Application of the Acoustic Integration Model (AIM) to predict and minimize environmental impacts

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Abstract - **Minimizing and mitigating the potential effect of sound upon the environment is an increasing concern for many activities. Naval operations, seismic exploration, vessel and aircraft operations, and scientific investigations now need to consider the potential effect of underwater acoustic sources. Marine mammals are usually the primary concern, due to their widespread distribution and excellent hearing. Predicting the exposure of marine mammals is complicated by their diving behavior, which causes them to 'sample' many depth strata within the water column. Acoustic propagation and sound received levels are a function of depth as well as range. The Acoustic Integration Model (AIM) addresses this specific complication. A principal component of the central engine of AIM is a movement simulator. Both sound sources and animals, collectively addressed as 'ANIMATS', are programmed to move in location and depth over time in a realistic fashion. Animal movement is based on documented regional and seasonal behavioral data for each species evaluated. Acoustic sources and receivers are programmed to move through a virtual acoustic environment based on external environmental databases and radiated sound fields created from a choice of several propagation models. The integration component of the AIM engine then predicts the exposure level of each simulated animal at successive operator-selected time steps. Furthermore, each animat can evaluate its environment at each time step, and can be programmed to alter direction or diving behavior in response to any variable, such as sound level or sea depth. The model therefore allows the user to predict the effects of different operational scenarios and animal response levels, thereby allowing the selection of the alternative that produces the least impact and still meets operation requirements.**

I. INTRODUCTION

Conservation and protection of the marine environment is becoming an increasingly important goal for many ocean users. Marine mammals are one of the most visible components of the environment and have engendered tremendous interest and affection from the general public. Furthermore, marine mammals are vulnerable to many different types of interactions with humans. They must come to the surface to breathe, thus they are susceptible to ship strikes [1]. Marine mammals have very good hearing, making them susceptible to acoustic disturbance and injury [2]. Marine mammals are susceptible to toxic contamination [3]. Then, of course, there is a continuing whale fishery, which does not appear to be limiting itself to legally caught species [4]. Historical whaling has reduced the population size of many marine mammal species. While there are some examples of remarkable recovery (*e.g.*, eastern gray whales) others remain at dangerously low population levels (*e.g.*, northern right whales, western gray whales). For these and other reasons there is continuing concern about the welfare of marine mammals and the effects of their interaction with anthropogenic factors.

In most stimulus-response relationships there is a direct, if not linear, relationship between the exposure, or dosage, and the response, or effect. When considering marine mammals, measuring the dosage can be difficult. This is especially true when considering acoustic stimuli. The propagation of sound in the ocean is very complex, and varies with depth as well as range. Furthermore, different species can have very different dive patterns. Figure 1 shows a stylized sperm whale and a dolphin dive pattern, displaying clear differences between the two species in dive depth, time at depth, and time spent on the surface. Some species rarely dive deeper than 100 meters, while sperm whales and elephant seals regularly dive to depths of 1-3 kilometers. These dives result in animals sampling different strata of the water column, and therefore potentially exposed to different sound levels.

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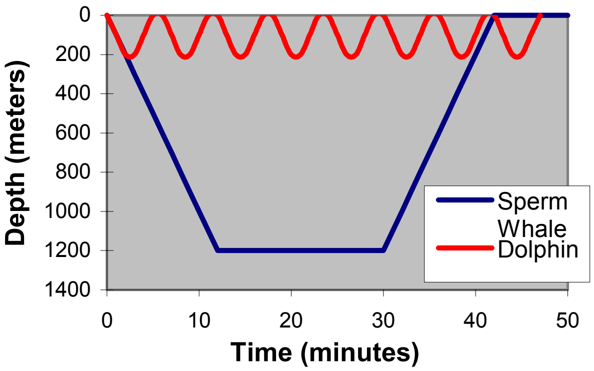

Fig. 1.A stylized time-depth record illustrates some of the range of variation in dive patterns between species.

