration of exposure (that causes risk)?**
- Compare spectral overlap of baleen whale calls with distribution of third octave levels (TOLs) of shipping noise
- Compare spectral overlap of other ecologically important sounds with distribution of third octave levels (TOLs) of shipping noise
- Modelled sound in important habitats near shipping channels, etc.
- Empirical measurements of sound field and modelling
- Analysis of historical data on source characteristics and long-term traffic and ambient noise levels

**What is the effect of propagation conditions?**
- Map distribution of animals as a function of noise to test whether noise fields affect distribution
- Modelling and measurement of sound fields under varying propagation conditions

**Are there unique habitat characteristics that create a hazard?**
- Survey of historical data sets with varying coastal characteristics and ship tracks and marine mammal distributions
- Studies using surrogate species

**Does shipping traffic noise affect risk of collision?**
- Epidemiological analysis of historical data on collision/other threats and vessel/traffic noise
- Experimental studies by changing vessel noise and monitoring reactions
- Modelling sound fields

**Where are the noise sources?**
- Shipping company databases, vessel monitoring systems and logs
- Ocean observing systems

**How do behavioural changes mediate exposure?**
- Instrumented animals
- Acoustic tracking in three dimensions
- Behavioural models
- Typify behavioural states and relate to exposure
- Visual behavioural observation

**What are the received sound characteristics?**
- Instrumented animal
- Long- and short-term acoustic monitoring
- Model received sound characteristics

**Do baleen whales respond to compounds of increased vessel noise?**
- Acoustic behaviour in detail with measurements of noise level at animal and source level of calls (instrumented animals)
- Baseline observations of calling behaviour from hydrophones
- Measure behaviour (e.g. spacing of animals in high and low noise environments)
- What are the functions or sound produced by baleen whales?
- Passively acoustic measurement of calling behaviour in signaler and responder
- Acoustic measurement of caller, measure responses on instrumented animal

**How do baleen whales utilize sounds from other sources (e.g. predator calls, ambient noise)?**
- Modelled sound in important habitats near shipping channels, etc.
- Models that integrate exposure and response of individuals
- Models that integrate exposure and response of populations
- Models that integrate exposure and changes of population parameters

**Could chronic vessel noise cause threshold shifts?**
- Compare the auditory brain stem response (ABR) of whales from noisy and quiet environments
- Experiments and modelling with surrogate species
- Models that integrate exposure and response of individuals
- Models that integrate exposure and response of populations

**Can chronic vessel noise cause threshold shifts?**
- Measure changes in behaviour to playback in presence/absence of vessel, using tags, acoustic and visual observation

**Is there habitat displacement and over what temporal and spatial scales?**
- Statistical analysis of tracks relative to bathymetry
- Baseline observations of calling behaviour from hydrophones
- Previous and current call characteristics

**How has vessel noise and traffic noise changed as a component of ambient sound across space and time?**
- Map distribution of animals as a function of noise to test whether noise fields affect distribution
- Modelling and measurement of sound fields under varying propagation conditions

**Where are the sources?**
- Surveys (acoustic or visual) throughout year and all oceans
- Recording diving behaviour (instrumented animals, remote observation incl. Acoustics)
- Recording movement data (long-term telemetry, photo id, focal follow)
- Habitat utilisation models (based on data from surveys, telemetry, catch data)

**What is the overlap of marine mammal distribution with sound sources?**
- Compare output of two approaches using geospatial and temporal model

**Do baleen whales respond to ship traffic noise changes?**
- Statistical analysis of tracks relative to bathymetry
- Baseline observations of calling behaviour from hydrophones
- Experiments and modelling with surrogate species
- Models that integrate exposure and response of individuals
- Models that integrate exposure and response of populations

**How do populations and their vital rates affected?**
- Long-term studies of identified individuals (multiple techniques) in different noise conditions
- Studies of population and social structure
- Compare populations in quiet and noisy areas

**What is the productivity or immune response of individuals?**
- Models that integrate the exposure and response of individuals

**What is the effect of shipping traffic noise on marine mammal populations and communities?**
- Re-argue vessel propulsion to reduce sound levels in frequency range of whale calls
- Modelling informed by the above
- Experimental variation in source acoustic/operation/location and monitor response
- Monitoring effects of uncontrolled variation in source/operation/location

**How can baleen whales be detected in real time in order to reduce vessel collisions?**
- Acoustic detection
- Passive acoustic
- Visual
- Radars
- Infrasound

**How can the overlap between baleen whales and vessel noise be reduced?**
- Develop new routing methods informed by the geospatial temporal models

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Annex IV


Marine Board-ESF and NSF Workshop

Marine Mammals and Acoustic Geo-Surveying Techniques


This Annex gathers abstracts and presentations given during a joint Marine Board-ESF/NSF workshop held in London on September 27, 2004. This event gathered 34 international experts, of which 10 came from the United States.

The workshop was jointly chaired by Howard Roe (Director, Southampton Oceanographic Centre, representing the Marine Board - ESF) and Mike Purdy (Director, Lamont Doherty Earth Observatory, Columbia University, representing NSF); it was co-ordinated by the Marine Board-ESF secretariat.

Objectives and Outcome

The workshop addressed the impacts of acoustic surveying techniques on marine mammals, including legal and practical implications for survey work. It was agreed that a smaller joint Marine Board-NSF working group would be convened, to ultimately produce this position paper, based in part on the workshop proceedings.

The group agreed on the following recommendations:

1. establish some mechanism to allow better co-ordination of research between the US and Europe, ultimately leading to jointly funded research programmes between the two;

2. establish database to enhance the sharing of data; US and European data must be made compatible;
Agenda

09:00 Coffee

09:15 Welcome by Marine Board (N. Connolly)
Introduction to workshop’s Co-Chairs - M. Purdy (LDEO/Columbia University) - H. Roe (Southampton Oceanography Centre)

09:30 Topic 1: Marine geo-surveying techniques
An overview of the surveying techniques employed during the Irish National Seabed Survey & mitigation measures adopted during recent Irish Surveys onboard the RV Celtic Explorer to avoid disturbance to cetaceans
Discussion - 30 min.

10:15 Topic 2: Recent results relating acoustics to marine mammal strandings and how these are being interpreted by government and other officials in respective countries
Presentation: (P. Tyack) – 20 min
Facts related to acoustics and strandings.
Discussion - lead: Richardson

11:00 Coffee Break

11:20 Topic 3: What is known about beaked whales and “the bends”? Is there a scientifically viable “bends” scenario that could explain some stranding events?
Presentation (P. Jepson, Zoological Society of London) – 20 min.
Bubble lesions
Discussion - lead: Natchigall plus P. Jepson.

12:05 Topic 4: What is the impact of regulations on the use of active acoustics for ocean research? What is the impact on research on marine mammals?
Presentation (C. Burt, Naval Systems UK; R. Rogers QinetiQ) – 20 min.
The Royal Navy Environmental Research Programme
Discussion - lead: Hastings plus C. Burt.

12:50 Lunch Break
13:50 **Topic 5:** Mitigation strategies - best practices. From a scientific perspective, what works and what doesn’t. Status of new technologies such as passive/active detection

**Presentation** (G. West, Southampton Oceanography Centre) – 20 min.  
*Can we adopt coherent/uniform mitigation strategies across NSF/ESF*  
**Discussion** - lead: Gentry plus G. West

14:35 **Topic 6:** Scientific techniques and results for assessing acoustical impacts on marine mammals. How does the science community rate the impact of acoustics on marine mammals in comparison to other potential threats to marine mammal populations?

**Presentation** (J. Gordon, University of St Andrews) – 20 min.  
*Scientific techniques and results for assessing acoustical impacts on marine mammals; marine mammal acoustic research and expertise at SMRU*  
**Discussion** - lead: Tolstoy plus J. Gordon.

15:20 **Coffee Break**

15:40 **General discussion - What can we do together?** (lead: M. Purdy and H. Roe)

Topics to include: Possibilities for joint research projects, sharing of new and existing marine mammal data bases; new technologies, cooperation on response to strandings including measurement protocols.

