Considerations for Evaluating Passive Acoustic Monitoring Systems Proposed for Use During Mitigation

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There are a number of technical aspects to consider when evaluating the scope and application of a passive acoustic monitoring (PAM) system as a mitigation tool, particularly when required under current marine mammal acoustic exposure criteria and associated mitigation measure requirements. Evaluation must be considered for a complete PAM plan, not single components of a PAM system because the system, as a whole (including the operator), must meet mitigation objectives through appropriate training and experience. A PAM system is a combination of hydrophone(s), cables, pre-amplifiers, array control, analog-to-digital converters, data processing hardware, sound analysis software, display hardware and software, data assemblage methods, and PAM operator(s). This paper identifies key technical specifications that should be evaluated and secured for each of these components before applying any specific PAM system to a monitoring or mitigation program.

1.0 Monitoring Versus Mitigation

Different systems are applicable for monitoring programs versus mitigation programs. Monitoring regimes can vary in time, areal coverage, and goals; therefore, the specifications of those systems will be driven largely by the project and have much greater flexibility in the applicable system components. Consequently, monitoring outside of real-time mitigation requirements is not addressed in this summary. Mitigation on the other hand, needs to meet very specific time- and space-constrained parameters often in operation-critical situations. The primary goal of a PAM system used in this manner is to discern the real-time location of a received signal in support of the need for immediate mitigation implementation and resource protection.

It is critical to understand and accept the concept of “real-time” mitigation when applied to PAM systems. Even with visual observation and detection, an observer will need to identify the animal, determine its distance, and notify the vessel master to properly implement mitigation (e.g., powering down an array). This may take a few seconds to a few minutes to fully implement. Likewise, acoustic monitoring and, in particular, range determination is never instantaneous. For most systems, with or without the aid of automatic detection, the operator must make a determination on a biological signal, often requiring multiple signals over a period of time to determine if mitigation measures and vessel master notifications are necessary. Therefore, the term “real time” monitoring may be possible for visual and acoustic monitoring, but there will always be some level of delay for mitigation. This delay must be acceptable and understood among operators and regulatory personnel. This fact provides credence to the use of remote systems,

including PAM; high-quality PAM data provided to monitoring personnel allow for a more rapid determination of marine mammal presence and range.

In this discussion, emphasis has been placed on towed system applications related to the seismic industry. A general summary of each evaluation topic is provided, followed by a highlighted check box designed to identify the questions regarding what can be expected of a PAM system for each topic. This document is not intended to be a detailed technical manual for bioacoustic monitoring or a thorough study of bioacoustics; it is simply a primer on PAM, including questions to be asked by regulators and other stakeholders to help make better decisions about how a PAM plan is applied to real-time mitigation regimes on a project-by-project basis.

2.0 Passive Acoustic Monitoring Components

Hydrophones

Many hydrophones are available today, or can be readily manufactured, that convert sound pressure waves into electrical current for further processing. Hydrophones suitable for converting marine mammal vocalizations into usable electrical current have a nominal frequency response between 10 Hz and 150 kHz (150,000 Hz). This broad bandwidth is accomplished by the use of multiple hydrophones in an array with low and high response ranges. The fact that a hydrophone operates at an acceptable bandwidth has no bearing on whether the signal can be processed, recognized, and monitored effectively in a mitigation or compliance monitoring situation. As a general rule (not separating tonal from impulse calls), low-frequency callers (includes mainly baleen whales) require hydrophones with a bandwidth of 16 Hz to 8 kHz. Most mid-frequency odontocetes require hydrophones with a bandwidth of 5 to 25 kHz, and high frequency odontocetes, such as the harbor porpoise and beaked whales, require a bandwidth of 40 to 150 kHz.

In addition to bandwidth, hydrophone sensitivity is an important and possibly limiting factor. A hydrophone needs to have adequate sensitivity to receive signals from distant sources. However, a hydrophone must also be built to withstand potentially damaging signal amplitudes produced by some applications (e.g., airgun firing, blasting). Most hydrophones that are robust enough to survive the seismic environment are rated for sensitivity in the range of 160 to 190 dB re 1 V/µPa. Additionally, there are options in hydrophone directionality not discussed here because it does not affect the basic functionality.

