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Improvements to Passive Acoustic Monitoring systems.

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1 Introduction

This report has been prepared by Subacoustech Ltd., for the UK Department of Trade and Industry under programme RDCZ/011/00018 entitled 'A feasibility and demonstration study; active and passive detection of marine mammals'. This is the final report delivered as part of this programme aimed at summarising the requirements for a Passive Acoustic Monitoring system and reporting investigations into the potential for improved systems. The overall aim of the project is to identify the limits of performance of methods of acoustically detecting marine mammals during offshore activity such as construction and seismic survey.

The use of the seas and seabed as a natural resource has increased greatly over recent years, and consequently the number and scale of offshore activities has increased in proportion. Many of man's offshore activities cause underwater noise, from the noise created by ship movements through to the extreme levels of sound generated during the use of explosives underwater, for instance for decommissioning of unwanted oil and gas installations.

The noise from offshore activity has the capacity to directly cause disturbance to marine mammals such as seals, whales, dolphins and porpoises. It may be noted, however, that secondary effects can occur, for instance by disturbance of the fish that are their food.

The effects of noise can include death or lethal injury, physical injuries that can have longer term consequences for the animal such as deafness, and sub-lethal behavioural effects such as the avoidance of an area. All of these may have significant consequences for individuals or stocks of a species.

Hence, it is generally a condition of consents issued for offshore activity that

1. the likely level of noise created by various activities is estimated prior to an operation being undertaken,
2. where the noise component of an activity may be significant, the noise levels are kept at the lowest reasonable level,
3. and that where the noise of an activity is sufficient to create an adverse effect, mitigation measures are introduced.

Of these, a primary measure where sensitive species inhabit a proposed area of activity is the monitoring of the area for the presence of the species. This enables the activity to be terminated if there are marine animals present. Generally, use is made of Marine Mammal Observers (MMOs) in an attempt to visually detect marine mammals. However, this approach is ineffective and in darkness or poor visibility detection is impossible. Under these circumstances acoustic detection offers significant advantages. There are three approaches for an Acoustic Detection System (ADS) that might be used, comprising

Passive Acoustic Monitoring (PAM). In this approach, a sonar-type system monitors for vocalisations or echolocation signals from the animals. The systems that have been fielded to date are of generally poor quality, have left-right ambiguity (i.e. cannot determine which side the signal is from) and have no range-finding ability.

Active Acoustic Monitoring (AAM). In this, a sonar "ping" is broadcast in the water and the system looks for a returning signal when it encounters a target. There are systems that have been well developed for military and other purposes, but they all suffer from the fact that they use a "beam" of sound and hence the area of water that is covered at any one time is small. In addition, the sonar may itself cause environmental effects, albeit at a low level.

Acoustic Daylight Monitoring (ADM). This class of sonar is new, and relies on detecting existing background noise being scattered from a target. It has significant potential advantages, including broad area coverage, lack of need for insonification and the ability to also act in PAM mode, but is "cutting edge" technology at the limits of achievability.

The limits of performance of active AAM and AD systems have been considered in a previous report [1]. The report found that while the data available for the Target Strength of common species was rather limited, it was sufficient to initially calculate the range of an AAM system. It was found to be sufficient for detecting marine mammals during many offshore activities. An advantage of AAM systems is that they work for non-vocalising species. However, a major disadvantage is that they use a “beam” of sound and hence the area of water that they cover at any one time is limited.

A further report [2] estimated the range at which injury might occur for various classes of offshore activities, and summarised the state of knowledge regarding the Source Level of vocalisations by marine mammals. By combining this data with the expected levels of background noise, the maximum theoretical range at which the mammals might be detected was calculated. It was found that for most offshore activities other than very large blasting operations, a well designed PAM system should be suitable for detecting large whale (mysticete) and large odontocetes (such as delphinid species) at sufficient range that an activity could be suspended until the animal has moved away, in accordance with current JNCC guidelines [3]. The theoretical detection ranges for smaller animals such as seals and porpoises were much smaller, such that PAM is unsuitable for detecting these animals during some blasting operations using unconfined charges.

These considerations confirmed that for vocalising marine mammals, Passive Acoustic Monitoring potentially offered a more reliable approach than might be expected using visual detection by Marine Mammal Observers alone.

The purpose of this report is therefore to consider the technical requirements of a Passive Acoustic Monitoring system, and to report on a feasibility study aimed at indicating the feasibility of enhanced capability at reasonable cost for PAM systems.

2 Prospective requirements for PAM systems.

2.1 Introduction

The technology that underlies PAM systems is at an early stage of development. The systems available are in many cases rudimentary, and the principles underlying better systems are a developing science where further research and development is needed. PAM could undoubtedly provide a very effective tool for minimising risks to the environment, but research is needed both at a hardware level, and also in terms of understanding the importance of an impact and hence, identifying the requirements of an ideal system for preventing it. This underpinning work is required to identify the basis of operation and requirements for PAM technology, to identify improvements that might be possible, and hence to drive the development of better systems.

However, underlying any development of hardware is the question of what is required to be accomplished by PAM systems. First steps have been taken to standardise some of the functions of systems. For instance, the PAMGUARD programme, funded by the International Association of Oil and Gas Producers, is aimed at standardising the detection algorithms currently used to detect marine mammals. The steering group draws members from the oil exploration and production industry, from MMO providers and from the marine mammal research community.

