Fixed passive acoustic marine mammal monitoring for estimating species abundance and mitigating the effect of operations on the marine environment

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Measuring the Health of the Field:
Fixed Passive Acoustic Marine Mammal Monitoring for Estimating Species Abundance and Mitigating the Effect of Operations on the Marine Environment

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Table of Acronyms

1.	AUTEC	Atlantic Test and Evaluation Center
2.	AUV	Autonomous Undersea Vehicles
3.	BMMRO	Bahamas Marine Mammal Research Organization
4.	COTS	Commercial Off The Shelf
5.	dB	Decibel
6.	D/E	Depression/Elevation Angle
7.	DCLD	Detection, Classification, Localization, and Density estimation
8.	DET	Detection Error Tradeoff
9.	FFT	Fast Fourier Transform
10.	GDOP	Geometric Dilution of Precision
11.	GPS	Global Positioning System
12.	HF	High Frequency
13.	HARP	High-frequency Acoustic Recording Package
14.	HALT/HASS	Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Screening (HASS)
15.	kHz	kiloHertz
16.	M&O	Maintenance and Operations
17.	NEPTUNE	North-East Pacific Time-series Undersea Networked Experiments
18.	MHz	MegaHertz
19.	NGO	Non-Governmental Organization
20.	PAM	Passive Acoustic Monitoring
21.	P_D	Probability of Detection
22.	RHIB	Rigid Hull Inflatable Boat
23.	ROMA	Range Only Motion Analysis
24.	SES	Shore Electronics System
25.	SVP	Sound Velocity Profile
26.	TNO	The Netherlands Organisation for Applied Scientific Research
27.	TDOA	Time Difference of Arrival
28.	TOTO	Tongue of the Ocean
29.	ROC	Range Operating Characteristics
30.	USSI	Undersea Sensor Systems Incorporated
31.	WHOI	Woods Hole Oceanographic Institution

1. Introduction

Industries that operate in marine environments are under increasing pressure to document the effect of their activity on marine mammals and to evaluate the long-term environmental consequences of such activity. Although small numbers of marine mammals have been harmed by anthropogenic sounds [1,2] and Non-Governmental Organizations (NGOs) drive public sentiment with definitive statements, little is actually known as to the direct effect of such activities on marine mammal populations. It is therefore critical to document these populations before, during, and after development of an oil production field by providing long-term, on-going monitoring over the life of the field.

Determining the "health of the field" requires extended species monitoring and population density estimates, which traditionally have been derived using visual line transect methods. Long-term monitoring requires multiple surveys for many years. Such monitoring is expensive, intermittent, limited in scope, and highly dependent on environmental conditions. Surveys must be completed during daylight hours, are weather dependent, and require either a ship or plane. A plane can cover a significant area within a relatively short period of time, but its use entails significant risk. The efficacy of visual surveys for critical deep-diving species such as Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales is questionable.

Acoustic monitoring has proven highly effective for detecting vocalizing marine mammals [3]. Cetacean vocalizations vary widely from the low-frequency (< 100 Hz) songs of blue whales (*Balaenoptera musculus*), humpback whales (*Megaptera novaeangliae*), and other mysticetes (baleen whales) to the high-frequency (> 100 kHz) echolocation clicks of porpoises. These vocalizations can be readily detected using widely spaced sensors.
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The ability to classify animals is species dependent. Vocalizations from many large mysticete species such as blue whales are distinct and easily recognized as are the echolocation clicks from large odontocetes like sperm whales (*Physeter macrocephalus*), though very similar calls are sometimes made by some mysticetes, such as right (*Eubalaena glacialis*) and humpback whales. Small delphinids such as rough-toothed dolphins (*Steno bredanensis*) and melon-headed whales (*Peponocephala electra*) produce both echolocation clicks and whistles which are similar and difficult to distinguish. Development of automatic classifiers is a priority.

Of the over 21 species of beaked whales in the family Ziphiidae, the vocal and dive behavior of Cuvier's and Blainville's beaked whales, which only 4 years ago were poorly documented, are now well understood. These species, which have been involved in several stranding incidences associated with anthropogenic sound [4], produce distinct echolocation clicks. Of the remaining 19 animals in the family, vocalizations for bottle-nosed whales (*Hyperoodon* sp.), and Baird's (*Berardius bairdii),* Arnoux's (*B. arnuxii*), and Hubb's (*Mesoplodon carlshubbi*) beaked whales have been recorded. Little or no information exists on the vocalizations or habits of the remaining species. Increasingly, this knowledge gap is being filled as the vocalizations and foraging patterns of more and more species are documented.

At the same time, passive acoustics has emerged as a viable monitoring option. Implementation of fixed Passive Acoustic Monitoring (PAM) systems can provide a safe, cost-effective means of documenting the health of the field for many species. Increasingly, these data are critically required to address questions raised as to the cause and effect relationship of field development and production with the environment. By adopting a proactive approach to environmental compliance and long-term monitoring, the environmental effect of these activities can be documented and defended. Adverse environmental effects can be identified and addressed early in field development. These steps will give the regulator the best chance of designing reasonable mitigation methods that will allow field activities while protecting the environment, along with the tools to document the effectiveness of these measures.

The implementation of long-term environmental monitoring and the data it provides promote positive public relations. Such intangible gains are hard to quantify but their effect should not be underestimated. Failure to address environmental issues up-front and head-on can lead to significant delays and potentially intractable lawsuits. In the absence of real data, the industry will be held hostage to endless anecdotes that are impossible to refute. The precautionary principle will be amplified and applied, and with it will come extensive development delays and regulatory entanglements.

Passive acoustic monitoring is an evolving science. There are numerous areas that require further development. However, embedding the technology now as part of the infrastructure of the field would provide a powerful tool that rapidly drives this development forward. The breadth and depth of the data such technology provides acts as a multiplier which will continue to pay dividends into the future.

Several technologies will be explored and compared. Generally, in a downward refractive environment, a widely-space array of bottom-mounted hydrophones offer the potential to detect, classify, localize, and estimate the density of animals present. Such a system designed with a 20-year usable life can be deployed over a broad area and provide wideband continual data creating an in-situ laboratory that will drive forward passive acoustic method development at an accelerated pace.

The development and installation cost of a permanent multi-sensor array is significant (>$10M). However, the payback in terms of enhanced compliance, public perception, and future research is high. Such a system could also be used for several dual-use applications including tracking of undersea cooperative targets equipped with pingers that emit a known signal at a known repetition rate and in-situ sub-bottom profiling. Passive acoustic monitoring technology should be considered an integral part of the infrastructure of a field.

2.0 Overview of Passive Acoustic Monitoring

The use of passive acoustic monitoring as a tool to study marine mammals in-situ has been established. The challenge addressed in this report is to define PAM systems that can be applied to this end, and to document critical knowledge gaps that still must be addressed.

PAM system requirements will be defined for three separate field phases; exploration, drilling, and production.

During the exploration phase where no oil infrastructure exists, a portable system is expected to be the best solution to collect preliminary field measurements required to document the species present, their distribution, and densities. On the other hand, during the drilling and production phases, when oil platforms exists, a fixed PAM system connected to and powered from the platforms may be the most robust and cost-effective solution for long-term monitoring of the health of the field.

The amount of instrumentation needed to assess the health of the field is a function of several parameters including the required measurements (detection, classification, localization, and density estimation), the size of the field, the species present, and the hearing radius for each receiver element (node) in the field. The area of coverage for each node in a PAM system is defined by the receiver hearing radius (*r*), i.e. the horizontal distance from a node at which a vocalization signal can be recognized. If the health of the field can be assessed by detecting the presence of and/or classifying the type of animal(s) present, this measurement can be accomplished with a single receiver node for each sub area of the field. The number of nodes required to assess the whole field is determined by the individual node hearing radius and the probability of detecting the vocalization. On the other hand, if the "health of the field" requires localization of the animals, then the number of sensors required, given a specific hearing radius, is determined by the positioning algorithm. Specifically, localizing an acoustic source in three dimensions (3-D) with an unknown time of acoustic emission (asynchronous) and assuming a homogeneous effective sound speed, is achieved by using time-of-arrival measurements from a minimum of four receiver nodes to cover the common area within the hearing radius of all four receivers. If the animal depth is somehow known, only three receivers are required. In general, for localization using multilateration algorithms, approximately four times the number of nodes is needed as compared to the detection and classification requirement. If a bearing node measures the bearing to an asynchronous source, then a minimum of two nodes is required to localize the source in 2-D. A more complex node that also measures the elevation angle could estimate the position in 3-D. If the propagation path from the source to the receiver is indirect, algorithms to determine the ray path are required to calculate the slant range between the source and receiver in order to calculate the source position [5].

Systems designed to detect and track marine mammals can be used to track cooperative undersea vehicles, i.e. vehicles equipped with acoustic pingers. Also, fixed arrays could be fitted with geophones for use during acoustic substrata surveys. **By exploiting dual use opportunities, the cost of investment could be amortized over multiple applications.**

2.1 Passive Acoustic Monitoring Systems Node Hearing Radius

Whether the PAM system is composed of battery-powered anchored or real-time cabled nodes, several factors determine the number of nodes that compose the field. These include the size of the field, the hearing radius around each node, and the localization technique employed. The parameters that affect the acoustic hearing radius for each node in the PAM system include the vocalization source level, the vocalization bandwidth, the background noise level, and the acoustic propagation characteristics between source and receiver.

Vocalizations for marine mammals as a whole range from less than 10 Hz to greater than 200 kHz [6, 21], and source levels range as high as 228 dB [7]. For purposes of demonstrating the impact of the hearing radius on the design of a PAM system, two signal sources are considered: Baleen with a source level of 180 dB at a frequency of 800 Hz and odontocete with a source level of 200 dB at a peak frequency of 16 kHz. It is recognized that the directionality of the acoustic source also plays a role in detection; however, this will be addressed when localization algorithms are discussed.

The sources of background noise in the ocean are [8]

- Natural biological sources (snapping shrimp, fish chorus, etc.)
- Natural physical sources (waves, precipitation, thermal molecular agitation)
- Anthropogenic noise (vessel noise, sonar, seismic surveys, industrial activity, etc.)

From Figure 1 the dominant noise spectral level for sea state 4 at 800 Hz and 16 kHz is 65 and 45 dB respectively. For transmission loss assume spherical spreading with a frequency dependent absorption as shown in Figure 2 [7]. Figure 3 plots the received Signal to Noise Ratio (SNR) in a 1 Hz band as a function of distance from the receiver for the propagation parameters identified. Based on detection thresholds reported by Ward et. al. for a Fast Fourier Transform (FFT) based marine mammal click detector, a 30 dB detection threshold level provides adequate performance for detection, classification, and localization [9]. From figure 3 we observe that for signals received on an omni-directional node at 800 Hz and 16 kHz in sea-state 4 with a 30 dB detection threshold results in a hearing radius of 16.5 kyds (≈ 15 km). This hearing radius will be used for the systems analysis in this report

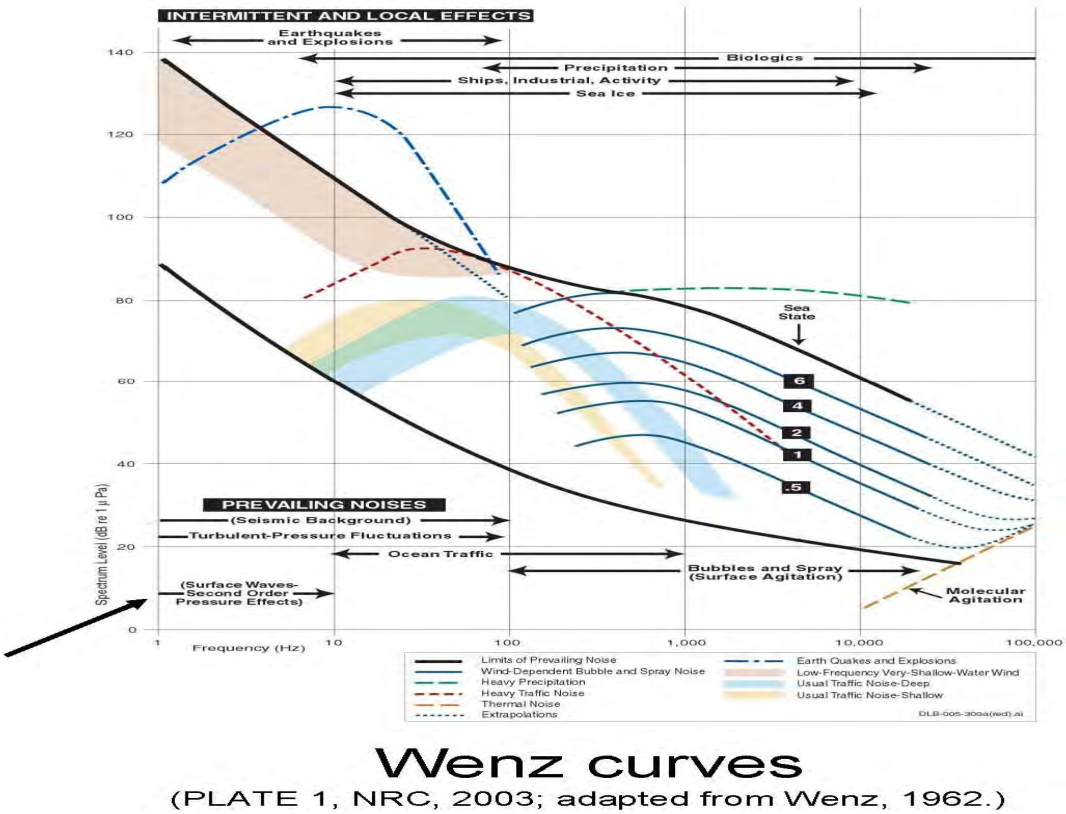

Figure 1. Background Ocean Noise Levels

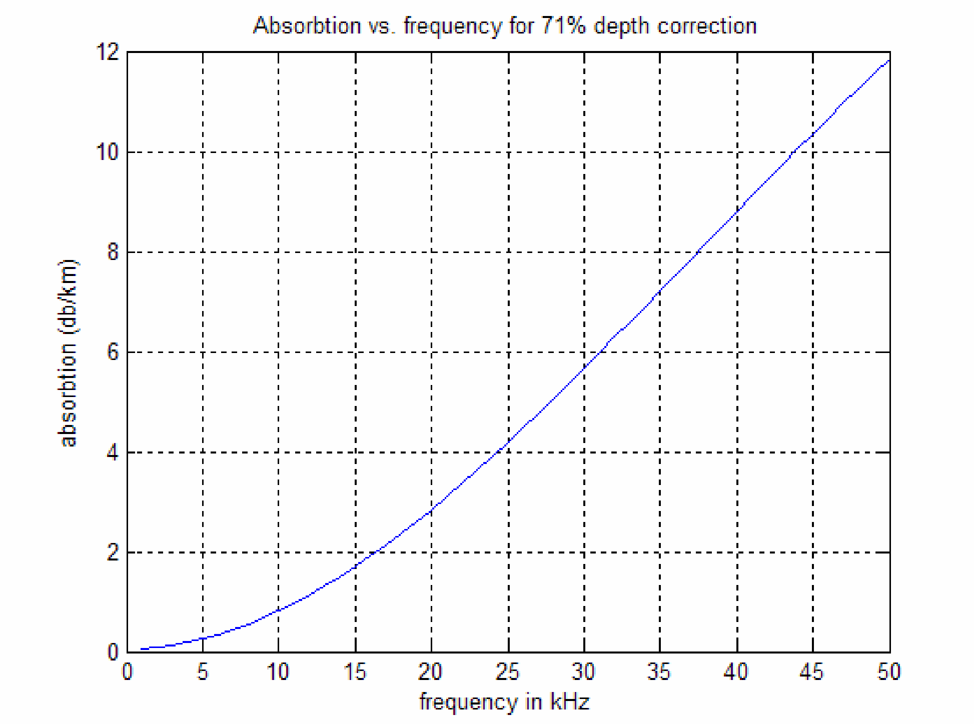

Figure 2 Absorption (Thorpe)