17:30 **End of the Workshop**
**Topic 1: Marine geo-surveying techniques**

*Mitigation measures adopted during Celtic Explorer geophysical surveys to minimise disturbance to Cetaceans*

John Breslin (Marine Institute, Ireland) and Mick Geoghegan (Geological Survey of Ireland)

The Marine Institute and GSI observe the Joint Nature Conservation Committee (JNCC) regulations as a precautionary measure to avoid disturbance to marine mammals.

All cetacean species in Irish waters are protected by the 1976 Wildlife Act (and Wildlife Amendment Act 2000). Irish waters, including the EEZ were declared a whale and dolphin sanctuary in 1991. All cetacean species are also protected under the EU Habitats Directive 92/43/EEC Article 12 and the harbour porpoise and bottlenose dolphin are listed under Annexe II of the Habitats Directive, requiring the designation of special areas of conservation (SACs) for their protection.

Currently the waters covered by the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS) do not extend to Irish waters and Ireland is not a signatory. However it is expected that offshore operators carrying out seismic surveys have due regard for the aforementioned guidelines.

During the Irish National Seabed Survey (INSS) and seismic surveys the Irish Whale and Dolphin Group are invited by the Marine Institute to place an observer on board the Celtic Explorer. Observers are required to oversee the implementation of JNCC guidelines along with providing a report detailing sightings, methods of detection, problems encountered, and recommendations for improving future mitigation strategies. At the survey planning stage, consultation with mammal experts is undertaken and literature searches are carried out to determine the likelihood that mammals will be encountered.

During the INSS surveys a ‘soft start’ procedure has been established to allow mammals to move away from the area. Prior to beginning operations within an SAC the Marine Institute were notified that it would be prudent to avoid surveying within the area due to presence of calving dolphins within the SAC at the time of the survey. The survey vessel maintained an exclusion zone of 1km from the Western boundary of the SAC throughout the survey. If a pod of cetaceans came within 500m of the vessel, all systems were switched off until they departed. The utilisation of PAM devices for the 2005 survey may be investigated.
Mitigation measures adopted during Celtic Explorer geophysical surveys to minimise disturbance Cetaceans

John Breslin
Manager Research Vessel Operations
Marine Institute, Ireland

Observation of JNCC Guidelines

- The Marine Institute and GSI observe the JNCC regulations as a precautionary measure to avoid disturbance to marine mammals.
- All cetacean species in Irish waters are protected by the 1976 Wildlife Act (and Wildlife Amendment Act 2000) and Irish waters, including the EEZ were declared a whale and dolphin sanctuary in 1991.
- All cetacean species are protected under the EU Habitats Directive 92/43/EEC Article 12 and the harbour porpoise and bottlenose dolphin are listed under Annex II of the Habitats Directive, requiring the designation of special areas of conservation (SACs) for their protection.

Observation of JNCC Guidelines

- Currently the waters covered by ASCOBANS do not extend to Irish waters and Ireland is not a signatory. However, it is expected that offshore Operators carrying out, or commissioning seismic surveys, will have due regard for the guidelines, produced by the Joint Nature Conservation Committee (JNCC) and the agreement on the Conservation of Small Cetaceans of the Baltic and North Sea (ASCOBANS). The requirements of the guidelines are readily adaptable to Irish conditions.
- The rules and procedures manual for offshore exploration and appraisal operations issued by the Petroleum Affairs Division requires that a local fisheries liaison officer should be on board the vessel for the duration of the survey. Specifically, during seismic surveys, the Operator will ensure that current best industry practices are applied with regard to impact, mitigation and monitoring measures in relation to marine mammals.

IRISH WHALE AND DOLPHIN GROUP

- During the INSS the Irish Whale and Dolphin Group are invited by the Marine Institute to place an observer on board the Celtic Explorer during the course of the Irish National Seabed Survey and during seismic surveys. The IWDG utilise the INSS to conduct a distribution and relative abundance survey of cetaceans in Irish Waters. Observers are required to oversee the implementation of Joint Nature Conservation Committee (JNCC) guidelines for minimising acoustic disturbance to marine mammals from seismic surveys (JNCC 2004).

Mitigation Measures to avoid disturbance

Planning Stage

- Consultation with mammal experts and literature searches to determine the likelihood that mammals will be encountered
- Planning – Ensure work carried out outside calfng and breeding seasons when animals are likely to concentrate in discrete locations
- Ensure that appropriately qualified personnel are available to act as mammal observers onboard the vessel
- Use the lowest practicable power levels throughout the surveys
**Mitigation Measures Cont.**

- **During Surveys**
  - Follow the correct ‘soft start’ procedure to allow mammals to move away from the area should they wish to.
  - No unnecessary shooting of guns and no protracted shooting of guns which is not part of a survey line.
  - Marine mammal observers to provide a detailed report to the Marine Institute and GSI detailing sightings, methods of detection, problems encountered, and recommendations for improving future mitigation strategies.

**Soft Start Mitigation Strategy used during INSS**

- 20min before soft start begins. Mammal Observer must scan to give all clear.
- Once all clear given. All acoustic systems are started at low power at 1min intervals for 10min.
- If no mammals observed – commence survey.
- During turns the survey operations continued with all systems operational and on full power.

**Soft Start Measures used during air gun (60cu inch) work for Site Survey**

- 50min before commencement of the survey line and 20min before starting the air guns a 30min survey for mammals was conducted from the observation platform.
- Provided no mammals were present within 500m of the vessel in those 30min, the soft start process was initiated 20minutes prior to commencement of the survey line.
- Once all clear given. Pop gun at 1000psi at 1min intervals for 10min.

**Soft Start Measures - air gun (60cu inch) work Cont.**

- Increase pressure to full (2000psi) and pop at 1min interval for 5min.
- Keep pressure on full and pop at 30sec intervals for 5min.
- If no mammals observed – commence survey.
- Transects were only 100m apart so gun firing was maintained at full pressure during turns.

**RV Celtic Explorer – Summary of acoustic systems**

- Multibeam echo sounder Kongsberg Simrad EM1002 (95kHz)
- Kongsberg Simrad EA600 Hydrographic Echosounder capable of operating in passive or active mode (12kHz, 18kHz, 38kHz, 120kHz, 200kHz)
- SES Sub-bottom profiler (4kHz)

**SAC –Mitigation Strategy**

- Prior to beginning operations within an SAC the Marine Institute were notified that it would be prudent to avoid surveying within the area due to presence of calving dolphins within the SAC at the time of the survey.
- The survey vessel maintained an exclusion zone of 1km from the Western boundary of the SAC through the survey.
- If a pod of cetaceans came within 500m of the vessel whilst operational, all systems were switched off until they departed.
- Soft start guidelines were adhered to on start up.
- The utilisation of PAM devices may be investigated for the 2005 survey.
Survey effort and sightings recorded on approaches to the Shannon Estuary – May 2004
Irish National Seabed Survey

Marine Board ESF and NSF Marine Mammals & Acoustic Surveying Workshop

London September 27th
Michael Geoghegan, GSI & John Breslin, MI

Background to INSS Project
- 1999 - Government decision to allocate funds to carry out survey
- Managed by the Geological Survey of Ireland (GSI) with the Marine Institute as a strategic partner.
- Project area encompasses the majority of Ireland’s designated waters.
- Total allocation, over a seven year period of almost €32m
- Surveying began in July 2000

National Seabed Survey
Science Serving Society

- Sovereignty
- Marine Safety
- Fishing
- Offshore Aquaculture
- Oil and Gas Exploration
- European Celtic Sea
- Renewable Energy
- Marine Aggregates
- Coastal Zone Management
- Integrated Ocean Management
- Marine Heritage
- Research
- Celtic Explorer

National Seabed Survey
Techniques

- Multibeam Echo Sounding
- Sub Bottom Profiling
- Side Scan Sonar
- Magnetics and Gravity
- Deep Seismic Data
- High resolution Seismics
- Ground Truthing
- SVP/CTD
- Laser Airborne
- Ancilliary Projects

Vessels

Ocean Seeker
Professor Logachev
Akademic Boris Petrov
SV BLIGH
SV Siren
Granuaile
RV Celtic Voyager
Celtic Explorer
Marine Mammals and the INSS

- Irish Whale and Dolphin Gp. (IWDG) Representative on Technical Advisory Committee
- Cetacean Observers on Vessels from CMRC in Cork
  - Direct observations
  - Acoustic recording of cetacean vocalisations
- HADES deep seismic survey Hatton area.
- High resolution seismic survey West of Rockall – Hatton
- IWDG observation forms on all vessels
- Attention to SAC’s
Seismic work – Observers Role

- To carry out duties of marine mammal observers as outlined in JNCC guidelines on minimising acoustic disturbance to marine mammals during periods of active seismic survey
- To observe Cetacean and bird activity in areas surveyed

Actions taken to minimise disturbance

- Tech Advisory Comm laid down broad guidelines
- 1995 UK DoE and JNCC guidelines implemented e.g. 500m range visual obs taken for 30 mins before seismic activity
- Two observers present
- Hydrophone array

HADES seismic profiles

Source array on RV Akademik Boris Petrov

High Resolution Seismics 2004
Pre-soft Start Observations.

