PROCEEDINGS

WORKSHOP ON THE EFFECTS OF ANTHROPOGENIC NOISE IN THE MARINE ENVIRONMENT,

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MONITORING AND MITIGATION

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INTRODUCTION

Section 101(a)(5) of the U.S. Marine Mammal Protection Act (MMPA) directs the Secretaries of Commerce and the Interior to authorize the taking of small numbers of marine mammals incidental to activities other than commercial fishing in U.S. waters when the taking would have a negligible impact on the affected species or stock and certain other conditions are met. One of the conditions is that appropriate monitoring be done to confirm that animals are not taken in ways or numbers not authorized and that the impacts are in fact negligible. Such monitoring can be termed "compliance monitoring". There is also a need to document marine mammal numbers, movements, calls, and other behaviors during research projects on marine mammals in the field. Many of the same observation techniques are suitable both for compliance monitoring and for field research.

Mitigation measures designed to reduce potential impacts on marine mammals are frequently an integral part of monitoring and research projects on marine mammals. One purpose of monitoring is often to implement real-time mitigation procedures, e.g., to shut down a noise source when mammals are detected within some designated radius.

Mitigation often requires a multi-tiered approach to the development of acoustic exposure criteria for species of concern. One type of criterion is a safety radius, designed to protect animals from physical harm. Additional levels of mitigation, often applied at greater distances from the sound source, may be designed to provide additional protection from physical harm or to reduce or avoid unwanted behavioral responses. To meet the mitigation requirements for each of these levels, different monitoring procedures may be needed. Procedures and equipment needed for this monitoring are themselves often in only the first stages of development.

Implementing the mitigation requirements can take several forms depending on the nature of the sound source. This may include restrictions on the locations or times of year when the activity is authorized, source shutdown, reduction in source level, reduction in transmit schedule, change in transmission characteristics (frequency, duration, etc.), or movement of the source away from a specific area.

Limited abilities to monitor marine mammals can substantially affect the effectiveness of mitigation. To introduce some of the problems, W.J. Richardson summarized visual and acoustic monitoring methods used during a recent open-water seismic project in the Alaskan arctic. He emphasized the results pertaining to ringed seals (Harris et al., 1997), although bowhead whales were also a major focus of the work (Richardson [ed.], 1998). Disturbance of small numbers of marine mammals was authorized by Incidental Harassment Authorizations issued for whales and seals by NMFS (NMFS, 1996a,b, 1997) and by Letters of Authorization issued for walruses and polar bears by the U.S. Fish & Wildlife Service. The IHAs required extensive visual and acoustic monitoring programs and various types of mitigation.

During this seismic program, the designated safety (=shutdown) criterion for seals was a received level of 190 dB re 1 μPa_{rms}. Here "rms" refers to average pressure level over the effective pulse duration. The measured 190 dB_{rms} radius was up to 260 m, depending on the airgun configuration in use and other factors (Greene, 1997). The effective source level for horizontal propagation was about 222 dB re 1 μPa_{rms} and 230 dB_{peak}. The latter was well below the nominal peak source level for downward propagation (Greene, 1997).

The detectability of seals in relation to distance from the observers began to decline well inside the safety radius (Harris et al., 1997; Richardson [ed.], 1998). The normal requirement during recent seismic programs has been for one "biologically qualified" observer to be on watch at any given time. However, in this project the sighting rate was notably higher at times with two observers than with one, indicating that many seals were being missed when just one observer was on watch. Visual monitoring at night was largely ineffective even using an image intensifier, and effective acoustical monitoring for seals was not practical. Furthermore, seals did not show sufficiently strong avoidance reactions to keep them outside the designated safety radius around the airgun array. Despite the inability to detect all seals present within the designated safety radius, seals were detected often, requiring 135 shutdowns of the airgun array during one 57-day operating season. That constituted a significant operational disruption.

Subsequent detailed discussions during the Monitoring and Mitigation session addressed many of these issues. Notwithstanding the broader title of the workshop, this session addressed monitoring and mitigation only with respect to marine mammals.

MONITORING

This group's discussions encompassed monitoring techniques suitable for both compliance monitoring and for field research. However, it was recognized that somewhat different monitoring techniques (or combinations of techniques) may be optimal for different purposes. For example, in some studies, one objective is to implement mitigation measures (such as shutdown of potentially harmful human activity) when marine mammals are within a designated "safety radius". In this situation, it is important to use methods that detect a high proportion of the mammals present. However, if the objective is to compare numbers of mammals in one area vs. another (e.g., ensonified vs. control area), it may be sufficient to detect a consistent proportion of the mammals present in both areas even if that proportion is well below 100%.

The discussion of monitoring methods dealt with visual methods, electro-optic and photographic methods, passive acoustics, active sonar, dataloggers and telemetry, and estimation of sound exposure. Particular attention was given to the need for combinations of methods that complement one another.

As an example of this, the LFA SURTASS Scientific Research Program (LFA-SRP) has used a multi-faceted approach integrating several forms of visual observation (aircraft-, shore- and ship-based) along with various methods of acoustical tracking (bottom mounted autonomous systems, shore-based Navy systems, and ship-based towed arrays), as well as depth-logging tagging methods (Clark et al., 1998). This approach served several objectives: (1) The various techniques, singly and jointly, provided a methodology for meeting the various mitigation requirements of the research permit, (2) the resultant data will be used both for analysis of behavioral responses and to update existing databases, and (3) the methodologies themselves will be further tested and refined for use in future similar projects.