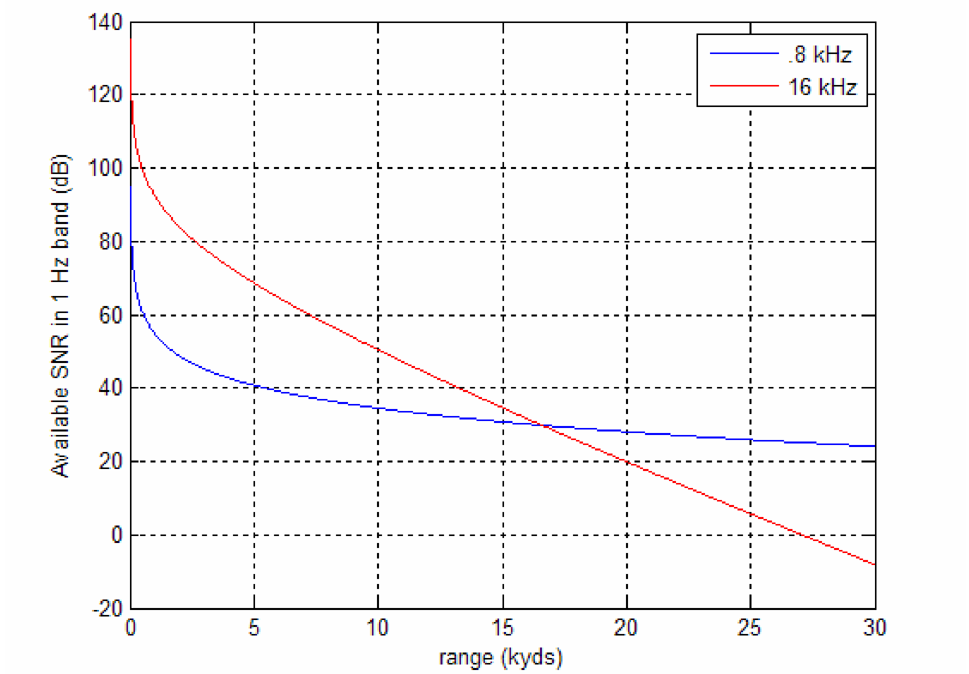

Figure 3 Detection Thresholds for 8 kHz and 16 kHz.

2.2 Passive Acoustic Monitoring System Node Density

2.2.1 Node Density for Detection and Classification

Given the size of a field and the node hearing radius, the number of nodes needed can be estimated. If the objective is limited to detection and classification, then the node density will be a function of the size of the field and the probability of detecting the mammals when they vocalize. If each node in a PAM system has a hearing radius of *r* and the number of non-overlapping nodes is *N*, then for a field size of area *A*, assuming a marine mammal is equally likely to be anywhere in the field, the probability that the mammal is within the hearing radius of a node is

$$P_d = \frac{n\pi^2}{A}$$

Figure 4 shows a field with an area, A=1600 square kilometers, and a single node with a hearing radius of 15 kilometers. Ignoring the source beam pattern, the probability of a mammal being detected within one of the nodes hearing radius is 44%. Two non-overlapping nodes will result in an 88% probability of detection. For the 40km x 40km area it will take six overlapping nodes to get approximately 100% coverage as shown in Figure 5.

For shore-linked (cabled or radio-transmitted) receiver nodes the acoustic data can be processed in real-time or recorded for future analysis. For battery-powered portable nodes, recording the vocalizations for post-processing is the only viable approach. Several strategies can be employed to record the vocalizations; continuous recording, record when vocalizations are detected, or a time-sampled recording plan using a preset duty cycle. The tradeoff for cabled systems is the volume of data storage and surveillance fidelity, while for battery-powered nodes the tradeoff is between battery size requirements, data storage requirements, and surveillance fidelity.

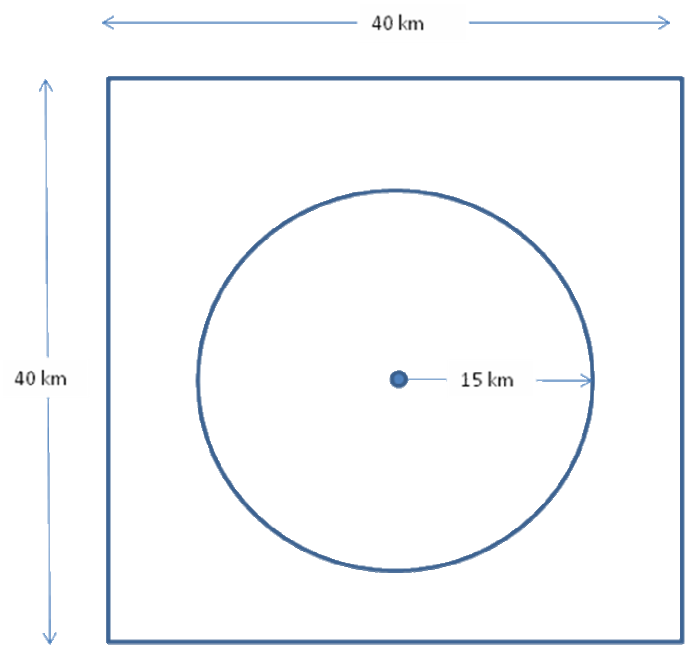

Figure 4 Single Node Area of Coverage

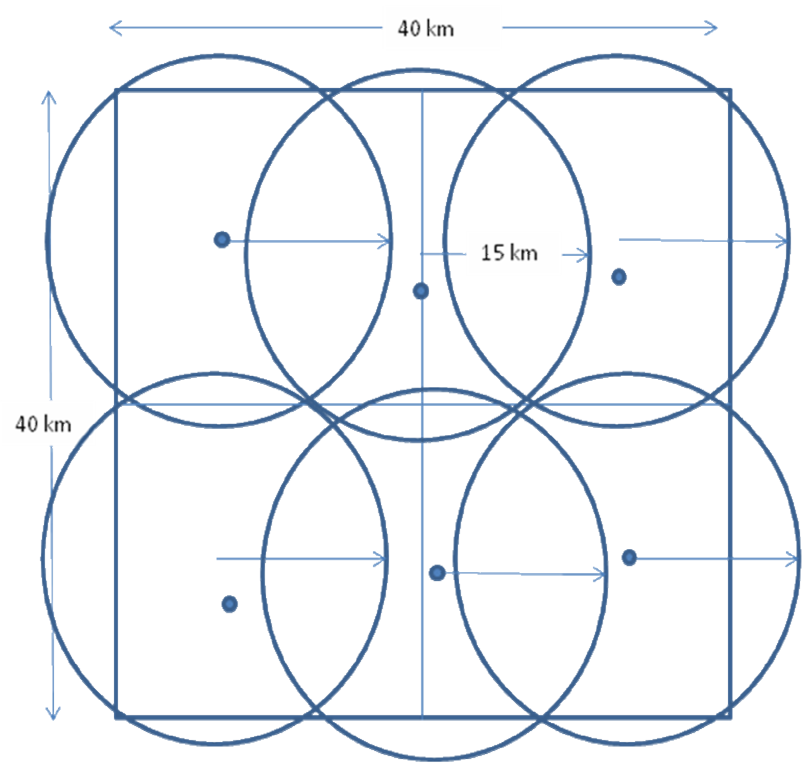

Figure 5. Multi-Node Area of Coverage

2.2.2 Localization

Marine mammal localization requires a higher density of receiver nodes than surveillance and classification (detection only). Localization of an acoustic source with unknown time of emission (asynchronous) is traditionally accomplished by measuring its Time Difference Of Arrival (TDOA) at multiple receiving nodes. For a homogeneous medium, the TDOAs along with an estimate of the effective sound speed are used to solve the intersection of hyperboloids [5,10, 11]. With four receiving nodes, the estimated horizontal position (x, y), the depth (z), and the time of emission (T_E) of a pulsed acoustic source can be calculated, With three nodes given depth, horizontal position and time of emission are achievable. Localization can be accomplished with either short or long receiver node baselines defined by the distance between receiving nodes as compared to the hearing radius. The basic node geometry for a 3 phone hyperbolic localization array is an equilateral triangle. Short baseline localization arrays are defined as having baseline separations (b) much shorter than the node hearing radius (r). Short baseline systems trade off positional accuracy to achieve the largest uniform tracking area. Conversely, long baseline localization arrays have baseline separations close to the hearing radius. Figures 6a and 6b depict the area of coverage for a 3 node short and long baseline localization array. The nodes are located at the vertices of the triangles in these figures.

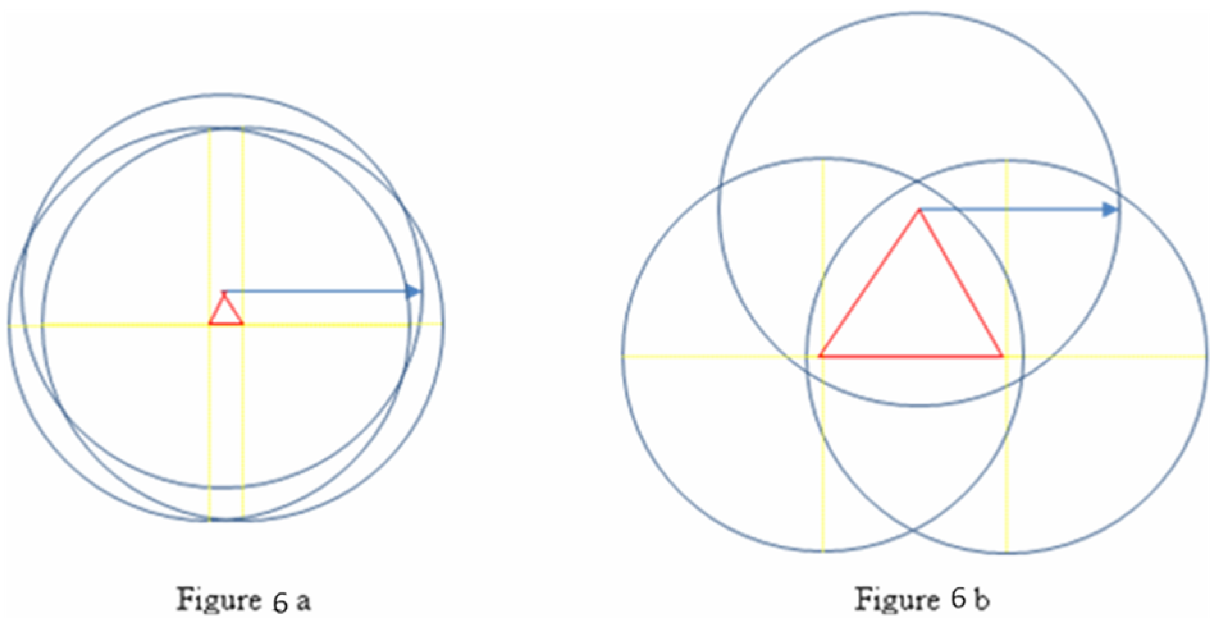

Figure 6 a&b. Short and Long Baseline Array

Figure 7 shows the Geometric Dilution of Precision (GDOP) for a 3- phone array using a hyperbolic algorithm to calculate the position [12]. The value of the GDOP for various locations within the area of coverage is a non-dimensional quantity that is multiplied by the range measurement variance to estimate the horizontal position errors at each location. The area inside the triangle has the lowest GDOP and therefore the most accurate positions. Long baseline arrays have a smaller overall tracking area but a larger area of high accuracy track compared to short baseline arrays.

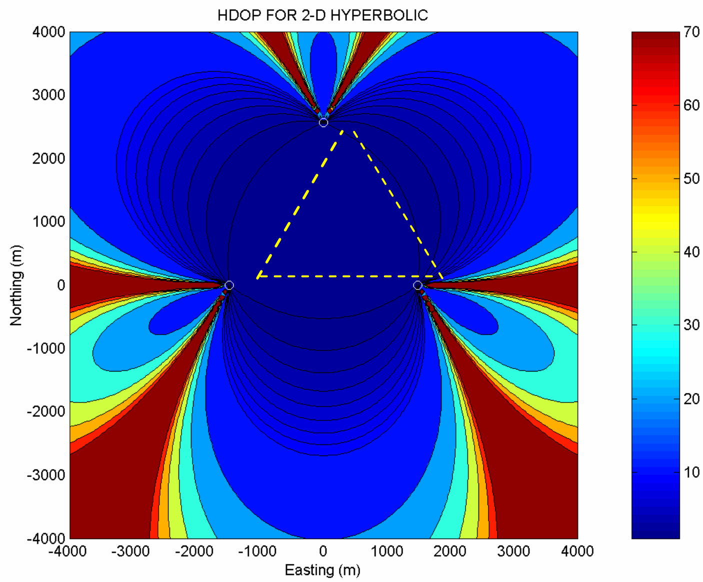

Figure 7. Equilateral 2-D Hyperbolic Horizontal Geometric Dilution of Precision (GDOP)

Larger coverage areas can be accommodated by adding additional sensor nodes forming additional triangles. The next fundamental building block, the hexagon array, is formed by adding an additional four sensor nodes as shown in Figure 8. The hexagon array has a baseline separation between hydrophones of *b* meters. For long baseline arrays using asynchronous hyperbolic tracking algorithms to solve for position (x, y, z) and time of emission (t), the baseline separation b must be sized as a fraction of the acoustic hearing radius to insure four phones receive the tracking signal. Figure 8 depicts an acoustic source located near the baseline of a 3- phone equilateral triangle (target indicated by a circle near equilateral triangle formed by nodes 1, 2 and 3). The next closest node, which is the fourth node required for solving a 3-D hyperbolic tracking algorithm, is either node 4 or 7. Based on the hexagon array geometry the distance and hence the acoustic hearing radius to the fourth hydrophone is equal to 1.414 times the baseline b. This means that for a given hearing radius, the maximum baseline distance is calculated as approximately 0.707 times the hearing radius. In contrast if we assume a known mammal depth and use 2-D hyperbolic positioning algorithms with only three receiver nodes required the baseline b could be expanded to equal the hearing radius thus improving position accuracy. As the hexagon array building blocks are combined to form larger instrumented underwater areas, the number of nodes for long baseline tracking grows accordingly. Additional receiver nodes are combined to create multiple hexagon arrays (or portions of a hexagonal array) in order to further expand the instrumented coverage area. Figure 9 shows the GDOP for a typical expanded area, in this case 13 nodes using a hyperbolic positioning algorithm.