It was the realization of the need to consider dive depth as well as range from a source to determine received sound level that helped spur development of the Acoustic Integration Model (AIM) [5, 6] (see Figure 2). The main goal of AIM is to realistically model or predict the exposure level of marine mammals exposed to a stimulus. While all applications to date have involved acoustic stimuli, the model has been designed to be generalizable to accommodate any stimuli, such as chemical pollution or ice cover. In order to accurately model the exposure of a marine mammal, a wide variety of factors have to be considered and incorporated into the model.

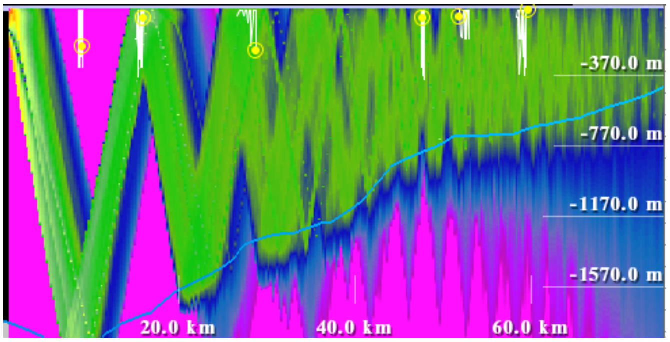

Fig. 2. A side view of a modeled acoustic propagation path. The different colors represent different sound levels. Several simulated whales (yellow circles) and their dive patterns (white lines) are shown. As they move through different depths, they experience different sound levels.

Review of Monte Carlo Modeling

The Monte Carlo approach is a popular numerical modeling technique. The Monte Carlo method is typically applied to problems where there are both variability and uncertainty in the model inputs. The typical approach is to select a random, or pseudo-random value from the input variable distribution, and run the model as if it were a deterministic model. This is repeated *n* times until an appropriately large distribution of outputs is collected. Traditional statistical measures (*e.g.,* means and variances) can then be applied to describe the distribution of the output values. The output of the Monte Carlo modeling therefore accounts for both known variability in the inputs, as well as uncertainty.

II. MODEL DESIGN APPROACH

AIM is a Monte Carlo-based statistical model, strongly based on two earlier models; a whale movement and tracking model developed for the census of the bowhead whale, *Balaena mysticetus* [7], and an underwater acoustic back-scattering model for a moving sound source in an under-ice Arctic environment [8]. Because the exact positions of sources and receivers cannot be known, multiple runs of realistic predictions are used to provide statistical validity. The movement and/or behavioral patterns of sources and receivers can be known, and these data are incorporated into the model. Accurate representation of the movements of sources and receivers is necessary for realistic predictions. Each source and/or receiver is modeled via the “animat” concept. Each animat has parameters that control its speed and direction in three dimensions. Thus, it is possible to recreate the type of diving pattern that an animal shows in the real world. Furthermore, the movement of the animat can be programmed to respond to environmental factors, such as water depth and sound level. In this way, species that normally inhabit specific environments can be constrained in the model to stay within that habitat.

Once the behavior of the animats has been programmed, the model is run. The run consists of a user-specified number of steps forward in time. For each time step, each animat is moved according to the rules describing its behavior. For each time step of the model run, the received stimuli values are updated. In the case of acoustic stimuli, this is done in two steps. First the pre-programmed acoustic characteristics (*e.g.,* frequency, duration, source level) are read from the source animats. These acoustic parameters are then input into an acoustic propagation model to determine the received level at all of the receiver animats.

At the end of each time step, each animat evaluates its environment. If an environmental variable has exceeded the user-specified boundary value (*e.g.,* water too shallow), the animat will then alter its course to react appropriately to the environment. These responses to the environment are entitled ‘aversions’, although the animat can move toward a stimuli as well as avoid one. There are a number of potential aversion variables that can be used to build an animat’s behavioral pattern. The modular nature of the AIM infrastructure allows for additional variables (*e.g.,* response to prey concentration) to be added as needed.

The animal movement engine is the core of the program. It is where all of the rules for moving animats, their characteristics, and responses to the environment are implemented.