The group also discussed the need for long-term studies. In addition, the group felt that, to maximize both productivity and cost-effectiveness, it would sometimes be advantageous to combine the monitoring efforts for various related projects rather than to monitor them in isolation. For similar reasons, there was a widespread opinion that better access to data from previous survey and monitoring projects would help in monitoring long-term effects and in planning mitigation measures.

The following subsections summarize the discussion on each topic. It was not possible within the available time to discuss all topics in detail.

WHAT TO MONITOR, AND WHY?

Dr. R. Hofman summarized the U.S. legal requirements for monitoring. "Taking" of marine mammals is defined under the MMPA to include disturbance ("Level B harassment") as well as injuring, killing or capturing. Taking is prohibited by the MMPA unless a waiver or small take exemption is obtained. Waivers are very rare. Small take exemptions can be of two types: (1) Rulemaking under MMPA §101(a)(5)(A), which may authorize issuance of Letters of Authorization for harassment, injury or even mortality of small numbers of marine mammals by specified human activities over a 5-year period. (2) Incidental Harassment Authorizations under MMPA §101(a)(5)(D), which may authorize harassment but not serious injury or mortality by specified human activities during a 1-year period. The two small-take authorization processes have been used to authorize small takes of marine mammals by various noisy human activities including oil and seismic exploration activities, missile launches, explosive removal of obsolete oil platforms, and ship shock trials.

Under both small-take exemption processes, monitoring may be prescribed to confirm that animals are taken only in the ways and numbers authorized, that the impacts on the affected species or stocks are negligible, and that (in Alaska) there are no unmitigable adverse effects on the availability of the species or stock for taking by Alaskan Natives for subsistence purposes. Monitoring is also important to assess whether required mitigation measures are effective.

Dr. Hofman noted that, to date, monitoring has been project specific and locality specific. He noted that Swartz and Hofman (1991) had assessed the intent and possible means for meeting the monitoring requirements and suggested that it would be reasonable to ask whether this type of project- and locality specific monitoring is the most effective approach. To change this approach, there might be a need to change the MMPA and associated regulations to be able to require broader population-specific monitoring. This might be possible if there were good justification.

VISUAL SURVEYS FROM SHIP, SHORE OR AIRCRAFT

A memo circulated in advance of the meeting identified the following as being potentially worthy of discussion:

- speed and altitude standards,
- standard monitoring ranges for different species/sizes, correction factors for time spent at surface, visibility, etc.
- standards for number of watch standers, rotation schedules,
- standards for training of "qualified" observers,

The attendees did not attempt to discuss these topics in sequence, but touched on most of these points in one form or another.

It was noted at the outset that conventional visual monitoring is a two-dimensional technique that is largely limited to detecting mammals during the times when they are at the surface. (Aerial observers often can see large mammals when they are as much as a few meters below the surface.) Some species are at the surface for as little as 10% of the time. Recently, there has been a tendency to use combinations of methods, including visual, acoustic and tagging, to complement one another. The use of multiple techniques was discussed in more detail later in the workshop. One of the benefits of multiple techniques is cross-validation of methods. This provides the potential for improvement in both technique and quality of data. This applies not only to population surveys but also to behavioral response observations.

There is often concern that some visual observations, especially from small craft near the animals, may be confounded by the presence of the craft itself. This is also a concern for aircraft-based observations. The use of coordinated monitoring techniques, including shore-based observations, tagging, and acoustic methods, can help evaluate such concerns.

Visual as well as acoustic survey methods provide information about *relative* numbers of animals present. Absolute numbers can only be estimated if appropriate correction factors are available, although visual methods do provide direct information about the minimum numbers present. In general, correction factors are better developed for visual than for acoustic surveys, but improvements are needed for both types of surveys.

Despite their limitations, visual techniques are the standard methods for many types of surveys and behavioral observations. Visual procedures are relatively well developed as compared with some other methods. However, significant improvements still can and should be made in developing or improving correction factors for missed animals. The probability of sighting marine mammals depends on observer ability and alertness, survey procedures, visibility, sea state, and behavior of the animals, all of which vary. These factors are widely discussed in the literature. However, for many combinations of species, survey type, and environmental condition, little information is available about the proportion of the animals detected by visual observers.

It is often possible to develop correction factors for missed animals based on data collected during surveys. Useful approaches during routine surveys include double-survey methods, analysis of sighting distances, and analysis of sighting rates vs. environmental conditions and individual observer. However, there are situations when special studies are needed, e.g., behavioral observations and/or tagging to document surfacing/dive cycles.

It was suggested that visual techniques tend to be more applicable in coastal areas, but are difficult and costly far offshore. However, there is a long history of visual surveys both for large whales and for dolphins in offshore areas. Methodologies for ship-based visual surveys in offshore waters are well developed. Attendees were advised that results from a combined visual-acoustic survey in offshore waters of the North Pacific will soon be available, and that this study showed that some species were often detected acoustically when they were not seen (see also "Combinations of Complementary Methods", below).