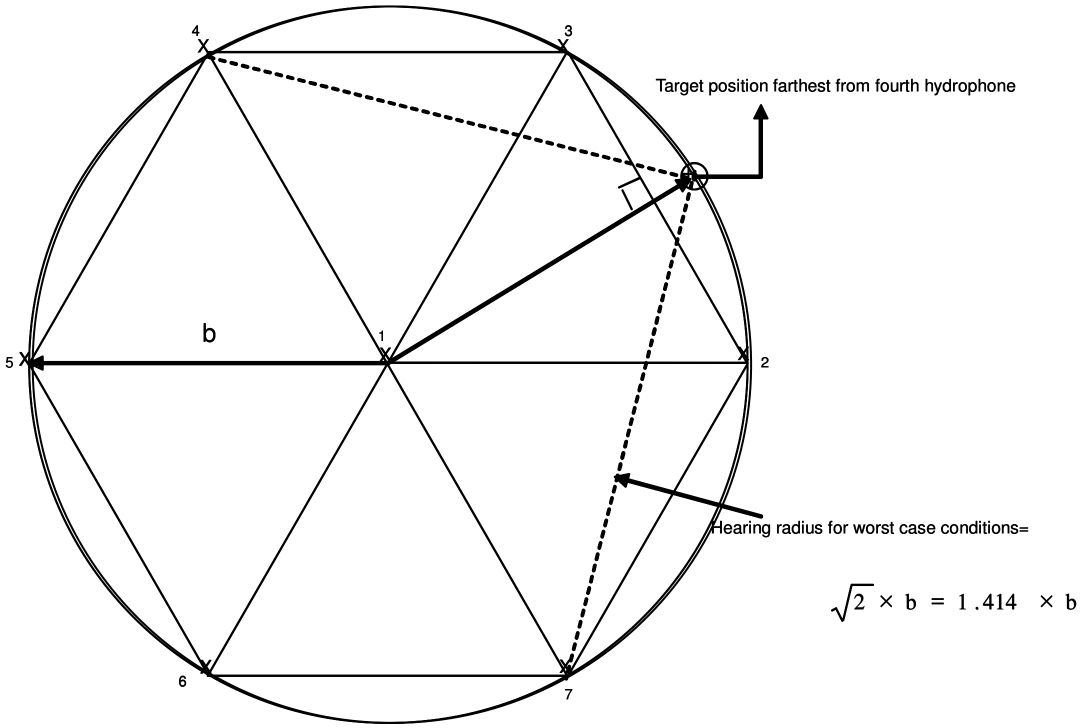

Figure 8 Hexagonal Array of Receiving Nodes

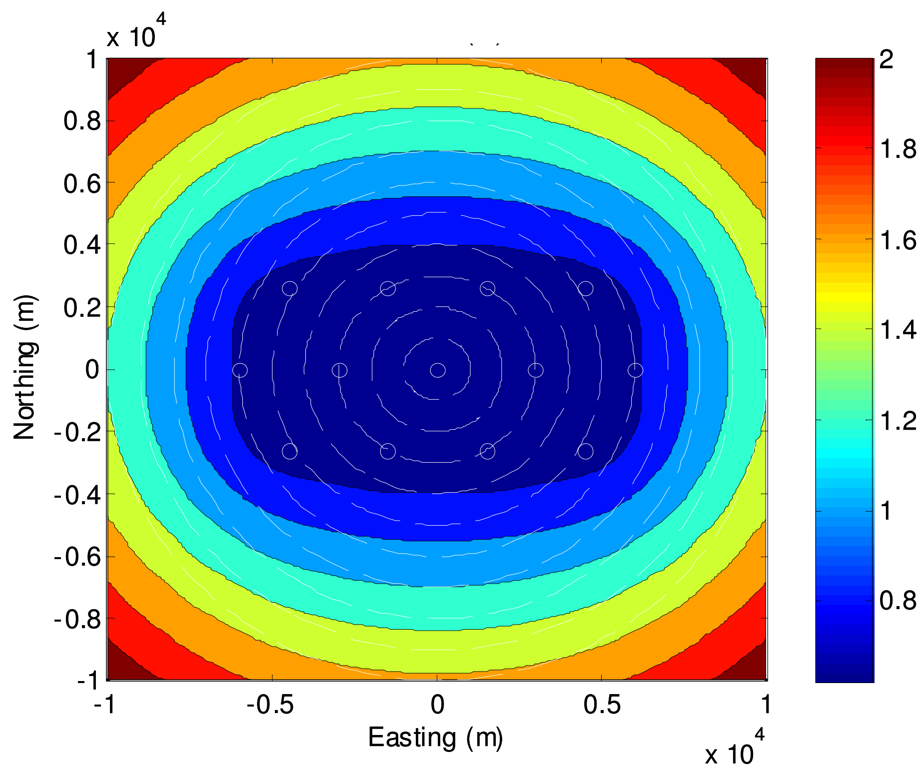

Figure 9 GDOP for Expanded Hyperbolic Tracking Array

2.3 Portable Passive Acoustic Monitoring Systems

2.3.1 Portable Systems

There are many options for implementing portable receiver nodes but the discussion will be limited to the two most practicable approaches for battery powered devices; moored surface buoy or bottom-mounted pressure vessel instrumentation packages.

The moored surface buoy instrumentation package has the advantage of access to electromagnetic telemetry either by line of site to an aircraft or ship or over the horizon communications via HF or a satellite data link. If this surface buoy has the ability to record and periodically transfer its stored acoustic data, the data storage requirements will be less and the deployment period will be limited by the battery endurance. Solar cells can be used to increase the on-station time. Another advantage of the surface buoy node is the ease of maintaining synchronization between nodes with access to GPS time. The disadvantage to the moored surface buoy approach is its vulnerability to being loss or destroyed from shipping or severe weather.

The bottom-mounted instrumentation package has the advantage of being invulnerable to weather or transiting surface craft, however as with a moored surface buoy, it is vulnerable to fishing activities such as bottom dragging. The disadvantage of the bottom moored node is the need to record the acoustic activity for the full period of observation and the need for precision time standards to maintain synchronization between nodes for localization. If the health of the field can be evaluated by detection and/or classification alone then the time synchronization requirements are trivial.

A combination of bottom moored nodes and a “surface buoy relay” can be implemented were a number of bottom-mounted devices periodically acoustically telemeter recorded data to a surface buoy for relay via electromagnetic telemetry. Depending on the physical parameters such as water depth and node baseline separation a single surface relay buoy can communicate with up to seven (or more) bottom-mounted nodes forming a hexagonal array. This structure can be repeated with multiple hexagonal arrays and surface relays covering a larger area. The surface relay buoy could also be used to synchronize the bottom-mounted nodes’ clocks with acoustic pings.

Before and during field development, bottom moored instruments can be deployed which record animal vocalizations. A typical bottom moored instrumentation package shown in Figure 10 is the MIKEL Inc. transponder/beacon that has recording, acoustic telemetry, and localization capability. The instrumentation package cost, deployment time, data storage, sensor bandwidth, and battery capacity are parameters that must be considered in designing the monitoring system. Instrumentation packages can be designed as dual-use beacons or transponders for tracking of undersea vehicles and other objects that may be used in field development. Such dual-use could significantly offset the cost.

Typically, instrumentation packages with recording capability are deployed for a predetermined period. If low frequency baleen species and high frequency species such as

Cuvier's beaked whales are to be detected, the instrumentation package must provide a minimum measurement bandwidth from 10 Hz to 40 kHz. This suggests a minimum sample rate of 96 kHz which requires 16 GBytes of storage per day if data is continually recorded with an 80 dB dynamic range.

Monitoring over broad temporal scales (months to years) is required to determine normal population variability over days, months, and seasons.

Although the costs of instrumentation package procurement, deployment, and recovery are significant, they are often greatly outweighed by the costs of analysis and the costs incurred due to the delays in field development. Any preprocessing completed in real-time within the buoy will greatly decrease post-recovery analysis and will reduce the buoy storage requirements resulting in a reduction in cost.

Detection of marine mammal vocalizations is a complex problem. Vocalizations vary widely between species and within a species. Vocalizations produced by a single animal may also vary. The time of emission is unknown and the same vocalization must be detected and associated on at least 4 hydrophones for 3-D localization using a hyperbolic algorithm.

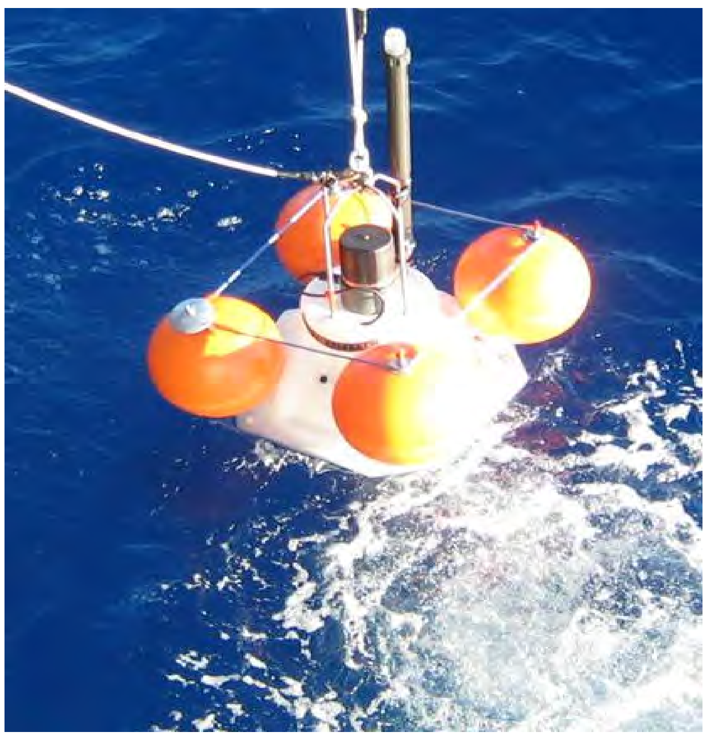

Figure 10. MIKEL Inc. Dual use Recording Smart Transponder/Beacon

A number of recording options are available given current technology. These include direct recording or acoustic signals, periodic time sampling, or detect and sample methods. The use of a simple hard-limited Fast Fourier Transform (FFT) has been developed [3] to provide a broadband detection scheme which preserves most relevant signal parameters. Such a detector utilizes an adaptive threshold in each bin of the FFT. If energy is detected above threshold, the bin is set to a 1 and a detection report is generated. The report includes a binary bit map that documents the bins above threshold, the detection time, and the bin with the maximum energy. This technique allows detection and time-tagging of transient signals while at the same time reducing the storage requirements by a factor of 100.

Data recording within the buoy can also be keyed to the detection of a transient signal enabling a recording of a signal for a preprogrammed length of time. If the buoy continues to detect signals of interest, the recorder remains enabled. This reduces the data load and analysis time by capturing only high-value data.

Precise localization of vocalizing animals requires precise knowledge of the sensor position. For surface moored buoys equipped with GPS, the position is continuously transmitted in the buoys message. For bottom moored nodes typically a mark-on-top, based on a GPS drop point provides marginally adequate buoy position in very shallow water. Positional accuracy can be greatly improved with a careful acoustic survey using GPS or preferably carrier-phase GPS. Such surveys require the recording buoy act as a transponder. A pole-mounted transducer fitted with GPS antenna as shown in Figure 11, is used to produce the round trip travel times that are used by the acoustic survey algorithms to locate the bottom-mounted nodes position. The transducer acts as both a transmitter interrogating the bottom node and a receiver detecting the nodes transponder replies. The vessel runs a predefined course through the sensor field. Down-link pings are received on the bottom nodes. Each node responds with a unique up-link signal. The range to the node is measured. These range measurements are combined with the known ship position at the time of the ping transmission to calculate the position of the each node. With care, bottom node position can be calculated to sub meter accuracy [13].

To localize an asynchronous signal such as an animal vocalization in 3 dimensions, a signal must be detected on at least 4 nodes. For a homogeneous medium the Time Difference of Arrivals (TDOA) between node pairs is used to calculate a position using hyperbolic multilateration [11]. As discussed earlier, this assumes that the nodes are time-synchronized. In addition to the methods of synchronization previously discussed, bottom-mounted node synchronization can be accomplished by initializing the time on each node to a common reference such as GPS and using a computer compensated oscillator within each buoy to handle oscillator drift. Time offsets can be further refined by programming each node to transmit a unique ping at know intervals. The ping is received on the surrounding nodes. If the location of each node is established via an acoustic survey, the ping transit time to surrounding nodes can be calculated given reasonable knowledge of the Sound Velocity Profile (SVP).

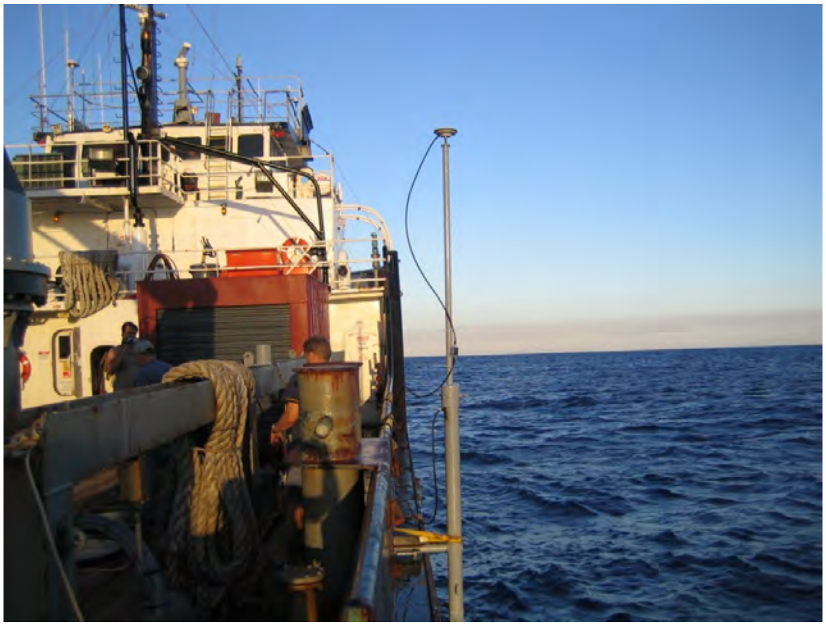

Figure 11 Pinger Pole with GPS

Often marine mammals will emit a series of vocalizations. To localize, the vocalizations received on multiple nodes must be properly associated. This step in localization is often overlooked or trivialized. While this can be done using techniques such as pattern-matching for click trains and spectrogram correlation for signals such as whistles [14], it is in fact difficult to execute effectively in real-time. Real world signals from multiple animals may contain a multitude of overlapped vocalizations. Individual vocalizations may not be received on at least 4 hydrophones due to factors such as source-sensor geometry, propagation effects, and animal beam patterns. Real-time data association for systems using multiple widely spaces sensors is an area that requires additional research.