The acoustic propagation model, and all supporting databases are kept as separate programs and files. The data and programs are accessed from AIM by small pieces of interface or “glue” code. This approach allows for additional models or databases to be interfaced with AIM with minimal additional coding. Currently, AIM supports the Bellhop and PE models, and the ETOPO5 bathymetry database and GDEM sound velocity profile database.

III. BUILDING A MODEL RUN

All of the components of a model run can be stored in a project file. This facilitates the easy modification of existing projects and rapid implementation of runs with a single modified value.

A. Location

The first step in creating a run is to determine the location and time of year of the activity. This is necessary to determine the environmental conditions, as well as which species are present, in what numbers, and their behavioral state. All of these factors vary seasonally and spatially.

B. Create Animats

Once the location and time are known, the species that are present as well as their behavioral state, distribution and abundance can be estimated. There is no database that possesses all of this information. LIMRIS provides rough abundance estimates, but on a very broad scale. National Marine Fisheries Service's stock assessment reports [9] have always been consulted. Other sources of data include research papers, reports and unpublished data. All of this is used to determine an estimated density of each species. Sometimes this density is also structured within a run. For example, the nearshore density of a dolphin may be much higher than the offshore density.

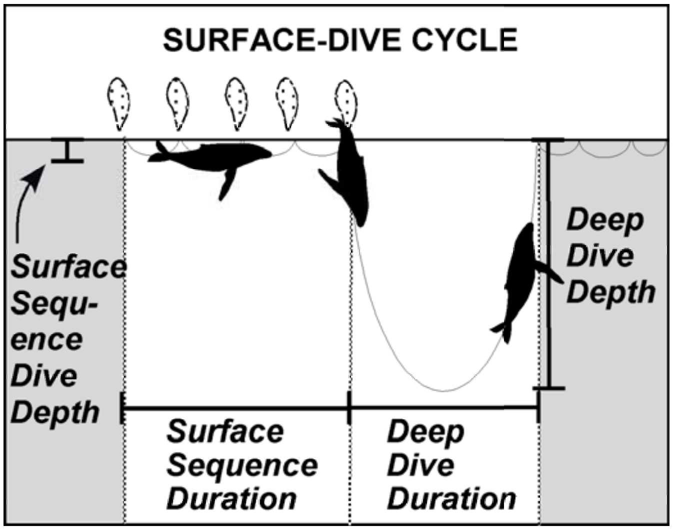

Fig. 3. An illustration of a typical cetacean dive. The surface sequence consists of several short shallow dives each including a respiration. This is followed by a longer, deeper dive. AIM describes these as separate dive types separately.

Once the numbers of animals has been determined, it is necessary to program in their behavioral characteristics. MAI has been building a database of parameters necessary to describe the behavior of different species in different contexts. Figure 3 shows a typical diving pattern consisting of a short series of shallow dives between respirations. This is followed by a single longer, deeper dive. Each of these is treated as a separate type of dive pattern. The duration, depth, speed and direction characteristics of each dive type are input separately (Table 1). By creating as many dive types as necessary, complex movement patterns can be created. The goal is not to perfectly recreate actual individual paths, but to create a population of animats that capture the "typical" movements of a population of individuals.

Table 1: Movement Parameters used in AIM
Dive Time (min/max)
Dive Depth (min/max)
Speed (min/max)
Initial Course
Variance in Course

C. Characterize Stimuli

Once the movement and behavior of the receiver animats are programmed, the next step is to describe the stimuli to be modeled, and the propagation of those stimuli through the environment to determine received level or dosage. For acoustic stimuli, the source characteristics of frequency, source level, duration and ping interval are specified. Either the Bellhop or PE model currently calculates acoustic propagation, although additional models can be added as needed. AIM currently also has the ability to model underwater sonic booms. This is a two-step process, with the PCBOOM3 model [10] used to determine the sonic boom footprint on the water's surface. A model written by Cambridge Acoustics, Inc. then predicts the in-water propagation of the signal.

These models require environmental data inputs to work properly. Environmental data are automatically extracted from the ETOPO5 bathymetry database and the GDEM sound velocity database. Future plans include incorporating bottom loss databases and higher resolution bathymetry databases.