The merits of consistency in survey procedures vs. adaptability to particular circumstances was discussed briefly. Tradeoffs are inevitable. The stricter the requirement for consistent survey conditions, the lower the proportion of time when surveys can be done and thus the lower the sample size. At the least, there needs to be careful documentation of the conditions under which all surveys were done. This is necessary to allow appropriate data selection, post-stratification, and correction factors.

PHOTOGRAPHIC, ELECTRO-OPTIC, AND REMOTE METHODS

Photo-identification methods can be useful for long-term monitoring of survival, population size, and movements, especially of site-tenacious populations. This can be directly relevant in assessing long-term changes in population status. Long-term effects of human activities are, in general, of more concern than the easier-studied short-term behavioral effects, and photo-identification provides one method for assessing long-term effects. However, ascribing any changes in population status to a particular human activity is difficult.

Photographic re-identifications over the short term can also be useful in assessing whether marine mammals return after being displaced by human activities.

For some species, e.g., pinnipeds that haul out in large groups or cetaceans that congregate in large pods, photographic methods are also important in allowing precise counts. However, correction factors are needed to allow for the proportion of the animals that are on land or at the water's surface and available to be photographed.

Nighttime observations of marine mammals are difficult. There is often a need for nighttime observations, e.g., during censuses of animals migrating past fixed census locations, or when noisy activities are to be shut down when marine mammals are present within some distance. Image intensifiers work well at close range and under some lighting conditions, but have not proven very useful during some recent seismic monitoring/mitigation projects (Arnold, 1996; Harris et al., 1997). Long-wavelength passive infrared sensors can be effective in detecting whale blows (Perryman and Laake, 1995), and are to be used in an imminent seismic monitoring project (NMFS, 1998). Forward-looking infrared (FLIR) sensors may sometimes be useful in detecting seal lairs and polar bear dens under snowdrifts (Kingsley et al., 1990).

Some other types of sensors have been tested or suggested for use in a few situations. Sensors operating in the ultraviolet can also be useful in detecting polar bears and seal pups on white ice (Lavigne and Øritsland, 1974; Lavigne, 1976). Airborne synthetic aperture radar (SAR) can detect whale wakes under some conditions (Radford et al., 1994). SAR works through clouds and at night. An aerosol detector might be useful in detecting whale blows.

Non-conventional platforms for deployment of photographic, video and electro-optic sensors were not discussed. In addition to conventional shore, ship and aerial platforms, blimps, kites, aerostats, and remotely-piloted aircraft have been tried or suggested at various times.

PASSIVE ACOUSTICAL METHODS

Calling whales have been heard on passive sonars for many years, and sometimes (but not always) recognized as such. Detection and tracking by passive acoustical methods is a particularly suitable approach given the fact that many marine mammals are below the surface much of the time, call often, and can be heard over long distances. One result from the recent SOSUS studies of calling whales is that species like blue and fin whales are more vociferous than previously suspected. However, even the more vocal species can be silent at some times, and then they are impossible to detect or track by passive acoustical methods. Also, acoustical monitoring programs can have significant costs, as do visual programs involving ships and/or aerial surveys. Choices often must be made regarding the level of effort to be devoted to acoustical, visual, or other forms of monitoring.

Dr. C. Fox and Dr. C. Clark summarized the usefulness of the U.S. Navy's SOSUS system for acoustical monitoring in deep water. SOSUS is effective for species whose calls contain significant energy at low frequencies. SOSUS has provided good acoustical coverage of the North Atlantic (Nishimura and Conlon, 1993; Clark, 1995) and North Pacific (Moore et al., 1998a,b). However, coverage is now reduced because some arrays and shore facilities have been decommissioned. Advantages of SOSUS include its real-time and beamforming capabilities. With beamforming, the approximate direction of the calling animal from the sensor can be determined. However, SOSUS is costly to operate and maintain. Also, security issues when using the beamforming mode are a complication. However, single-element techniques can also provide excellent seasonal data on calling activity. By monitoring acoustic activity on a widely-spaced network of SOSUS arrays over an extended period, seasonal movement patterns and relative vocal activity in various deep-water areas has been (or can be) documented (e.g., Moore et al., 1998b). The same dataset can be examined at a finer temporal scale to examine individual calls and shorter-term variation in calling.

Dr. Fox also described the usefulness of autonomous underwater recorders to monitor low-frequency calls in deep-water areas over extended periods (up to 6-12 mo). These can be spaced widely for single-sensor operation, or deployed in grids (e.g., 15 km apart) to allow localization (Moore et al., 1998a). These devices can be deployed in areas where there is little or no SOSUS coverage, or where SOSUS operations have ceased. However, they provide data from a much smaller geographic area as compared with SOSUS. In addition to being useful for economical long-term monitoring, they can be deployed to monitor marine mammal calling activity during a particular project. These recorders can be placed on the bottom or buoyed up to channel depth. In addition to their deep-water applications, they can also be used to monitor whales in shallow water (as demonstrated by Drs. C. Clark and C. Greene). Most workers have used acoustic releases to retrieve their recorders, but Greene retrieves them from shallow water by grappling for a tag line at coordinates determined by D-GPS.