Nodes designed for dual use may increase the cost effectiveness of the system. For instance the MIKEL Inc. Recording Transponder/Beacons can be used to provide a real-time track for cooperative vehicles when operating in Transponder Mode or Beacon Mode. When operating in Transponder mode each transponder node detecting a coded ping from a vehicle responds with its own ping sequence echoing the coded ping as well as a second coded ping identifying the specific transponder node replying. The round trip time for interrogation and reply is used to determine the transit time between the vehicle and each replying transponder. With knowledge of the effective sound velocity these times are converted to ranges that are used by the tracking algorithms to calculate position. With calculated ranges from three transponders the position of the vehicle can be estimated by an algorithm that determines the intersection of three spheroids. This method, referred to as spherical tracking, can reduce to only two transponders replying when the vehicle depth is known. Calculating the transponders time of emission for third party tracking requires knowing the transponder to third party (uplink) acoustic transit time. The uplink transit time can be estimated given the third party's GPS position and knowing the position of the transponders and the local SVP, or measured with occasional coded ping interrogations from the pinger. To use the spherical algorithms for third party tracking requires the vehicle pinger time of emission is known (synchronized), otherwise localization of the vehicle is done by measuring the time difference of arrival of the vehicle downlink detections applying a hyperbolic multilateration algorithm.

An alternate to a single hydrophone node is a bearing node, comprised of ultra-short baseline hydrophones measuring the signal phase difference. A single bearing node can provide an angle to a source of sound, either a pinger or mammal vocalizing. To localize in 2-D, the angle to at least 2 distributed bearing nodes and depth of the source is required. This technique offers the advantage of only requiring two bearing nodes to localize an unsynchronized emission; however the uncertainty in position grows as the distance between the source and receiver gets larger. The same bearing node can be used for single sensor range-bearing track of cooperative targets configured with a synchronous source. Thus bearing nodes reduce the number of sensors required to localize the target. However, such systems increase the system complexity as multi-element arrays are required. If the depth of the acoustic source must be calculated, the complexity increases further as an estimate of the Depression/Elevation (D/E) angle must be determined along with the bearing angle. Experience on fixed ranges has shown that for a given area of coverage, the number of sensors required for simple hyperbolic track may incur only a slight increase compared to the number of multi-element arrays required for bearing track.

For animals with a discrete beam pattern such as beaked whales, bearing arrays may provide an advantage. The animal's vocalization is transmitted with a distinct beam much like the beam of a flashlight. A single vocalization may only be detectable on-axis to the beam unless the animal is extremely close to the sensor. This means detecting the same vocalization on at least 3 widely spaced sensors is difficult. Bearing sensors would require only 2 sensors detect the vocalization to localize the animal's position.

A third technology that has been investigated is the use of matched-field processing [15]. Matched field processing requires intimate knowledge of the sound field surrounding the sensor and variations in the field at any angle relative to the sensors. Typically, a vertical line array is used. The field is gridded on discrete radials around the array. At each range and depth along the radial, the modal properties of the receive signal are pre-calculated. Upon detection of a signal, the modes are matched to those for each grid space, and an ambiguity surface is created. Matches are displayed as "hot-spots" on the surface. This method can significantly reduce the number of sensors required to localize an animal. However, it comes with significant computational complexity, assumes intimate knowledge of the sound field, and that the field is stationary within the measurement period. Often, to characterize the acoustic field, a beacon(s) at a precisely known location, that transmits a precisely known signal at a precisely know time is included.

A final method for self track of *cooperative* undersea vehicles has recently been demonstrated by MIKEL Inc. Although not applicable to marine mammal localization, it would increase the number of potential dual-use applications. This method uses a single Transponder/Beacon operating in Beacon Mode (acoustically commanded to emit pings at a prescribed duty rate for a specified period of time) to track the vehicle using a unique Range Only Motion Analysis (ROMA) algorithms operating within the vehicle. Multiple beacons can be deployed without overlapping hearing radii to allow the greatest area of tracking coverage for the lowest sensor node density. Beacon tracking allows the vehicle to be passive, once the beacon is initialized and covers a track area equal to the hearing radius with a single node. Since the MIKEL's Recording Transponder/Beacons are acoustically commanded to act as beacons, transponders and passive recording devices they can be planted as passive detection and classification nodes for marine mammal monitoring while having the capability to provide a either a transponder or beacon track for undersea vehicles. Using the ROMA algorithms with cabled bi-directional (transmit and receive) acoustic nodes can provide the same dual use marine mammal surveillance and undersea vehicle tracking with the low node density as with the battery operated beacons.

2.3.2 Deployable Buoys and Gliders

Deployable systems can be used when short-term monitoring is required. Several options are possible including free-floating buoys, and ship deployed arrays. Although these are not the focus of this report, they are summarized here for completeness.

Undersea Sensor System Incorporated (USSI) broadband GPS-enabled free floating sonobuoys are commercially available. These are modified Navy 53F sonobuoys that provide a bandwidth of ~10 Hz to 40 kHz when placed in the "extended" mode. The hydrophone is deployed to a depth of up to 1000 ft. The buoys include a GPS receiver. GPS position data are modulated on a sub-band from 40-45 kHz. The combined acoustic and modulated GPS signal are FM modulated on a carrier in 1-of-99 channels in the 135 to 165 MHz bandwidth and transmitted to a sonobuoy receiver. A separate demodulator is required after the RF receiver to demodulate the acoustic and GPS data.. The demodulated GPS data are provided on a network link.

Sonobuoys are easily deployed and expendable. At ~$1500 each, for short duration monitoring requirements they may be cost effective, especially when compared to overall operational costs of a ship and associated personnel. They can be deployed from either a ship or small RHIB. The buoy lasts for up to 8 hours. At the end of its life, the buoy scuttles and sinks to the ocean bottom.

Low-frequency towed arrays have been used to detect vocalizing animals. Typically, towed arrays are designed for low frequency (10Hz–3khz) sounds. Wide-band (100Hz–40kHz typical) towed arrays are becoming available [16]. As an example, the TNO Delphinus array includes 4 elements that expand the arrays capability to 150 kHz. Initial line transects surveys which incorporate towed line arrays have been conducted [17].

The use of gliders and Autonomous Undersea Vehicles (AUVs) has been postulated as a means of surveying and monitoring an area [18]. Potentially, a glider or AUV could be programmed to record or detect sounds of interest using passive acoustics. Gliders are easy to deploy and use little energy in movement and thus may offer a longer time on station than an AUV. In the near future (5-10 years) it is conceivable a glider-based survey of vocalizing animals present could be conducted. Given, current technology, the payload available is small which limits the size and power of the on-board electronics. However, systems have been tested for their ability to detect vocalizing animals including beaked whales with some success [19].

The efficacy of surfaced deployed systems remains to be quantified especially for beaked whales.

2.4 Fixed Passive Acoustic Monitoring Systems

2.4 1 Production Field Long-Term Monitoring

Within an established field, careful consideration should be given to a permanent field of sensors cabled to a platform or if possible to shore. Although the procurement and installation costs are significant, once complete, the M&O costs are less while the capabilities are considerably greater compared to portable systems.

Typically such systems consisted of single cabled, bottom-mounted hydrophones. Within the last 20 years, in an effort to reduce the acquisition and installation costs, bottom-mounted transducers multiplexed on a fiber-optic backbone are more common for tracking arrays located far from the receiving platform. The sensors are typically broadband (30 Hz – 50 kHz) and may be capable of transmitting acoustic signals over a narrower band of frequencies for such applications as acoustic communication and ROMA tracking. In-water signals are transmitted to the receiving platform and distributed as buffered outputs to systems for analysis and recording. The advent of cluster-based processing using commodity computers allows the application of multiple Detection, Classification, Localization and Density estimation (DCLD) algorithms. This architecture provides cost-effective maintenance and life-cycle support.

Multiplexed arrays can have variable node spacing and when deployed can be organized to provide high accuracy, long baseline hexagonal tracking arrays or low density detection and classification nodes. Combining the capability to transmit from selected nodes with high accuracy tracking arrays and low density surveillance nodes allows for marine mammal detection and classification over large areas and localization of the mammals in selected areas with a large area available for cooperative tracking of undersea vehicles equipped with an acoustic beacon.

As with a field of bottom-mounted portable nodes, an acoustic survey is used to precisely (<.25 m) map the position of the cabled nodes. Generally, data are synchronously sampled to maintain precise timing (<5 μsec) between nodes. By minimizing both errors in sensor position and timing, combined with an understanding of the SVP, the hexagon array can be used to both detect and track signals of interest with great precision.

As the output of the sensors are provided within a dry-lab, raw acoustic data for DCLD are available in real-time. These real-time sensor data may include both transient marine mammal signals and acoustic tracking signals from undersea vehicles. Unlike portable systems, full bandwidth data can be immediately processed in real-time and are available for recording on a long-term, continual basis. Typically, hard disk recorders are used. Such systems can handle multiple sensors (>>100) by synchronously digitizing analog outputs or by accepting direct digital data from the array.

2.4.2 Fixed, Portable, Passive Acoustic Systems and Methods Comparison

2.4.2.1 Portable Arrays

As discussed in section 2.3.1 portable recording devices have been used successfully to determine the presence of or absence of marine mammals. These include such buoys as Cornell pop-ups, and Scripps High-frequency Acoustic Recording Packages (HARPs). These packages generally include a broadband (~10Hz–100kHz) hydrophone, analog to digital converter, memory, batteries, control electronics, embedded controller to schedule recordings, and acoustic release. They are typically deployed on the ocean bottom and recovered at a later date [20].

Such devices can be installed in semi-permanent configurations. Bottom-mounted buoys must be retrieved to download data and re-battery. In shallow water, moored surface buoys can be installed with data links to back to shore or in the case of an oil field to a platform. Current installations include Cornell right whale detection buoys off Cape Cod (www.listenforwhales.org), which uplink detection reports along with short sound clips for analysis on shore via a satellite link. The cost of such systems tends to be less than a cabled system but the processing and storage are limited. Once installed, changes to any embedded processing are cumbersome and costly. Also, such systems are likely to require repeat maintenance as surface buoys are susceptible to damage from collisions and weather. They typically have a lower acquisition and installation cost but higher maintenance and operation costs. If required, these systems can be recovered and moved to a different location.

2.4.2.2 Fixed Arrays

For long-term monitoring at a specific location a fixed multi-sensor system that is cabled to land or to a platform is the preferred alternative. Typically, such systems are designed for a 20 year life. Once installed, a fixed system with bottom-mounted sensors is virtually maintenance free. There are three general variants of fixed-cabled sensors. The first and simplest configuration is an array of sensors each connected to a dry lab on a single copper or fiber optic cable. There are several advantages to these systems. Each node is independent and its failure does not affect others in the array thus creating a high degree of fault isolation. This simple design leads to simple node mechanics and electronics. There are cases of military systems with single-cabled nodes operating over 40 years.

More recent designs use a fiber optic backbone with multiplexed nodes. Such systems digitize the sensor data at the node and telemeter the digitized data. These systems may also include bidirectional nodes that are capable of both listening and transmitting signals. This capability can be used for acoustic communication and to augment vehicle tracking with synchronous beacons. By multiplexing the sensors on a single backbone, the acquisition cost of the cable can be minimized. However, such architectures increase the complexity of the in-water electronics and also the cost of each node. The risk of a catastrophic failure also increases as a cable failure could cause the entire array to fail.

Recent scientific arrays, such as the Victoria Experimental Network Under the Sea (VENUS) array, use a "hub-and-spoke" design on a network backbone. Underwater junction boxes are provided to which various instruments can be connected. A network interface is used allowing disparate devices to connect. Each junction box provides an Ethernet switch, a serial port server, and power. These systems represent an increase in flexibility and configurability but with a significant increase in complexity and cost. A summary of existing arrays is presented in Table 1.

Array	Location	Transport/Cable	Type	Max Depth	Status
Scientific/Environmental Arrays					
VENUS: Victoria Experimental Network Under the Sea	Vancover Island, British Columbia, Canada	ENET/Fiber Optic	Scientific/Hub and Spoke multi-sensor	300m	3 nodes installed: Straight of Georgia, Frasier River Delta, Saanich Inlet
NEPTUNE: North-East Pacific Time-series Undersea Networked Experiments	Vancover Island, British Columbia, Canada	ENET/Fiber Optic	Scientific/Hub and Spoke multi-sensor	2660m	Main network cable install November, 2007, node and instrument install scheduled April 2009.
MARS: Monterey Accelerated Research System	Monterey Bay, CA	ENET/Fiber Optic	Scientific/Hub and Spoke multi-sensor	891m	Science node installed
Right Whale Monitoring Array	Stellwagon Bank, MA	Buoys/Iridium Uplink	Fixed Buoy Imbedded Processing	50m	Operational/www.listenforwhales.org
Military Arrays					
BUTEC: British Underwater Test and Evaluation Centre	Isle of Skye, UK	Copper, Single Cable	Acoustic Elements Rx/Tx	200m	Operational
Kwajalein Missile Range	Mashall Islands	Copper, Single Cable	Acoustic Elements Rx	3000m	Operational
AURA: Australian Undersea Range	Freemantle, Australia	Analog Mutliplexed			Operational
AUTEC: Atlantic Undersea Test and Evaluation Center	Andros, Bahamas	Copper, Single Cable, Mutliplexed fiber optic	Acoustic Elements Rx/Tx	2000m	Operational
SOAR: Southern California Acoustic Range	San Clemente Island, CA	Copper Single Cable, Analog Mutliplexed	Acoustic Elements Rx/Tx	2300m	Operational
PMRF: Pacific Missile Range Facility	Kauii, HI	Copper, Single Cable, Analog Mutliplex , Multiplexed Fiber Optic	Acoustic Elements Rx/Tx	4000m	Operational

Table 1: Summary of Fixed Arrays

All of these systems deliver raw broadband data to a dry-lab where power and space are not limitations. Consequently, significant processing and data recording can be provided around the clock without interruption. Robust data sets can be collected and archived. Such an installation creates in essence an in-situ passive acoustic laboratory where when combined with on-site visual observations, verified acoustic data can be collected. The significance of *verified* passive acoustic data cannot be understated. Such a field site provides a means of validating vocalizations rates, detection statistics including false negatives and false positives, detection ranges, and potentially source beam-patterns. All are necessary for passive acoustic density estimation of cetaceans.