The guidelines for minimising acoustic disturbance to marine mammals during seismic surveys, devised by the JNCC, have been adhered to throughout the survey. Specific 360° scans for cetaceans were conducted around the vessel for 30 minutes before all soft-start seismic activities. The only cetaceans recorded during this pre-soft start period involved a group of unidentified dolphins actively swimming 1000m from the ship, which is twice the recommended distance listed in the JNCC guidelines. As such, no downtime due to the presence of whales and dolphins has been incurred during the current survey.

Cetacean Observation example

Nine cetacean species have been recorded during the first two weeks of the survey. As has been during previous seismic surveys in the Hatton-Rockall region, the Long-finned Pilot Whale is the most abundant and frequently encountered cetacean species. Of the 58 cetacean encounters (n=27) already recorded thus far, approximately 40% involved Long-finned Pilot Whales (n=11). The most interesting observations have been recorded southwest of the Hatton Bank and along the eastern slope of the Iceland Basin. Eight of the nine species recorded, were observed in this region in a two-day period. These included rarely encountered species such as Northern Bottlenose Whales, False Killer Whales, Sowerby’s Beaked Whales and Killer Whales. The only baleen whale species recorded to date involved the sighting of a single Humpback Whale breaching 3-4km ahead of the ship southwest of the Hatton Bank. Approximately 75% of all sightings were recorded during seismic operations.

Groundtruthing

Profile of box core. Finer sediment on top.
**Biological Analysis**

- New species are being identified and one specimen that cannot be identified to family level – which is exciting.
- Opheliidae, Ophelina farallonensis - tiny worm (7mm in length) - previously only described in deep water off the central Californian coast.
- New Key for deep waters.
- Many new species which will be lodged with the National Museum of Ireland at the end of the study.
- Important baseline work.

Ophelina farallonensis

**Laser Airborne Depth Sounder (LADS) Technology**

- LADS provides high speed data collection in clear shallow areas.
- 900 soundings per second in a 5m x 5m grid.
- 70 metre depth capability.
- Up to 7 hours on task.

**Clew Bay**

**Progress**

- PAD 1996
- Celtic Explorer 2003
- Granuaile 2003
- Celtic Voyager 2003
- Concat 2004
Topic 2: Recent results relating acoustics to marine mammal strandings and how these are being interpreted by government and other officials in respective countries

Recent results relating atypical marine mammal strandings to anthropogenic sound.

Peter L. Tyack (Biology Department, Woods Hole Oceanographic Institution)

Records of strandings of marine mammals go back two millennia, and most strandings are thought to be caused by natural factors such as storms and disease. Mass strandings are usually defined as involving >2 or 3 animals, usually stranding in same place and time. Since 1963 there have been atypical mass strandings of beaked whales, often species not sighted in same group, within a few hours but over tens of km of coast. Atypical mass strandings have been defined by Frantzis (1996) as involving many beaked whales, especially Ziphius cavirostris and Mesoplodon sp. stranding within a few hours in dispersed groupings over tens of km of shore. They have been reported to coincide with naval maneuvers off Greece (1), Canary Islands (7), Italy (2), Bahamas (1), Madeira (1) [List from US Marine Mammal Commission Beaked Whale Workshop Report submitted to Journal of Cetacean Research and Management]. All cases in which the ships are known involve ships with mid-frequency sonars.

The actual acoustic fields have only been estimated for two cases: Greece 1996 and Bahamas 2000. The Greek case involved a NATO sonar research exercise. 16 Ziphius strand alive along 30-35 km of coast within hours of sonar transmissions (D’Amico 1998). The Bahamas case involved a multinational anti-submarine training exercise with several ships operating in New Providence channel (US NMFS and Navy 2001). 17 cetaceans stranded within 36 hr over 240 km. 7 died (5 Ziphius, 1 Mesoplodon densirostris, 1 Stenella frontalis). Necropsies have been conducted of stranded whales in 3 cases. Ketten (in Evans & Miller 2004) detailed necropy results from examination of heads of beaked whales from strandings in Madeira and the Bahamas. She reported hemorrhage in the space between brain and outer membrane, inner ear, and small hemorrhage in acoustic fats. Fernández (in Evans & Miller 2004) necropsied whole bodies of beaked whales stranded in the Canaries and reported severe, diffuse congestion and hemorrhage especially within the ears, brain, lungs, kidneys and the acoustic fat of the jaws. Jepson et al. (2004) report from the same necropsies, vascular and tissue changes consistent with gas bubble lesions and fat emboli in vital organs.

While there is a correlation between these atypical mass strandings of beaked whales and naval exercises, the cause is unknown. The US NMFS and Navy (2001) Interim report on Bahamas strandings states “acoustic or impulse trauma [that] led to their stranding and subsequent death.” One hypothesis suggested for injury at relatively low levels concerns the idea that resonant structures in beaked whales might be particularly sensitive to sound at the resonant frequency. A US NMFS (2002) workshop concluded resonance unlikely cause of injury or strandings. Jepson et al. (2004) reported evidence for gas emboli in stranded cetaceans, and they suggest that emboli may be caused by a direct acoustic effect on supersaturated tissue or an abnormal behavioral reaction to sound.
Experimental results from other species suggest different ranges of exposures may relate to each of these hypotheses. For lung resonance, 184 dB re 1 μPa marks the onset of tissue damage in mouse for 5 min at the resonant freq (US NMFS 2002). Larger animals require higher exposures, and the resonant frequency estimated for beaked whales is <30 Hz. Acoustically enhanced bubble growth is a function of supersaturation, duration, and intensity. Crum and Mao expect little risk for exposures <190-200 dB re 1 μPa. By contrast a behavioral reaction could occur at any level that is detectable to the animal. For an example from a different species, right whales rapidly ascend to surface on exposure to similar sounds at RL in the 130-150 dB re 1 μPa (Nowacek et al. 2004)

References

Recent results relating acoustics to marine mammal strandings and how these are being interpreted by government and other officials in respective countries

Peter L. Tyack
Biology Department
Woods Hole Oceanographic Inst

Marine Board-ESF and NSF Workshop
Marine Mammals and Acoustic Geo-Surveying Techniques
Sept 27th2004, IEE, London

Atypical mass stranding events

- >10 Beaked whales, especially *Ziphius cavirostris* and *Mesoplodon* sp. strand within a few hours in dispersed groupings over tens of km of shore.
- Reported to coincide with naval maneuvers off Greece (1), Canary Islands (7), Italy (2), Bahamas (1), Madeira (1) [List from MMC Beaked Whale Workshop Report]
- All known cases involve ships with mid-frequency sonars

Strandings

- Strandings of marine mammals are normal events. Records of strandings go back two millennia
- Mass strandings involve >2or3 animals, usually stranding in same place and time
- Since 1963 there have been atypical mass strandings of beaked whales, often species not sighted in same group, within a few hours but over tens of km of coast

Actual acoustic fields only known for two cases: Greece 1996 and Bahamas 2000

- Greece: NATO sonar exercise. 16 *Ziphius* strand alive along 30-35 km of coast within hours of sonar transmissions
- Bahamas: multinational ASW exercise with several ships operating in New Providence channel. 17 cetaceans stranded within 36 hr over 240 km. 7 died (5 *Ziphius*, 1 *Mesoplodon densirostris*, 1 *Stenella frontalis*).