D. Run the Model

Once the project is completed, the user initiates the AIM run. The run consists of moving the through time at a fixed interval according the rules defining its behavior and environment. At the end of each interval, each animat reevaluates the environmental variables (i.e. the aversions) to which it has been programmed to respond. If a variable has exceeded the set limit, the animat will alter its behavior accordingly. The model then continues to iterate until the end of the run. It is important to emphasize the iterative nature of the model. This allows for the alteration of behavior in response to a changing environment, a critical ability in the attempt to accurately reproduce animal behavior.

E. Output

The output of the model is a text file record of all the variables in the model for each time step for each animat. Simple tools are built into the model to display the exposure history of each individual animat. AIM can export any or all of the variables to an ASCII file, for subsequent detailed analysis.

IV. APPLICATIONS

A. Take Estimation / Pre-mission planning

In a typical application, AIM can be used to estimate the effect of any sound producing system. The system's geographic operating range and schedule of operations are established. In order to estimate the exposure of animals to the operation of the system, numerous sites within the geographic range are selected and modeled. If the scope of operations is planned over different seasons, the individual oceanographic conditions for each season as well as changes in the behavior and distribution of the animals present must be described. The most common use of the model is one where the net sound exposure on individual animals is similar to that of a 'dosimeter'. In this application the history of sound exposure for each virtual animal is tabulated and available at the end of the run. Animats can also be programmed to respond to a variety of stimuli including the received sound level. Typical programmed responses can include varying levels of changes in motion or dive pattern. The choice of variations and the degree of response are programmable by the user, allowing a parametric evaluation of this feature.

This approach can be broadened to consider additional sources of stimuli, operated in different areas and in varying fashions. Essentially, AIM can be used as a 'what-if' tool, to predict the potential impact and compare the impacts of different operational scenarios. Simulations can alter the location of tests or operations, the sources used and the parameters of those sources. Different times of year can be evaluated. At a finer scale, different operational procedures or duty cycles can be evaluated and predicted. Thus, the impact of an operation and be minimized by optimizing parameters before going to sea.

B. Behavioral Modeling

AIM can also be used to develop behavioral reaction models. There are examples of real-world events, where both the stimuli and animal responses are known. These examples can be simulated in AIM, with the goal of developing aversion rules that most accurately reproduce the actual event. For example, there was a recent stranding as the result of the passage of noise-producing vessels [11]. The acoustic characteristics of the vessels are known, as are the numbers and locations of the stranding events. It is a relatively easy procedure to program AIM to reproduce the movements and acoustic transmissions of the vessels and a distribution of receiver animats representing whales. A series of five different aversion rules were developed based on known responses of other species to acoustic stimuli. The first three were strong avoidance of sound at 180, 150 and 120 dB received levels. The next was a scaled response, with strong avoidance at 180 dB, moderate avoidance at 150 dB and weak avoidance at 120 dB. The fifth response was no aversion to sound. The simulation was then run multiple times with each of the behavioral rules. The results indicated that the scaled response to sound level produced the result that most closely matched the actual event. This finding suggests that the response of the whales may scale with received level. Additional values, such as persistence of response and thresholds for return to baseline behavior can also be tested.

V. INTERPRETATION

AIM is capable of very accurate predictions of exposure to a stimuli or dosage. These data represent the first step in assessing the effect of the stimuli on the animal. The dosage-response curve or relationship is more difficult to establish. However, there has been a recent large body of work on responses of marine mammals to noise. Richardson *et al.* summarized work conducted through 1994 [12]. Since then, there have been investigations in the levels necessary to produce behavioral responses as well as physiological responses, such as temporary threshold shift (TTS). These data can be used to bound the levels of exposure necessary for behavioral reactions and physiological response. For example, most marine mammal researchers would agree that behavioral responses begin well before the onset of TTS, which probably begins around 180 dB for mysticetes and 190 dB for dolphins (*e.g.,* [13]).