Unlike past vendor specific COTS-based signal processors, a scalable, Linux cluster commodity-based processor can be applied to the incoming data streams. Such processors are composed of a set standard commercial grade computers available from multiple vendors. The use of commodity hardware improves purchasing flexibility, maintenance, and ultimately the overall cost of the system. Cluster technology allows software to be easily upgraded and algorithms to be added as they are developed. Evolving technology can be integrated into the signal processor as it becomes available making long-term maintenance far more straight-forward and highly cost effective. Unlike past dedicated vendor specific processor hardware, real-time algorithms can be implemented in a higher language such as C or Java and ported to newer replacement hardware. With in-water systems designed to last +20 years, the costs savings over the life of the system are significant.

2.5 Case Studies of Fixed Long-Term, Production Field Monitoring Systems

2.5.1 Overview

The use of a portable or fixed cabled system is application dependent. During preproduction, a portable system of widely-spaced detection and classification nodes could document species vocalizations present and potentially the temporal and spatial distribution of these species. Once drilling has begun and a manned infrastructure is in place, a fixed cable system combining elements of high sensor density arrays with cabled low density nodes is considered. Such a field would provide a means of isolating the species present, mapping their distribution, and in the area of high sensor density, precisely localizing an animal's position. This system architecture would provide an affordable robust capability to monitor the field as compared to a long-term monitoring plan which relies heavily on visual surveys and portable monitoring systems. The cabled system will also provide a large area of dual use undersea vehicle, high and moderate accuracy tracking.

Two case studies are presented. They assume portable nodes will be used for pre-production monitoring. Nodes must be capable of detecting and recording transient signals including marine mammal vocalizations. Both cases use a fixed-cabled system for the drilling and production phases of the field. The two case studies also assume a 40 km x 40 km field with an average depth of 300 meters. Case 1 assumes an environment with a negative gradient sound velocity profile resulting in downward refraction and case 2 is a cold water isothermal environment with a positive gradient sound velocity profile resulting in upward refraction.

Previous analysis of the acoustic hearing radius for baleen and odontocete species based on spherical spreading was determined to be 15 km. For both cases the propagation distances are much greater than the water depth so spherical spreading can no longer be assumed to be an accurate model of propagation loss. The shallow water channel is very complex and propagation effects are difficult to predict. Empirical models for transmission loss are reported by Urick [21] for short, intermediate and long ranges. The empirical models for the short and intermediate range transmission loss were run for sea state 4 with a mud bottom. The predicted hearing radius results are nearly the same as calculated in section 2.1 for spherical spreading. Therefore the 15 km hearing radius results are adequate for these case studies. The effects of refraction will also limit the hearing radius depending on the location of the source and receiver. For purposes of this study the downward refraction environment in case 1 will result in acoustic nodes being located on the ocean bottom to maximize the hearing radius and for similar reasoning the case 2 nodes will be located near the surface. This study uses the 15 km hearing radius for purposes of comparison, recognizing that an actual design must be tailored to the site environment.

2.5.2 Case 1: Downward Refraction

Figure 7 shows the SVP and ray trace for a source near the surface for a downward refracting environment. For this environment the receiving nodes are on the bottom. For the pre-drilling phase six battery powered recording nodes distributed over the field as previously shown in Figure 5 would provide nearly 100% coverage for detection and classification and at the same time provide limited localization for some signal sources. Given the distribution of sensors, the area of coverage depends on multipath propagation of the signal to the receiver. If these nodes possess a beacon function, i.e. acoustically commanded to emit a synchronized tracking ping signal at a fixed repetition rate, undersea vehicles could be tracked using the ROMA algorithms described above.

During the drilling and production phases of the field, a cabled array of nodes is proposed to provide the maximum capability and lowest lifetime cost. If the nodes consist of hydrophones with selected nodes possessing a bi-directional transducer to both transmit and receive acoustic energy (bi-directional nodes) this configuration will provide a robust marine mammal detection, classification and localization capability as well as providing a full field undersea tracking capability for cooperative targets.

Figure 8 provides a view of the distribution of the nodes with respect to a hypothetical layout of drilling platforms. While this configuration will provide slightly less than the 100% coverage of marine mammal detections compared to that of Figure 5, it provides areas of marine mammal localization centered about each platform.

Additionally this configuration provides a high accuracy undersea vehicle external track capability for vehicles equipped with a pinger using hyperbolic positioning algorithms located at each platform. Using pings emitted from the bi-directional nodes and the onboard vehicle ROMA algorithms a self tracking capability is available with medium accuracy over the full field. Assuming a vehicle equipped with a pinger emitting a 45 msec spread spectrum coded signal at ~15 kHz with a source level of 185 dB with the propagation path limited to direct path rays to maximize tracking accuracy, the expected hearing radius for tracking is expected to be about six km. Using the baseline calculation of .707 times the hearing radius presented for hyperbolic tracking the estimated baseline for the hexagon arrays around each platform is about 4.2 km providing an approximate 55 square kilometer high accuracy track area around each platform. For any specific location the assumption of a direct path propagation out the the 4.2 km would need to be verified by running a ray trace for the expected seasonal variations in SVP. Figure 7 provides a single example using for a downward refracting environment. As the distance of the acoustic source from the center of the hexagon array increases the tracking accuracy degrades. The referenced mammal acoustic vocalizations would be monitored only when they were within a 15 km hearing radius previously discussed. Additional sensors are required to expand the localization area. The number of sensors can be reduced if non-direct path techniques such as acoustic model-based algorithms are applied [22, 56]. Such algorithms required intimate knowledge of the sound field.

2.5.3 Case 2 Upward Refraction

In an upward refracting environment the maximum hearing radius is maintained by locating nodes near the surface. For the pre-drilling phase this could be implemented using moored GPS-equipped buoys. These buoys are moored to the bottom with a single mechanical cable. Acoustic signals received within its acoustic bandwidth are radioed to a receiver, along with the measured GPS position of the buoy, to a ship or land based receiver. Over the horizon telemetry using satellite links are also available. Installing these buoys at the locations shown in Figure 5 will provide 100% coverage for detection and classification.

During the production and drilling phases the buoys can be replaced with suspended hydrophones and bi-directional acoustic nodes. The layout shown in Figure 7 should provide the same coverage for both marine mammals and undersea vehicles as shown in case 1. Sensors suspended high in the water column may present unique challenges. The nodes become more susceptible to currents and the tethers require additional engineering. Unlike bottom-mounted sensors in a downward refracting environment, such applications are considerably more depth sensitive and may be limited by the tether length.

All installations must be considered on a site-by-site basis. Depth and bathymetry play a major role in the design of the in-water system. Deep applications must include nodes capable of withstanding intense pressure. However, once installed, nodes are typically exposed to a stable environment. Temperatures are cold and constant. Generally, currents along the bottom in the deep ocean are low. The nodes are free from the danger of ship strike and anchoring. However, recovery and repair of deep ocean cabled arrays is difficult and generally not cost effective.

In shallow water where fishing including dragging is possible, the node design must prevent entanglement. Typically the inter-node cable must be buried or secured. Without such protection the in-water system is subject to repeated failure. However, repair in shallow water becomes more feasible but still costly.

Cables terminated on-shore must be protected through the shallow sea-shore interface. A cable path created by slant drilling from shore to an area outside the surf zone is the preferred method. This avoids damage from weather and waves and also near shore anchoring.

Careful systems engineering which documents the base requirements and assesses the risks is critical to the successful installation of a fixed system designed for a 20 year life.

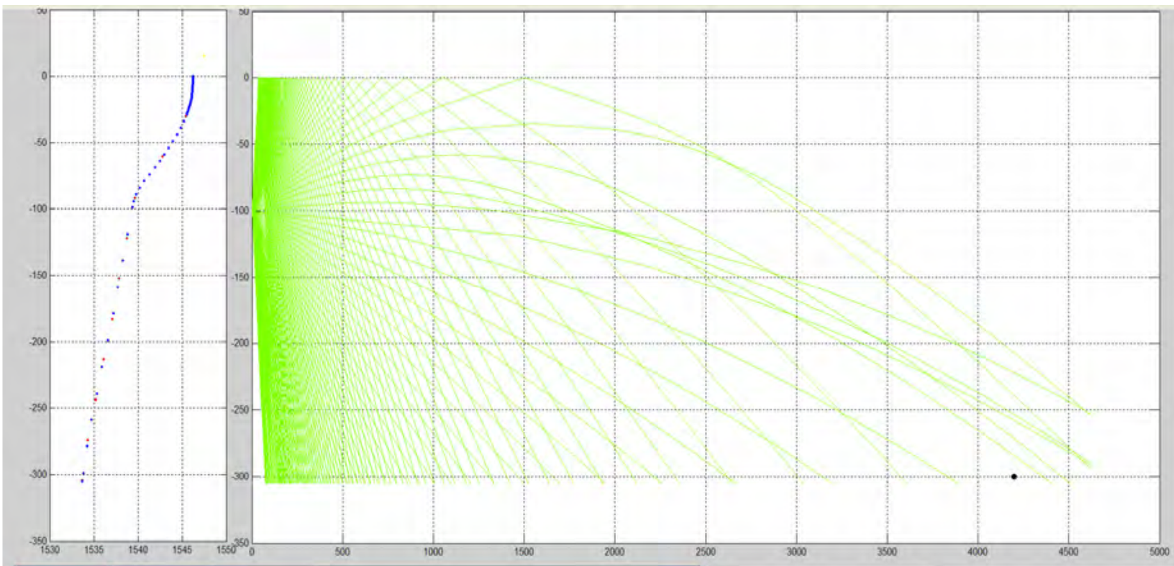

Figure 7. SVP and raytrace for downward refracting environment with source at 100m depth and bottom-mounted hydrophone at 4.2 km distance in 300 m water depth.

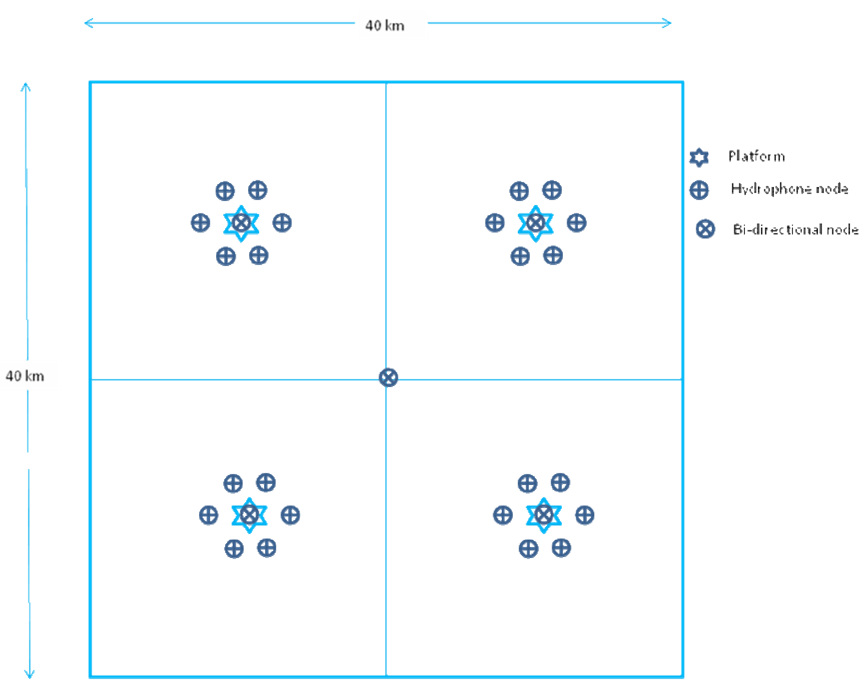

Figure 8 Post Production Field Node Configuration

2.5.4 Rough Estimate of Costs

Referring to figure 8 and using about 10% slack to the length of the cable from any one of the four platforms to the center node is approximately 15 km. The nodes are laid out with the maximum baseline that supports a direct path hearing radius (Fig. 7). Using the calculated 4.2 km baseline between hexagon nodes and adding the 10% slack the inter node cable lengths are rounded to 5km. For a multiplexed hexagon array a total of 30km of cable is required. For an individual cabled node array with each cable originating at a platform as shown in Figure 7 the total cable length is also approximately 30 km. For this example the multiplexed node is more complex than the individual node and therefore has a higher cost. The total cable length is approximately 135km for all four arrays plus the center node. Using an estimated cable cost of $12/meter, the cable cost is $1.62M. Installation costs are estimated at $35k a day for mobilization and demobilization and $70k a day for install. Assuming two days for mobilization, one day demobilization, and 5 days for installation the total installation cost is $455K. The estimated cost for each multiplexed node is $150K while a single cable node cost is $40K. With 7 phones per hexagon array and one in the center the total node count is 29. Adding five spare nodes the total node count is 34. The total 34 node cost is $5.1M for multiplexed nodes and $1.36M for individual cabled system. The total multiplexed node cost including installation is $7.175M and for individual nodes the total cost is $3.44M**.** Because the individual cabled approach has a lower cost and is more reliable it is the preferred solution for this example

The portable nodes are estimated at $40K each. In the exploration phase, to monitor the same area for detection and classification without marine mammal localization, 6 nodes are required. Assuming 4 spares a total of 10 nodes are needed for a cost of $400K. Assuming two days boat mobilization and one day demobilization at a cost of $10K a day and 3 days installation and survey at $20K per day the total cost of installation is $100K. The total combined cost estimate of the portable nodes is $500K. The ship cost is significantly cheaper for installing portable nodes without the need to handle the deployment of long cable lengths.

3.0 Long-Term Systems Comparison

A conservative comparison of candidate technologies used to monitor a field for a 20 year life span is provided in Table 1. The comparison does not consider dual-use applications for the fixed systems. A fixed system deployed for marine mammal localization could be readily adapted for cooperative tracking of vehicle equipped with an acoustic pinger.

For this comparison, an idealized deep water (2000m depth) field of 49 hydrophones uniformly distributed on 5 km baselines was considered (Fig. 9). Such a field covers an area of roughly 1000 km^2. The layout assumes detection of 200 dB sources by at least 3 sensors on a direct path ray. Unlike the previous case study, the sensor layout supports localization over the entire field and tracking of cooperative targets equipped with a 12 kHz pinger with a source level of 192 dB. It assumes that the cables are terminated at a site adjacent to the field at a distance of approximately 15 km. The hydrophones are bottom-mounted and arranged in offset rows. For localization, the sensors can be grouped in hexagonal arrays with a center phone.

This comparison provides direct insight into the trade-offs and the cost considerations including Maintenance and Operations (M&O) that affect the choice of technologies. Rough estimates for program management, systems engineering, contracting, and miscellaneous costs are provided. An actual site specific design must consider the overall requirements, the sources to be monitored, and the local environment including bathymetry and sound velocity profiles.

There are many sensor variants that can be considered. These range from individually cabled sensors, to multiplexed sensors, to hub and spoke high-bandwidth arrays. The simplest and most robust system consists of individual cabled sensors. Such a system requires a minimum number of components in each node. Each hydrophone is connected via a single cable and is therefore independent. A failure of one sensor or cable will not affect the adjacent nodes. Cable is typically the most expensive single element in a fixed system where cost is driven by the total length. For the prior case studies with hex arrays immediately around platforms and a single sensor in the middle of the area, the difference in cable length was negligible and the cost of the bearing array node was the driver. For large distributed systems, the cost of cable must be considered.