Sonobuoys, either off-the-shelf or modified for particular applications, can also be used (Richardson et al., 1995:38*ff*). Sonobuoys dropped or otherwise deployed near marine mammals have often been used to measure the man-made (and ambient) sounds to which the animals were being exposed (e.g., Richardson et al., 1986, 1990; Bowles et al., 1994). Hand-deployed arrays of modified sonobuoys have been the basis for the acoustic component of the spring bowhead census at Point Barrow (Clark et al., 1986). An array of sonobuoys is planned for deployment as a monitoring tool during the Seawolf ship shock trial (U.S. Navy, 1996). Various procedures have been developed to use data from sparse arrays of sonobuoys and other acoustic sensors to locate and track vocalizing whales. Relatively inexpensive systems that can determine direction to a sound source are available, including DIFAR (Directional low-Frequency Analysis and Recording) sonobuoys. These have occasionally been used in marine mammal studies (e.g., Ljungblad, 1986).

Towed arrays of hydrophones can determine the bearing to a calling mammal (or other source). With a very long array, the location of a vocalizing animal can be determined using nearfield time-of-arrival techniques out to ranges of approximately four times the array aperture. For any type of towed array work, it is important to take account of site-specific sound velocity profile data in order to compensate for local acoustic propagation characteristics. Towed arrays have occasionally been used in marine mammal studies, often in combination with visual surveys (Thomas et al., 1986; Evans, 1994; Spikes and Clark, 1996; Clark and Fristrup, 1998; Clark et al., 1998). Line arrays are becoming less expensive, and the computing power needed to process the data is now widely available. However, it takes new users significant time to learn how to use the array effectively and to implement the software.

In tests to study responses of marine animals to noise, there is also reason to employ arrays with vertical, as well as horizontal, aperture. One reason is the hypothesis that some marine mammals use the vertical arrival structure of the noise to estimate distance to the noise source (D'Spain et al., 1995; Premus and Spiesberger, 1997). Another is the information on sound propagation and depth dependence derivable from vertical directionality.

Procedures for use of passive acoustic methods in marine mammal studies are still evolving. Many approaches are possible, e.g., real-time vs. non-real-time monitoring; with or without localization; fixed, towed or drifting sensors. There is a need to select appropriate approaches for the purpose at hand. General advantages of acoustical methods include the fact that they work during periods with poor visibility (night, high sea state, fog) and in some cases can operate without the need for continuous human monitoring. Passive acoustic methods also can monitor the natural and man-made sounds to which marine mammals near the hydrophones are exposed.

Acoustic methods have obvious value, but even the species that call frequently can be quiet at certain times. Quieting sometimes occurs when whales are exposed to man-made noise (Watkins and Schevill, 1975; Watkins et al., 1985; Bowles et al., 1994). Also, when the frequencies of man-made noise overlap those of the mammal calls, calls with low received levels can be masked and undetectable. Thus, caution is needed in using call detection rate as an index of mammal numbers or calling activity in the presence and absence of man-made noise. A further complication is that, for most species, we know little about the functions of the calls or the circumstances in which they are made. A better understanding of calling behavior will be very helpful in interpreting the results of acoustical monitoring, and the proportion of the individual mammals that will be detectable acoustically in various situations.

Even without additional information about calling behavior, passive acoustic monitoring can provide data about relative calling activity under different conditions, and about the occurrence, locations and sometimes the movements of those individual animals that call. This can be very valuable in monitoring and mitigation projects as well as for research purposes. However, it cannot be assumed that passive acoustic techniques alone will detect all the mammals that are present.

Several participants emphasized the value of using acoustical methods in combination with other monitoring techniques. These combined approaches can include two acoustical methods (e.g., SOSUS plus autonomous recorders), or one acoustic method plus one or more non-acoustic methods such as ship surveys, aerial surveys, tagging, and photo-identification. Visual methods can provide calibration data including typical group sizes and minimum estimates of the number of animals in the area.

ACTIVE SONAR

Participants briefly discussed the potential use of active sonar systems to detect and monitor marine mammals underwater. In general, the detection of animals by active sonar is controlled by several interrelated factors: source level, frequency, transmitted waveform, target strength, ambient noise, receive array gain, and two-way transmission loss.

High frequency systems will generally yield a higher target strength because of the short wavelength of the sound and relatively higher surface impedance of the animals. It is also easier to generate a high source level with a high frequency system, and the ambient and array gain issues are also better handled. However, high frequency systems are somewhat limited in range because of increased absorption and scattering. Very high frequency systems (>100 kHz) may be the best solution at very close ranges where the issue is detection and mitigation for nearby animals. Low-frequency systems may have some utility at longer ranges (on the order of miles), but in general will not work well closer in.

The signal levels needed to get a high SNR echo with an active system may themselves require mitigation, with baleen whales being the main concern with low frequency systems and odontocetes and perhaps pinnipeds with higher-frequency systems.

The most promising application could be in detecting submerged animals at close range when they are not calling. There have been reports of submerged mammals being detected by high-frequency fish-finding and mine-hunting sonars (e.g., Mullins et al., 1988). Sonar target strengths of various cetaceans have been measured (e.g., Dunn, 1969; Love, 1973; Levenson, 1974). If effective in detecting marine mammals at short-range, active sonar could be important for collision avoidance and other mitigation purposes, given the inability of alternative methods (visual and passive acoustics) to detect silent submerged animals.