Sonar Signals used in Greece

D’Amico 1998 Saclantcen M-133

- **SL 700 Hz**
  - 228 dB re 1 μPa at 1 m
- **SL 3000 Hz**
  - 228 dB re 1 μPa at 1 m

Sonar runs and strandings 12 May 1996
Marine Board – ESF Position Paper: The effects of anthropogenic sound on marine mammals – A draft research strategy

Italian Strandings wrt Sonar Test

D’Amico 1998
Saclantcen M-133

Sonar runs and strandings 13 May 1996

Bahamas 15 March 2000

• Naval sonar exercise as ships passed through New Providence Channel near Abaco
• 4 of 5 ships used mid freq sonars
  – AN/SQS-53C 2.6-3.3 kHz ~235 dB re 1 µPa
  – AN/SQS-56 6.8-8.2 kHz ~223 dB re 1 µPa
• 17 cetaceans stranded within 36 hr over 240 km. 7 died (5 Ziphius, 1 Mesoplodon densirostris, 1 Stenella frontalis).

BAHAMAS Peak Sound Pressure Level for all Ships over 21 hr period

Hildebrand presentation to July MMC

Duration of exposure to received levels from 165-170 dB(rms) re 1µPa at 15 m depth

Hildebrand presentation to July MMC
Duration of exposure to received levels from 175-180 dB re 1μPa at 15 m depth

Reverberation with ping, Rep Rate 24 s, Total time 5 min

Sighting Data with Exposure to Sound Pressure Levels between 160-163 dB using SPL at 15 m depth

Simulations can compensate for limited observational data

Parameters for Simulations
- Acoustic propagation: e.g. In situ surface duct v. downward refracting
- Distribution – Uniform v. Field Data
- Dive behavior: Normal Diver v. Duct-only diver
- Horizontal swim behavior: No aversion to sound level v. Graded aversion to sound level

Example Exposure History

Mean exposure level = 131.1 dB
Necropsies of stranded whales in 3 cases:
- Bahamas (Ketten: detailed necropy limited to heads): hemorrhage in space between brain and outer membrane, inner ear, and small hemorrhage in acoustic fats.
- Madeira (Ketten: detailed necropy limited to heads): similar to Bahamas.
- Canaries (Fernández: whole body): severe, diffuse congestion and hemorrhage especially within the ears, brain, lungs, kidneys and the acoustic fat of the jaws. Vascular and tissue changes consistent with gas bubble lesions and fat emboli in vital organs.

Hypotheses re cause of strandings:
- While there is a correlation between strandings and naval exercises, the cause is unknown.
- US NMFS and Navy (2000) Interim report on Bahamas strandings: “acoustic or impulse trauma that led to their stranding and subsequent death.”
- Jepson et al. (2004) covered in next talk. Gas emboli caused by:
  - Acoustic effect on supersaturated tissue
  - Abnormal behavioral reaction to sound

Exposures related to hypotheses:
- Lung resonance: 184 dB re 1 μPa onset of tissue damage in mouse for 5 min @ resonant freq (<30 Hz for beaked whale)
- Acoustically enhanced bubble growth: function of supersaturation, duration, and intensity. Little risk <190-200 dB re 1 μPa
- Behavioral reaction could occur at any level that is detectable to the animal (right whales rapidly ascend to surface on exposure to similar sounds at RL in the 130-150 dB re 1 μPa)

Other cases of typical strandings where association with manmade sound is controversial:
- Beaked whale stranding and seismic signals
  - Gulf of California
  - Galapagos
- Mid-frequency sonar and
  - Harbor porpoise strandings (Pac NW US)
  - Melon-headed whales (swam into bay, Hawaii)

Gulf of California:
- 2 Ziphias found stranded together freshly dead
- RV surveying within tens of km on same day with following sources:
  - Airgun array broadband impulse directed downwards SL 236-262 dBp re 1 μPa at 1 m
  - Multi-beam sonar 15.5 kHz omnidirectional SL 237 dBrms re 1μPa at 1 m
  - Sub-bottom profiler 3.5 kHz directed downwards SL 204 dBms re 1μPa at 1 m
Track of Seismic RV wrt Stranding of 2 Ziphius
Range ~75nmi @ stranding and approaching for 1st time

Official government interpretations

- US on beaked whales and mid-freq tactical sonar
- NATO (Italian Navy similar)
- US, UK guidelines for seismic
- Technical reports for Royal Dutch Navy

Galapagos stranding during seismic survey
6-7 April 20 airgun array operates 400 nmi from stranding
9-11 April 10 airgun array operates 270 nmi from stranding

US NMFS and Navy

- Bahamas: “tactical mid-range frequency sonars aboard US Navy ships that were in use during the sonar exercise in question were the most plausible source of this acoustic or impulse trauma.” [definition of trauma may be more generalized in final report]

NATO Research Rules
( Italian Navy working on similar draft rules)

- Select area away from breeding grounds, sanctuary. Advance public comment
- Minimum SL to meet science objectives
- Trained visual observers, passive acoustic monitoring 30 min before to 30 min after ops
- Max RL at animal <160 dB re 1 μPa
- Only start if no animals near exclusion zone
- Ramp up from SL = 150 dB re 1 μPa
- Stop if animals detected that might enter exclusion zone

D’Amico 1998 Saclantcen M-133

US, UK guidelines for commercial seismic operations

- Visually monitor 500m exclusion zone for 30 min
- If no whales, begin rampup for 20-40 min
- Shutdown if whale detected <500m
- As long as transmissions maintain SL >=160 dB can continue operations when monitoring is ineffective (night, fog, high seas)
- UK encourages passive acoustic monitoring and requires in some settings. US allows ramp up during reduced visibility only if passive monitoring is used.

US MMS Notice to Lessees Gulf of Mexico 2004-G01
UK DTI Pos’n paper Sept 2003 (www.og.dti.gov.uk)
**Technical Reports to Royal Netherlands Navy**

- Based upon hearing sensitivity groups
- Max Exposure Levels TTS-15 or 20 dB
  - Baleen whales and dolphins 160-185 dB
  - Sperm and killer whales 140-160 dB
  - Porpoise 135-155 dB
- Monitoring and Mitigation
  - Visual and Passive Acoustic Monitoring (0 Hz-200 kHz)
  - Active whale detection not advised because of additional potential for impact
  - Exclusion zones (hearing group specific)
  - Ramp up (but notes unproven; may attract odontocetes)

Verboom 2000 TNO-HAG-RPT-000037; Verboom 2001 TNO-HAG-RPT-010056

**Melon-headed whales swim into Hawaii Bay during sonar exercise**

- Sonar exercise 60-80 nm away from Hanalei Bay the afternoon before the event, ending shortly after midnight. 1-2 ships transmitting at a time.
- Sonar exercise 26 nm away from the bay on the day animals sighted in bay at 0730. A ship tested sonar at 0645, and the exercise involved intermittent sonar use until 1624. Noise level from sonar would have been below ambient at Hanalei Bay.
- At 1624, Navy officials were notified of the whales in the bay and ceased all sonar transmissions. They didn’t resume sonar until 6 July. A single juvenile stranded and died of starvation.

**Strandings of Porpoise and Track of USN Destroyer using mid freq sonar**
**Topic 3: What is known about beaked whales and "the bends"? Is there a scientifically viable "bends" scenario that could explain some stranding events?**

**Beaked whales and “the bends”**

Paul D. Jepson (Zoological Society of London) & Antonio Fernández (Institute of Animal Health, Veterinary School, University of Las Palmas de Gran Canaria)

The demonstration of spatio-temporal links between some deployments of active mid-frequency naval sonar and mass cetacean strandings (predominantly involving beaked whales) is now widely accepted to be indicative of cause (sonar) and effect (stranding), although the underlying mechanism(s) have remained a topic of intense scientific debate.

Among potential mechanisms proposed for these stranding events, theoretical mechanisms for *in vivo* bubble formation in marine mammals mediated by exposure to loud anthropogenic sound sources (e.g. naval sonar) have been proposed. More recently, pathological findings consistent with *in vivo* bubble formation and decompression sickness (DCS) has been reported in three beaked whale species (involving 10 necropsied individuals) that mass stranded in the Canary Islands in 2002 contemporaneously with naval sonar use.