Fixed-multiplexed systems allow multiple sensors to share a single cable. For large systems and for systems with the nodes located far from the receiving platform sensor multiplexing reduces the in-water cable costs but significantly increases node complexity. Given a typical design life of 20 years, such increases in node complexity must be taken into account when considering reliability and survivability. This is particularly true in deep water (>1000m) applications where recovery of an array is extremely difficult. Hub and spoke designs provide the opportunity to connect multiple sensor types to the backbone. However, for deep water applications this becomes progressively more difficult and expensive. Achieving the reliability necessary to support 20 year survivability is questionable. For these reasons, this architecture was not considered in the analysis.

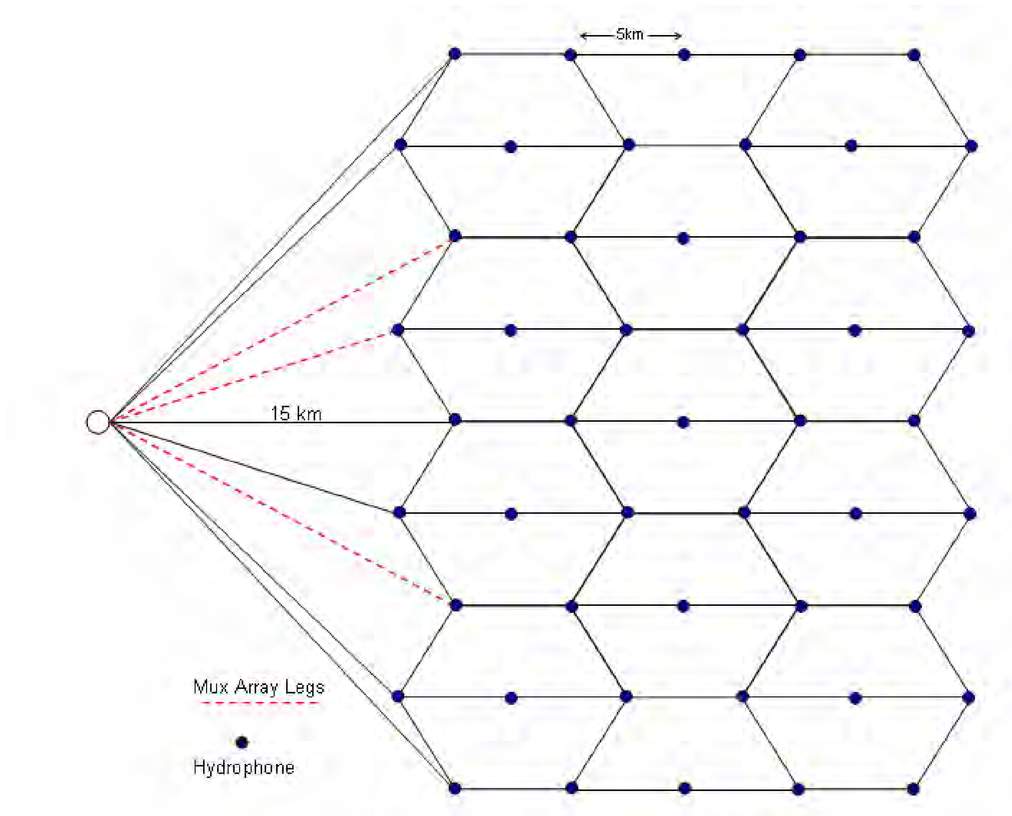

Figure 9. Idealized Range Layout for ~1000 km area with 5 km senor baseline

Permanent fixed arrays are compared to 3 recoverable technologies. The first, a portable multiplex array allows installation of multiple sensors typically in water depths less than 1000m. Such arrays are designed for reuse. The array is deployed and recovered from a ship equipped with a linear cable engine. The second, recording buoys are typically deployed from a ship of opportunity with an acoustic release used to separate the buoy from the anchor on recovery. The third, moored surface buoys, require a mooring system to withstand maximum sea-states. The sensor typically is positioned near the bottom of the water column.

The acquisition cost of a portable multiplexed array is comparable to a fixed array. The installation and recovery costs of such an array are substantial. Assuming installation and recovery of the system every 2 years, the total system cost over 20 years is $15.9M. This cost, is comparable to that of a permanent single-cable system. The ability to recover the array is its primary advantage. The nodes are built with less component redundancy and in case of failure, the array can be recovered and repaired. However, recovery comes with significant cost and risk.

Recording buoys represent the lowest acquisition cost. These systems tend to be the least complicated and easiest to install. However, data must be stored onboard. The buoys can be installed for up to a year and data can only be accessed on recovery. Data storage becomes a major design issue. Full bandwidth (60 kHz) data cannot be easily stored for such an extended period without giving major design consideration to the package size and power requirements. Repeated recovery, replacement of batteries, and reinstallation represents a significant effort. When considered over a 20 year life, the total system costs are estimated at $7.7M which is less than that of the fixed-multiplexed array. However, the lack of access to continuous data is a major drawback.

Moored surface buoys are typically configured with a data link. The bandwidth of the link is a function of the transmission distance. For systems using a satellite uplink, these rates are generally under 10 kbits per second. This allows the transfer of detection reports and data clips but does not support the transfer of real-time data. Signal processing and/or data recording must be provided onboard the buoy. If the buoys are within line-of-sight of a platform, wideband data can be transmitted over an RF link which greatly increases the systems capability. In this example, the number of buoys and the total area would likely preclude the use of RF data links. For cases with fewer buoys within line-of sight of a platform, wideband data links are more applicable. The use of surface buoys does increase the complexity and acquisition cost of the system. The buoys are exposed to the elements and over the life of the systems will require repeat maintenance. The cost of the system is estimated at $9.4M over the life of the system.

Bottom-mounted fixed-cabled arrays which transmit wide-band data provide the greatest capability and flexibility as data processing occurs in a dry lab on a constant flow of multi-sensor data. The acquisition cost of fixed-cabled system exceeds buoy based systems. For large systems cable costs may dominate the overall system cost. These can be reduced by multiplexing multiple sensors onto a single fiber optic backbone. In the example (Table 2), an individually cabled system incurs cable costs of $11.6M compared to $3.4M for a multiplexed system. Multiplexing sensors does lead to increased node complexity. The estimated per node cost is $150k/node compared to $40K for individually cabled nodes. Combining the acquisition and installation costs, the total estimate for the multiplexed design is $13.4 versus $16.5M for the single cabled system. For both single and multiplexed cabled arrays, over the 20 year life of the system, the costs rise by $1M as shore system upgrades of $50K/year are anticipated. This is a conservative yearly maintenance cost estimate. However, over a 20 year life it is reasonable to assume the shore systems will undergo at least one major upgrade. The 20 year total system cost estimate including program management and systems engineering is $17.3M for the individually cabled arrays and $14.2M for multiplexed arrays.

The cost of the buoyed system has the lowest estimated overall cost but provides the least capability. The moored surface buoy can potentially be configured with a data link but must be designed to withstand surface conditions. Also, the complexity and cost of the mooring is directly proportional to the water depth. It is therefore practical only in water depths less than 1000m.

In certain shallow water environments, consideration must be given to potential activities such as dragging and anchoring that could damage the system. Cabled systems must be buried and the nodes protected. This adds significantly to the cost of installation. Bottom-mounted recording buoys are highly susceptible to damage and are difficult to protect. The replacement cost of lost buoys must be considered in the total system cost. Moored surface buoys can be protected using low-cost guard buoys.

This comparison suggests a fixed cabled system provides **significant** increased capability at a modest increase in cost over the life of the system. The potential advances made possible with access to continual broadband data cannot be understated and should be considered as part of the system design. With the Installation of such sensors, the field becomes an in-situ passive acoustic laboratory. This is an enabling technology that will immediately allow continual documentation of the presence and absence of species. At the same time, it allows verification of vocal behavior and temporal and spatial distribution of vocalizing marine mammals. When combined with tags, basic measurements of animal beam-patterns, detection ranges, and false positives and false negatives can be determined on a species by species basis.

Additional sensors such as geophones can be included on the array. Such sensors are low bandwidth and can be added at a modest increase in cost. Once in place, bottom profiles could potentially be performed over the life of the field without the use of towed arrays.

	Fixed/Mux Array	Single Cabled Hydrophone Array	Portable Mux Array	Recording Buoy	Moored Surface Buoy
Water Depth (feet)	100 - 20,000	101 - 20,000	< 1000	100 - 20000	< 1000
Area of Coverage (nmi^2)	50 - 1,000	51 - 1,000	< 100	50-500	< 50
Maximum Number of Sensors	100's	100's	50	~50	20
Track Accuracy	<10m	<10m	<10m	<15m	<20m
Hazards	None	None	Bottom Drag	Bottom Drag	Prop foul, Collission, Line cut
Usable deployment period	20 Years	20 Years	2 - 3 years	1 year max	5 year*
#Sensors for Analysis Case	49	49	49	49	49
Node Cost ($K)	$150	$40	$75	$40	$100
Installation (days) Best / Worst Case	12/24	20/30	12/24	5/10	10/20
Survey (days) Best / Worst Case	7/14	7/15	7/14	7/14	0.5 / 2
Retrieval (days) Best / Worst Case	N / A	N / A	8/13	2/5	3/8
Installation Costs -Best Case ($k)	$500	$780	$500	$120	$220
Retreival Costs			$500	$300	
Refurb Costs (per install)			$50	$100	
Yearly Maintenance			$50		$300
Operating Costs (per day) ship/personnel/hardware			$30		
Cable Cost ($k)	$3,360	$11,566	$3,780	$0	$0
Node Costs	$7,350	$1,960	$3,675	$1,960	$4,900
NRE	$300	$300	$300	$50	$100
Acquisition Cost ($K) w/ Installation	$11,510	$14,606	$8,255	$2,130	$5,220
M&O per year	$50	$50	$50	$200	$250
20 year w/ M&O costs	$12,510	$15,606	$14,255	$6,130	$7,720
Systems Engineering	1,200	1,200	$1,200	$500	$1,200
Program Management	500	500	500	500	500
Program Cost	***$14,210***	***$17,306***	***$15,955***	***$7,130***	***$9,420***

*assumes yearly required maintenance with refurb on 5-year basis
** assumes portable mux array recovery every 2 years
***For tests: 2 tests x ship ($15k/day x 10days) + staff (5 * 2.4K/day*10)

Table 2. System cost comparison for monitoring technologies

4.0 Passive Acoustic Methods

4.1 Methods Overview

Passive Acoustic Monitoring (PAM) technology and algorithms continue to improve. The ability to detect vocalizing animals, including sensitive species such as beaked whales, has been demonstrated. Methods of classification of small odontocetes continue to improve but clearly much remains to be done. This steady but slow improvement is illustrated by participation in the 3rd International Workshop on Passive Acoustic Detection and Classification of Marine Mammals, held in Boston, July, 2007. An odontocete click data set was provided for comparison of methods and ten research groups chose to process the data. This compares to three groups who processed the data set at the previous such conference, held two years earlier in Monaco. Several distinct areas of research should be pursued. The current state of this research is discussed below.

4.2. Detection, Classification, Localization, and Density Estimation (DCLD) Methods

4.2.1 Species-Verified Data Sets

Development and characterization of DCLD methods depends on the availability of verified acoustic data sets. Typically, these data must be collected in cooperation with trained observers who definitively identify the species, group size, and surface behavior. These data are used to develop, test and verify the efficacy of DCLD algorithms and as a means of comparing alternative methods. Examples of such data sets include MobySound [23] as well as the datasets provided for the 2003, 2005, and 2007 International Workshops on the Detection and Localization of Marine Mammals using Passive Acoustics (available at the MobySound web site, MobySound.org).

Data in these data sets are most useful if they are accompanied by metadata that indicates where the calls of interest are located. Many detection and classification systems incorporate separate training and testing steps, and this type of metadata is useful for both. For training of a method, it allows the extraction of only those periods of time when the call of interest is present, so that the method may "learn" the appropriate sounds. For testing, it allows comparison of a test run of the method with an established ground truth, so that correct and incorrect detections can be measured and missed calls can likewise be counted. These measures are typically part of the performance evaluation of a detection method, and this evaluation in turn is what allows one to choose the best detection/classification method for a given monitoring task.

4.2.2 Detection

The most basic passive acoustic monitoring problem is detection of vocalizing animals. This is true for fixed, portable, and deployed systems like towed arrays and vertical arrays. Within the field of signals processing, general detection methods are well understood and documented [24, 25]. The application of these methods to marine mammal vocalizations must be quantified. Animal vocalizations are extremely diverse. A general FFT-based energy detector may work across a broad range of species while a linear matched filter may work for systems designed specifically for beaked whales. Consequently, the detection method used may be as much a function of the system requirements as the signals themselves. Certainly it is unlikely there is a single algorithm that is the optimum detector for all species vocalizations. The efficacy of the general algorithms against multiple species must be tested and documented.

The aim of a detection and classification system is to process an incoming sound signal and find the sounds of interest – marine mammal calls – in it. *Detection* refers to processing an incoming sound signal to find periods of time when a sound of interest, such as a marine mammal call, might be present. Often a portion of the sound signal surrounding and including a detection is extracted for storage or further analysis. *Classification* refers to analyzing the extracted portion and assigning it to one of several categories, or classes. The categories might be as simple as desired call type and noise, the latter including all other call types, or as complex as the hundreds of call types produced by more than 80 species of cetaceans.

There is no sharp boundary between the concepts of detection and classification. Every detector performs some amount of classification, for it has to classify an incoming signal, at each time step, into at least the classes of either background noise (and perhaps unwanted sounds), to be ignored, and target sounds, to be analyzed further or stored. Some methods, such as matched filtering, combine detection and classification into a single step, such that their aim is to detect a certain call type of one species in an incoming sound signal.

Detection and classification systems can be assessed on a spectrum from most general to most specific. For instance, a system requirement for a very general detector might be to "detect any marine mammal call." At the other extreme are extremely specific requirements, such as "detect all 'regular clicks' of sperm whales."

4.2.2.1 Detection System Performance Measurement

Detection and classification systems are best evaluated using a dataset of recorded sound files containing some known calls [26, 27]. The detector is run with these sound files as input, and the resulting detections are compared to the known calls in the recordings. It is best if the dataset contains calls ranging from high-quality – i.e., calls with a high signal-to-noise ratio and no interfering sounds – and to low-quality, as the detector must be able to function well in all conditions.

The detector registering a detection when in fact no call is present is known as a false alarm (or "false positive"). Similarly, the detector not registering a detection when a call is present is known as a missed call (or "false negative"). Similarly, the detector detecting a call is called a correct detection (or "true positive"). The true positive rate is one minus the missed-call rate.

It is tempting to think that the goal of a detection system is simply to detect all calls present, or all calls of some specific type. This is a misleading, as there will always be increasingly faint calls at greater distances from a hydrophone. At what point, as calls become fainter and fainter and fade into background noise, are the calls "not present" any longer? A better way to evaluate a detection system is to examine the tradeoff between false alarms and missed calls.

