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Responsible Practices for Minimizing and Monitoring Environmental Impacts of Marine Seismic Surveys with an Emphasis on Marine Mammals

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Abstract

Marine seismic surveys, which use loud, primarily low-frequency sound to penetrate the sea floor, are known to disturb and could harm marine life. The use of these surveys for conventional and alternative offshore energy development as well as research is expanding. Given their proliferation and potential for negative environmental impact, there is a growing need for systematic planning and operational standards to eliminate or at least minimize impacts, especially when surveys occur in sensitive areas. Mitigating immediate impacts is obviously critical, but monitoring for short- as well as long-term effects and impacts is also needed. Regulatory requirements for both mitigation and monitoring vary widely from one country or jurisdiction to another. Historically, most have focused on acute effects but share a common objective of minimizing potential adverse impacts. Specific examples in different areas are given to illustrate general approaches for predicting, minimizing, and measuring impacts for operations in essentially any marine environment. The critical elements of a robust mitigation and monitoring plan for responsibly conducting marine seismic surveys include obtaining baseline ecological data; substantial advance planning, communication, and critical review; integrated acoustic and visual monitoring during operations; and systematic analysis of results to inform future planning and mitigation.

Key Words: seismic, survey, planning, mammal, mitigation, monitoring, marine, Sakhalin

Introduction

As hydrocarbon exploration and extraction continue to expand in the oceans, particularly at higher latitudes, there is a growing need for operational standards to minimize impacts, especially when the activities occur in environmentally sensitive areas. This is particularly true for invasive sensing technologies that use loud sounds to image geophysical properties but incidentally expose large ocean areas to potentially damaging or disturbing noise. Sufficient scientific data exist to conclude that seismic airguns used in geophysical exploration have a low probability of directly harming most marine life, except at close range where physical injury is a real danger. While the use of airguns does not appear to disturb animals in some circumstances, in other conditions it can result in moderate to extreme behavioral responses and/or acoustic masking over large areas (see reviews by Nowacek et al., 2007; Southall et al., 2007; Clark et al., 2009); indeed, recent studies have reported the transmission of sound energy from seismic surveys over vast ranges of nearly 4,000 km (Nieukirk et al., 2012). Most documented responses to seismic exploration or other intermittent human activities involving loud sounds include apparently temporary changes in behavior, but scientific understanding of the prevalence and implications of these effects is limited.

While mitigation measures to reduce immediate potential impacts (primarily direct harm) have understandably been the historical focus of operational protocols, measuring and understanding reactions in a systematic way is in fact an important aspect of any responsible development program. However, a distinction must be made between understanding (1) the potential impacts of discrete activities of a single company or seismic survey over a relatively short time period and (2) the general industrialization of a biologically important area, which can result in more severe and sustained impacts on marine life (e.g., gray whales [*Eschrichtius robustus*] in response to noise in breeding lagoons; Gard, 1974). Another important distinction is between the terms *monitoring* and *mitigation*. We discuss the former as it applies to a program for collecting data both to test for effects after the seismic survey has concluded and to apply the results to the planning of future surveys (e.g., revise exposure criteria). Mitigation, on the other hand, represents the measures designed for and implemented during the survey specifically to eliminate or minimize the impacts on animals in the area; such measures range widely from the implementation of a safety radius to the timing of the survey.

Regulatory requirements for both monitoring and mitigation of seismic activity vary from one country or jurisdiction to another, despite the common objective of seeking to limit the potential adverse impacts of this invasive sensing technology. This paper does not seek to provide a comprehensive review or comparison of these disparate approaches in different jurisdictions (for such a review, see Weir & Dolman, 2007). Specific requirements in different areas and for different species create significant challenges for those responsible for planning and managing the effects of seismic surveys. When activities are planned and conducted in environmentally sensitive areas (e.g., those containing endangered species or critical breeding/feeding habitat for multiple species or large numbers of individual organisms), particular attention to planning, mitigation/monitoring, and analysis of potential effects is required.

Whether legally required or not, as a matter of responsible practice, those conducting seismic survey operations should devote particular effort and attention to risk mitigation that has both a protective immediate function for near-source effects (e.g., operational "shut-down" measure) as well as considerations with an environmental or biological basis (e.g., time or area restrictions based on environmental baseline assessment). Such attention, and a more precautionary approach to the interpretation of available data, is especially warranted when either endangered or particularly sensitive species are present, operations occur in critical feeding or breeding habitat, surveys occur in pristine areas with naïve animals, or multiple operations are to occur simultaneously or sequentially in the same general area. A variety of sampling regimes, sophisticated analyses, and archival and real-time technologies may need to be integrated into the suite of mitigation and monitoring measures employed. Finally, in addition to the focus on activities involving intense sound generation, the program we describe must logically extend to periods before, during, and following the seismic work itself and consider other potentially disturbing or confounding elements of the operation (e.g., vessel traffic, cable laying).

This paper describes what we consider the state-of-the-art in mitigation and monitoring, with regard to discrete exploration activities. It is not the first time such an attempt has been made (e.g., Gordon et al., 2003; Joint Nature Conservation Committee [JNCC], 2010; New Zealand Department of Conservation, 2012), but we believe the approach described herein constitutes the most comprehensive and, with respect to logistical planning of a survey, the most practical description to date. The idea of preparing this paper arose largely from the interactions among the co-authors in the planning, execution, and analysis of responses of gray whales to a 2010 seismic survey conducted in the whales' shallow-water feeding habitat off northeastern Sakhalin Island, Russia. Our collaboration was part of an ongoing effort between industry and a panel, convened by the International Union for Conservation of Nature (IUCN),[1] whose mission is to minimize the risk of industrial activities to western gray whales.

Although many of the examples and operational elements described herein relate to a 4-dimensional (4-D) repeat survey (aka *4D seismic survey*, i.e., surveying the same area at a later time in which the 4th dimension is time) conducted by Sakhalin Energy in its Astokh license area in 2010 (hereafter referred to as the "2010 Sakhalin Energy survey"), several of the authors have also been involved in the planning and execution of other seismic survey mitigation and monitoring programs elsewhere. The conditions and requirements for any given survey will depend on *inter alia* the local species, environmental parameters, and the history and nature of other operations in the area; no two surveys will be exactly alike in these regards. However, rapid recent advances in technology and the accumulated experience of scientists, resource managers, and the oil and gas industry over the past 30 to 40 y make it possible to establish some generalized approaches to the responsible execution of seismic surveys in environmentally sensitive areas.

We describe a series of elements in each phase from planning to execution to analysis in order to minimize and measure the environmental impacts. The examples provided could apply to a wide range of specific situations and various aspects of marine seismic surveys, but the general approach for predicting, minimizing, and measuring impacts is meant to be relevant to operations in essentially any marine environment. We describe in text boxes throughout the paper detailed aspects of the 2010 Sakhalin Energy survey, which are intended to illustrate points in the main text that are more broadly applicable. The critical elements of a robust plan for conducting seismic surveys responsibly include baseline (multi-year) ecological data for planning, integrated acoustic and visual monitoring during operations, and systematic analysis of results to inform future planning and mitigation efforts. We recognize and acknowledge that the elements described herein will not apply to every situation; indeed, we identify the need for "local" information on, for example, ocean conditions and characteristics of species potentially affected. However, we believe that this framework is generally applicable and can be adapted to enable seismic surveys to be conducted in a more environmentally responsible manner, regardless of whether they are for research, assessment of hydrocarbon reserves, or other exploration or whether the marine species of concern are fish, birds, turtles, or mammals.

Elements and Methods for Mitigation and Monitoring

We attempt to present each element related to mitigation and monitoring in a chronologically sensible order, although in practice some would occur in parallel (Figure 1). Specific suggestions are often buttressed by examples from actual seismic surveys, primarily the 2010 Sakhalin Energy survey. In those instances in which technical details of a given element are especially complex or specialized, we point to appropriate reference information (e.g., sources for sound propagation models).

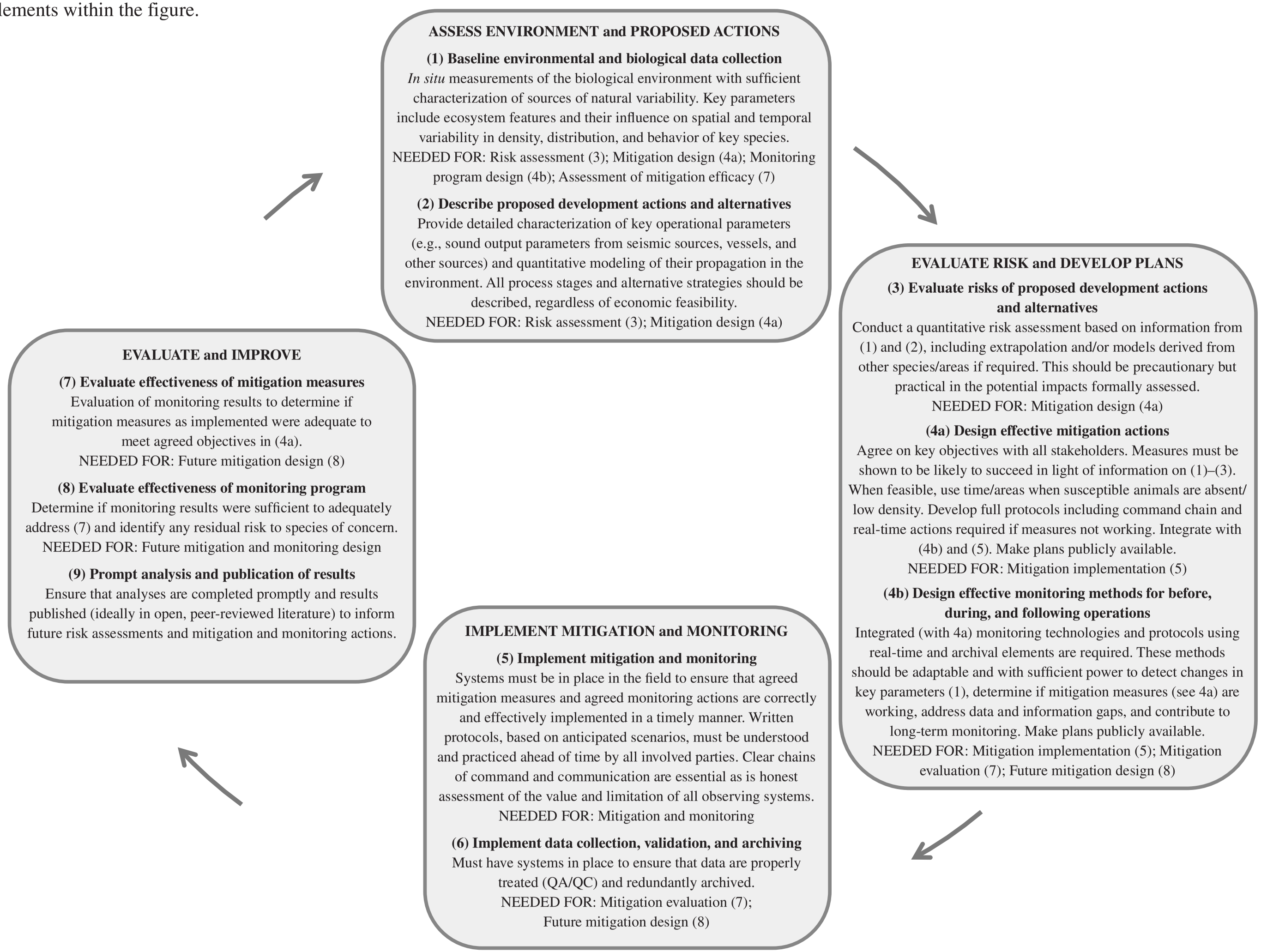
Baseline Information and Impact Assessment

The concept of environmental impact assessment (EIA) arose during the 1960s, a time of rapid industrial expansion coincident with rising awareness of how development often threatens wild living resources. Such assessment is intended to ensure that those who make decisions on whether and how a development project can proceed are well-informed about the likely consequences and compromises involved. Since first being codified in legislation in the United States in 1969 (i.e., the National Environmental Policy Act), the generic EIA process has been adopted and incorporated into the legal and regulatory systems of many countries (e.g., *U.S. Federal Register*, 43 FR 55994, 29 November 1978; European Union Environmental Assessment, http://ec.europa.eu/environment/eia/home.htm; New Zealand Department of Conservation, www.doc.govt.nz/conservation/marine-and-coastal/seismic-surveys-code-of-conduct). Although not always explicitly required by law, operators aspiring to be regarded as adhering to the highest standards of environmental responsibility should make environmental impact assessment an intrinsic part of project planning.