Sonar detection of objects floating at the surface is a particular challenge. If the sonar were effective in detecting floating containers and logs as well as marine mammals, this could greatly increase the market for the device, given the hazard that these floating objects pose to vessels. To be effective for detecting mammals and other objects floating at the surface, a very high frequency would be needed. In any case, further consideration would need to be given to the effects of the active sonar signals on nearby mammals.

DATALOGGERS AND TELEMETRY

The NRC Committee on Low-frequency Sound and Marine Mammals (1994) recommended that development of improved tagging techniques was a high priority in order to have better tools for studying acoustic effects. Since then, considerable advances have been made. Time Depth Recorders, VHF and satellite telemetry, and sound-recording tags are providing data that are important in understanding noise effects on marine mammals. The use of a sound-recording tag on northern elephant seals swimming near the ATOC sound transmitter is a particularly notable example; these results were summarized by Dr. P. Tyack in a previous session of the workshop (see also Fletcher et al., 1996; Burgess et al., 1998).

The tagging and telemetry devices themselves are rapidly becoming more and more capable of recording relevant data, but there are still some significant problems. (1) Methods of long-term attachment to animals remain problematic. However, there have been important recent advances in the design and use of tags for short-term attachment. (2) Disturbance associated with deploying tags is a concern, especially for highly endangered species like northern right whales. (2) The failure rate of tags is still undesirably high, as is the cost. To date, the market has not been large enough to support the engineering development required for improved reliability, or to reduce costs through mass production. (3) The very limited amount of information that can be relayed via the ARGOS satellite system is also a severe limitation. It is hoped that this can be overcome as new satellite systems designed for worldwide communication are deployed.

Some attendees indicated that it may be an appropriate time to devote significant funding toward development of improved tagging and telemetry technology. The costs of this may be beyond the capabilities of any one funding agency. If the sound-recording tag mentioned above were developed from the current prototype stage to be an "off-the-shelf" device, there would probably be considerable demand for it. It was pointed out that TDRs were initially prototypes and then specialized research tools, but are now widely used in many research and monitoring studies. The same sequence can be envisioned for sound-recording tags if attachment and self-noise issues can be resolved.

DETERMINING SOUND EXPOSURE

Determining the sound levels to which marine mammals are exposed is critical when evaluating reactions to man-made sounds. It is also important when implementing mitigation procedures that are intended to avoid exposure to sound levels exceeding a specified received level. Measuring received sound level by a sound-recording tag attached to the mammal may become more practical in the future (Fletcher et al., 1996; Burgess et al., 1998). However, more studies are needed to determine the shadowing (at high frequencies) and impedance (at low frequencies) effects of the animal itself on the recorded level. Also, there will be a continuing need to estimate received levels near animals not carrying such a sensor. Even when acoustic tags are used, there will be a need to predict sound exposure before or during experiments, before the data from the acoustic tag can be accessed.

Until recently, underwater sound levels received by marine mammals during most acoustic disturbance studies were estimated based on simple propagation models, with or without calibration of the model by point measurements of received sound levels. In some studies, hydrophones or sonobuoys have been used to measure received sound levels near some of the mammals under observation. However, this is often difficult. Most workers have recognized that, even for a fixed projector source in a stratified ocean, the sound field can exhibit significant fluctuations in time, and may show large changes as functions of receiver depth, range, and azimuth. For a moving source, a broadband source, or a range-varying environment, the dependencies can be compounded.

In testing or interpreting the responses of animals to sound, it is thus important to keep in mind that the field can vary dramatically over short distances at all frequencies. Most of the physical mechanisms are understood. The larger scale variations can usually be estimated with deterministic models to a degree of accuracy consistent with knowledge of the ocean environment and source/receiver geometries. Modern data analysis and modeling techniques can often explain and predict the effect of such mechanisms as focusing at caustics (e.g., convergence zones), topographic blockage, multipath interference (including surface image interference), fronts, and shoaling. However, few marine mammal studies have attempted to take this small-scale horizontal or vertical variation into account in relating disturbance reactions to received sound levels.

The local variations are especially dramatic at low frequencies when the animal is near the surface (Urick, 1983:131). Here the level can drop by as much as 30 dB depending on the frequency of concern and the depth of the animal (Jensen, 1981). In a less extreme case, seismic survey pulses received within 3 m of the surface were confirmed to be several decibels weaker than at 9 m and especially 18 m depth (Greene and Richardson, 1988). This phenomenon is commonly described as the pressure release surface effect or the Lloyd mirror effect.

Some recent impact assessments and disturbance studies have attempted to estimate received sound levels based on sophisticated propagation models such as the parabolic equation or PE model (e.g., ARPA, 1995; Au et al., 1997). Versions of these models have been in use for many years, and their capabilities have improved in recent years. However, much care is still needed in choice and implementation of these models. Accuracy can be further improved by incorporating measurements of sound velocity profile taken along the propagation path at the time of interest. Standard physical oceanographic databases do not adequately characterize water-column and boundary properties for some areas and problems of interest. When site-specific measurements or extrapolations of key features of the acoustic environment are available, modern propagation models have good capabilities to predict the important properties of the sound field.

Dr. W. Ellison described a further elaboration of this approach, which he calls an *Acoustic Integration Model* (AIM), as applied during the LFA-SRP Phase I research in September-October 1997 involving blue and fin whales off southern California (Clark et al., 1998). This model combines an empirically-validated PE model of sound propagation with information (modeled or measured) about whale movements and diving behavior. The results include the time sequence of estimated received levels, the proportion of time exposed to various levels, and the cumulative acoustic exposure.