A detector must typically use some threshold (see Fig. 10) or, more generally, a decision criterion, to decide whether a given sound should be considered a detection. For instance, a process that listens for marine mammal calls in background noise must apply some kind of decision process to determine whether a given portion of the input signal is a call or just random background noise. All detection systems must have a step essentially similar to applying a threshold to choose whether to accept or reject the incoming sound signal as a call. If a relatively high threshold is used, then relatively few background noises will be (wrongly) accepted as calls, so the false alarm rate is relatively low. But also any fainter calls (e.g., more distant ones), or calls that are distorted, or calls with more interfering noise, are also more likely to be wrongly rejected as not being calls – so the missed call rate is higher. Conversely, if a relatively low threshold is used, then the missed call rate is lower, as the detection system misses fewer calls, but the false alarm rate is higher, as the detection system also "detects" more sounds that are not actually calls.

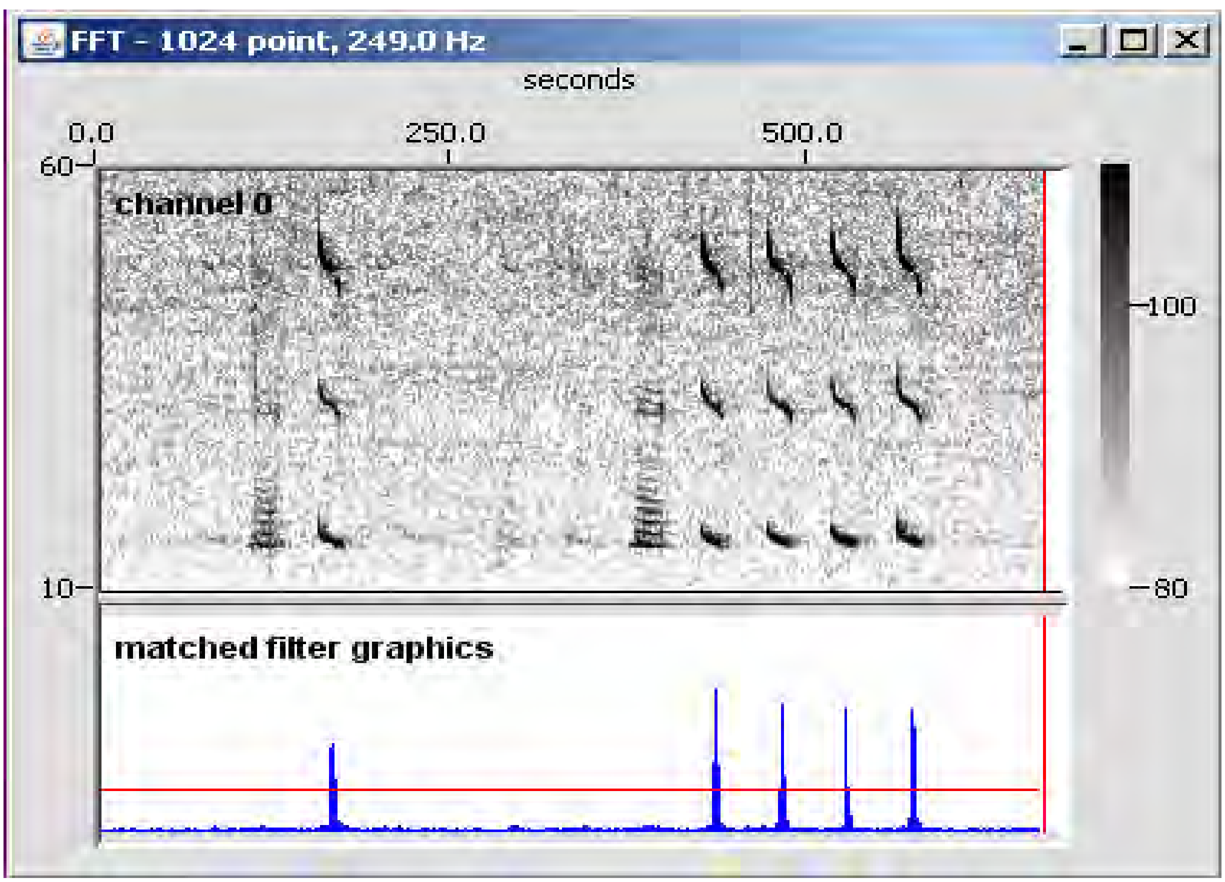

Figure 10. Example of a detection threshold used in detection of blue whale calls. The detection threshold is the red line in the lower panel; any time the detection function (blue) exceeds this threshold, a detection is registered. From [28].

The performance of a detection system is described using a Receiver Operating Characteristic (ROC) curve. This curve is generated by running a detection system using a range of different detection thresholds. Each threshold results in certain rates of missed calls and false alarms. By plotting the corresponding parametric curve, the overall performance of the detection system can be assessed. [ROC curves are traditionally plotted with the false alarm rate on the X-axis and the true positive rate on the Y-axis. A closely related concept is the Detection Error Tradeoff (DET) curve, which is simply the ROC curve with the Y-axis flipped upside down, thus showing the missed call rate. With error rates on both axes, both axes may be logarithmically scaled, which helps reveal more detail about the detector's performance at low error rates.]

The operator of a detection system must choose how high to set the threshold or more generally, how certain the system must be that the target sound is present. Different tasks require different choices of the threshold. For searching for a rare species, such as a right whale, it is important to miss very few calls; correspondingly, a relatively low threshold should be used. At the opposite extreme is the problem of producing an "index of calling" that accurately measures how much calling is occurring by a relatively common species such as sperm whales. This index is meant to have good *relative* accuracy, such that changes in the amount of calling are measured accurately. Because calls are common, and many loud calls will be present, it is more important to accurately count the loud ones – and reject sounds that are not calls – than it is to find every faint call and risk counting non-calls. Therefore a high threshold should be used. In the middle is the task of counting the total number of calls present greater than some noise background, for which one may want the number of false alarms to equal the number of missed calls. In this case, an intermediate threshold is preferred.

4.2.2.2 Signal Conditioning

Many detection and classification methods condition the sound signal, or some representation of it, such as a spectrogram, in various ways to make the subsequent processing easier.

Gain control. Conditioning can be as simple as changing the gain (amplification) of the signal to make the average level of the signal be constant. Having the average be constant makes it easier to detect a call in background noise. Averaging necessarily uses a time constant, chosen by the user, to average over. It helps eliminate the impact of wideband noise sources such as wind and waves and some flow noise over a hydrophone.

Frequency-band gain control. This is a similar concept, but applied to each frequency band of a spectrogram, wavelet-gram, or other time-frequency representation. It helps reduce the effect of narrow-band, long-duration noise sources such as ship propellers, electric motors, etc. Again, a time constant is supplied by the user; different time constants may be appropriate for different frequencies.

Image filtering. This is a technique for removing speckle noise from spectrograms by smoothing it out. Morphological filters [29], such as median filters or open and close operations, are passed over the spectrogram image, resulting in more even backgrounds when no call is present and smoother frequency contours when a whistle or moan is present.

4.2.2.3 Detection Methods

A summary of the more widely used detection methods:

***Energy sum*.** This is the simplest detection method, and still one of the most widespread. It consists of simply summing the energy within some specified frequency band. (The value summed is not actually “energy” in the physics sense, but the term energy sum is nevertheless widely used.) Usually this sum is compared, at each time step, to the average sum. When a transient sound arrives, such as an odontocete click or other vocalization, it causes the sum to increase and potentially cross the detection threshold. Duration requirements may be applied, such as requiring the call to last more than a specified minimum time and less and a maximum time.

Energy sum can operate in the time domain, using bandpass filtering to obtain the required frequency band, or in a spectrogram or other time-frequency representation, by using just certain bins of the spectrogram. The time series method is faster, since the FFT of incoming sound samples need not be computed, but in a spectrogram, it is possible to eliminate narrow-band ship sounds with frequency-band gain control.

Energy sum is a very general method, since it finds all transient sounds in the frequency band of interest. It is widely used for detecting clicks of odontocetes [30, 31, 32, 33] as well as highly variable sounds of many marine mammal species, such as song units of humpback whales.

***The Teager-Kaiser energy operator*.** This method operates in the time domain (sound signal) and detects sudden changes in the signal level, much like the energy sum method. As such, it is most often used to detect odontocete clicks [20]. Its advantages are (1) that is has greater sensitivity for very rapid changes in the signal, such as are present with many odontocete clicks, and (2) it is very simple computationally, so it can be easily implemented for real-time operations. It can be combined with pre-filtering, either on the analog signal (before acquisition) or on the digital one, to reduce the impact of noise in other bands than the desired one.

The Teager-Kaiser energy operator is moderately general, in that it can be used to detect click sounds made by all toothed whales and dolphins. It is less useful for long-duration moans, such as produced by baleen whales.

***Image-based frequency contour detection*.** This term encompasses a variety of methods that operate on a 2-dimensional time-frequency representation – an image – such as a spectrogram. The methods find frequency contours in the image that satisfy certain requirements, such as being in a certain frequency range, changing frequency upward or downward at a certain rate, lasting a certain length of time, etc. Depending on the specificity of the requirements, an image-based detection method could be viewed as either detection or classification.

One such method is contour tracking [34, 35], which finds peaks in a short-time spectrum (e.g., a spectrogram slice) and tracks them over time. Any peak that persists long enough, stays within the specified frequency bounds, and satisfies the user's other requirements is considered a detection. Image-based frequency contour tracking is useful for finding narrowband tonal calls, including whistles of dolphins and other odontocetes, moans of baleen whales, and hums of fish.

4.2.2.4 Combined Detection and Classification Methods

These methods are find more specific types of sounds (call types), but they operate on a continuous sound signal like other detection methods.

Matched filtering**.** With this method, a user-specified kernel is cross-correlated with the incoming sound signal. Typically the kernel is a very clear version of a desired call type, either a synthesized one or a very clear recording. (Very clear versions are desired because noise degrades the cross-correlation.) The result is another time series that has a peak whenever the incoming sound signal has a call that matches the kernel; applying a threshold to this time series allows triggering of detection events. The cross-correlation peak is highest when the call in the incoming sound signal exactly matches the kernel, with peaks getting lower and lower as the call in the incoming signal varies more and more from the kernel.

This method is useful for detection of highly stereotyped calls, including calls of most baleen whales and clicks of many odontocetes. (It is in fact the (provably) optimum method for detecting a known call in white Gaussian noise [36], although marine noise is rarely white and whale calls are not "known" because they vary from one instance to the next.) Odontocete clicks in fact vary considerably as the angle of emission from the animal changes – e.g., on-axis clicks sound different from off-axis ones. Cross-correlation can be used with one click in a sequence to reliably find the next click in the sequence, since the change from one click to the next is slight.

Image cross-correlation**.** This method is similar to matched filtering, in that it involves cross-correlation of a template with the incoming sound signal. But the cross-correlation is performed using an image of the incoming sound signal, such as a spectrogram, and an image template, either may be recorded or synthetic. The advantages of this method are that (1) narrow-band noise, such as ship propeller noise, may be reduced or eliminated via frequency-band gain control (see above), before the cross-correlation is performed; (2) by changing the design of a synthetic kernel, variation in the target call type may be accommodated to a greater or lesser degree; and (3) the kernel may be designed to reject interfering sounds, such as other frequency contours, that occur at the same time and frequency as the call to be detected [37, 38].

Image edge detection. In this method, frequency contours are found by locating cells in a time-frequency representation image that are close in time and frequency and follow a consistent contour over time. Additional constraints are usually applied to make the method specific to detecting one call type [28].

Although this method has not yet been widely used, it shows promise, and it has been successfully used to detect relatively faint calls in noise [39].

4.2.3 Classification

Perhaps the largest disadvantage of passive acoustic monitoring is the inability to visually identify the animal in question. Species identification must be based on classification of the vocalization. Large baleen whale species such as blue and fin whales produce highly distinctive vocalizations, making the development of species specific classifiers tenable. Small odontocete vocalizations which include both clicks and whistles often are very similar in both structure and frequency. If species-level classification is required, better methods must be developed and tested.

In addition, testing of these methods has been historically done using relatively small data sets, often recorded in just one acoustic environment. Testing must be expanded to complex real-world environments that may include multiple species along with mixed groups of vocalizing animals.

Multiple methods are being applied to the classification of marine mammals. These methods operate on short segments of sounds extracted by a detection method that may or may not contain calls. They assign the sound to one of several classes, or categories. These categories may or may not include a “noise” category for sounds that do not match any other category well.

Clustering. The sound segment is measured in various ways to determine characteristics of the call in the segment, such as the call’s duration, maximum and minimum frequency bounds, rate of amplitude modulation, etc. One such system for making these measurements accurately in noise was devised by Fristrup [40, 41]. These measurements are then used in a clustering algorithm – there are many [42] – that matches the set of parameters to other sets derived from other calls. Clustering may be done as *supervised clustering*, in which a person has specified a training set in which the type of each call is known and provided to the clustering algorithm. Alternatively it may be done as *unsupervised clustering*, in which calls with similar parameters are grouped together into a class. The large number of clustering algorithms differ in how this grouping is done.

After training is complete, determining the class to which a new call belongs is done by measuring its parameters and comparing the resulting parameter set to the established clusters. In this comparison, the variance, and ideally covariance, of the clusters is used to estimate how similar the new call is to the established clusters. Whichever cluster is most similar is the class of the new call; if no cluster matches well, the "call" may be judged to be noise. Examples of clustering include grouping of killer whale vocalizations into recognizable classes [43] and analysis of humpback whale song units [44].

***Decision Trees*.** In this method, the sound segment is also measured in various ways, then used in a tree-based classification system. The tree has a decision criterion at each node, such as "minimum frequency < 12.3 kHz" or "duration > 0.65 s". A given sound is classified in the tree by starting at the tree's root, applying the decision criterion, and traversing either the left or right branch depending on the criterion. The process is repeated at each successive node until a leaf is reached; the leaves correspond to the categories that the tree can represent. Sometimes trees can have multiple leaves for a given class.

Decision trees have been used fairly widely for classification of marine mammal sounds [e.g., 45, 46, 47]. They are useful because they can handle a large degree of variability in the types of call classified, and so can classify many species relatively accurately. Their performance depends critically on the measurements that are applied to the calls.

Method	Pamguard (Pamguard Consort-ium)	Ishmael (NOAA Pacific Marine Environ. Lab.)	XBAT (Cornell Univ.)	Raven (Cornell Univ.)	SeaPro (Univ. Pavia)	Sound Analysis Pro (City Coll. New York)	ROCCA (Univ. Hawaii)
Energy sum	●	●		●	●	●	
Energy ratio	●	●					
Image contour detection	●	●					
Matched filtering	●	●		●			
Image cross-correlation	●	●	●	●			
Image edge detection	●						
Tree-based classification	in develop-ment					●	●

Table 3. Detection methods available in several of the more widely-used software systems for marine and terrestrial bioacoustics. The systems are described in references[25,48,49, 50**,** 51**,** 52**,** 53**,** 54**,** 55**].**

4.2.4 Localization

Localization of transients depends on a large number of factors including the environment, sensor, sensor geometry, signal detection and timing, and data association across sensors.