Preamplifier circuits used on towed hydrophone arrays need to be able to transmit the current produced in response to a signal at the hydrophone along the distance of the entire lead-in cable. Increased cable length allows the array to be towed farther behind the boat in a quieter environment; however, a stronger preamplifier is required then to transmit along the length of the lead-in cable.

- **Is the hydrophone's functional bandwidth between 10 Hz and 150 kHz?**
- **Is the hydrophone durable enough to withstand amplitudes for the intended application?**
- **What is the hydrophone's sensitivity and is it appropriate for the application?**
- **How long is the lead-in cable and how far behind the vessel is the array towed?**
- **Are the preamplifiers on the hydrophone array sufficient to transmit the length of the lead-in cable?**

Hydrophone Arrays

The hydrophones and their grouping, the electronic cabling, and the hydrophone housing are considered the "hydrophone array." The array design and build is crucial to how the hydrophone signals can be further processed and ultimately how a PAM system can be correctly applied. Hydrophone arrays vary greatly from a basic two-hydrophone (dipole) system connected by waterproof cables to multi-hydrophone arrays built for maximum signal acquisition capabilities. An array provides the acoustic gain and source separation that is critical for this particular application. Asking appropriate questions about the hydrophone array will allow an evaluation of its applicability to specific mitigation conditions.

Dipole Hydrophone Arrays

Dipole arrays often contain four hydrophones, two for low frequency and two for high frequency; however, processing of a received signal is accomplished using grouped pairs appropriate to the signal bandwidth. It is possible to ascertain bearing from two grouped hydrophones using one signal. Dipoles are primarily used to determine bearing based on arrival time phase difference. It is not possible to get range from two hydrophones using one signal (note – all two-dimensional arrays will have spatial ambiguity for bearing).

The only way to get a range determination from a two hydrophone array is to have the array moving on a consistent bearing; hydrophones must receive multiple signals (e.g., calls) temporally spaced to allow for triangulation; further, the operator must be confident that signals are from the same source. This scenario, however, does not provide a true real-time range measurement, but rather it is a near-real-time measurement; this characteristic (i.e., near-real-time, delay) must be an acceptable parameter in the determination.

These arrays exhibit varying accuracy depending on the frequency bandwidth of the received signal relative to the spacing of the grouped pair of hydrophones. Accurate bearing calculation requires hydrophone spacing (i.e., aperture) of one-half the wavelength of the received signal. For example, the wavelength for a 15-Hz signal is 100 m, for a 15-kHz signal is 10 cm, and for a 150-kHz signal is 10 mm. As such, a pair

of hydrophones would need an aperture of 50 m to calculate bearing of a vocalizing marine mammal.

Multiple Hydrophone Arrays

Multiple or multi-hydrophone arrays are typically considered an array with four or more hydrophones that are within the same bandwidth and therefore are used together for bearing and range determination. Multi-hydrophone arrays are preferred for most bioacoustic applications and for real-time mitigation. The advantages and general conditions for using an array include the following:

- Allows operators to determine bearing and range in near-real-time, potentially on a single signal.
- Hydrophones can be grouped and spaced to allow for greater accuracy in bearing and range finding. For multiple hydrophone (high gain) arrays, a group is a subset of hydrophones within the array and the spacing is the distance between those subsets. The aperture is the distance between hydrophones within a group. Aperture of a group will influence accuracy in localization determination while the spacing of groups will enable triangulation on a single call.
- Grouping and spacing of hydrophones tend to be unique and proprietary in each array design.
- Hydrophones are best grouped by target source bandwidth-specific apertures.
- Baleen whale species generally require large apertures due to the low frequency of their calls. However, the difficulty in detection and localization is usually due to the inability to obtain high quality signals in the low frequency range due to the overriding ship noise masking. See the discussion on noise abatement and software.
- Odontocetes require specific aperture configurations to localize on their wide-ranging call frequency among species.
- Time-delay summation allows bearing determination on a single signal.
- Increasing the number of hydrophones allows the operator to select different spacing options for beamforming, thus allowing more accurate range and bearing determination on single signal over a broader bandwidth.