Bubble formation associated with acute and chronic tissue injury has been conclusively demonstrated in some individually-stranded cetaceans in the UK, although the definitive cause of these bubbles has not been established. These pathological findings demonstrate that cetaceans can suffer tissue injury associated with gas bubble development, most probably through a mechanism similar to DCS.

Emerging data from beaked whale dive profiles suggest that these species may be adapted to deep-diving through a combination of slow ascent rates and short surface intervals. There is now a growing scientific consensus that an initial behavioural disruption to normal beaked whale dive profiles (e.g. accelerated ascent combined with extended surface interval) induced by loud acoustic exposure such as naval sonar may precipitate a potentially fatal physiological response resulting in bubble formation in tissues and leading to mass stranding events.

The confirmation of *in vivo* bubble formation in cetaceans as a mechanism in sonar-induced beaked whale mass strandings, including the quantification of received levels of acoustic sonar activity necessary to trigger a specific and adverse behavioural response, undoubtedly necessitates the adoption of an experimental approach.
Beaked whales & “the bends”

Paul Jepson
BVMS PhD MRCVS

ZSL Institute of Zoology
LIVING CONSERVATION

In this figure, we took fresh rabbit liver, infused it with gassy water, compressed it for 2 hours, then slowly decompressed it. Note that there are a few bubbles that formed. The bar is 0.5 mm.

In this figure, the procedure was repeated, except here we insonified it with just 3 pulses of 37 kHz ultrasound, one second in duration, after decompression. The bar is 0.5 mm.

Demonstration of acoustically mediated bubble growth in liver (data courtesy of Larry Crum)

HISTOPATHOLOGY


summary of UK cases...

- 4/24 Risso’s dolphins, 4/400 common dolphins, 1/1 Blainville’s beaked whale, 1/1150 harbour porpoises
- In vivo bubble formation (gas embolism) associated with acute and chronic tissue injury
- Air embolism >> considered unlikely
- Nitrogen embolism possible
  - Decompression sickness-like mechanism
  - Acoustically-induced bubble growth (e.g. Crum & Mai 1996, Fossas et al. 2001)

UK-stranded cetaceans: new disease – unusual hepatic renal pathology

• Naval sonar-related cetacean mass strandings
  - Naval sonar activity linked (spatio-temporally) to numerous cetacean mass strandings
  - Events mainly involve beaked whales (esp. Cuvier’s beaked whale)
  - No beaked whale mass strandings recorded prior to 1963
  - Sonar-related mass stranding locations:
    - Bahamas
    - Bonaire
    - Canary Islands (6+)
    - Corsica
    - Greece
    - Madeira
    - Puerto Rico (multiple)
    - Japan (multiple)
  - Causal mechanism(s) not established
Table of Whale Stranding Instances:

<table>
<thead>
<tr>
<th>Ref</th>
<th>Species</th>
<th>Sex</th>
<th>Island</th>
<th>Preser. status</th>
<th>Necropsy</th>
<th>Temperature</th>
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<tr>
<td>CET180</td>
<td>Ziphius cavirostris</td>
<td>male</td>
<td>Fuerteventura</td>
<td>fresh</td>
<td>36 h.p.m. (4ºC, 24h.)</td>
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<td>36 h.p.m. (4ºC, 24h.)</td>
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<td>CET182</td>
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<td>Mesoplodon europaeus</td>
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<td>36 h.p.m. (4ºC, 24h.)</td>
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<td>54 h.p.m. (Env. T)</td>
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<tr>
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<td>Lanzarote</td>
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<td>54 h.p.m. (Env. T)</td>
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<td>72 h.p.m. (Env. T)</td>
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**PATHOLOGICAL FINDINGS IN MASS STRANDED BEAKED WHALES IN THE CANARY ISLANDS, 24-27 SEP 2002**

**24th September 2002**

- 3am - naval sonar exercise began (40km from nearest island)
- 5-6am - beaked whale strandings began
- 7am - most/all stranded beaked whales found were dead

**PATHOLOGICAL FINDINGS IN BEAKED WHALES STRANDED MASSIVELY IN THE CANARY ISLANDS, 24-27 SEP 2002**

- Ref: Reference number
- Species: Scientific name of the species
- Sex: Gender of the whale
- Island: Name of the island
- Preser. status: Condition of the whale at the time of necropsy
- Necropsy: Details of the necropsy
- Temperature: Temperature details at the time of necropsy (Environmental Temperature, necropsy temperature)

**24th September 2002**

- 3am - naval sonar exercise began (40km from nearest island)
- 5-6am - beaked whale strandings began
- 7am - most/all stranded beaked whales found were dead
• CNS immunohistochemistry (e.g. HSP70, GFAP)
• protein markers expressed within 1-2 hours of cellular insult
• timing of CNS lesion development consistent with 4hr period from initial sonar exposure (3am) to death (6-7am)
Northern bottlenose whale dive profiles

- slow ascent rates (for a cetacean!)
- absence of extended surface intervals


Hypothetical mechanism

- Environmental conditions (e.g. surface ducts) can enhance acoustic propagation
- Initial behavioural response to mid-freq. sonar exposure, e.g.
  - accelerated surface ascent
  - extended surface interval
  - >> induce high/excessive levels of nitrogen supersaturation >> predispose/induce bubble generation
  - +/- physical effect (nuclei destabilisation) of sonar ping >> may enhance bubble growth in supersaturated tissues
  - Continued sonar exposure/shelf edge topography prevents whales from diving (& recompressing bubbles)
- Patho-physiological consequences >> massive bubble formation/gas embolism >> death


Joint publication of UK/Canaries pathology

- Gas bubble lesions exist in cetacea
- UK cases: acute and chronic (predominantly hepatic) lesions
- Canaries cases: acute and widely disseminated lesions (similar to DCS)
- Suggest decompression sickness-like mechanism for bubble genesis
- Propose hypothetical mechanism for sonar-exposed whales or stranded animals via sonar-induced behavioural response (+/- acoustically mediated bubble growth) >> fatal gas bubbles/emboli


Evidence for altered dive profiles in northern right whales

 MMC BW Workshop (Baltimore, April 2004): testing the "bubble hypothesis"

- Behavioural
  - normal dive profiles
  - controlled acoustic exposure experiments (bottom-up)
- Physiological
  - confirm bubble formation in cetacea (e.g. *Tursiops*)
  - quantify critical level of nitrogen supersaturation
- Physical
  - acoustically-mediated bubble growth (in vitro)
- Pathological
  - revise necropsy protocols (detect emboli)
  - retrospective/prospective investigation of cetacean gas-bubble lesions

Acknowledgements

- Canary Islands research funded by the Ministry of Science and Research (Ren-2002-04105-C02-01/MAR), GD Fisheries (EU), Ministry of Defence and Canary Islands Regional Government
- UK research funded by UK Department for Environment, Food, and Rural Affairs (defra)
**Topic 4: What is the impact of regulations on the use of active acoustics for ocean research? What is the impact on research on marine mammals?**

**The Royal Navy Environmental Protection Research Programme**

Claire Burt (Naval Systems Department, Defense Science and Technology Laboratories, UK)

This presentation describes the current UK policy and research on the Impact of Sound on marine mammals.

It stated the Secretary of States policy that all practicable and reasonable steps, consistent with maintaining operational effectiveness, are to be taken within the RN with due regard for environmental legislation by taking any necessary measures to protect the environment.

The mitigation measures currently undertaken at sea including current command guidance are explained.

The shortfalls and capability gaps identified from above has resulted in a comprehensive research programme to close those gaps. All aspects of the research programme are discussed and presented including future aspirations. The realisation into an Environmental Risk Management capability for the Fleet was shown.
Background Requirements

MoD Environmental Protection Requirements are Policy Driven

MoD Environmental Protection Requirements are Policy Driven

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MoD Environmental Protection Requirements are Policy Driven
Top-Level Requirement

- The MoD requirement is to apply the Policy of the Secretary of State for Defence on protection of
  the natural environment
- This Policy requires that legislation is applied except where the MoD has been granted specific exemption
- For active sonar the primary goal is to minimise the risk to marine environment from acoustic transmissions whilst maintaining operational capability
- To rapidly transition the technical capabilities to the Fleet

Environmental Protection Requirements for Active Sonar Operations

- MoD must undertake an Environmental Impact Assessment for:
  - New equipment
  - New training activities
  - Trials
  - Exercises

Global EIA

Impact on Receptors (Humans/Mammals/Fish)
- Likely Areas of Operation
- Legal & Policy

Trial Specific EIA

Migration into Operational use

Mitigation Procedures

Before each Trial:
- Assess Area. Avoidance areas to be implemented with respect to sensitive areas and habitats for marine mammals (Based on PIS/TTS)
- Establish Mitigation Action (Zones etc.)