At the start of planning for a seismic survey (or preferably well beforehand), multi-year data on the general characteristics and natural variability of the relevant biological and ecological systems should be identified. If necessary, the gathering of such data should be initiated as soon as possible after the decision has been made that the project will proceed. At the very least, basic information on species of concern must be collated and evaluated, based on either direct observations in the action area or reasonable expectations inferred from observations in similar areas and situations. Often, the assembly and presentation of such information takes place as part of the preparation of an EIA. However, this initial review and analysis is frequently less rigorous, and consequently less useful, than it could be. For example, just knowing that a species or population of concern (e.g., one that is considered at high risk and is consequently accorded special status in national or international conservation processes) occurs in the action area is not sufficient. A thorough understanding of seasonal occurrence and density, behavior, reproduction, foraging, and habitat use is needed to guide survey planning and the design of appropriate mitigation. Also, information on physical properties of the area (e.g., water temperatures, timing of formation, and recession of sea ice) and how these influence the phenology and activities of the animals (e.g., calving/pupping, mating, foraging) may show that the number of animals exposed to seismic survey operations can be greatly reduced simply by adjusting the timing of the survey.

When establishing the "baseline" (in quotes because it is important to be mindful of shifting baselines; Pauly, 1995), it is in the interests of operators as well as conservation managers to know something about environmental stochasticity, which will likely require a long time series of ecological and biological data. Without the perspectives that such data provide, the true causes of observed changes in animal populations can be confounded. An extreme case would be one where the animal population shifts its distribution following a potentially disturbing activity such as a seismic survey. Knowing whether such shifts have occurred historically and, if they have, understanding their relations to natural variability in the environment would be highly relevant to how the observed shift is interpreted. An example of baseline ecological monitoring comes

Figure 1. A practical roadmap for planning, executing, evaluating, and improving the design of a responsible seismic survey; the numbers in parentheses throughout the figure refer to other elements within the figure.



from the west coast of sub-Saharan Africa (Nigeria to Angola), a region rich in hydrocarbon resources that are being explored and exploited both on- and offshore. Before one development project was initiated, the Wildlife Conservation Society (WCS) in collaboration with Angola LNG, a liquified natural gas (LNG) producer based in Soyo, Angola, initiated a series of industry-sponsored field studies of cetaceans off the coast of Angola. These included passive acoustic monitoring to improve understanding of spatial and temporal trends in humpback whale (*Megaptera novaeangliae*) distribution. When compared to the baseline information, passive acoustic monitoring detected effects of seismic activity on the singing behavior of humpback whales (Cerchio et al., 2010). Even though the LNG facility was not scheduled to become operational until 2014 and there was no governmental regulatory requirement for baseline studies, efforts were under way 8 y in advance of this date to collect baseline biological data, and those data are being used to develop mitigation protocols for application once the facility is operational. We recommend that long-term monitoring in regions where seismic surveys are anticipated begin as early as possible.

Pre-Survey Planning

Options for Spatial and Temporal Restrictions for Limiting Operations—As an unavoidably site-specific activity, a seismic survey offers little flexibility with regard to where it occurs, though the area to be surveyed should be absolutely minimized. Even drilling, given the extended-reach or slant drilling options, offers the possibility of spatially separating the action itself from highly sensitive areas. For example, the Exxon-Neftegas Limited (ENL) development in eastern Russia (Sakhalin-I) uses assets on shore to drill wells to reach and extract oil and gas from deposits 5 to 10 km offshore. It was nonetheless impossible for ENL to avoid its 2001 Odoptu 3-D seismic survey in support of the Sakhalin-I development (Johnson et al., 2007), and further 4-D seismic surveys of the Odoptu field will inevitably be required as the development proceeds.

Without the option of re-siting a seismic survey or conducting it with alternative remote sensing technologies other than seismic airguns, the most promising approach to mitigation is to coordinate survey timing such that the fewest possible individuals of species of concern are present in the area. Obviously, this approach presupposes that the number of individuals in the area fluctuates seasonally. Again, the 2001 Odoptu survey provides an instructive example (see Johnson et al., 2007). In planning that survey, operators recognized the desirability of conducting the survey "when the fewest gray whales are present (early spring or late fall)" (p. 9), given that winter and early spring (when gray whales are generally not present off northeastern Sakhalin) had to be ruled out because of sea ice conditions. That survey occurred from 17 August to 9 September. In contrast, the gray whale mitigation and monitoring plan for the 2010 Sakhalin Energy survey called for operations to begin literally as early in the season as ice conditions would allow (see seismic survey monitoring and mitigation plan, www.iucn.org/wgwap/wgwap/seismic_survey_monitoring_and_mitigation_plan). The company invested heavily in efforts to ensure early arrival of the seismic and support vessels, installation of onshore infrastructure for visual and acoustic monitoring, deployment of listening buoys along the perimeter monitoring line to record sounds for comparison with modeled levels (see Figures 2 & 3), and positioning key personnel so that the survey could begin in early June and be completed before the end of June (i.e., prior to the arrival of most gray whales).

The surest way to reduce, minimize, or even completely eliminate impacts of seismic surveys on whales (and other species) is to separate them in space, time, or both if feasible. Unfortunately, in high latitudes where sea ice occurs, conventional use of towed airgun arrays for marine seismic surveys has not been possible except in the open-water season when the whales also use the areas (for instance, see the Arctic Open Water process coordinated by the U.S. National Marine Fisheries Service, www.nmfs.noaa.gov/pr/permits/openwater.htm). If the whales and the seismic vessels are subject to the same or similar environmental constraints, the temporal window for avoiding overlap can be extremely narrow, which has been the case off Sakhalin as well as in the U.S. and Canadian Arctic where bowhead whales (*Balaena mysticetus*) are the greatest concern. Recently, the tandem use of ice-breaking vessels to allow seismic surveys to proceed has been attempted with some success in the spring in the Arctic, well before the ice has cleared. It must be acknowledged, however, that such disruption of natural sea ice conditions could have adverse consequences for ice-dependent species such as pinnipeds or polar bears (*Ursus maritimus*). The potential for unintended and sometimes indirect effects of mitigation measures on "non-target" organisms is an important consideration that should also be part of the planning process.

Generation of Exposure Criteria—A key element in the assessment of potential impacts and the development of operational rules for seismic operations is either the use of well-established and widely accepted exposure criteria or the generation of such criteria if the operation in question warrants a distinct or tailored approach. The use of quantitative, level-only exposure thresholds is generally considered more appropriate for preventing auditory impacts than effects on behavior, given that context-specific factors may be at least as important as SPL in mediating behavioral responsiveness

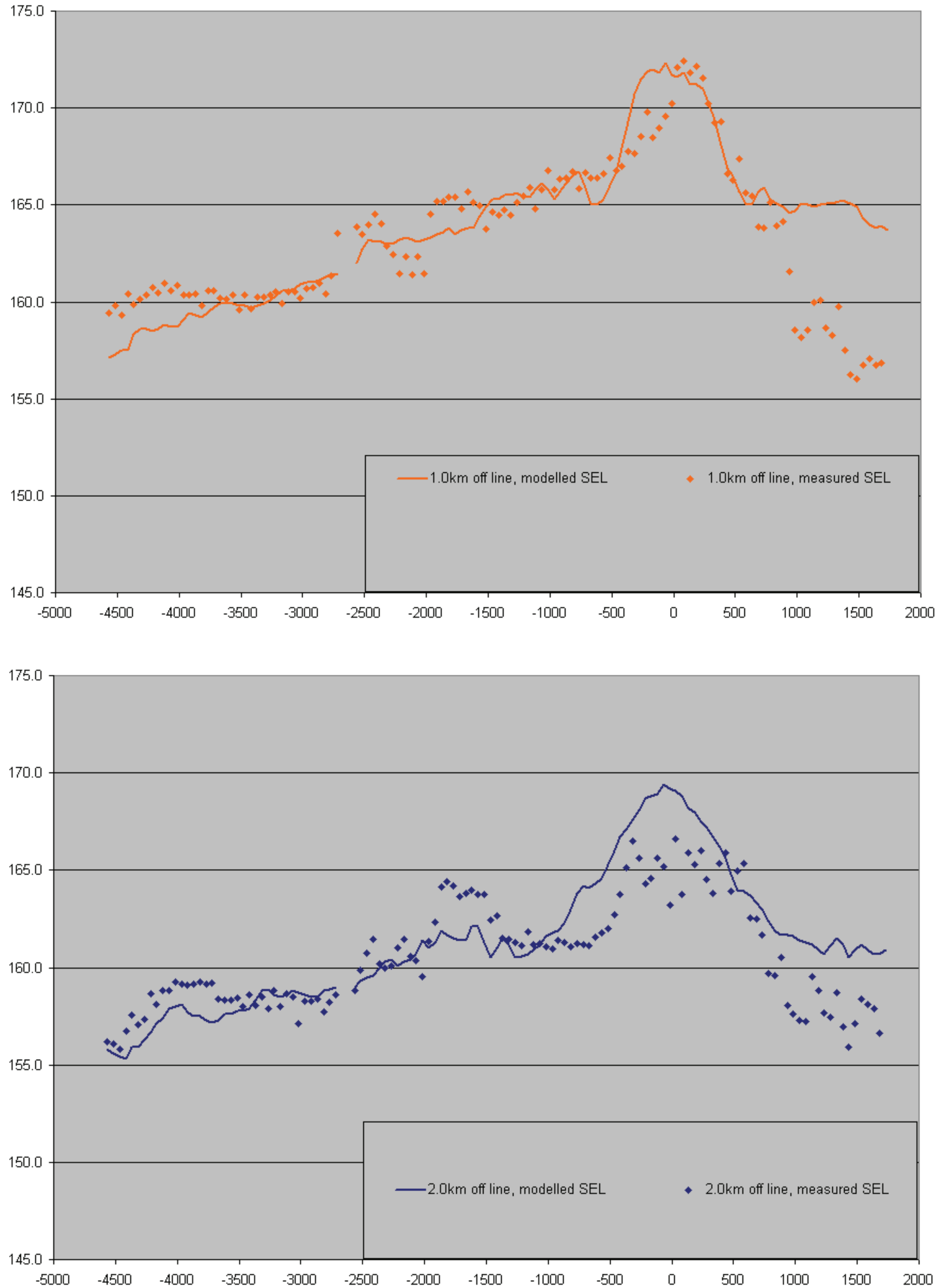


Figure 2. Measured (individual dots) and modeled (continuous line) per-shot SEL metric in dB re μPa²-s for a receiver 1 km (upper panel) and 2 km (lower panel) off the track line, plotted against along-line offset in m from CPA (see Text Box 3; Racca, 2009)