- **What are the target species' predominant call frequencies?**
- **How many hydrophones are in the array and how can they be grouped and spaced?**
- **Are apertures suitable to determine bearing for all target species?**
- **Are mitigation decisions required in near-real-time? What is the acceptable delay time in mitigation decision making?**
- **Accuracy of bearing determination will increase accuracy range determination; how is this accuracy maximized?**
- **In the evaluated system, can bearing and range be determined from a single signal?**

3.0 Noise Abatement

Noise in a commercial mitigation setting will always be one of the greatest challenges for acoustic monitoring. Moored arrays or arrays deployed from dedicated platforms outside the influence of vessels or machinery have a distinct advantage of working in a relatively quiet environment. However, many mitigation applications require real-time monitoring of a specific area in a high-noise environment. Boat and drilling rig noise is by far the greatest interference for these applications. In seismic applications, the inclusion of the airgun array, seismic streamers, and support vessels add to the noise environment. The hydrophone array must be able to collect and transmit signals in this environment and the processing must be able to detect target species with enough clarity to initiate mitigation. Therefore, the noise abatement effort must begin with the array deployment design.

A hydrophone array towed behind any sizable or commercial vessel will produce data containing significant levels of low frequency noise unless significant measures are taken in the deployment methods and hardware to reduce or eliminate the vessel noise. Low-frequency noise abatement cannot be left only to software solutions.

Array Construction

The array (i.e., hydrophones and connecting members) must be streamlined, hydrodynamically tuned, and density neutral. Streamlining and encasement reduces the profile in the water to reduce drag and cavitations, which are major sources of noise in towed systems. Hydrodynamic tuning refers to how the array tows through the water column and its ability to stay on a single axis, which reduces vibration noise and increases accuracy of bearing and range determinations.

Noise abatement in the array is the first and best line of defense against loss of signal quality for further processing. If the array does not reduce unwanted noise, particularly the low-frequency noise from the tow vessel, the resulting signal processing capabilities are severely compromised. This becomes critical for the detection of low-frequency callers, namely the baleen whales, whose calls can be "drowned out" by noise if the PAM plan does not meet the above criteria.

Array Control

In conjunction with the design of the array to maximize signal quality, control of the array is important to reduce noise and ensure proper signal acquisition. Basic array control will enable the operator to place the hydrophones where they want them and keep the array safely deployed. To improve signal acquisition, reduce unwanted noise, and maximize accuracy in range and bearing determination, the array depth and attitude must be controlled and monitored continuously. Tow depth and distance of the array can play a major role in noise abatement as well. Towing deeper and farther behind the vessel will result in a quieter acquisition environment. Tow distances of less than 100 m and tow depths less than 10 m result in largely ineffective detection ability, particularly in low-frequency callers, because of the amount of low-frequency noise encountered with a large commercial vessel. While increased tow distance can provide a better acquisition environment, caution should be taken to ensure effective monitoring of the required mitigation zone.

The array can be monitored via depth sensors built into the hydrophones, depth sensors within the array, or an external depth control device. All methods should relay depth information to the operator who can, in turn, make adjustments as needed. Different levels of control can be obtained using various methods. Some examples of array control include the following:

- Modification of the lead-in length or adjusting tow speed;
- Use of "birds" or external depth controllers attached to the array, as used on seismic streamers. This allows active adjustment of tow depth by the operator without the need for back deck activity; and
- Ballasting is possible but not a preferred method of control due to the increase in drag and potential for strumming and other introduced noise. Ballasting should be integrated along the array or designed specifically for the towed cables so as not to increase drag or flow noise. Adding fishing leads to the cable is not an acceptable method for array control.

Cabling and Wiring

Signals transmitted through cables will be affected by background electronic emissions, shielding methods, vibration, and connection quality. Cable durability will be influenced by the strength member (if any), exterior coating, connection types, and deployment/retrieval and storage methods. Important considerations regarding cabling and wiring include the following:

- Towed lead-in cables need to have a built in strength member adequate to withstand the drag pressures created by the hydrophone(s) during use;
- Lead-in and deck cabling should contain adequate shielding to prevent interference from undesirable electronic signals (e.g., florescent or other lighting or electric motors that may operate near the cables; static electricity from environmental effects);
- Cable connectors should be sturdy enough to handle strain pressures from deployment, retrieval, and long-term operation; and
- Vibration in cables can produce significant noise that can mask and interfere with signal processing. Methods to minimize vibration include cable texture and diameter, faring, ballasting, and tension control.