During the LFA-SRP Phase I experiments, PE calculations done in advance of the fieldwork provided estimates of anticipated received levels under various scenarios. By modeling the movements and dive profiles of whales relative to the acoustic source, received level as a function of time was predicted for hypothetical whales. This procedure helped to determine what source level should be used in order to expose a whale at a given location to a chosen received level. The dive profile of a blue whale exposed to the LFA sounds was determined using a short-term tagging system developed by D. Croll (Univ. Calif. Santa Cruz). After the experiment, the received level of LFA sounds as a function of time was calculated by the AIM model based on the validated PE model and the measured depth vs. time profile of this whale. From this, the AIM model also calculated the proportion of the time the whale was exposed to various received levels.

Dr. Ellison indicated that, at least during the LFA-SRP Phase I test, the dive profile data were a critical factor in estimating acoustic exposure. Received level sometimes varied drastically as a function of depth in the water column. He recommended that tagging, to document diving behavior, should be a high priority in future acoustic disturbance experiments. In more general terms, when received levels are strongly related to positions of the animal and source (horizontal and/or vertical), estimation of noise exposure will require detailed knowledge of these positions and of the ocean environment between them. Alternatively, direct measurements by an animal-borne acoustic sensor may be feasible in some situations (Fletcher et al., 1996; Burgess et al., 1998).

COMBINATIONS OF COMPLEMENTARY METHODS

All methods for detecting and observing marine mammals have significant limitations. However, different monitoring methods have varying limitations and strengths, and thus can often complement one another when used in combination. The merits of using visual, acoustic and tagging methods in various combinations have been mentioned above. In studies of acoustic effects, the received sound levels also need to be determined. This requires physical acoustic measurements and modeling along with whatever combination of observational methods is used to study the animals.

The combination of visual and acoustic techniques can offer a significant improvement in population assessment efforts. One of the most extensive efforts of this type has been the census of the Bering-Chukchi-Beaufort population of bowhead whales, which is conducted during their spring migration past Point Barrow, Alaska. These studies revealed that use of wholly visual methods (shore-based and aerial) dramatically underestimates the population size (e.g., Clark et al., 1986; Ko et al., 1986; Clark and Ellison, 1989; Raftery et al., 1990; Zeh et al., 1993). To a large degree this discrepancy was a result of severe environmental limitations (ice and frequent fog) for visual studies in the Arctic during spring. Combined acoustic and visual methods (seafloor recorders and aerial surveys) have recently been shown to complement one another in monitoring the autumn migration of bowheads with and without marine seismic exploration (Greene, 1997; Richardson [ed.], 1998).

Several "dual-mode surveys" of baleen whales have been conducted recently combining traditional visual survey methods with passive acoustic methods using towed arrays, sonobuoys, or bottom-mounted sensors (Clark and Fristrup, 1997; Moore et al., 1998a). Results indicate that the acoustic detection rates and ranges for blue and fin whales are greater than the visual detection rates and ranges for these species. The integration of dual-mode visual and acoustic survey data into statistically meaningful results remains a challenge but is expected to offer improvement in survey reliability and confidence limits (Fristrup and Clark, 1997).

The LFA-SRP Phase I experiment employed a particularly extensive set of complementary monitoring methods, as summarized by Dr. C. Clark (see also Clark et al., 1998). Both the source vessel *Cory Chouest* and the observation vessel *Dariabar* used towed arrays of hydrophones to detect calling mammals and determine the bearings to them in real time. The towed array behind *Dariabar* also measured the received level of the LFA sounds for comparison with the results of the PE model running in real time. Four autonomous seafloor recorders ("pop ups") were deployed for 10 days in the area where the whales were expected to concentrate their foraging. These recorders provided non-real-time data on calling rates as detected at four fixed locations in the presence and absence of LFA signals.

Visual observations were conducted from both the source vessel *Cory Chouest* and the observation vessel *Dariabar*, simultaneous with acoustic monitoring from both vessels. Visual observations from the source vessel were needed to implement the shutdown requirements when mammals were detected close to the source. Visual observations from *Dariabar* as she followed "focal" whales provided data on the behavior of whales in the presence and absence of LFA sounds. Short-term photoidentification was used to confirm that the same whales were being observed from one time to another. As mentioned previously, short-term TDR and radio tagging was done to document dive profiles of foraging whales; this was important in determining sound exposure. These dive profile data, in conjunction with an echosounder suitable for plankton surveys, showed that the whales were indeed diving to the depths where their prey was concentrated. Aerial surveys were also conducted to document the distribution and relative numbers of whales in a broad region around the test site.

In the LFA-SRP Phase I experiment, no one method was sufficient to answer questions about the effects of the LFA sounds on whales. Integration of the results from the several observation techniques that were used is expected to allow meaningful interpretation. Fieldwork involving so many interrelated components was complex to perform, and required compromises among the requirements of the different techniques and investigators. However, the combined approach had much better capabilities to address the key questions than would any one observation method.

The attendees also discussed some opportunities for further coordination of fieldwork, e.g., between physical oceanographers, marine mammalogists conducting visual surveys, and acoustical surveys. The cost of ship time is high, and opportunities for joint use of ship time should be followed up. Some institutions (e.g., Scripps) have procedures for publicizing their future cruise schedules. It could be useful to develop a more systematic mechanism for coordination of ocean science research. Some group would need to be identified to take on this function.