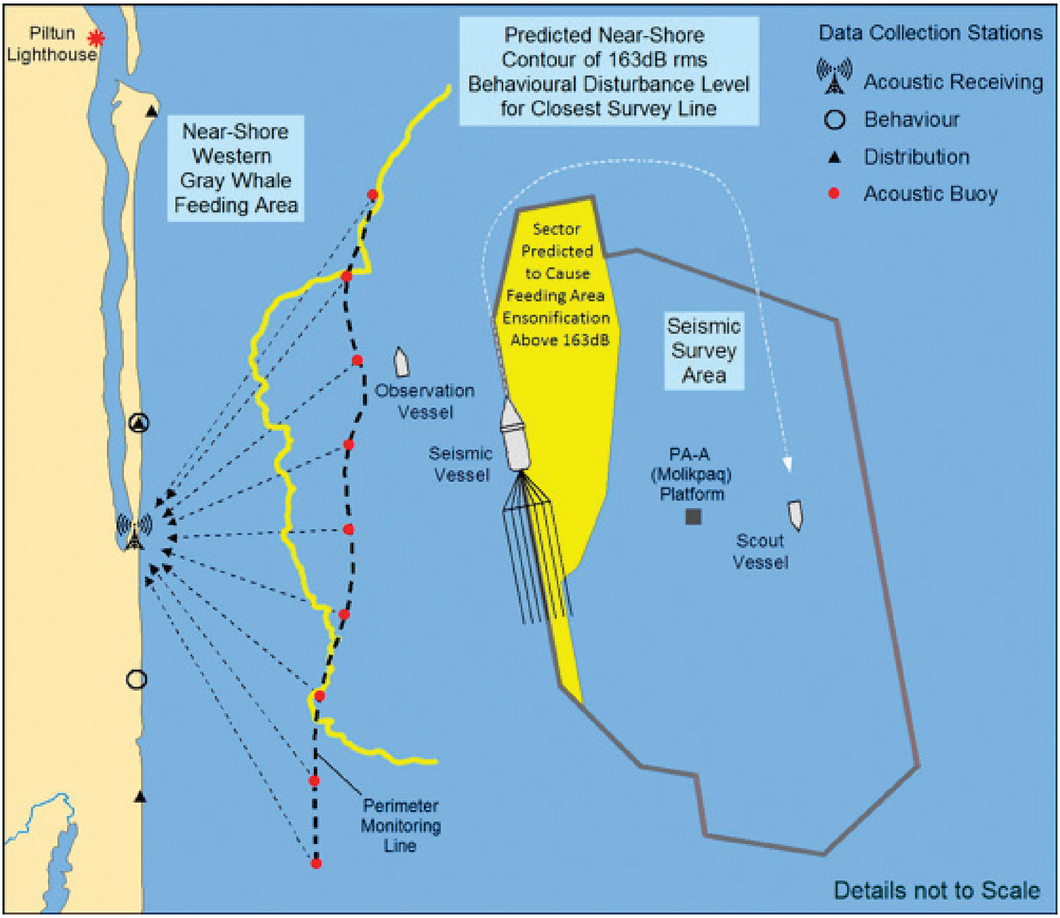


Figure 3. The 2010 Sakhalin Energy survey mitigation and monitoring theater. The irregularly shaped survey area in the right half of the figure represents the smallest possible region necessary to obtain the needed seismic data (the original survey area was nearly twice as large). The scout vessel "cleared" survey lines in advance of the survey vessel both for safety and for the presence of whales. The yellow region indicates the sector of the survey where additional precautions were in force as it was forecast to produce sound levels in excess of the behavioral disturbance threshold inside the 95% whale distribution area—that is, the area shoreward of the Perimeter Monitoring Line (PML) labeled in the figure as "Near-Shore Western Gray Whale Feeding Area." Correspondingly, the yellow contour indicates the modeled sound exposure boundary at the behavioral disturbance threshold of 163 $dB_{(RMS)}$ SPL from the seismic array following the survey line closest to shore.

(Nowacek et al., 2007; Southall et al., 2007; Ellison et al., 2012). Nonetheless, received-level thresholds are often used as a proxy for the high likelihood of behavioral effects, although if they are to be used, it is critical that such thresholds have been derived under conditions similar to those of the proposed survey. Relatively simple, straightforward metrics for predicting zones of potential effect—so-called safety radii—are needed for field application, and thresholds based on received sound levels provide these. Criteria for predicting effects should be specified for the primary species of concern or animal groups present in a given operational area, and they may require consideration of impulse noise sources (e.g., airguns, pile driving) as well as more continuous noise sources (e.g., drilling, construction, vessel noise; *sensu* Southall et al., 2007).

Historically, the U.S. National Marine Fisheries Service (NMFS) used a 180 dB re 1μPa (RMS received SPL over an interval enclosing 90% of the pulse energy, hereafter SPL) received level threshold for predicting injury to mysticete cetaceans from exposure to impulse noise (National Oceanic and Atmospheric Administration [NOAA], 1998). Subsequently, the High Energy Seismic Survey (HESS) Team (1999) concluded that exposure to impulse noise with pulse-averaged received levels exceeding 180 dB SPL would likely result

Text Box 1. Development of exposure criteria for gray whales during the 2010 Sakhalin Energy survey

The 2010 Sakhalin Energy case applied a unique approach based to some extent on the Southall et al. (2007) conclusions and recommendations. This project used the best available scientific data for conditions of exposure approximating as closely as possible those of the planned survey, and it integrated additional precautions in view of the critically endangered status of the local whale population. Pertinent details regarding the derivation of these impact criteria are summarized here (for additional details, see Nowacek et al., 2012). The industrial development off Sakhalin exposes a variety of marine mammals, including gray whales, to both "continuous" or non-impulsive noise and impulses such as those from seismic airguns and pile driving. Consequently, exposure criteria for both types of noise were generated, with impacts considered for both auditory injury and significant behavioral disturbance, particularly the potential for indirect nutritional consequences from the whales' avoidance of prime feeding areas. The focus here is on impulsive noise as airguns are the dominant noise source in seismic surveys.

The Southall et al. (2007) impulse noise criterion for the onset of physical injury (198 dB SEL, which was based on temporary hearing loss in odontocetes extrapolated to higher levels for estimating injury and then extrapolated to mysticetes) was considered. However, given the limited underlying data and subsequent extrapolation methods, as well as the critically endangered status of western gray whales, the typically more conservative or risk-averse (in most conditions) historical 180 dB SPL criterion was used as a proxy for injury. This kind of deviation from the recommended criterion given the specific conditions of the exposure situation here was clearly anticipated by Southall et al. (2007), particularly in specific conditions where data are lacking and endangered species are involved.

Regarding behavioral responses to impulse noise, the Malme et al. (1984) measurements for eastern gray whales exposed to such noise represented the basis for predicting avoidance behavior. These data indicate estimated 10, 50, and 90% probabilities of gray whale avoidance reactions at 164, 170, and 180 dB SPL, respectively. Given the desire to use an approach that considered both magnitude and duration of exposure (i.e., using SEL), and considering the general recommendations of Southall et al. (2007), we reviewed additional Malme et al. (1986, 1988) reports containing the raw field data on gray whale responses to determine if SEL values could be derived. However, details regarding the range of exposures of many individuals or other pertinent details were lacking, and it was impossible to estimate exposures in terms of SEL.

Given this limitation, we assumed a behavioral disturbance threshold of 163 dB SPL for impulse noise, corresponding to approximately a 10% probability that whales would cease feeding according to the results in Malme et al. (1984). Based on both acoustic modeling and actual measurements of airgun pulses in the Sakhalin area (Figure 2), this SPL value was determined to correspond to 156 dB SEL, the level ultimately used as the impact criterion for significant behavioral response in contingency planning and the design of mitigation measures for the 2010 survey. The broader message and conclusion is that in planning a seismic survey, a thorough search for pertinent data is necessary so all available data can be incorporated into protective measures.

in significant behavioral, physiological, and/or hearing impacts. The NMFS continued to use the 180 dB SPL criterion for predicting injury, as well as a behavioral effect level of 160 dB SPL based primarily on observations of mysticete responses to airgun operations (e.g., Malme et al., 1983a, 1983b; Richardson et al., 1986). Southall et al. (2007) reviewed and applied available scientific literature in proposing noise exposure criteria for marine mammals. Their dual-metric criteria were derived largely from more recent scientific findings, which were quite different from the simplistic NMFS (1998) and HESS Team (1999) criteria. Specifically, Southall et al. (2007) proposed peak SPL (dB_{peak} re 1µPa, hereafter PEAK) and sound exposure level (dB re 1µPa^2-s, hereafter SEL) for injury thresholds, as well as frequency-weighting functions to account for the differential hearing capabilities of marine mammals across different frequency bands. These general considerations should be taken into account when deriving exposure threshold criteria.

We provide an example describing the derivation of impact criteria for assessing potential effects of a specific noise source, a single species, and a specific area (Text Box 1): gray whales exposed to seismic airguns off Sakhalin Island. The aim of this example is to inform the reader as to the *process* we followed for *generating agreed exposure criteria*.

Agreements Among Stakeholders on Mitigation Objectives and Measures—Various mitigation measures and monitoring protocols have been adopted, or are being considered, for marine seismic surveys around the world. While there are no internationally accepted standards, a number of jurisdictions (e.g., UK, Australia, U.S., and New Zealand) have developed their own guidelines with varying degrees of regulatory oversight (see Table 1 and Supplementary Data in Weir & Dolman, 2007), all of which do tend to share some common elements.

Mitigation measures are meant to reduce or eliminate the impacts of seismic activities on marine mammals and other animals. Specific monitoring activities, as we have defined them, can be implemented alongside or as part of mitigation measures with the objectives of (1) determining the effectiveness of the applied mitigation measures and (2) increasing understanding of the impacts of seismic exposure on the animals. Although a

Table 1. Basic elements for planning and conducting a marine seismic survey

Primary components for conducting a responsible marine seismic survey	References
Assessment of background data with respect to species of concern (habitat, habits, life history) and environment (bathymetry, sound propagation)	SEIC, 2010; New Zealand Department of Conservation, 2012; EU Environmental Assessment
Spatial and/or temporal restrictions and requirements	e.g., Grech et al., 2008
Generation of acceptable exposure criteria	Southall et al., 2007
Mitigation measures: which to use and how/when they will be implemented	New Zealand Department of Conservation, 2012
Understanding the acoustic footprint of the survey: modeling of the acoustic source and the propagation environment	Racca et al., 2012
Pre-survey validation of source and propagation models	Nowacek et al., 2012
Selection of appropriate techniques for implementing mitigation and monitoring elements (e.g., visual or acoustic survey methods)	Barlow & Gisiner, 2006; Gailey et al., 2007
Creation of robust communication plan, including explicit chain of command	SEIC, 2010
Post-survey assessment of mitigation measures	Johnson et al., 2007
Publication of monitoring data to describe effects or lack thereof, and to improve mitigation and monitoring of future surveys	Gailey et al., 2007; Johnson et al., 2007; Yazvenko et al., 2007a, 2007b

number of studies have been published on the effects of seismic exposure on marine mammals (Malme et al., 1986; Gailey et al., 2007; Yazvenko et al., 2007a, 2007b), greater insight is needed on both the immediate and long-term impacts. Monitoring can help fill knowledge gaps and increase understanding.