Monitoring Before, During & After Trial
-
Mitigation Measures (2)

• Visual and passive acoustic monitoring for marine mammals to be undertaken from the source ship and during trials from an independent environmental monitoring platform

• Avoidance of areas where fish spawning is likely to occur and monitoring for potentially visible fish species (e.g. Basking Shark)

• Modification of the sonar trials programme in response to environmental monitoring (e.g. cessation, temporary reduction or relocation of sonar transmissions, use of “soft start”)

Example of MoD Environmental Assessment Capability

• Environmental Strategy
• Screening/Scoping Study
• Global & Trials EIA
• Support to Business Case
• PR Strategy - Web Page, Conference Papers, Mitigation Migration Strategy
• Organic monitoring
• EP Support for Trials

Current Research Projects

Comprehensive environmental protection measures in support of S2087 STUFT1 Trials 2002

Comprehensive environmental protection measures in support of S2087 STUFT2 Trials 2004

Critical capability gaps defined by Royal Navy

• Capability of 24-hour all-weather marine mammal detection
• UK databases of marine mammal distribution and abundance
• Understanding of natural marine mammal behaviour and that in response to acoustic transmissions
  - e.g. exposure to prolonged low level transmissions or multiple frequencies, pulse types etc
**Marine Mammal DCL**

- MoD's aim is to have an integrated 24-hour all-weather marine mammal Detection, Classification and Localisation capability
- Envisaged primary methodology is via passive acoustics
- Passive acoustics will be supported by other detection technologies

**Passive Acoustics**

- Development of a passive acoustic marine mammal DCL capability integrated with in-service sonar
- QinetiQ undertaken research and are producing MMADS software
- Current version has excellent detection capability and can classify down to class level
- Tested at sea including during recent S2087 trials in the NW Approaches

**Visual Monitoring**

- All RN vessels maintain a watch
- RN watch keepers now undergo basic training
- MoD currently involved with ‘Ocean Eye’ project to quantify observer performance and identify where improvements to MMO training can be made.
- Results will lead to further developments in RN watch training programme

**Ocean Eye Full Bridge Simulator**

- Research ongoing into detecting, classifying and localising marine mammals by:
  - Passive Acoustics
  - Visual Monitoring
  - Radar
  - Electro-optical sensors

**Radar and Electro-Optical Sensors**

- A US/UK funded study has recently completed looking at utilising shipborne radar to detect and localise marine mammals
- MoD funded follow on work looking at using the Type 23 frigate radar to detect and localise marine mammals
- Electro-Optical Sensors fitted to the Type 23 Frigate have been assessed to examine their suitability for marine mammal DCL
- Sensors assessed include T23 IR pod and Night Vision Goggles
Marine Mammal Behaviour

- Various projects being conducted by QinetiQ and Sea Mammal Research Unit
- Assessment of the reliability of determining the temporal & spatial probabilities of encountering marine mammals in military training and exercise areas
- Acquire & assess current information on marine mammal behaviour
- Assess current MoD biological databases
- Will improve knowledge of risks to marine mammals

SMRU - JGS Funded Work

- Two Joint Grants Scheme projects, started Dec 02 (50% MOD, 50% UK research councils)
- 3 Year research projects on mitigating the effects of high power sonar systems on marine mammals:
  - Distribution of small cetaceans in shallow/shelf sea water and their responses to exposure to acoustic energy
  - Correlation of cetacean distribution with oceanographic features in the deep/shallow waters of the NW Approaches
- The outcomes will feed into the Fleet

Future Research Projects

- Platform Based DCL
  - Dstl studying RAF Nimrod and RN Merlin contribution to support MoD Environmental Protection requirements
  - Study concentrates on Searchwater and Blue Kestrel radars, but EO sensors also to be considered
  - Also study looking into potential to use submarine passive acoustic sonar arrays to achieve marine mammal DCL

Environmental Risk Management Capability (ERMC)

- **AIM** - To develop and procure an EIA “toolkit”
- **Commences late 2004**
- **Initial capability provided mid-2006**
ERMC

- Two applications of the ERMC:
  - Planning aid component to replace the existing EIA process
  - Real-time at sea guidance to command about the current levels of risk to the environment

- The ERMC will draw on research undertaken across MoD and other National/International Programmes
  - Dstl takes the MoD lead on knowledge integration process

- Initial 2006 in-service date will support S2087 equipped platforms, with other active sonar equipped platforms to follow

Any Questions?
**Topic 5: Mitigation strategies - best practices. From a scientific perspective, what works and what doesn’t. Status of new technologies such as passive/active detection**

**Acoustics & Marine Mammals - Mitigation Strategies**

Geraint West (UK Ocean Research Services, Southampton Oceanography Centre)

This presentation is an examination of general mitigation methodology in the context of practical experience on a UK Natural Environmental Research Council (NERC) seismic cruise in the Indian Ocean as well as a number of guidelines issued by the following:

- UK Joint Nature conservancy Council (JNCC) – adopted by NERC in the practical example.
- NATO SA CLANTCEN
- Environment Australia
- US Minerals Management Service (MMS)

Although these guidelines all adopt a common approach to mitigation strategy comparison of them highlights quite extreme divergence in detail, especially as far as applicability is concerned. In general though, mitigation measures can be examined under a simple set of headings (as adopted by the UK Royal Navy):

**Plan**
- Use of marine mammal distribution/habitat information sources;
- Identification of populations at risk (particularly protected species);
- Evaluation of impact of acoustic source;
- Adoption of appropriate protocols.

**Look**
- Visual methods
  - Requirement for and training of Marine Mammal Observers (MMO)
  - Recording of observations;
- Other aids including
  - Radar;
  - IR;
  - Electro-optical;

**Listen**
- Passive acoustics;
- Active

**Act**
- Pre-start observation
- Soft start protocols
- Turn/interruption protocol
- (feasibility of meeting guidelines, e.g. how measure every 2km?. Procedure adopted for Sonar 2087 trial - don’t want to be doing this for scientific surveys. Aim should be to reduce risk.
These areas all have significant outstanding issues which need further work or clarification:

**Planning**
- Marine mammal distribution/habitats is sparse or non-existent for some species and/or some geographical areas.
- Modelling of acoustic source can be extremely difficult in some areas, especially shallow waters.
- There is little scientific knowledge of how marine mammals actually react to sources and therefore how effective protocols such as ‘soft start’ really are.

**Look**
- There is no international standard for MMO training and considerable variability in the standards published by different guidelines.
- Reduced visibility at night, in fog or high sea-states significantly degrades the effectiveness of visual observational methods; in some cases cessation of acoustic transmission may therefore be necessary.

**Listen**
- Deployment of passive acoustic devices is costly both in terms of the capital costs of the equipment and the deployment scenarios which may be appropriate especially if this requires use of a separate platform from the source ship.
- Even with advances in software, interpretation of information from passive sources can be extremely difficult.
- Acoustic sources may offer an alternative, but their use is likely to be highly controversial.

**Act**
- Given that we have little information on how marine mammals react to acoustic sources; it can be difficult to assess how information from monitoring techniques should be used to modify operational protocols.