The effect of the environment is one that demands consideration especially in non-traditional environments like the Arctic in which the Sound Velocity Profile (SVP) may be upward refracting. Such propagation conditions will strongly affect how and where sensors should be deployed. Traditional hyperbolic tracking algorithms that are typically used in downward refracting environments must account for these “reversed” propagation paths.

The species of interest also must be considered for each location of interest. Where and how animals vocalize within the water column directly affects sensor efficacy at detecting and thus localizing vocalizations as well as system accuracy. Large baleen species produce low frequency vocalizations that propagate many miles. While they may be detected outside a field of sensors, the Geometric Dilution of Precision (GDOP) may be large resulting in extremely poor localization accuracy. Methods to track with improved localization outside the field must be developed.

Within a sensor field, species such as Cuvier's and Blainville's beaked whales have a narrow beam pattern and can forage and vocalize at depths in excess of 1500 meters. Even in a distributed field of sensors, it may be difficult to receive the same vocalization on 3 sensors making traditional hyperbolic localization difficult. Many small odontocetes may produce high frequency (>10 kHz) clicks that are difficult to detect on multiple sensors to produce the TDOAs required for hyperbolic localization algorithms. In addition to produce these TDOAs, real-time data association algorithms [37] must be developed that provide methods of matching the same time delayed vocalization on multiple sensors. As previously discussed sensors are typically arranged into hexagonal arrays. Detection times from a “master phone” (generally the center phone) is compared to each of the surrounding phones. The inter-click times between successive vocalizations are not precisely the equal and form a unique pattern. The master phone detection times are correlated against the times from surrounding phones. When the correlator peak exceeds an adaptive threshold, a match is declared and the associated times are used in a hyperbolic localization algorithm to determine the position of the source.

For species vocalizations that are hard to detect or for those with narrow beam patterns like beaked whales, consistent but lossy TDOA lines are often produced. Methods to interpolate these lossy data without compromising localization precision must be developed.

Alternate localization methods such as bearing-bearing tracking and model-based approaches should be considered [56]. Care must be taken in comparing these methods. Bearing sensors are far more complex as compared to multiplexed or individually cabled sensors. A field designed for hyperbolic tracking may require, a few additional single sensor nodes to provide the same coverage at a significantly reduced system costs. However, for species with low source levels and narrow beam patterns, such approaches may provide an advantage as only two sensors are required to localize a source.

4.2.5 Density Estimation

Ultimately, questions regarding the health of the field will require measurement of animal density. Passive acoustic density estimation [57] is a nascent science that may offer significant advantages over traditional visual line transect surveys within the near future. Visual methods rely on boat or aerial platforms for survey. Such surveys are expensive and in the case of aerial surveys confer an increased human safety risk. These surveys must operate during daylight hours and are severely restricted by weather and sea-state conditions. For deep-diving cetaceans which spend little time on the surface and provide a small visual profile, such as beaked whales, collecting a statistically significant number of sightings is often a struggle. With a fixed passive acoustic system, there is no time, weather, or duration limit for data collection. Continuous measurements can be made that provide insight into the spatial, temporal, and seasonal distribution within the field. Such detail may be particularly important in determining the nature and timing of operations within the field. Consequently, the long-term cost and safety risks of performing repeated visual line transect surveys may be avoided.

Multiple methods for passive acoustic density estimation are under development. These include cue counting, point sampling, and group counting. The method chosen will be species dependent and this must be considered when designing a passive system.

The efficacy of these methods is closely entwined with DCLD methods. The probability of detection, maximum detection distance, and the false positive, and false negative rates for the species in question are often required. These statistics are directly related to the detection algorithm applied, animal source level, beam pattern, and site-specific acoustic propagation. In addition, the species call rate and variability must be determined. Vocalizations must be tied to an animal behavior such as foraging, movement, group cohesion, and group size.F

For example, Blainville's beaked whale density estimates based on group size depend on knowledge of the animals social, diving, and vocal behavior. Beaked whale detection methods must be characterized for range and probability of detection. The animal's vocalizations must be detected and classified and the group must be localized.

Collection of DCL statistics is best accomplished by combining data from a tagged animal with data collected on the fixed measurement system. Devices such as the Woods Hole Oceanographic Institution (WHOI) DTag provide the animal’s pitch, roll, depth, and heading along with recordings of the surrounding sound field. These recordings can be used to obtain a baseline reference for vocalizations produced by the animal. Vocalizations collected on a fixed system can be directly compared to the reference tag data. The detection probability at distance and angle can be calculated [58]. At the same time, data collected by visual observers can be used to place the vocalizations in a behavioral context and critical group size measurements can be obtained.

Such methodologies are steadily developing. The availability of fixed systems will directly drive this development.

5.0 Basic Biological Understanding of Species

A basic understanding of the species biology, including the animals' relationship to the environment, is a key element in improving the efficacy of passive acoustic monitoring. For example, as interest in Cuvier's and Blainville's beaked whales increased, tag data collected by teams at the WHOI and Cascadia Research Collective documented dive patterns, vocal behavior, and movements of Cuvier's and Blainville's beaked whales [59,60]. Surface observations from research groups including Cascadia Research and the Bahamas Marine Mammal Research Organization (BMMRO) assembled photo-ID catalogs for animals off the island of Hawaii and in the Bahamas. Such observations have help unravel the animals' social behavior.

Data primarily from WHOI recording tags were used to document the time-frequency structure of the animals' vocalization, when these vocalizations are produced, and how these vocalizations relate to foraging behavior. This allowed passive acoustic detection, classification, and localization algorithms to be designed specifically for these two species [61,62].

These data have led to opportunistic, passive acoustic study of the animals with and without anthropogenic sound on the Navy's AUTEC and SCORE ranges using fields of fixed bottom-mounted sensors. From tag data analysis, scientists determined both Cuvier's and Blainville's beaked whales vocalize only during deep foraging dives. This knowledge of vocalizations provided a means of measuring the duration and frequency of foraging and their temporal and spatial distributional with and without sound sources present.

Data sets derived from fixed Navy arrays are being used in the design of passive acoustic density estimation algorithms. Prototype passive acoustic methods have been used to estimate the number of animals present in the Tongue Of The Ocean (TOTO) in the Bahamas [63, 64]. The average group size of Blainville's beaked whales has been measured through direct observation of the animals. Marine biologists were vectored to beaked whales based on passive acoustics detection and localization of animals using fixed arrays. The group size and surface behavior were recorded. A basic understanding of the animals' social behavior allowed the design of a group counting algorithm. The number of animal groups present within the field of sensors was determined using passive acoustics. The population size was calculated by multiplying the number of groups by the average group size. A basic understanding of animal biology was critical in the development of passive acoustic methods.

As long-term monitoring of the health of the field is implemented, it is critical to understand the species biology and to monitor environmental parameters. Over the development and production life of the field, changes in the population and distribution of a species are likely. Determining the cause and effect relationships for such changes is critical as a decrease in population size or redistribution of animals will be intensely reviewed. These changes may be unrelated to the production activities, but rather may be due to ancillary environmental changes. Documenting these changes is extremely important. Conversely, it is also important to document positive population changes and robust populations in areas of development. Again, these data must be coupled with an understanding of the environment.

6.0 Future Roadmap

There are numerous technical areas cited that require additional development. However, it is clear from the examples presented that technology drives this development. Therefore, incorporating passive acoustic monitoring technology into the infrastructure of the field is critical.

The design of such systems is not trivial and should be undertaken with care using a spiral development approach. An initial installation on a limited scale in a temperate or warm environment with a downward refracting sound velocity profile is recommended. Such an installation provides a test bed for the design of the hardware, installation procedures, and monitoring and data analysis strategies. Several steps are necessary to complete such an installation, these include the following:

- 1.0 Site Selection
- 2.0 System Design
  - 2.1 In-Water Hardware
    - 2.1.1 Array Design
    - 2.1.2 Shore Electronics Systems
    - 2.1.3 Installation & Survey
  - 2.2 Shore Systems
    - 2.2.1 Signal Processing Hardware/Software
    - 2.2.2 Tracking and Display Hardware/Software
    - 2.2.3 Recording Hardware
- 3.0 Monitoring and Data Analysis

The initial installation will serve as a proof of concept. A site of high environmental interest should be selected. The array would be limited in scope and cover a subset of the overall area. Installation of six nodes around a platform with a seventh in the middle laid out for direct path hyperbolic multilateration would provide the ability to test the prototype hardware and software including 3-D localization.

A site specific plan will be required. Much of the necessary environmental data including precise bathymetry and bottom-type should be readily available. Installation plans must consider activities within the field, range layout for localization of anticipated species, and cable landings. Laboratory space must be available for the Shore Electronics System (SES), signal processor, recorder, and localization, control, and display computers. Once the array is installed, an acoustic survey must be completed to determine the exact location of the hydrophones.

The dry-end systems including the recorder and signal processor will be based on commodity components. A Linux cluster-based processor will be used. This scalable processor architecture will allow simultaneous testing of multiple DCLD methods.

Once in-place, the efficacy of the system must be evaluated. This evaluation will take at least a year and must include analysis of the acoustic data along with the in-water and dry-end systems. An extended burn-in of the in-water system is particularly critical. Identification of component failures in the prototype will prevent their use in the larger system which is designed for a 20-year life expectancy. It is recommended that at least one additional node and cable be completed and remain powered up on-shore. Experience has shown, extended burn-in of an array can help uncover components which prematurely fail. HALT and HASS testing should be completed on all critical in-water components. Verification of a long-life design requires exhaustive testing as once installed, repair of the in-water system is extremely difficult and costly. The prototype installation is sure to highlight numerous issues in advance of a major large-scale installation.

The utility of the prototype should not be underestimated. Once in place, such a site provides an in-situ laboratory for the development of a host of passive acoustic technologies and algorithms. The platform itself offers the potential of combining visual observations with passive acoustics. This in turn leads to verified marine mammal vocalization datasets that are critical to the design of species-specific classifiers. These algorithms can then be implemented and tested directly on-site. Basic data as to the species present can be collected. Statistics related to the detection range and false positive and false negative rates for various detectors required for passive acoustic density estimation algorithms can be examined.

The sensors can also be used to test dual-use applications such as tracking of cooperative targets equipped with pingers. Alternate experiments such as playbacks with active sources to measure the reaction of animals to sound are possible.

The implementation of such embedded technology will reflect positively on the industry's willingness to commit to direct long-term monitoring of the effect of operations on the marine environment.

Once the prototype system has been installed and tested, installation of sensors over the larger field can be undertaken. As the bulk of the Non-Recurring Engineering (NRE) will have been completed as part of the prototype, this phase should be mainly focused on building and installing the appropriate hardware. As discussed earlier, up-scaling cluster-based processing hardware is straight-forward.

The development cost of such a prototype is estimated at approximately $4.9 M (Table 4). This includes the development and installation of a prototype signal processor, software infrastructure, and data recording.

Task	Single-Cabled Hydrophone Array
Water Depth (m)	300
Number of Sensors	7
Track Accuracy	<10m
Usable deployment period	20 Years
#Sensors for Analysis Case	8
Node Cost ($K)	$40
Installation (days) Best / Worst Case	20/30
Survey (days) Best / Worst Case	3/6
Installation Costs -Best Case ($k)	$57
Sensor Survey	$40
Cable Cost ($k)	$106
Node Costs	$320
NRE	$1,000
Acquisition Cost ($K) w/ Installation	$1,523
MM Signal Processor /Display	$1,200
Initial Data Analysis	$500
Systems Engineering	1,200
Program Management	500
Program Cost	***$4,923***

Table 4: ROM cost estimate for a prototype array and signal processing hardware/software system.

Technology for passive acoustic monitoring using fixed hydrophones was initially developed in the 1960s. Some early Navy arrays such as the original AUTEC array are still being used after 40 years of service. However, every site presents its own challenges. Certainly, installation of hardware into a producing oil field has unique design issues which do not require development of new but rather the application of existing technologies. As with oil production, the way to tap the potential of this technology is to move forward in a stepwise fashion. This will neither be simple nor easy, but the roadmap is clear and the payoff for both the industry and the environment worth the investment.

7.0 Conclusions

Monitoring the health of the field will become a critical element in meeting environmental requirements. Passive acoustic techniques can be used to augment and at times replace standard visual line transect methods. Investment in fixed monitoring technology will make passive monitoring an integral component of field development which will be used to document the health of the field.

Marine mammal passive acoustics is a rapidly developing science. Effective detection of marine mammal vocalizations has been demonstrated. As our understanding of species' vocal behavior grows, the ability to classify to a species level and to estimate the density of animals will improve. These tools are also being used to document the reaction of animals to anthropogenic sound sources and human activity. By combining passive acoustic data with an understanding of animal biology, the health of the populations can be measured.

Access to such technology drives this development. Embedding passive acoustic monitoring in the field provides an immediate capability to detect the presence and distribution of vocalizing animals. When these vocalizations are understood in a biological context as is the case with beaked whales, foraging behavior and spatial and temporal distribution can be measured. If monitoring starts ahead of development and continues through the life of the field, data which documents long term population trends can be collected. Such data provides direct evidence as to the effect of field development and production on marine mammal populations. In the absence of such data, the precautionary principle drives compliance.

Embedded passive acoustic monitoring technology fosters advances in research. Consider the data required for density estimation. An understanding of vocal rates and how vocalizations relate to dive behavior is required. An instrumented field provides a means of first documenting the species and their distribution within the field. To directly measure vocal rates, recording tags can be placed on animals with surface observers vectored to animals using passive acoustic detection and localization. By combining tag data with passive acoustic data from surrounding field sensors, detector statistics can be obtained. These include the probability of detection, false positive and negative rates, detection ranges, animal beam patterns, and source levels. Once these statistics are established, passive acoustic density estimation methods can be developed and tested. The verified acoustic data collected as part of this effort can be used to developed advanced classification and detection methods which in turn be used to enhance field monitoring.

There is no doubt such technology requires the investment of capital. However, the return on investment begins even before the first sensor is in place. By including monitoring hardware as part of the infrastructure of the field and committing to long-term monitoring, the likelihood of meeting compliance requirements and speeding the permitting process increases. The benefit of taking a proactive approach and adopting such new technology demonstrates willingness to document long-term effects of field development and production. The impact of such an approach on public sentiment can not be understated.

If the permit application for field development creates a lengthy debate, the industry will be at a distinct disadvantage, especially if such debate results in NGO lawsuits. Given the paucity of hard data regarding the effect of anthropogenic activity on marine mammals, the precautionary principle will be applied based on a myriad of anecdotal evidence. Incorporating monitoring into field development and production will help avoid such entanglements. A commitment to long-term passive acoustic monitoring will help document the health of the field and if necessary, guide mitigation.

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