VI. FUTURE APPLICATIONS

A. Acoustic Censusing

A vital measurement when conducting censuses is determining the effort, or area covered by the census. For visual censuses this is typically the product of a ship track length multiplied by the visual swath width. The result is the area covered. However, acoustic censuses are less straightforward. Many areas that are inhabited by marine mammals have downward refracting environments that complicate acoustic propagation. One can imagine towing a hydrophone array through a convergence zone (CZ) environment. While the CZ paths can be modeled, marine mammals do not necessarily use the entire water column. If one knows, or has reasonable information on the diving behavior of the species present, then the effective acoustic search area could be determined by convolving the vertical distribution of the each species with the propagation pattern to determine how much of the ocean is being 'listened to'. The great unknown in acoustic censuses is the proportion of animals that are vocalizing. It is possible that with an increasing number of acoustic and visual surveys the comparison of acoustic and visual detection rates, corrected for propagation, will allow this value to be bounded, if not determined.

B. Ship Strike

Ship strikes are a long-standing threat to marine mammals. For healthy populations, it is an unfortunate event. However, for populations that are critically reduced in numbers, such as the northern right whale, a single death represents a significant decrease in the population viability [1]. Recent tagging efforts have revealed more information about the habitat usage patterns of some marine mammals. This has led to suggestions to relocate shipping lanes to reduce the ship strike threats. The feasibility and effectiveness of these changes could be evaluated with AIM runs.

C. Ship Noise Exposure

One of the hardest questions to answer is the long-term effect of any stimulus on the viability of a population. The first question is to answer concerns about the exposure or dosage of individuals within the population. It would be feasible to recreate the shipping routes and whale migratory routes within an ocean basin. Historical databases describe the levels of vessel traffic. It would be straightforward to create an AIM simulation that tracked the noise exposure of an individual throughout its life. Present day conditions could be compared with historical data. This approach would also allow the evaluation of the potential of noise, such as that from shipping, to mask biological sounds that may be important to the survival of a given species.

D. Air Gun Surveys

The issue of seismic exploration is becoming an increasingly important as the role of airguns expands and the need for data collection continues. Currently airgun operations are required to use very strong mitigation measures, up to and including prevention of nighttime operations and very large safety ranges. Any marine mammal or turtle in this range requires the airgun vessel to stop firing. These are expensive efforts. AIM could be used to model air gun operations and model the sound exposures. The parametric evaluation of different operational methods could be used to reduce exposures. However, much better data on the responses of marine mammals to airgun acoustic exposure are needed.

E. Pollution

The broad spectrum of pollution in the world's oceans is a growing concern to all nations. The ability of AIM to simulate the exposure level of animals residing in the path of pollution provides a powerful tool to estimate the first order of exposure resulting from such an event. The modification of AIM in this instance is one of developing the JAVA interface to the appropriate pollution distribution model, such as migration of an oil spill plume over time. As with the acoustic models already in use, the key result needed by the AIM engine is the pollution "level" over time at any given point in the water column (latitude, longitude, depth and time).

F. Masking

Masking is one of the issues frequently raised when considering the effects of sound in the ocean. Masking is essentially a reduction in signal excess as the level of masking noise rises. The reduced signal excess can limit the effective range of the animal's own signals as well as the range over which it can hear. As all animats (both man-made and animal) can both produce and receive (hear) sounds, it is a straightforward adaptation to determine the ability of a given animat to hear a sound produced at a distance by another animat in terms of such parameters as signal level, duration, frequency and background noise.

G. Sonic Boom Impact

In collaboration with Anteon Corp/CAA, the AIM model is being adapted to interface with a Sonic Boom model [10] developed for the U.S. Air Force. This emulation of AIM will allow for the assessment of sonic boom over-flights on the marine habitat.

VII. CONCLUSIONS

AIM began as a tool to measure the acoustic dosage of underwater sound. It has been shown to be very effective at this task. At the same time, the infrastructure of the program was designed to be very generalizable; specifically, that stimuli other than sound can be modeled. We have already built an underwater sonic boom propagation model into AIM.

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