LONG-TERM MONITORING

Long-term effects are generally more difficult to study than are shorter-term effects. However, long-term effects on reproduction and populations are widely acknowledged to be of greatest biological significance. One of the problems is that pre-impact baseline studies often are not done, or are not started early enough to provide adequate baseline data. For example, the autumn migration corridor of bowhead whales through the Alaskan Beaufort Sea has been monitored annually since 1979 (e.g., Moore and Reeves, 1993; Treacy, 1997). However, seismic exploration was already underway by the time the whale surveys began. Without pre-impact data, the long-term effects of industrial activity on the bowhead migration corridor remain controversial (e.g., MMS, 1997).

Time constraints prevented a broad discussion of approaches for monitoring of long-term and cumulative acoustic effects on marine mammals. Richardson et al. (1995:397*ff*) include some discussion of this topic.

One approach that was discussed in some detail was the increasing interest in combining data across projects. Several workshop participants mentioned that they are involved in ongoing efforts to access and combine previously collected marine mammal survey data. These data can be valuable in selecting sites and seasons where marine mammals are either scarce or abundant (depending on the objective). If systematic, these data may also be valuable as baseline data for comparison with post-impact data.

There are problems in using previously collected data. Some researchers may be reluctant to share their original data. However, such reticence seems to be infrequent when the prospective users of the data are well qualified to interpret them, and when procedures to avoid potential misuses of the data are implemented. A more common problem is that the original data are often difficult to access and not well documented. Also, methods used during different surveys are often inconsistent. A further complication in using data collected a decade or more in the past is that population sizes of many species may have changed appreciably. In some cases, there may also have been qualitative changes in distributions.

Even so, previously collected data can, when used carefully, be valuable in identifying "hot spots" where marine mammals have been found to congregate. However, one should not assume that the absence of sightings means that an area is unimportant unless there is good information about the survey effort in the area.

Workshop participants also mentioned the desirability of incorporating the results of ongoing and future research and monitoring studies into a longer-term framework. Field procedures and data formats should be well documented, and the data should be archived so that they will be accessible to qualified future researchers. Standardization of field procedures and data formats should be encouraged where feasible.

BEYOND PROJECT-SPECIFIC MONITORING

Incidental take exemptions issued under the U.S. MMPA require project-specific monitoring. However, as more and more exemptions are issued and more monitoring projects are done, questions arise as to whether monitoring might be more effective (and less costly) if done in some way that was not so project specific. For example, in areas with many human activities, acoustical monitoring could provide information about marine mammals that are exposed to sounds from a variety of different human activities.

A monitoring approach designed to document overall effects of a variety of noisy human activities might be more successful than present project-specific approaches in evaluating potential long-term and cumulative effects. When mitigation measures are needed, measures appropriate to the individual project should be applied. However, the associated monitoring might be done as part of a broader monitoring effort designed to assess the effects of more than one human activity. This approach might provide a way to handle noise-generating projects that cannot afford to fund project-specific monitoring. At present, some of these projects may fail to go ahead because of concerns about the costs of marine mammal monitoring. Others may go ahead without regulatory review, incidental take exemptions, or monitoring. With a more practical monitoring approach, it might be possible to bring more projects that have the potential to affect marine mammals into the monitoring and mitigation process.

A non-project-specific monitoring approach would differ from the monitoring now required under incidental take exemptions. Changes in the MMPA or related regulations may be necessary to require non-project-specific monitoring. However, these changes might be possible if there were a good rationale.

It may be appropriate to recognize a distinction between

1. a minimum level of project-specific compliance monitoring needed to confirm that each project satisfies the incidental take requirements, and
2. research designed to evaluate impacts; this would probably be done over a longer time and would be less closely tied to specific noisy human activities at sea.

Both types of monitoring, but especially type (2), should be based on hypothesis testing. During type (1) work, it may be important to detect a high proportion of the mammals present near the noise source. During type (2) work, methods that show relative but not absolute numbers may be sufficient for many purposes.

Some of the concepts of Adaptive Resource Management (ARM) may be applicable in this field. ARM is a general approach for gaining knowledge about complex environmental problems through an iterative, hypothesis-testing approach to management, regulation and monitoring (Walters, 1986; Lancia et al., 1993, 1996).

MITIGATION

Mitigation measures designed to reduce acoustic or other human impacts on marine mammals are often required by research permits, incidental take exemptions, or the environmental protection policies of operators or regulators. When a planned or ongoing human activity has significant impacts on marine mammals, effective, practical mitigation measures should be incorporated. Several categories of mitigation measures are often used to minimize noise effects on marine mammals. These can include appropriate seasonal and hourly timing, routing and positioning, equipment design, shutdown when mammals are nearby, and other operational procedures (Richardson et al., 1995:417*ff*). Shutdown when mammals are nearby requires detection of the marine mammals. Various combinations of visual, electro-optic, and acoustical monitoring methods have been used to accomplish this.

Time limitations prevented an extensive discussion of all of these known or potential mitigation measures. Instead, attention focused on three approaches that were considered especially worthy of discussion: ramping up, bubble screens, and active noise cancellation.