Available measures to be considered in survey planning include the following:

- Seasonal restrictions
- Avoidance of sensitive areas
- Aerial surveys—manned and unmanned
- Thermal and satellite imaging
- Passive and active acoustic monitoring
- Airgun specifications, array size, and configuration
- Minimization of the survey area
- Orientation/selection of seismic survey lines (segments of the area in which seismic data are obtained in sequence)
- Pre-survey observations
- Ramp-up or soft-start
- Planned shutdowns
- Operational shutdowns based on field observations of behavior and sound-level criteria for behavioral disturbance and injury
- Safety distances/exclusion zones
- Onboard marine mammal observers (MMOs)
- Provisions for night-time operations and periods of poor visibility
- Acoustic modeling
- Real-time acoustic monitoring

No two seismic surveys are identical in terms of area, airgun array size, animal species present, animal distribution and abundance, water depth, duration, distance from shore, etc. Consequently, there is no single standard set of mitigation measures suitable for every survey. Instead, a tailored suite of mitigation and monitoring measures should be selected for each seismic program and included in a program-specific mitigation and monitoring plan. Such a plan should be developed in a broadly collaborative manner, led by company representatives but with meaningful input from scientists with relevant expertise as well as government regulators, the seismic contractors, vessel owners, and NGOs. For the 2010 Sakhalin Energy survey, the Seismic Survey Task Force, formed under the WGWAP Terms of Reference to address the specific issues surrounding the 2010 Sakhalin Energy survey (see the Panel's IUCN website for details: www.iucn.org/wgwap/wgwap/task_forces), spent more than 2 y developing the plan. Novel approaches were studied and assessed for technical and logistical feasibility, and the final plan was science-based and precautionary but also practical in terms of field deployment and enabling the company to acquire the needed geophysical data (Sakhalin Energy Investment Company [SEIC], 2010).

Whereas some mitigation measures are relatively easy to implement (e.g., use of soft start), others can have serious impacts on the duration and cost of a survey, and even on the feasibility of completing it within a single season. For example, restricting airgun operations to daytime hours (e.g., to allow visual detection of the animals) can result in a significant increase in duration, and thus cost, of a survey. This is especially the case in high latitudes where daylight hours become limited late in the open-water season. In those instances where the window of opportunity for acquiring seismic data is relatively small due to seasonal weather patterns and presence of marine mammals, the value of restrictive measures must be carefully weighed against the value of completing the survey quickly, given that the most effective way of eliminating risk is to separate the seismic activity from the animals in space and/or time. In other words, mitigation or monitoring measures that affect the duration of a survey can conflict with this ultimate measure, requiring a cost-benefit analysis to be carried out, sometimes on a day-by-day basis in the field by the operations team. This underscores the importance of having biological expertise within field operations.

As an empirical example, a post-hoc analysis was conducted of the time budget for the 2010 Sakhalin Energy survey (Text Box 2).

The lack of internationally accepted standards regarding response thresholds, mitigation measures, etc., and the fact that national or regional standards, where they exist, tend to be inconsistent (see Weir & Dolman, 2007, for a review), adds to the difficulty of reaching agreement on the details of a mitigation and monitoring plan for a given seismic survey. Whereas the guidelines provided by the Joint Nature Conservation Committee (JNCC) (2010) do not specify levels of protection by species, the HESS Team (1999) recognizes marine mammals at three priority levels based on (1) known or inferred sensitivity to low-frequency sounds (e.g., from airguns) and (2) protection status of the species or population. First-priority species are blue (*Balaenoptera musculus*), humpback, fin (*B. physalus*), and gray whales; second-priority species are sperm whales (*Physeter macrocephalus*), elephant seals (*Mirounga* spp.), and the other mysticetes; and third-priority species are the rest of the odontocetes and pinnipeds. The HESS Team applies this priority classification only to determine monitoring requirements and not mitigation measures (e.g., shutdown criteria). Furthermore, whereas the JNCC (2010) guidelines recommend a fixed exclusion zone of 500 m, the NMFS uses underwater "do not exceed" sound-level criteria for exposure of marine mammals to underwater impulses from seismic airguns. These criteria are currently set at 190 dB SPL for pinnipeds and 180 dB SPL for cetaceans. None of the guidelines distinguish protective measures based on species or population status (e.g., vulnerable, threatened, endangered, and critically endangered).

Sound Propagation Modeling and Measurements to Assess the Extent of the Sound Field

Overview of Seismic Survey Acoustic Modeling Practices—A seismic survey generates a complex and constantly changing underwater sound field as a vessel towing a pulsed sound source follows tracks (Johnson et al., 2007). With the exception of the relatively uncommon "wide azimuth" approach in which multiple source vessels operate in coiled orbital patterns without interruption, seismic surveys are characterized by periodic breaks in the geophysical sounding while the source vessel travels from the end of one line to the start of the next. Depending on the survey area and pattern and the number and spacing of the streamers, these line changes may last hours and account for a sizable portion of the total operation time. In addition to the pulsed sounds from the airguns, a seismic survey creates an associated moving field of continuous noise from the seismic ship itself and a few ancillary vessels in scout, guard, support, and observation roles. While contributions from the vessels to the overall acoustic exposure of animals must be taken into account in any post-survey analytical studies aimed at detecting potential correlation between acoustic levels and the distribution or behavior of the animals, their importance in the context of operational mitigation is commonly regarded as second-order relative to the seismic source itself.

Text Box 2. Example of the trade-offs between time added to overall duration of a survey due to the implementation of mitigation measures in the 2010 Sakhalin Energy survey

The time of the seismic vessel operation was broken down into various categories. Those labeled as "whale," "fog," and "darkness standby" were grouped into a single category called "Monitoring and Mitigation Plan Delays." The analysis showed that implementation of the mitigation and monitoring measures was nominally responsible for 3.7 d of delay out of ~19.5 d of total survey duration (i.e., 19% of the total time). The category "Mobilization Issues" caused approximately 5 d of delay (25.4% of the survey duration), and even this relatively short delay meant increased overlap of the survey timing and whale presence since whale numbers in the action area continued to build during the period of delayed start-up. Relatively few whales were in the area at the time when the survey had been planned to begin, and very few fog days occurred during the delay interval. Without the mobilisation problems, the time "cost" of the mitigation and monitoring measures certainly would have been less than 3.7 d. Time budget analyses of this type can be conducted prior to a survey as part of the planning process and may provide field managers with valuable insight into the kinds of practical trade-offs that need to be considered in order to minimize impacts.

Text Box 3. Description of the source validation efforts for the seismic source used in the 2010 Sakhalin Energy survey

For the 2010 Sakhalin Energy survey, the directional source levels from the planned array and their propagation through the acoustic environment were modeled respectively using the *Airgun Array Source Model* (AASM) and *Marine Operations Noise Model* (MONM) software packages (JASCO Applied Sciences, Victoria, BC, Canada). The average characteristics of the propagation environment were based on a standard dataset of geo-acoustic properties and bathymetry that had been matched to the region and used for a number of estimations of offshore industrial noise levels over various construction seasons. Next, a dedicated validation measurement of seismic source pulses was performed in the year prior to the survey (Racca, 2009). The trial was limited to a period of a few hours in October, past the period of significant peak presence of gray whales in the area. Acoustic recording of the seismic source signal under controlled conditions was carried out by special arrangement with a seismic survey operator, taking advantage of the passage of the vessel through the area en route to its next assignment. A field team deployed three recording stations along a perpendicular to the planned trial line at various ranges from the closest point of approach (CPA). The source properties of the trial array (which was comparable in volume but different in design from the planned source for the 2010 Sakhalin Energy survey) were modeled entirely from the airgun specifications and placement as would be the case for the predictive estimation, with no adjustment based on field measurements. Likewise, the water sound velocity profile was based purely on historical seasonal trends, and the bathymetry and bottom geo-acoustic properties came from the standard environment databases used for all propagation modeling in the region. Model results were computed for every seismic shot position at each of the receiver locations and depths, and then overlaid on the corresponding measurements. The results for receiver offsets of 1 and 2 km from the CPA are shown in Figure 2 as an example of the comparative information yielded by the validation trial.

A numerical modeling approach (i.e., sound propagation model) used to define safety zones must be capable of reproducing all the salient acoustic propagation properties of the region, which can sometimes be complex and even counterintuitive, with down-range levels being higher than those closer to the source (Madsen et al., 2006). Computational methods, such as Parabolic Equation algorithms, are capable of modeling fully range-dependent propagation environments (properties change with distance from the source) in shallow and deep water, and are among the most favored for seismic survey noise footprint estimation (Porter, 1993; Jensen et al., 2011). The environmental parameters selected, including the water sound speed profile and the geo-acoustic properties of the bottom, should be as close as possible to the prevailing local properties and, for the water column, to the time of year when the operation is planned to take place. The seismic array itself should be modeled from its physical specifications (depth of operation being a critical variable) as a directional point source that produces the same volumetric far-field levels as those generated by the underwater pressure release interactions between the airguns in the array.

Site-Specific Pre-Season Field Validation of a Model—If at all possible, a site-specific validation should be conducted of any acoustic modeling approach used to estimate sound propagation and zones of influence. Such a validation will ideally be based on field measurements from some other operation that occurred previously at or near the location of the planned survey and for which it is possible to create a modeling scenario comparable to the current model (Text Box 3). This requires access not only to the field measurements but also to the exact specifications of the earlier operation. Less specific validations may be based on measurements from a different type of activity or on calibrated source-transmission loss studies; often, these can reveal the accuracy of certain aspects of the estimation but fall short of providing an end-to-end verification that encompasses both source and propagation modeling. In some circumstances, it may be possible to stage a limited trial of an activity similar to the planned one, thus achieving the twin benefits of a closely matching scenario and a controlled study environment. For a seismic survey, this would take the form of operating a comparable airgun array for some period of time without the onerous requirement of deploying the receiving streamers. The cost and logistical complexity of mobilizing a full-sized geo-seismic source for the sole purpose of a validation study would generally make the concept untenable; it is often the case, however, that seismic sources are active in nearby regions and available "opportunistically" during pauses or transfers between assignments for a relatively lighter demand in cost and planning. The other critical aspect to consider is that the trial itself should be designed to avoid potential harm to the ecosystem.

The increase in estimation confidence afforded by the validation described in Text Box 3 and Figure 2 make it a highly advisable practice as part of standard mitigation and monitoring planning. Aside from enabling the verification of model results just described, the availability of a reference set of realistic airgun array pulses received in the target environment allowed a comprehensive test of the signal processing algorithms to be used in the field for real-time pulse detection and the calculation of sound-level metrics. This prior verification of processing codes on realistic target data is another key practice to be endorsed and promoted, especially when impact mitigation strategies rely on the real-time calculation of pulse sound-level metrics.

Use of Modeling in Mitigating Effects of Seismic Surveys—In situ measures for mitigating acoustic impacts of seismic surveys consist of the estimation of a sound level threshold boundary centered at the seismic source (i.e., safety zone) and visual and/or acoustic monitoring of this zone to ensure that the source is shut down whenever an animal is observed within or about to enter the zone. Historically, exclusion boundaries (safety zones) have been set at relatively short distances from the source at which auditory injury could be inflicted on an animal. Modeling of lower sound-level boundaries at which sub-injury effects (e.g., altered behavior) could occur is most often used to allow estimation of the number of animals likely to be affected over the duration of the survey; this is known as a *take-based* approach to managing potential effects. However, when the population of concern is considered severely at risk or individuals are easily disturbed and/or heavily dependent on undisturbed behavior to complete their seasonal life cycle (e.g., satisfy annual nutritional requirements), it may be necessary to implement active mitigation (operational shutdown) at a behavioral threshold boundary. For a typical seismic survey, this boundary can extend several kilometers from the source and have an irregular outline caused by directional properties of airgun array sources and non-uniformities in the sound propagation environment—chiefly, bathymetry. No well-established, practical methods are available for implementing comprehensive real-time monitoring of animals within a behavioral boundary when the population is wholly unbounded (e.g., by a land or ice barrier) as is the case for most offshore seismic surveys. Still, there are instances in which the animals are dependent for certain life functions (e.g., feeding, calf rearing) on a localized patch of habitat, and avoidance or some other behavioral response can result in their losing access to optimal conditions.