At the most basic level it would clearly be highly desirable to harmonise guidelines, however the variety of these suggest that there is little international agreement on how high the bar should be set and how operational protocols might be rationalised: Unfortunately this is a particularly difficult issue when set in the context of national regulatory regimes which also vary quite widely.
Acoustics & Marine Mammals Mitigation Strategies

Geraint West
UK Ocean Research Services

Marine Mammals Mitigation Strategies

- General Mitigation Methodology
  - Charles Darwin Cruise 144
  - Comparison of Guidelines
- Joint Nature Conservancy Council (JNCC)
- SACLANTCEN
- Environment Australia
- USA Minerals Management Service (MMS)

Guidelines - Applicability

US-JNCC
SACLANTCEN
Environment Australia
Gulf of Mexico (MMS)

- ‘all seismic operations… in waters greater than 200m’
- Mentions some marine mammals, specifically sperm whale are protected under ESA, and all under MMPA.
- ‘refer only to seismic operations and interactions with those cetaceans or whales listed…’
- ‘do NOT relate to… small cetaceans (dolphins) or other marine species (turtles or dugong)’
- ‘ANY… experimental activity in which it is intended to use high level sound sources’
- Specifically includes: divers & swimmers
  - Fish

- ‘aimed at minimising acoustic disturbance from seismic surveys and other operations where acoustic energy is released.’
- ‘Apply to ALL marine mammals…’
- ‘ALL surveys using higher energy sources sought’

General Mitigation

- Use of minimum level to achieve intended scientific result.
- Use of ‘soft starts’ whereby power is increased gradually over periods of >20 mins.
- Care should be taken with line lay-outs to avoid restricting animals’ ability to avoid the source.
- Equipment should be shut down if cetaceans are observed within a potentially harmful distance of the vessel defined by the source power, directionality and power characteristics.
- Surveys should be planned to minimise repeated surveying of areas in consecutive years with high risk equipment.
- Care should be exercised to minimise impacts in known biologically sensitive areas and times.

CINCFLEET Interim Command Guidance 28 Nov 03
MMO Requirements

- Visual
  - Day
  - Night
  - Night vision goggles (NVG)
- Other sensors
  - Infrared
  - Night
  - Day
  - Possible to detect the effects of surfacing possibly the body of the animal and vapour in the blow, and give good range of surfacing animal, the blow and the wake, and give good range

JNCC Recording

- A report should still be submitted to the JNCC containing information before and during start up (See B During the Seismic Survey)
- A watch should be kept for marine mammals particularly when a dedicated MMO is requested, the MMO should be employed solely for the purpose of minimising disturbance to marine mammals during the MMO must also be an experienced cetacean biologist or similar

UK Requirements for MMOs

- A prerequisite for an MMO is the attendance on a short course on marine mammal observation
- The MMO should be onboard the source vessel. (i.e. the vessel towing the airguns).
- In most cases aerial additional surveys are required where aerial is impractical
- But Stand-off vessel additional surveys are required where aerial is impractical
- In most cases aerial
- But Stand-off vessel
- Additional surveys are considered an adequate substitute for a dedicated MMO. The use of a crewmember with other onboard responsibilities is not considered an adequate substitute for a dedicated MMO.

Recommended Mitigation Measures – Before Survey

<table>
<thead>
<tr>
<th>Recommended Mitigation</th>
<th>Broadcast warnings over the ship’s radio to alert users in the area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended Mitigation</td>
<td>Undertake simultaneous monitoring for marine mammals using passive acoustic</td>
</tr>
<tr>
<td>Recommended Mitigation</td>
<td>Essential Delay start of airgun firings until area is clear</td>
</tr>
<tr>
<td>Recommended Mitigation</td>
<td>Essential Undertake monitoring for marine mammals using visual techniques for a minimum</td>
</tr>
<tr>
<td>Recommended Mitigation</td>
<td>Essential Use agreed ramp-up procedure before airgun firing</td>
</tr>
</tbody>
</table>

Marine Mammal Observers

- A prerequisite for an MMO is the attendance on a short course on marine mammal observation
- The MMO should be employed solely for the purpose of minimising disturbance to marine mammals during
- All surveys taking place between 1st April and 1st November north of 57º latitude will require two dedicated MMOs due to the longer daylight hours.
- All surveys requiring MMOs taking place between 1st April and 1st November north of 57º latitude will require two dedicated MMOs.
- MMOs due to the longer daylight hours.

- The MMO should be onboard the source vessel. (i.e. the vessel towing the airguns).
- During the planning phase, all seismic survey operations are to be considered.
- The JNCC are able to provide information on the need to embark MMOs.
Listen

- Passive acoustic monitoring (PAM)
  - Uses array of hydrophones
  - Strengths: no disturbance
  - Weaknesses: limited range, background noise

- Active acoustic monitoring
  - Using sound source to detect marine mammals
  - Strengths: can detect further, faster
  - Weaknesses: potentially disturbing to animals

Classification/Localisation

Act

<table>
<thead>
<tr>
<th>UK</th>
<th>JNCC</th>
<th>SKOLANTCEN</th>
<th>Environment</th>
<th>Australia</th>
<th>Gulf of Mexico (MMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ramp-up Period</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Pre-ramp-up Observation Period</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Turn/Turn/Interruption Procedure</td>
<td></td>
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</tr>
</tbody>
</table>

- Monitor for the absence of sperm whales
- Ramp-up period
- Monitoring continuously during airgun firings
- If marine mammals are observed within the recommended distance from the array, shooting should be delayed until the animals move out of range
- Undertake monitoring continuously during airgun firings
- Use agreed ramp-up procedure after any substantial break in activity
- Record all monitoring activity

Sonar 2087 Trial

Outstanding Issues

- Planning
  - Data adequacy
  - Source
  - Responsibility of receptors

- Look
  - MIGS hearing
  - Reduced visibility
  - Night
  - Site-specific

- Listen
  - Deployment
  - Interpretation

- Act
  - How do we use the information?
  - Harmonising guidelines
  - How high do we set the bar?
  - What is reasonable?
Acknowledgement

The assistance from Roland Rogers and Sam Healy of Qinetiq in the preparation of this presentation is gratefully acknowledged.
**Topic 6: Scientific techniques and results for assessing acoustical impacts on marine mammals.** How does the science community rate the impact of acoustics on marine mammals in comparison to other potential threats to marine mammal populations?

*Scientific techniques and results for assessing acoustical impacts on marine mammals; marine mammal acoustic research and expertise at SMRU*
Techniques for Assessing Acoustical Impacts on Marine Mammals
With some examples from SMRU

Jonathan Gordon

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EPA framework

Hazard Identification → Exposing an organism → Exposure-response assessment → Risk Characterisation → Risk Management

The standard approach to environmental (and human) risk mitigation is a framework initially developed by the US Environmental Protection Agency.

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Dose/Response studies using controlled exposure experiment with common seals

Reactions of harbour seals to seismic airguns
Part of the EU funded Bromma project with

NINA, Norway
Swedish University of Agricultural Science, Umeå

• An example of what telemetry systems are capable of
• And of how much information is needed to identify a response

---

Components of UW Noise/Mammal Interaction

Hazard Identification → Exposure Assessment → Risk Characterisation → Risk Management

The classic approach to environmental (and human) risk mitigation uses a framework initially developed by the US Environmental Protection Agency.

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Increasing Knowledge Gap

VHF Telemetry for Tracking
Acoustic Telemetry for Heart rate
Heart Rate
Swim Speed
Stomach temperature

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Marine Board–ESF Position Paper: The effects of anthropogenic sound on marine mammals – A draft research strategy | 83
Real Time Tracking

Monitored heart rate, movements, dive behaviour, feeding events in 14 controlled exposure experiment. 7 met criteria for successful experiment:

- Intense initial reaction, usually moved rapidly away from source of disturbance.
- Complete disruption of foraging behaviour, quickly reverted to normal behaviour.
- No apparent avoidance of disturbed areas.

Preliminary conclusions:

- Seals seems to show adaptive responses, which given appropriate soft start should minimise risk of hearing damage.
- Potential for long term habitat exclusion by full scale survey a matter for concern.
- A preliminary study that should be followed up with a more extensive program of research.
Generic Points

- Capacity founded on long experience of telemetry and field studies knowledge of typical/natural behaviour and biology
- Which provided:
  - Understanding of behaviour and heart rate response to a range of variables/conditions
  - Development of appropriate equipment and techniques and study sites
  - Appreciation of when and where components of the population most vulnerable to disturbance

- Low cost approach appropriate for an initial feasibility study
- Replicates
- Longer term exposures and observations around full scale surveys

Therefore studies must include sufficient replicates to capture variability

- This should be budgeted and planned for from the start
- May require development of low cost methods – cost as important as sophistication
- When there is a trade off between fewer detailed precise measurements and simpler (cheaper) ones favour the latter

Cetacean Telemetry - Catching up

- Simone Panigada
  - Telemetry of fin whales

- Patrick Miller
  - WHOI working detailed telemetry including onboard recording of sperm whales

- Sasha Hooker
  - Telemetry and acoustic recordings of bottlenose whales

Cetaceans

- For some species passive acoustic monitoring and tracking can provide useful information on underwater behaviour
- Telemetry has always been more difficult because of attachment difficulties but...