For a commercial towed array, lead-in cabling should:

- have a smooth or slick exterior;
- have faring;
- have integrated ballasting along the entire array member that does not create added noise or vibration; and
- tow with sufficient tension to eliminate slacking, avoiding high tension levels that might compromise strength members.

- **Is the entire array streamlined in the water when towed to minimize flow noise?**
- **What is the tow depth of the array?**
- **How is array depth and attitude monitored and controlled?**
- **How is array depth and attitude documented and verified during mitigation activities?**
- **Have tow tests been conducted on the array? Can performance tables be provided that specifies the tow depth at a given tow speed, ballast, and lead-in length?**
- **Does the tow distance provide both the quietest practical acquisition environment and effective zone monitoring of the target species?**
- **Is the array towed on its own cable system or does it need to be connected to a secure tow cable or rope thus adding vibration and noise?**
- **Does the lead-in cable contain a strength member, and if so, of what type?**
- **What measures are taken, prior to and after installation, to identify and eliminate electronic interference?**

4.0 Software

This section discusses software tools needed to deal with signal processing in a high noise environment. There are a number of good software packages on the market. The primary purpose of any software package is to process and display visual representations of the signals that are received from the array in a way that allows the operator to detect, identify, and localize target species. Differences in software occur mainly in user interface capabilities, degree of user adjustability in processing and display, automation, and methods of localization.

The degree of user adjustability and the methods of localization set the higher standards of software capabilities. Addition of automation enhances the operator's capabilities for continuous monitoring and provides a reliable method for extensive post-processing of large amounts of data, which is critical in evaluating the PAM system.

Increasing the degree of adjustability in real-time processing, while requiring an experienced operator, provides an operator with the ability to control noise interference and increase target signal detection. The alternative is a more automated approach where more users can operate the software but the software is not as adjustable to varying conditions; under these conditions, signal detection may be reduced. Other software attributes of importance include the following:

- Amplitude limiting – prevents stronger noises from overcrowding weaker signals.
- Multiple channel selection – allows the user to select "quieter" hydrophones for signal monitoring. The more channels (hydrophones) that are available, the more options available to an operator to maximize localization.
- Bandwidth filtering – removes unwanted frequency bands. This is helpful when an operator encounters a narrow, consistent noise interference that can be filtered out without affecting target signals. It is not, however, suitable for broadband filtering that could result in loss of target signals (i.e., cannot not remove all low-frequency boat noise without affecting baleen whale signal acquisition).
- Signal enhancement – accomplished through a variety of available algorithms. The algorithms may be proprietary to the software package. The function of the algorithm is to recognize patterns in target signals and amplify those signals in the user display, allowing signal detection through noise interference.
- Signal-to-noise ratio definition – allows operator to define background noise thresholds to more easily detect target signals.
- Operator must be fully trained in software and hardware operations and experienced in making software adjustments and recognizing and solving potential noise-related masking issues in the field. Note: a single PAM course is not sufficient for this. A quality PAM course is necessary for introduction, but experience and oversight by qualified staff is equally, if not more, important.

- **What operator adjustments can be made during active use of the system to deal with changing noise conditions and signal detection ability?**
- **Does the operator have the ability to monitor multiple channels and different bandwidths simultaneously in real time? For example, can an operator monitor multiple hydrophones in the high-frequency and low-frequency ranges using combinations of hydrophones by selecting appropriate groupings and spacing within the array and adjust the display for target species?**
- **What filtering options are available in the software?**
- **Does the software provide signal enhancement capabilities? What methods are used?**
- **Does the software provide user-defined signal-to-noise-ratio adjustments?**
- **What training do the PAM operators have, and do they have documented hours of operation, detections, and supervisor recommendations?**
- **What methods are used to detect, identify, and localize high-frequency (ultrasonic) tonal calls, broadband impulse calls, and low-frequency (infrasonic) calls?**

5.0 Data Collection and Archiving

Data are acquired in terms of sample rates for each hydrophone channel. Sample rates are two times the maximum frequency displayed. For example, if an operator wants to monitor species with call frequencies up to 20 kHz, the sample rate must be set at 40 kHz. The sample rate has a direct effect on the amount of data produced and processing capability required. Statements of hydrophone bandwidth should not be equated to sample rates. To monitor the full spectrum of cetacean calls (i.e., blue whales to harbor porpoises), a sample rate of 300 kHz would be required. The data stream from this sample rate for just one hydrophone would equate to roughly 600 kB of data per second. Therefore, to process signals for localization (i.e., range and bearing), the computer processing capacity must be sufficient to handle this amount of data from multiple hydrophones.