Monitoring is easier if the optimal habitat is coastal and thus suited to surveillance from observation stations on shore. Conditions for the 2010 Sakhalin Energy survey were ideal in that much of the whale population (especially mother and calf pairs) congregates in a coastal feeding area extending only a few kilometers offshore, such that the notional outer reaches of their distribution could be observed from raised shore platforms with the aid of binoculars and theodolites under a fairly wide range of weather conditions (Gailey et al., 2007). With the ability to generate, through acoustic modeling, the expected limit of shoreward propagation of airgun array pulses at behaviorally significant sound levels, the complete mitigation approach was defined: a shutdown was to be called if gray whales were seen within the region enclosed by the predicted behavioral threshold boundary and the notional outer limit of the feeding area. To generalize, specific survey configuration features and the degree of requirement for especially precautionary assumptions will always shape the details of implementation. In the case of the 2010 Sakhalin Energy survey, the full region of potential ensonification at behaviorally relevant levels for a given survey line was considered as the exclusion zone within the feeding area (Figure 3)—that is, if whales were observed in this zone, the survey would shut down. Importantly, animals observed beyond (seaward of) the statistically defined outer edge of the feeding distribution did not trigger a shutdown despite their being closer to the seismic line (an implied "take" allowance). This decision reflected a compromise between the ideal of protecting all individual animals and the desire to avoid delaying survey completion, which would prolong the overall exposure of the whale population.

A further step in estimation accuracy involves ensuring that the variability in propagation conditions due to daily cycles, shifting environmental variables, and advancing season are captured in the modeling results. Since it is seldom possible to predefine the specific variations, a library of model results corresponding to a range of water column profiles can be pre-computed in advance of the field operation as the modeling is too slow to be performed *in situ* on a responsive basis with current processing capabilities (Text Box 4). In the field, the most appropriate library case for a seismic survey line about to be

Text Box 4. Generation of pre-modeled acoustic footprints for the 2010 Sakhalin Energy survey; generating such reference cases increases efficiency of response to changing environmental conditions

For the 2010 Sakhalin Energy survey, the library of pre-modeled footprints included three acoustic propagation environments—the "base case" and a high and a low propagation regime—which could be further tuned by adding or subtracting a uniform dB offset to the results. The best library footprint for a seismic survey line was selected by measuring the sound levels of the initial 60 s of pulses, in real time, at the nearest three hydrophones of a 20 km, nine-station telemetric monitoring line laid along the notional 95% perimeter of whale density in the near-shore feeding area (Figure 3). An algorithm automatically compared the averaged pulse levels with model estimates at the sensor sites from each of the library footprints and returned the noise propagation regime and offset that gave the least residual. The identity of the selected noise case was then communicated by radio to the observers, who would then call up the appropriate safety zone overlay on specialized GIS applications for immediate whale location referencing (see Figures 3 & 4).

Text Box 5. Real-time verification of received levels during the 2010 Sakhalin Energy survey

The commitment made as part of the 2010 Sakhalin Energy survey plan was to have the measured levels remain within a tolerance band of +3 dB maximum relative to the modeled estimate; if this condition was not met, then an adequately larger footprint would have to be selected immediately from a library of area-specific models and communicated to the observation teams for expansion of the safety boundary. As each line was acquired, a software application tracked the progress of the seismic vessel and plotted the received levels at all nine sensors as curves that progressively extended in time, each reaching a peak as the survey source passed the closest point of approach (CPA) for that station. The model-predicted pulse level curve for any one station could be viewed as an overlay for comparison with the real-time graph, with a +3 dB tolerance band reference curve facilitating the visual verification of the level tracking. This process was followed for every line that had been predicted to generate received levels above the behavioral threshold within the whale feeding area, and for several more distant lines as well. The outcome of this validation process confirmed that the desired level of model accuracy was consistently achieved in every CPA neighborhood throughout the full line.

acquired can be selected either through measurement of the water column properties and matching to the most similar modeling sound speed profile, or by monitoring in real time the received levels from the first pulses along the line at a few measurement sites and matching them to the footprint that best represents the received levels.

Intra-Line Real-Time Monitoring for Model Accuracy—Under most circumstances, the approach described in the previous section provides an acceptable degree of assurance that the boundary lines being used for safety or exclusion zone enforcement do in fact represent reliable exposure thresholds. A further practice, which is advisable in cases where there is minimal tolerance for any risk of behavioral disturbance should the noise level estimates be found to be even moderately inaccurate, is real-time monitoring of acoustic levels and their verification against model predictions throughout the course of every seismic line.

Having initially selected a behavioral safety zone based on the acoustic readings at the start of a line, the expectation is that the selected boundary remains valid all the way to the end of that line. This means that intermediate measurement stations deployed along the length of each line would have to record pulse levels consistent with the model estimates at those sites for the selected noise case. The use of complex real-time telemetered acoustic systems should be considered as an optional measure and considered mandatory only in the most critical circumstances, provided other verification and calibration practices have been followed. The deployment of such a system was part of the 2010 Sakhalin Energy survey and is described in Text Box 5.

Detailed Protocols for an Integrated, Site-Specific, Real-Time Acoustic and Visual Monitoring Effort

Observing animals during a seismic survey is an essential component of the predetermined mitigation measures outlined above, as well as of efforts to monitor and understand effects. The most common method for scouting and observing the animals is deployment of ship-based MMOs equipped with handheld reticle binoculars. MMOs are vitally important for detecting and identifying animals in close proximity to the seismic source and thus at risk of sustaining physical damage (Gailey et al., 2007; Johnson et al., 2007). As distance from the seismic source increases, ship-based MMOs become less effective at detecting animals; and their ability to estimate distances, and therefore the animals' geographic locations, becomes less reliable (Barlow & Gisiner, 2006). In addition, environmental conditions, such as sun glare, fog, darkness, and sea state, can limit the detectability of animals at sea. Passive acoustics (e.g., towed hydrophone arrays) can be used to supplement visual monitoring or replace it altogether in cases of poor weather or darkness (Zimmer, 2011). Acoustic monitoring can be particularly important for deep-diving cetaceans, such as beaked whales (Ziphiidae) and sperm whales, but it does require that the animals are actively vocalizing and that their vocalizations can be detected when the seismic survey is underway.

For coastal environments, shore-based methods, often employing theodolites, can be cost-effective and accurate for identifying and determining the locations of animals within about 15 km of shore, although this depends on the height above sea level of the observation point (e.g., Gailey et al., 2007). Theodolite observations, in particular, can greatly enhance spatial resolution and make it possible to track movements of individuals over time and document potential alterations of their motion parameters as they are exposed to varying sound levels (Gailey et al., 2007).

Real-time mitigation is typically challenging; it requires a seamless process of in-field data collection, processing, interpretation, and dissemination of information not only on where the animals are and what they are doing but also on vessel positions and received sound levels. The ability to accomplish real-time monitoring and implementation of mitigation protocols has been greatly enhanced by recent advances in GIS technology (e.g., database collection systems such as *Pythagoras*) (Gailey & Ortega-Ortiz, 2002), *Logger* (International Fund for Animal Welfare [IFAW], 2000), *PAMGUARD* (Pamguard, 2006), and

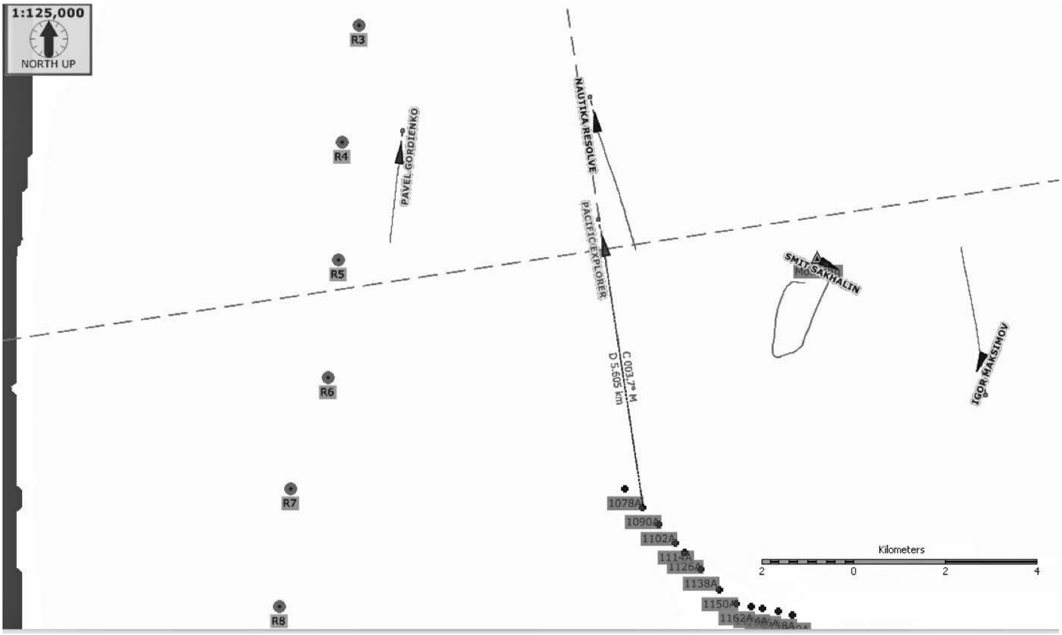


Figure 4. To improve situational awareness, various data streams can be combined into a single, real-time, geospatially explicit display. This image is a screen capture from one of the computers used during the 2010 Sakhalin Energy survey, thus its relatively unpolished nature. Data streams can include AIS from any/all vessels, locations of whales from visual or acoustic detections, and static positions (e.g., acoustic monitoring buoys). The acoustic monitoring buoys (R3, R4, etc.) correspond to the gray dots situated along the PML in Figure 3. The small black dots with associated gray boxes near the scale bar show start points of seismic lines, and the locations of the various ships are shown with black triangles and the names of the ships. Most of the ships shown fulfilled roles described in the text and in Figure 3: the *Igor Maksimov* was the scout vessel, the *Pavel Gordienko* was the observation vessel, the *Pacific Explorer* was the seismic vessel, the *Nautika Resolve* was a guard vessel responsible for maintaining and protecting the seismic vessel's in-water gear, and the *Smit Sakhalin* was a support vessel for the drilling platforms and not associated directly with the seismic survey.

WILD (D'Amico et al., 2010), and the availability of Automatic Information Systems (AIS) data to pinpoint vessel positions. Centralizing situational information from disparate sources into an ensemble view allows for better data management and a more informed, more efficient decision-making process (Figure 4). It is essential that the process incorporate recognition of the uncertainty (variability and measurement error) surrounding nearly all types of data (e.g., acoustics, animal locations, behavioral states, etc.), and, to the extent possible, this uncertainty be accounted for through precautionary judgments.