RAMPING UP

Marine mammal research permits and incidental take exemptions involving use of strong sources of underwater sound frequently require the source level to be increased gradually whenever operations are commencing after a period of silence. The rationale is that, if the sounds are aversive to marine mammals, any mammal close to the source will have time to move away before the source level reaches its maximum. If they do so, "ramping up" can be an effective mitigation measure even for mammals whose presence is unknown.

The ramping up concept has been used at least since the early-mid 1980s, when it was applied in industrial noise playback experiments with gray and bowhead whales (Malme et al., 1984; Richardson et al., 1990). Ramping up is a standard practice in the ATOC experiment (ARPA, 1995), during the U.S. Navy's LFA sonar operations and scientific tests (Johnson and Spikes, 1997; Clark et al., 1998), and during seismic exploration projects done under incidental take exemptions (e.g., NMFS, 1997, 1998).

Questions have been raised as the efficacy of ramping up. There have been no specific studies to determine whether marine mammals really do move away during the ramp-up phase. It has been suggested that ramping up may do more harm than good if it allows mammals to gradually accommodate to sound levels that are in fact harmful. Some mammals might even be attracted by the initially-weak sounds to move into the zone where exposure to the full-power sounds could be harmful. The frequent attraction of minke whales to slow-moving ships (references in Richardson et al., 1995:272) was mentioned as an indication that this type of effect is possible.

On the other hand, there is anecdotal evidence that bowhead whales sometimes move away during the ramp-up phase of industrial noise playbacks or when exposed to a single airgun (W.J. Richardson, pers. obs.). Also, gray and bowhead whales often show some avoidance when exposed to industrial sounds from small projectors operating at full power. These tests with small projectors have some similarities to ramp-up operations with more powerful sound sources. Thus, it is probable that, at times, ramping up will be effective in dispersing certain marine mammals.

Rather than ramping up a sound that has no intrinsic meaning to marine mammals, an alternative approach might be to project sounds known to be aversive. Playbacks of killer whale calls have sometimes (not always) been shown to cause strong reactions in some by other cetaceans (Cummings and Thompson, 1971; Fish and Vania, 1971; Malme et al., 1983). However, animals might habituate to repeated playbacks of killer whale calls, making them more vulnerable to actual killer whale predation.

The responses of marine mammals to ramping up and to potentially aversive sounds are amenable to empirical testing. Because of the short term nature of the desired responses, such tests should be comparatively easy to conduct. When sounds that seem effective in dispersing marine mammals are identified, it would be useful to conduct more refined tests to determine the optimum stimulus parameters, and whether repeated exposure results in accommodation. These tests should receive high priority. Ramping up or "aversive stimulus" approaches—if effective—could operate without the need to detect the presence of marine mammals near the sound source. However, it should be recognized that the effectiveness of ramping up or aversive stimuli is likely to vary with species and situation. A more detailed review of experience during past and ongoing projects could be a useful starting point in designing tests of ramping up or aversive stimuli.

BUBBLE SCREENS

Air bubbles in water can strongly attenuate underwater sound because they change the impedance (bulk modulus) of the propagation medium. Significant attenuation can be attained even without a high concentration of bubbles. Bubble screens can be effective not only at moderate and high frequencies, but also at reasonably low frequencies. For example, they can be used to minimize the effects of underwater blasting on nearby structures (*in* G. Greene et al., 1985). Dr. C. Greene described a recent test demonstrating that a bubble curtain around a pile-driving operation in Hong Kong Harbour resulted in significant attenuation of the pile-driving sounds, including low-frequency components. Dr. C. Erbe mentioned a study in Victoria, B.C., which used bubble screens to attenuate high-frequency (10-20 kHz) sounds by 30 dB. The self-noise of the bubble screen was 95 dB re 1 µPa at 1 m. Bubble screens can be very efficient at attenuating narrow-band noise and can in fact be tuned in frequency. Other participants mentioned tests of bubble screens to reduce horizontal propagation of noise from airguns and ship propellers. Bubble emission systems around propellers are effective and practical in reducing propeller cavitation noise (Urick, 1983:340). However, bubble screens are not effective in attenuating very low frequency sounds such as blade-rate tones from large propellers.

ACTIVE NOISE CANCELLATION

Physical acousticians participating in the workshop indicated that active noise cancellation through projection of out-of-phase sounds was unlikely to be very effective underwater. This approach does not work well in open environments. To be effective, the sound to be cancelled must be narrowband and consistent, and the geometry of the propagation environment must be highly regular and restricted. One situation where active noise cancellation might have some utility could be in reducing turbine noise emanating from powerplant outfalls.

MITIGATION CRITERIA

This group did not discuss specific criteria under which mitigation would be desirable in order to avoid deleterious effects on marine mammals. It was understood that a follow-up workshop on acoustic impact criteria was being planned by the National Marine Fisheries Service. [That workshop was held during September 1998.] However, the present group recognized that questions about acoustic impact criteria have important and ongoing practical implications. There are implications both for marine mammals that are now being exposed to strong man-made sounds, and for human activities that are now being regulated based on very limited data concerning acoustical impacts (Richardson, 1997). During this workshop, much of the discussion by the "Hearing Effects & Non-hearing Physiological Effects" group and the "Behavior" group was relevant to the question of acoustical impact criteria.

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