Post-Processing

Archiving capabilities should not be overlooked. Data collection needs to be discussed in terms of terabytes of data being generated on a daily basis. At a sampling rate of 64 kHz (sufficient for all but the high-frequency callers), PAM monitoring from 12 channels will produce 432 GB of uncompressed raw sound data per hour; the dataset needs to be archived either in its entirety (compressed) or subsampled prior to archiving. The data

should then be post-processed to determine the accuracy of real-time signal detection and localization. The archival capabilities of the software and hardware will have a direct correlation to successful data validation. While post-processing of full datasets is desirable, software that can sample 15 minutes of every hour of monitoring using automatic detection programs can reduce time and costs but still provide an unbiased post-processing avenue. While logging programs are important during monitoring, selective logging and saving only portions of the data selected by the operator does not provide any validation of results, nor does it provide archived data for further analysis in the future.

- **What is the sampling rate during the actual mitigation monitoring?**
- **How many hydrophone channels will be used for monitoring?**
- **What are the computing capabilities of the hardware?**
- **Do the computing capabilities meet the required needs at the given sampling rate and number of hydrophone channels intended for monitoring?**
- **Does the software support the computing requirements?**
- **What is the recording, archive and reporting (transfer of data) plan for the project?**
- **How will the acoustic data be post-processed for validation and efficacy evaluation?**

6.0 Use of a Dedicated Vessel or Remote PAM as Mitigation

Increased use of multi-vessel surveys in seismic programs has prompted development and implementation of new technologies, including using a dedicated PAM or guard vessel, using a single monitoring vessel from within the seismic survey, or using transmitted data to shore to monitor the exclusion zones and initiate the mitigation actions for all vessels in the survey. While the basic parameters of the PAM system will be the same for a remote system, there are some considerations that need to be addressed. Remote monitoring can be highly effective due to the ability to use highly skilled PAM operators who are supervised and have ample access to assistance and rest. Remote monitoring can be installed prior to a project, removing the need to have designated PAM personnel on board the vessel, thereby reducing personnel safety risk.

The two at-sea scenarios considered are 1) a dedicated PAM vessel, and 2) a collective PAM vessel. A dedicated PAM vessel contains the only cetacean monitoring system(s) but monitors the exclusion zones of all other vessels, with no data transmission from the other vessels. In a collective PAM vessel scenario, all vessels have cetacean monitoring streamers deployed but data are transmitted to a single vessel for monitoring the exclusion zones and implementing mitigation requirements.

In either scenario, it must be confirmed that all target species within all exclusion zones are detectable within the given distances of the vessel configuration. A dedicated PAM vessel will be required to detect calls well beyond its own visual range. Pre-selection of target species, therefore, is critical in determining detection limits.

A collective PAM vessel needs to ensure that target species are detectable within the range of each array. In this scenario, the main issues become data transmission, data processing, and operator efficacy.

Regardless of data acquisition methodology (i.e., data collected from two streamers on a single vessel or from individual streamers on multiple vessels), there will be a massive amount of data. Processing capabilities of the software and hardware must be sufficient to handle the high data load. Adequate bandwidth for data transmission is critical to ensure data integrity and allow for proper mitigation implementation.

7.0 Near Field and Far Field Determination and Passive Acoustic Mitigation and Monitoring

In general terms, the near field is considered the area located within one to two wave lengths (λ) of the source and where the signal does not lose amplitude proportionately to the distance traveled. The far field is the point at which the distance to the sound source is greater than $2D^2/\lambda$ where D is the array aperture.

There are many ways of defining near field and far field, due to the ambiguity of the actual point at which they occur in given conditions; however, all produce similar results. For example, if a right whale vocalization centered at 60 Hz is received using an array aperture of 10 m, it would need to be located more than 11 m from the array to get an accurate bearing (assuming a water velocity of 1,500 m/s). However, common dolphins with tonal vocalizations centered at 15 kHz would need to be at least 2 km from the array in order to ascertain accurate bearing. Given a standard 500-m exclusion zone distance, a common dolphin would be in the near field at any point in the exclusion zone.