Beyond the collection and processing of data for real-time mitigation, it is important to collect and archive data for *post-hoc* assessment of effectiveness and to improve understanding of effects. Acoustic monitoring that is tangential to immediate mitigation measures may be critically important for future analyses of sound propagation and estimating received levels at whale locations. In a 2001 seismic survey off Sakhalin, the acoustic footprint was monitored in real time only along the 20 m isobath (Rutenko et al., 2007). Although this was deemed adequate for mitigation, the lack of acoustic data for positions closer to shore hampered *post-hoc* analyses to determine exposure (received sound levels) of whales in the feeding area and evaluate their responses in terms of behavior, distribution, and abundance (Gailey et al., 2007; Yazvenko et al., 2007a, 2007b). In light of that experience, for the 2010 Sakhalin Energy survey, bottom-mounted acoustic receivers were deployed to archive data both offshore and inshore of the feeding area boundary to facilitate more accurate estimation of received sound levels. The number and placement of acoustic sensors should always be carefully considered in the monitoring plan for a seismic survey—not only to support real-time mitigation efforts but also to enable rigorous post-survey analyses.

Although behavioral changes may be apparent in direct observations of an individual's reaction to a specific activity, they can also be subtler. Movement of animals out of an area may not be a direct response to any particular seismic shot-line or surge in noise but, rather, a gradual response to the aggregate or cumulative level of disturbance as a survey progresses. Alternatively, such movement could be part of the animals' natural activity cycle or a response to stochastic environmental conditions unrelated to the seismic survey. Yazvenko et al. (2007a) inferred that gray whales were displaced from an area of seismic exploration by the cumulative sound energy to which they were exposed over a 3-d period; Gailey et al. (2007) found several indicators of behavioral response to sound that may have provided indications of disturbance prior to the displacement reported by Yazvenko et al. (2007a).

Behavioral effects can occur at greater distances from the seismic source than are being monitored. Received levels vary not only with distance from the source but also with propagation conditions; and, in some observed circumstances, received levels at more than 10 km from the source can be as high as those at less than 2 km (Madsen et al., 2006). Monitoring and contextualizing subtler behavioral changes (e.g., a slow avoidance reaction as opposed to multiple breaching and rapid movements) requires detailed, quantitative documentation and accurate knowledge of sound exposure. Although it is difficult to determine whether behavioral changes are likely to result in biologically significant impacts on individuals or the population, a precautionary approach is always appropriate in the case of critically small, endangered populations (National Research Council [NRC], 2005).

Collection and Archive Protocols for Biological and Operational Data

Given the complexity and diversity of synoptic data that are collected in a monitoring program, a detailed, comprehensive data collection and management plan is needed for any survey. Specific data collection protocols and standards are required within field teams, and an overarching structure for archiving and retrieving data for analysis should be established in advance, carefully maintained, and always backed-up.

While data collection protocols will necessarily vary according to the different kinds of observations and measurements being obtained, there should be sufficient consistency across teams to ensure that the following concerns are addressed:

- Are appropriate and robust multivariate data being collected and archived (these should include data on biological and environmental factors as well as human activities)?
- Are protocols in place for quality control of data?
- Are data from different teams being collected in compatible formats to enable synthetic analyses?
- Is an adequate data archiving infrastructure in place?
- Are detailed protocols in place to ensure that data integration is possible across teams, with specific attention to time and geospatial synchronization and visualization of data streams with consistent data formats?

Communication Protocols and Operational Command Structure

Communication is an obvious and critical element of any strategy involving observations intended to feed into a decision-making process. In the case of a seismic survey, operations necessarily involve multiple teams (1) to monitor the underwater acoustic environment and the distribution, movement, and behavior of animals, and (2) to use the resultant information to manage the seismic operations in real time. Therefore, clear and robust communication protocols are essential. It is hard to overstate the potential complexity of a communication and command structure when field data collected in differing modalities from multiple platforms are being transmitted, evaluated, and applied to real-time decision-making processes. The challenge can be even greater when the personnel involved need to cope with differences in language and culture. To achieve an effective communication infrastructure, it is important to strive for simplicity and clarity.

During the 2010 Sakhalin Energy survey, for example, observations of both the behavior and distribution of whales and the acoustic environment during the seismic survey were communicated on a continuous basis to a command center. If sound levels received at moored sonobuoys along the margin of the gray whale feeding area exceeded expected levels, or if aberrant behavior by whales (as predefined by the Seismic Survey Task Force) was observed, mitigation measures, including in some instances shutdown, would be initiated according to the communication protocols (SEIC, 2010). During the 2001 ENL seismic survey, aerial observation results reportedly were used in daily planning (Yazvenko et al., 2007a). Also during that survey (as well as the 2010 Sakhalin Energy survey), whale spotters (MMOs) aboard the seismic and support vessels made continuous observations for whales in the respective safety zones, and the lead MMO on the seismic vessel had the authority to call for an immediate shutdown of the airguns if whales were sighted within or approaching the relevant buffer distances (Johnson et al., 2007; SEIC, 2010). Reliable and redundant communication channels and a clearly defined chain of command are necessary to implement these measures and to foster the most effective and productive coordination of a project.

Due to the complexity of implementing a real-time mitigation and monitoring plan involving multiple teams operating independently of each other, all participants need to have a thorough understanding of their roles and responsibilities. Furthermore, the decision-making process relative to the operational protocols that are agreed to in advance should be both coherent and transparent. Finally, all teams need to be aware of the responsibilities of the other parties involved and understand how the different activities are linked. A communication plan should include the following:

- A description of the various parties involved in implementation of the mitigation and monitoring plan and those who will conduct the seismic survey
- Definition of the roles and responsibilities of all teams
- A description of shutdown criteria
- The chain of command and authority levels—for example, for ordering shutdowns, instructing teams, and directing survey and seismic vessels
- An explanation of how to use communication equipment, contact details of each team, and redundancy in case of equipment failure

Before the start of the survey, all participants should have received the plan and be familiar with its contents: training sessions may be needed to ensure this. Typically, experienced participants are able to improve the plan by providing constructive criticism, and potential issues can be discussed during the training sessions. In those situations in which more than one language is spoken, the plan needs to be translated. Language barriers can confuse operations at many levels, and an in-depth understanding of the overall monitoring and mitigation strategy as well as the communication plan by all team members, regardless of their native language, is important for reducing the potential for confusion. Also important in this regard is ensuring that communications with the captain and crew of all vessels can proceed with minimal interference due to language differences. Inclusion of bilingual members on all teams is highly desirable.

The communication plan should be reviewed periodically as the survey progresses to identify weaknesses, flaws, and elements that need clarification. Especially at the beginning of the survey, regular (daily) briefing sessions are essential. By monitoring the implementation of protocols, addressing weaknesses and flaws, updating the plan, and communicating changes to all staff, the efficiency and effectiveness of implementation of the mitigation and monitoring plan will be improved. If face-to-face meetings are infeasible, with teams placed on different platforms, regular radio or phone contact is essential.

Implementation of shutdown criteria is always stressful, and especially so when there are multiple observer platforms providing real-time status updates on the location and behavior of a single whale or multiple whales. For example, during the 2010 Sakhalin Energy survey, a central command center received real-time input and plotted the position of the seismic vessel (Figure 4), the marine acoustic environment from an onshore acoustics monitoring team, the behavior and distribution of whales from a vessel-based team and two onshore behavior teams, and the locations of whales from MMOs on the seismic and guard vessels. If mitigation was required, all teams had to know what and when to report, and in which format. Whenever there was a call for a potential shutdown, all input from the mitigation and monitoring teams was assessed when deciding whether to continue airgun operations or order them to cease. It is standard practice for only one person to have the authority to order a shutdown; typically, this is the responsibility of the lead MMO or another independent party.

Engagement of Stakeholders: Open and Transparent Communication

When it comes to identifying species or populations of concern and establishing risk tolerance, not all stakeholders will have the same views. Open and transparent communications throughout the planning, execution, and analysis processes can help engender mutual understanding and trust. This may include independent scientific assessment (such as IUCN's Western Gray Whale Advisory Panel), independent observation of the seismic survey and associated mitigation procedures (see "Survey Methods and Tools"), and, ultimately, public disclosure of reports on operations and mitigation efficacy (see "Integration of Independent Observations" below). Independent assessment of the status of and threats to species of concern would occur ideally in the very early planning stages when the exploitation of any hydrocarbon field is being contemplated (i.e., well in advance of a seismic survey). Often, the threats can be mitigated through operational scheduling, although the case of western gray whales has been particularly challenging due to the nearly complete overlap between the period when the whales need to be at Sakhalin to feed and the period when many industrial activities, including seismic surveys, can occur there—namely, the ice-free season. Especially when facing such significant challenges, constructive discussions among stakeholders can and do improve outcomes by ensuring critical scrutiny of arguments, prompting thorough consideration of alternatives, and generating novel approaches to risk reduction.

Survey Methods and Tools

The discussion in this section includes some redundancy with the planning elements just completed, but here we focus on how to implement the planning elements and make suggestions as to logistics. As part of the planning process, we emphasized the need for robust lines of communication, and one important use of those communications is to assess operational progress regularly throughout the survey. Furthermore, regular (e.g., daily) assessments of data collection quality and archiving are critical—for example, analyzing the effectiveness of the mitigation plans and drawing conclusions about effects of the survey, or the lack thereof, from the monitoring data.

Visual and Acoustic Marine Mammal Monitoring Methods

Visual observation is the standard method for detecting marine mammals during most seismic surveys. The effectiveness of MMOs, however, is highly dependent on environmental conditions and limited to daylight periods (see Barlow & Gisiner, 2006); night-vision technology currently holds little promise. The efficiency of observers, even during daylight and good viewing conditions, depends on their level of training, experience, fatigue, and motivation. While detection of marine mammals in near proximity to seismic operations is a critical component of any mitigation program in order to prevent injury, monitoring efforts to learn more about how the animals respond to different received noise levels is also important. Observation for both purposes—damage avoidance and dose-response study—relies on experienced observers (Gailey et al., 2007; Johnson et al., 2007).

All possible methods of detection should be investigated during the planning phase, recognizing that some, such as shore-based observation with binoculars, may only be relevant in particular settings, and others, such as aerial observation, may be technically or financially infeasible. While visual observation from vessels may be the only option for some seismic surveys, such as those far from shore, passive acoustic monitoring is another method that could aid detection. Although limited by the fact that the seismic source produces significantly more acoustic energy than an individual or even a group of marine mammals, passive acoustics can be used if the hydrophone array is located well away from the airguns and robust detection algorithms are used (Zimmer, 2011). Furthermore, many signals produced by marine mammals are outside of the primary frequencies produced by airguns, so use of such strategic frequency bands can enhance detection capability in what would otherwise be judged prohibitive circumstances. The level of effort (and expense) invested in improved detection efficiency can always be scaled with the level of concern for a particular species or animal densities.

Monitoring of Operations, Local Environmental Characteristics, and Other Human Activities

Software tools can provide valuable integration of the spatial interplay between human activities and individual animals. This includes real-time charting of the positions and tracks of vessels in the area via AIS or reported by observers, including all of those involved in survey activities as well as other nearby vessels not explicitly involved. A real-time means of visualizing where specific operations and ancillary activities are occurring in relation to observed animals provides the situational awareness for informed decision-making required to meet mitigation objectives (Figure 4). Seismic surveys are exceptional, independent events with the potential to have acute impacts on animals in their immediate vicinity; however, scientists and managers recognize the need to consider the cumulative or additive risks of all human activities to which the animals are subjected, including how various human activities and other factors may act synergistically. To the extent possible, other proximate human activities (e.g., shipping) that occur during a seismic survey should be accounted for in the overall assessment of risk and included in the situational awareness during the operation.