Cetacean Telemetry

- Telemetry of fin whales
  - Patrick Miller: WHOI working detailed telemetry including onboard recording of sperm whales
  - Sasha Hooker: Telemetry and acoustic recordings of bottlenose whales

Controlled Exposure Experiments Workshop

- Preliminary workshop on techniques at St Andrews
- Broader workshop at European Cetacean Society
- ECS Report and Marine Technology Journal paper

- Lessons to be learnt from Ethologists’ playback experiments
  - e.g. Peter Slater’s bird communication group

Behavioural responses are inherently variable. Must expect variation with:

- Species
- Sex
- Age
- Motivation
- Experience (habituation, sensitisation)
- Location

Simone Panigada

Telemetry of fin whales

Patrick Miller

WHOI working detailed telemetry including onboard recording of sperm whales

Sasha Hooker

Telemetry and acoustic recordings of bottlenose whales

Lessons to be learnt from Ethologists’ playback experiments

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Low cost approach appropriate for an initial feasibility study

Replicates

Longer term exposures and observations around full scale surveys

When there is a trade off between fewer detailed precise measurements and simpler (cheaper) ones favour the latter
Controlled Exposure Experiments Workshop: CEE vs Opportunistic

- Usually CEE will result in more observations per unit time
  - Can work in the best areas at the best times
  - Can apply stimuli when the needed control data has been collected
  - Can focus on the animals of most interest

- Can work in the best areas at the best times
- Can apply stimuli when the needed control data has been collected
- Can focus on the animals of most interest

Vincent Janik and co-workers at SMRU

Playbacks of signature whistles and feeding brays to wild bottlenose dolphins to understand their role in communication

Controlled Exposure Experiments Workshop: CEE vs Opportunistic

- NOT ALTERNATIVES!
- CEEs only useful for studying short-term responses
- Only approach available for new sound sources, e.g. new sonar
- Particularly useful for demonstrating cause and effect
- More likely to get a truly representative sample including more sensitive individuals

Exposure Experiments: Final Points

- Protocols to minimise the risk of harm to experimental animals
- Choosing focal animals
  - Precautionary approach would be to choose the most sensitive – Mothers and calves?
- Need for clarity in defining research questions
  - Address key at multiple scales
  - Measure biologically significant behaviour
  - Must be achievable
- Importance of collaboration

Full Scale Sound Sources Can Be Expensive

Not Alternatives. In many cases best to use both approaches
  e.g. McCauley airgun humpback study

Full Scale Sound Sources Can Be Expensive

Full Scale Sound Sources Can Be Expensive
Cetacean Sightings Surveys

Opportunist surveys: distribution, occurrence and relative abundance
Dedicated surveys: density and absolute abundance

Movements in three dimensions and responsive behaviour

- Approach and techniques rather similar to those for dose response studies
- Telemetry key technology
- Greater role for satellite data relay telemetry

Population assessment and models of distribution.

3D movements, including responses

In this case, water depth was the best predictor of porpoise density. Analysis conducted by Louise Burt (CREEM)

Results of these surveys are usually obtained using DISTANCE software (developed by CREEM) to provide estimates of total abundance. However, they can be used with more sophisticated statistical techniques to provide detailed spatial information.

The same approach can be applied to other data, e.g., Antarctic humpback whales.
Predicting Marine Mammal Distributions at Fine Scales off Scotland’s West Coast

- DSTL NERC Joint Grants Scheme
- Collaboration with SAMS in Oban
- 2003-2006 (March)
- Two research students (seals, cetaceans)
- Leveraged considerable advantage from other SMRU activities

Data on seal distribution

- Grey seals
  - Collonsay/Islay: 22
  - Tiree: 12
  - Wales: 20
- Harbour seals
  - Islay/Tiree: 12
  - Isle of Skye (future): 12

Analysis by Sharon Hedley and David Borchers for IWC/CCAMLR indicated that best predictors were
- Water density at 300m depth
- Temperature at 100m depth
- Latitude
- Longitude
- Krill density

Profiles of 193 marine mammal, seabird & turtle species are available

Ocean Biogeographic Information System - Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP)
http://obismap.env.duke.edu/
Collation of data from other institutions

- BGS sediment data
- Bathymetry (DigBath250)
- Remote sensing images (MODIS)
- POL and POLCOMS
- Sea bottom type, texture and depth (UKHO)

Cetaceans: Surveys from platforms of opportunity at a range of Spatial Scales

- FRS Scotia – oceanographic cruises to Faroe-Shetland Channel, Wyville-Thomson Ridge
- FRS herring surveys – July on chartered fishing vessel
- HWDT surveys – monthly 10 day visual & acoustic surveys

Pamguard IAGC funded project at HWU

Some results for Farnes seals

Scotia oceanographic cruise – Passive Acoustic Monitoring

Population assessment and models of distribution

Mitigation-
Effective passive acoustic and visual detection

Detailed field studies including telemetry

Mitigation-
Modelling visual and acoustic detection probabilities

MonDb
- coordinated interface
- database manager
- environmental database

MF signal
- narrow band tonal sounds
- dolphin small whale whistles

HF signal
- sperm whale
- pilot whale

MF Click detector
- sperm whale
- pilot whale

HF Click detector
- porpoise clicks
- dolphin clicks

Whistle detector
- marine bird vocalizations
- dolphin small whale whistles

ACM pipe

GPS signal

ADC pipe

Towed Hydrophone

VHF receiver

Sonobuoy

Depth panel

Sound card

USB-serial connection to GPS

Exposure Assessment

Exposure-Response Assessment

Risk Management

Risk Characterisation

Hazard Identification

Detailed field studies including telemetry

Population assessment and models of distribution

Mitigation - Effective passive acoustic and visual detection

Detailed field studies including telemetry

Mitigation - Modelling visual and acoustic detection probabilities

Some results for Farnes seals
What about distribution in the water column?

- Telemetric studies of individual animals
- VHF and archival tags provide large amounts of detailed information over short time periods
- Satellite-linked data loggers provide limited amounts of data (including location) over longer time periods

EPA Type Framework

1. Hazard Identification
2. Exposure Assessment
3. Exposure-Response Assessment
4. Risk Characterisation
5. Risk Management
6. Test and Refine
Modelling The Habitat Preference of Seals

Updates on:
- 1) Seal distribution data
- 2) Data collection of environmental variables
- 3) Analysis

Stanton Bank

Environmental variables
SAMS Primary Role

Types:
- 1) Collation of data from other institutions
- 2) Dedicated surveys (Calanus)

Sea bottom type, texture and depth (UKHO)

What have I been doing so far?
Scotia oceanographic cruise – May
• 1.6 hours of acoustic monitoring = 200 km
• 2 minute listening stations every 15 minutes
• 490 listening stations during which:
  - Sperm whales were detected in 25.3% of all stations
  - Dolphin species were detected in 20.6% of all stations
What have I been doing so far?

West Coast Herring Survey – July

- 16 days surveying from 3am-11pm daily
- Hydrophone deployed between trawls
- Visual surveys conducted during sea state < 4
- Simultaneous acoustic fish data

Good dolphin whistle data & sightings of white-beaked and common dolphins... very few porpoises

EPA Type Framework
- Exposure Assessment
- Exposure-Response Assessment
- Risk Management
- Risk Characterisation
- Hazard Identification

Detailed field studies including telemetry

Mitigation-Modelling visual and acoustic detection probabilities

Mitigation-Effective passive acoustic and visual detection

Population assessment and models of distribution

Detailed field studies including telemetry
European Science Foundation

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