The use of multiple hydrophones with many different apertures within the array is necessary to localize multiple species calling at different frequencies.

General rule: Given the same hydrophone spacing, low-frequency callers typically will be considered in the far field even when very close to the hydrophones; therefore, a basic bearing calculation can be used most of the time. High-frequency callers need to be farther from the hydrophones to be considered in the far field and, therefore, beamforming can become more important for real-time range and bearing calculation. Increasing the hydrophones to allow more variations of grouping and spacing options allow for more options in bearing and range calculation as well as measuring and eliminating unwanted noise.

Odontocetes vocalize at frequencies with short propagation distances and are, therefore, often already considered in the near field as soon as a signal is heard, making rapid far field calculations inaccurate.

Methods for obtaining bearing on a single signal depend on whether the calling animal is in the near field or the far field based on the caller signal frequency (**Figure 1**). Near field and far field calculations are separate from detectability, but are integral to how the animal is accurately localized.

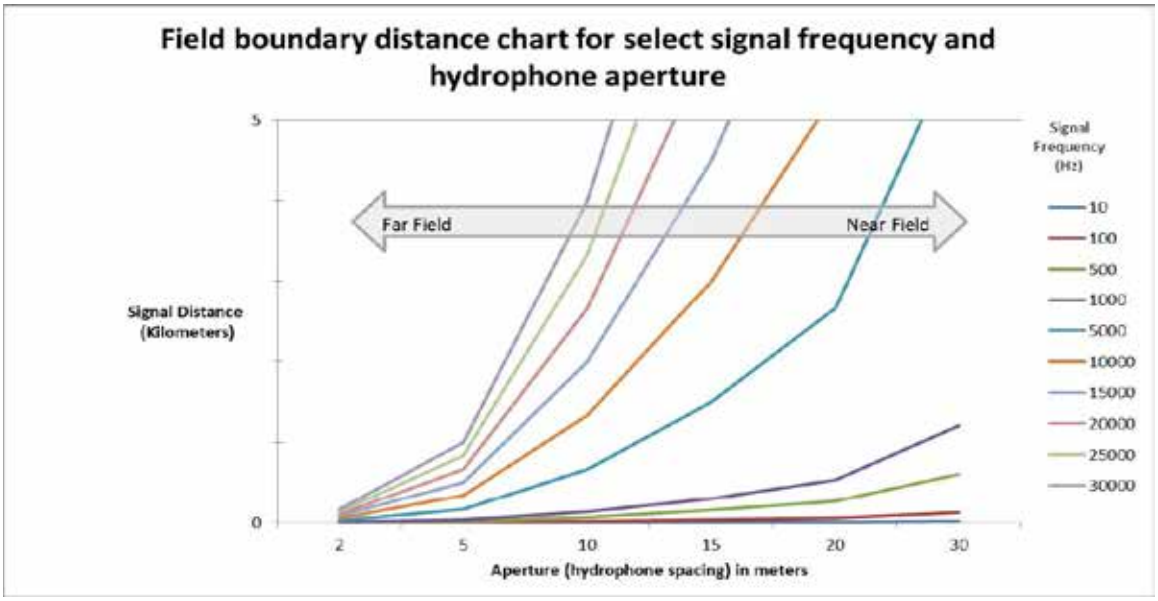


Figure 1. Approximate field boundary distances for a variety of call frequencies at different hydrophone apertures.

8.0 Summary

No single PAM configuration will be suitable for all applications. Careful evaluation of the project, survey goals, monitoring requirements, and environmental parameters will guide much of the PAM configuration. Some basic understanding of the capabilities and limits of PAM systems allows one to assess its utility in a project. PAM systems should be routinely calibrated with the recording of noise files and periodic review of sound data and detections by a skilled acoustician. Qualified installation and calibration of PAM systems is highly recommended and can provide all stakeholders with a realistic idea of detection limits and mitigation capabilities. As technology advances, systems are likely to become more automated and integrated; however, the same basic evaluation parameters will apply.