Numerous factors can affect schedules for execution of seismic surveys and implementation of mitigation and monitoring programs. Good planning and preparation can control some of these factors such as obtaining permits with ample lead-time and ensuring technical preparedness. Others, like weather and the movements of the animals, are beyond the control of survey planners. It goes without saying that the best remedy for unexpected deviations from a plan is to have contingency strategies, which although perhaps not optimal, will nonetheless ensure protection of the species of concern. Failure to undertake these and other preparations early enough can result in delays in start-up or even cancellation. The factors most commonly cited as causing unforeseen changes in survey duration are weather and sea state; aspects of marine mammal occurrence (leading to shutdowns); unsuitable feathering (i.e., precise towing angle of the hydrophone streamers to match previous surveys); and, in the case of 4-D surveys, technical malfunctions, crew changes, and quality of data acquisition (forcing repetition of lines).

Delays in survey initiation or prolonged survey duration often affect logistics and can lead to unavailability of vessels and crews because seismic survey contractors are often tightly subscribed. Operational permits and contracts with monitoring teams, vessels, and support resources might also expire before a survey is completed. When surveys are specifically scheduled to avoid overlap with the presence of migrating animals, delays can result in more animals arriving in the area, potentially resulting in increased exposure and survey interruptions. One strategy used in the 2010 Sakhalin Energy survey was to include incentives in the contract with the survey company—for example, a bonus for beginning and completing the survey on time while complying with mitigation requirements. Such measures may seem superfluous or unnecessary, but without incentives (or penalties) to encourage on-time performance, the most effective mitigation strategy (avoiding spatial or temporal overlap with the animals) could be negated.

In order to optimize the likelihood that a survey will be completed without delays, the window of opportunity needs to be assessed well in advance. This means systematically considering such elements as when seasonal weather changes are likely to affect data acquisition, what permit restrictions may be imposed, when the animals of concern are most likely to be present in high densities, and the effective period of availability of seismic and support vessels. Consideration also needs to be given to how any delays might trigger additional technical and logistical issues. Once this assessment has been completed, contingency plans can be made.

Integration of Independent Observation of Operations to Assess Mitigation and Monitoring Efficacy Relative to Stated Objectives

The value of independent observation to verify and validate claims of legitimacy is intuitive and widely recognized. An example is the International Whaling Commission's (IWC) International Observer Scheme (IOS), which was implemented in 1972 as a way of discouraging illegal whaling and falsification of catch data. The IOS fell short of expectations, probably in part because it involved only the exchange of observers between member countries actively whaling (IWC, 1974), and in part because it was unrealistic to think a single observer would have the fortitude, stamina, and integrity to carry out his assigned role under the circumstances faced aboard another nation's whale ship (Clapham & Ivashchenko, 2009). The inadequacy of that "traditional" approach to independent observation (e.g., note that all Japanese observers on Soviet whaling vessels were employees of the Japanese whaling industry) underlines the importance of ensuring that in any such scheme, conflict of interest is avoided and true independence is guaranteed. Modern technology that allows for methods such as videography, wireless (satellite-linked) communications, and remote surveillance to track vessel movements can be used to enhance or supplement the work of independent observers on ships at sea.

An independent observer program in the eastern tropical Pacific tuna purse seine fishery was introduced in 1972 primarily as a means of obtaining data on the incidental mortality of dolphins as well as various other types of environmental data (NRC, 1992). The tuna-dolphin program highlights several key considerations that apply more broadly to the use of independent observers. One is that for any program in which only a portion of the activities is observed (initially, tuna-dolphin observers were placed on only a sample of the fleet), there is risk of an "observer effect," which means that the presence of an observer influences regulatory compliance (assuming people behave better when under scrutiny than when not) and thus leads to a biased impression of overall performance (NRC, 1992). Another is that the observer's role must be clearly defined, and the distinction between data collector and enforcement agent made explicit. Independent observers are, by definition, placed in an awkward position at the best of times. Being at sea for months with a captain and crew who are highly motivated to maximize their catch and minimize their time away from home is bound to create pressure on the observer to overlook infractions or under-report compromising data.

In the case of the 2010 Sakhalin Energy survey, an independent observer was recruited and contracted to act on behalf of the IUCN panel. The WGWAP, the company, and IUCN developed terms of reference for the observer collaboratively. Selection of the individual by WGWAP was entirely independent of the energy company, and the observer reported directly to the panel and IUCN (the contracting body). Energy company representatives were asked to review the observer's draft report for factual accuracy before it was finalized; this is an important part of the process but one that needs to be managed carefully to ensure the observer's independence and objectivity throughout. The final report of the independent observer was made public after being accepted by the WGWAP (IUCN, 2010). Its conclusion was that the mitigation and monitoring program for this seismic survey had been "one of the most complex in the history of the marine seismic industry" and "the people responsible for implementing the program carried out their work in a serious, professional manner" (p. 23). The presence of the independent observer in the field, and the relatively positive tenor of his report, gave the panel, IUCN, and presumably those nongovernmental conservation organizations that had expressed concern about the potential impacts of this seismic survey on western gray whales, greater confidence that the agreed procedures were actually being followed and that a good-faith effort had been made to protect the whales from excessive noise exposure. Finally, a mechanism should be in place so feedback from the independent observer can be incorporated.

Recommendations for Post-Survey Tasks

Rapid Assessment, Team by Team (e.g., Behavior, Acoustic), of Data Collected, Lessons Learned, and Analyses Planned at End of Operations

Following completion, but while at least key field personnel are still assembled, an initial assessment of the mitigation and monitoring efforts should be conducted and should include a complete accounting of the data collected, with confirmation that data to be integrated from disparate teams are collated in comparable, time-synchronized formats. Additionally, the first-order lessons learned regarding the efficacy of field protocols, data acquisition, and data management should be documented.

Often, a preliminary report is prepared and disseminated to stakeholders. Such a report provides a general overview of operations, effort, major events (e.g., shutdowns triggered by mitigation protocols), initial data analyses, and short- and long-term plans for analyses. Some components of the preliminary report can also be used for public relations needs (e.g., company website, press releases).

A preliminary report might include the following:

- *All mitigation measures taken*
- *Acoustic Exposure Summary* – real-time and archival effort, levels recorded, whether thresholds were or were not exceeded
- *Sightings* – species of primary concern and other noteworthy organisms; observations of animals in mitigation areas
- *Behavior* – any aberrant behavior observed, for example
- *Data* – (1) proper archiving, (2) quality-control measures conducted or planned, and (3) analysis plans

Publication and Release of Detailed Assessment of Results

It is in the nature of any industrial or business enterprise to be forward-looking and future-oriented, and this can mean there is a natural reluctance to build retrospective analyses or assessments into budgets and work plans. Moreover, even when these are part of initial planning, they tend to be regarded as low priority in the aftermath of a completed survey. This is an area where regulators may need to insist that appropriate analyses are carried out and that rigorous, objective assessments (including publication in the peer-reviewed literature) are made of the efficacy of the mitigation and monitoring measures associated with a given seismic survey after its completion.

Two aspects deserve emphasis. First, just as there is a need for transparency with regard to the EIA process before development proceeds, it is essential that the public and decisionmakers are given access to the results of these assessments. Oil and gas operators frequently emphasize with good reason that the products they deliver are highly valued by societies and, in that sense, theirs is a service industry. However, the resources at risk from offshore development (marine mammals and other biodiversity in the present context) are equally valued. Therefore, consumers expect assurance that they will be in a position to make informed choices when purchasing energy products, with credible and complete information on the environmental impacts involved in bringing those products to the market.

Second, energy companies themselves are bound to improve their performance and reduce their own reputational risks by learning from strengths and weaknesses of past performance. This ought to be sufficient motivation for individual companies to examine performance, team by team, after an activity like a seismic survey has been completed. In addition, though, there is sound reason for carrying the presentation of results all the way through to publication in the open literature. Such sharing of results, providing an equitable overview of the positive and the negative outcomes, can only be seen as a mark of corporate responsibility that, in the long run if not immediately, benefits the industry as a whole and helps blunt criticism by those who question the industry's sincerity when it claims to be committed to environmental stewardship.

Detailed Analysis and Publication in Open Literature, Including Lessons

Data deficiency is a common problem when it comes to characterizing and quantifying the risks to marine mammals from seismic and other high-energy noise introduced into the marine environment by human activities. Therefore, helping fill data gaps should be considered a top priority for conservation biologists, resource managers (regulators), and industry. Even in areas where seismic surveys have been taking place for many years (e.g., the Gulf of Mexico), there is a dearth of information about effects and potential risks to wildlife. In designing mitigation plans, drafting

EIAs, and preparing applications for permits, project proponents are expected to use "the best scientific information available," which is understood to mean, first and foremost, the peer-reviewed literature. Where such literature is lacking or incomplete, as is the case when it comes to characterizing the effects of seismic airgun noise on baleen whales, there should be a strong incentive to collect relevant data, conduct appropriate analyses, and publish results in the peer-reviewed literature. We recommend that funds for analyses and publication be included in project budgeting and allocated at the outset of the planning process. Important as it may be to publish new findings from any monitoring program as elaborate and comprehensive as the one described herein for marine seismic surveys, the ultimate aim is to make sure that lessons learned are applied to future mitigation and monitoring efforts so as to minimize the effects of a survey. Such lessons learned should be included in materials published from the mitigation and monitoring efforts.

Conclusions

We have described a series of elements for the responsible planning and execution of a seismic survey for geophysical exploration, including, as much as possible, the rationale for them and relevant examples in an effort to assist those planning future surveys. The elements described represent the basic requirements for conducting a responsible survey by applying modern tools (e.g., acoustic models, animal distribution measurement) to predict the potential effects, mitigate acute risks, and monitor species involved so that information collected during a survey can improve our capability to understand and minimize impacts in the future. It must be noted, however, that biological monitoring data collected during seismic surveys need to be interpreted carefully given that the animals observed are being exposed to the source of a potential disturbance and therefore may not be behaving "normally." Few efforts have been made to conduct controlled exposure experiments (CEEs), which manipulate exposure and thus control the dose (Tyack, 2009). As much information as possible about the environment and species of concern should be collected or analyzed if data already exist in hopes that a "baseline" profile reflecting undisturbed conditions can be used for comparison. We also acknowledge that the tools we have described can and should be improved and that the elements themselves should be revised and improved with time.

A comprehensive mitigation and monitoring plan such as the one described herein certainly has financial implications for the company conducting the survey, although the balance of costs may not be intuitive. The obvious up-front financial impact is the additional cost of the mitigation and monitoring program itself (e.g., observers, acoustic equipment, and preparatory activities). A well-conceived mitigation and monitoring program, however, can shorten the time required for the survey and thus result in a savings, primarily by reducing the number of days the source vessel must be on site. An example of this comes from the 2010 Sakhalin Energy survey for which the primary mitigation tool was to conduct the survey as early in the season as possible—that is, at a time when the fewest whales were expected to be present—thus minimizing the potential for mitigation interruptions. Other cost savings could be achieved in future (e.g., repeat) surveys both by having a robust original plan already in hand and by leveraging that plan and the data gathered in the initial monitoring effort to enable a more streamlined completion of permit applications.

It should be acknowledged that many of the elements included in our approach were developed for shallow-water applications. This is understandable in that two of the most comprehensive mitigation and monitoring plans on record were developed for the protection of gray whales off the coast of Sakhalin Island, Russia (IUCN, 2010). Nevertheless, many of the techniques discussed herein can be used in deeper waters, although the specific platforms (e.g., visual observation posts) and equipment (e.g., acoustic monitoring devices) will differ.

Energy companies may not recognize a strong mandate from their stakeholders to collect information for use outside the immediate scope of their own activities or to engage in mitigation or monitoring efforts beyond what is required by law. Nonetheless, while producing valued products, companies are exploiting common-pool natural resources. Such production should occur as responsibly as possible by minimizing the risks to wildlife and the environment. Furthermore, the collection of information about potential impacts is critical for improving management, and public agencies need to take a more active role in assimilating this information into policy (Figure 1). Better understanding of the impacts of an activity should improve the quality and relevance of protective measures, including a relaxation of mitigation requirements if justified. It is, therefore, in the best interest of all parties to follow responsible practices that are as consistent as possible in the planning, execution, and analysis of seismic surveys as we strive for wiser use and conservation of valuable natural resources.

Endnote

[1] The Western Gray Whale Advisory Panel (WGWAP) was convened by the International Union for Conservation of Nature through a contract with the Sakhalin Energy Investment Company in 2007. Complete information about the WGWAP, its mission, activities, and documents can be found at www.iucn.org/wgwap.

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Literature Cited

Barlow, J., & Gisiner, R. (2006). Mitigating, monitoring and assessing the effects of anthropogenic sound on beaked whales. *Journal of Cetacean Research and Management*, *7*(3), 239-249.

Cerchio, S., Collins, T., Strindberg, S., Bennett, C., & Rosenbaum, H. (2010). *Humpback whale singing activity off northern Angola: An indication of the migratory cycle, breeding habitat and impact of seismic surveys on singer number in Breeding Stock B1* (Vol. 62). Cambridge, UK: International Whaling Commission.

Clapham, P. J., & Ivashchenko, Y. (2009). A whale of a deception. *Marine Fisheries Review*, *71*(1), 44-52.

Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series*, *395*, 201-222. http://dx.doi.org/10.3354/meps08402

D'Amico, A., Kyburg, C., & Carlson, R. (2010). Software tools for visual and acoustic real-time tracking of marine mammals. *The Journal of the Acoustical Society of America*, *128*(4), 237.

Ellison, W. T., Southall, B. L., Clark, C. W., & Frankel, A. S. (2012). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology*, *26*(1), 21-28. http://dx.doi.org/10.1111/j.1523-1739.2011.01803.x

Gailey, G. A., & Ortega-Ortiz, J. (2002). Pythagoras: A computer-based system for theodolite tracking. *Journal of Cetacean Research and Management*, *4*(2), 213-218.

Gailey, G., Würsig, B., & McDonald, T. L. (2007). Abundance, behavior, and movement patterns of western gray whales in relation to a 3-D seismic survey, Northeast Sakhalin Island, Russia. *Environmental Monitoring and Assessment*, *134*, 75-91. http://dx.doi.org/10.1007/s10661-007-9812-1

Gard, R. (1974). Aerial census of gray whales in Baja California lagoons, 1970 and 1973, with notes on behavior, mortality and conservation. *California Fish and Game*, *60*(3), 132-143.

Gordon, J., Gillespie, D., Potter, J., Frantzis, A., Simmonds, M. P., Swift, R., & Thompson, D. (2003). A review of the effects of seismic surveys on marine mammals [Review]. *Marine Technology Society Journal*, *37*(4), 16-34. http://dx.doi.org/10.4031/002533203787536998

Grech, A., Marsh, H., & Coles, R. (2008). A spatial assessment of the risks to a mobile marine mammal from bycatch. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *18*, 1127-1139. http://dx.doi.org/10.1002/aqc.943

High Energy Seismic Survey (HESS) Team. (Ed.). (1999). *High Energy Seismic Survey (HESS) review process and interim operational guidelines for marine surveys offshore southern California*. Camarillo: California State Lands Commission and U.S. Minerals Management Service.

International Fund for Animal Welfare (IFAW). (2000). *Logger: Field data logging software* (Version 2000). Retrieved 1 October 2013 from www.marineconservationresearch.co.uk/downloads/logger-2000-rainbowclick-software-downloads.

International Union for Conservation of Nature (IUCN). (2010). *Report of the 4-D Seismic Survey Task Force at its 6th Meeting*. Geneva, Switzerland: IUCN.

International Whaling Commission (IWC). (1974). *Twenty-fourth report of the Commission* (Vol. 24). Cambridge, UK: IWC.

Jensen, F. B., Kuperman, W. A., Porter, M. B., & Schmidt, H. (2011). *Computational ocean acoustics* (2nd ed.). New York: Springer.

Johnson, S. R., Richardson, W. J., Yazvenko, S. B., Blokhin, S. A., Gailey, G., Jenkerson, M. R., . . . Egging, D. E. (2007). A western gray whale mitigation and monitoring program for a 3-D seismic survey, Sakhalin Island, Russia. *Environmental Monitoring and Assessment*, *134*, 1-19. http://dx.doi.org/10.1007/s10661-007-9813-0

Joint Nature Conservation Committee (JNCC). (2010). *JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys*. Aberdeen, Scotland: JNCC. 16 pp.

Madsen, P. T., Johnson, M., Miller, P. J. O., Soto, N. A., Lynch, J., & Tyack, P. L. (2006). Quantitative measures of air-gun pulses recorded on sperm whales (*Physeter macrocephalus*) using acoustic tags during controlled exposure experiments. *The Journal of the Acoustical Society of America*, *120*(4), 2366-2379. http://dx.doi.org/10.1121/1.2229287

Malme, C., Würsig, B., Bird, J. E., & Tyack, P. L. (1986). *Behavioral responses of gray whales to industrial noise: Feeding observations and predictive modelling*. Washington, DC: National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

Malme, C., Würsig, B., Bird, J. E., & Tyack, P. L. (1988). Observations of feeding gray whale responses to controlled industrial noise exposure. In W. M. Sackinger, M. O. Jefferies, J. L. Imm, & S. D. Treacy (Eds.), *Port and ocean engineering under Arctic conditions* (pp. 55-73). Fairbanks: University of Alaska.

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P. L., & Bird, J. E. (1983a). *Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior*. Washington, DC: U.S. Department of the Interior, Minerals Management Service.

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P. L., & Bird, J. E. (1983b). *Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior*. Washington, DC: U.S. Department of the Interior, Minerals Management Service. 63 pp.

Malme, C. I., Miles, P. R., Clark, C. W., Tyack, P. L., & Bird, J. E. (1984). *Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. Phase II: January 1984 migration*. Washington, DC: U.S. Department of the Interior, Minerals Management Service.

National Oceanic and Atmospheric Administration (NOAA). (1998). Incidental taking of marine mammals: Acoustic harassment. *Federal Register*, *63*(143), 40103.

National Research Council (NRC). (1992). *Dolphins and the tuna industry: Committee on reducing porpoise mortality from tuna fishing*. Washington, DC: NRC.

NRC. (2005). *Marine mammal populations and ocean noise: Determining when noise causes biologically significant effects*. Washington, DC: National Academy of Sciences.

New Zealand Department of Conservation. (2012). *2012 code of conduct for minimising acoustic disturbance to marine mammals from seismic survey operations*. Wellington: New Zealand Department of Conservation.

Nieukirk, S. L., Mellinger, D. K., Moore, S. E., Klinck, K., Dziak, R. P., & Goslin, J. (2012). Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999-2009 (Research Support, Non-U.S. Government Research Support, U.S. Government, Non-P.H.S.). *The Journal of the Acoustical Society of America*, *131*(2), 1102-1112. http://dx.doi.org/10.1121/1.3672648

Nowacek, D. P., Thorne, L. H., Johnston, D. W., & Tyack, P. L. (2007). Responses of cetaceans to anthropogenic noise: An update and review of behavioural and some physiological effects. *Mammal Review*, *37*, 81-115. http://dx.doi.org/10.1111/j.1365-2907.2007.00104.x

Nowacek, D. P., Vedenev, A., Southall, B. L., & Racca, R. (2012). Development and implementation of criteria for exposure of western gray whales to oil and gas industry noise. *Advances in Experimental Medicine and Biology*, *730*, 523-528. http://dx.doi.org/10.1007/978-1-4419-7311-5_119

PAMGUARD. (2006). *PAMGUARD: Open-sourced software for passive acoustic monitoring*. Retrieved 1 October 2013 from www.pamguard.org.

Porter, M. B. (1993). Acoustic models and sonar systems. *IEEE Journal of Oceanic Engineering*, *18*(4), 425-437. http://dx.doi.org/10.1109/48.262293

Racca, R. (2009). Validation of seismic model against data from trial at PA-A in October 2009. In International Union for Conservation of Nature (IUCN) (Ed.), *Report of the 4-D Seismic Survey Task Force at its 4th meeting* (Vol. Annex G). Geneva, Switzerland: IUCN.

Racca, R., Rutenko, A., Bröker, K., & Austin, M. (2012). *A line in the water – Design and enactment of a closed loop, model based sound level boundary estimation strategy for mitigation of behavioural impacts from a seismic survey.* Paper presented at the 11th European Conference on Underwater Acoustics, Edinburgh, Scotland.

Richardson, W. J., Würsig, B., & Greene, C. R., Jr. (1986). Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. *The Journal of the Acoustical Society of America*, *79*(4), 1117-1128. http://dx.doi.org/10.1121/1.393384

Rutenko, A. N., Borisov, S. V., Gritsenko, A. V., & Jenkerson, M. R. (2007). Calibrating and monitoring the western gray whale mitigation zone and estimating acoustic transmission during a 3D seismic survey, Sakhalin Island, Russia. *Environmental Monitoring and Assessment*, *134*, 21-44. http://dx.doi.org/10.1007/s10661-007-9814-z

Sakhalin Energy Investment Company (SEIC). (Ed.). (2010). *Environmental impact MPACT assessment of Sakhalin Energy Investment Company's 3-D seismic programme in the Piltun-Astokh Area, Sakhalin Island, Russia*. Yuzhno-Sakhalinsk, Russia: SEIC.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., Jr., . . . Tyack, P. L. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals*, *33*(4), 411-521. http://dx.doi.org/10.1578/AM.33.4.2007.411

Tyack, P. L. (2009). Acoustic playback experiments to study behavioral responses of free-ranging marine animals to anthropogenic sound. *Marine Ecology Progress Series*, *395*, 187-200. http://dx.doi.org/10.3354/meps08363

Weir, C. R., & Dolman, S. J. (2007). Comparative review of the regional marine mammal mitigation guidelines implemented during industrial seismic surveys, and guidance towards a worldwide standard. *Journal of International Wildlife Law & Policy*, *10*(1), 1-27. http://dx.doi.org/10.1080/13880290701229838

Yazvenko, S. B., McDonald, T. L., Blokhin, S. A., Johnson, S. R., Meier, S. K., Melton, H. R., . . . Wainwright, P. W. (2007a). Distribution and abundance of western gray whales during a seismic survey near Sakhalin Island, Russia. *Environmental Monitoring and Assessment*, *134*, 45-73. http://dx.doi.org/10.1007/s10661-007-9809-9

Yazvenko, S. B., McDonald, T. L., Blokhin, S. A., Johnson, S. R., Melton, H. R., Newcomer, M. W., . . . Wainwright, P. W. (2007b). Feeding of western gray whales during a seismic survey near Sakhalin Island, Russia. *Environmental Monitoring and Assessment*, *134*, 93-106. http://dx.doi.org/10.1007/s10661-007-9810-3

Zimmer, W. M. X. (2011). *Passive acoustic monitoring of cetaceans*. Cambridge, UK: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511977107