The fundamental use of a PAM system is to detect whether marine mammals are present in an area, usually with the aim of shutting down a hazardous activity until the animal has left the area. It therefore complements the activity of Marine Mammal Observers (MMOs) who traditionally visually detect marine mammals near or at the water surface. There are several PAM systems that are available commercially, which range greatly in their specification and ability. At the simplest, systems may comprise a “listening” device where the operator simply listens for marine mammal vocalisations, or detects them with software that listens for their vocalisations such as that provided by the PAMGUARD suite. Typically, the system will comprise a hydrophone deployed on a buoy or over the side of a boat, along with associated amplifiers and signal processing equipment. These simple systems are easy to use and rugged, and offer a significant improvement in a MMO detection, especially in poor weather conditions or at night. The difficulty with such systems is that there is no explicit range information given. A common assumption made when using such systems therefore is that if a marine mammal can be heard, that it is within range of the activity, and the activity shuts down.

In many cases this may be operationally acceptable, and the cost of the shutdown to the operator may be small enough that the provision of a system with better performance is not worthwhile. However, in some cases such a solution may not be acceptable on operational grounds, for instance because it may cause an activity to be aborted unnecessarily, or on cost grounds, for instance because an operation in the presence of a high density of marine mammals may halt repeatedly. For instance, seismic surveys are extremely expensive to conduct, and better information may be required to assess accurately the position and bearing of a marine mammal. This will enable the operator to accurately know whether the marine mammal is in a hazardous area, or will shortly enter it, prior to a decision being made to shut down the seismic airguns.

For this reason, the standards applied to PAM systems may vary from activity to activity. In time, it is likely that an overall standard will evolve in the first case, possibly as a voluntary standard driven by the various sections of the offshore industry.

The benefits of a well drafted standard are that it encourages the use of best technology. It is however important that any standard also offers a vehicle whereby improvements in the technology may be rapidly adopted and shared by the industry. A situation to be avoided is one where the equipment can be said to “meet the industry standard” and hence removes any imperative to improve equipment

The use of PAM systems in UK waters currently falls into three categories. There is an additional category which may be regarded as nascent:

1. Simple “listening” PAM systems used to augment MMO activities in simple activities and as a fallback for more complex systems.
2. Towed array systems with directional ability, used chiefly in offshore seismic surveys.
3. Static PAM systems with a directional ability, used for activities such as wellhead severance using explosives.
4. Potentially, PAM systems for monitoring during piling for offshore windfarm construction, which may be required to work to long distance in relatively shallow water.

The requirements for effective PAM systems in all of these categories may be different, however, with all of these systems, there are underlying requirements which may form part of a standard in due course.

2.2 Specifying a system

The selection of a PAM system for an actual activity must primarily be driven by an assessment of the performance that is required to achieve an adequate level of detection. In addition to ensuring the system is adequate to achieve detection, careful design of the deployment of the PAM system will be critical, combined with knowledge of the behavior of the target species. In the overall strategy for detection, the use of a PAM system will almost always be integrated with visual detection by an MMO. Other techniques, such as active sonar, radar and infrared detection, may also have a future use in augmenting PAM systems.

The minimum requirements, that a PAM system must achieve in order to be capable of detecting marine mammals include:

1. The frequency range of operation must be sufficient to encompass the frequency range of vocalisations or clicks that the target species emits, from low frequency vocalisations to echolocation clicks.
2. In order to maximise the dynamic range of the system the noise level of the system (that is, its internal electronic noise) must be below the background noise level of the environment it is in.
3. The system must be capable of making a detection. In the simplest case, this may be the operator listening out for vocalisation using headphones. More sophisticated systems may use click detectors or sonagrams as an additional detection method.

Simple PAM detectors using one hydrophone may satisfy these requirements. However, operation requirements may dictate that the system must also locate the animal. Where a location is required in addition to a detection, the system must be capable of supplying information as to the bearing, and ideally range, of the vocalisations or clicks of the target.

2.3 Selection of a system.

Critical questions when selecting a system include:

1. What are the marine animals that might be affected, and how sensitive are they to sound?
2. Which critical species do not vocalise, and hence cannot be detected by PAM?
3. What is the level of sound generated by the activity, and how will it decay with distance?

4. What effect must be avoided, and what is the level of sound at which this might occur?
5. Therefore, at what range does the effect for each species occur?
6. What is the level of vocalisation from the marine animal?
7. What is the background noise in the area? Does it vary?
8. What, therefore, is the range at which this species can be detected?
9. Therefore, is the range at which they can be detected greater than the range at which the effect will occur?
10. Do I need precise location, or will a simple PAM detection of presence/absence suffice?
11. What is the risk? Is there a knowledge gap, and what is the quality of the data on which decisions are based?

Additional factors, such as whether the system has to be deployed from a tow boat by cable, or anchored in the vicinity of the operation with data telemetered to a remote vessel, will determine the system selected.

2.4 Operation of system

The use of a PAM system will depend on the detail of the system and its application. While both the systems and the methods for deployment may well be different from application to application, there are common features that may be considered to be good practice. These include:

1. Prior calibration of the system to International Standards so that the performance of the system, including dynamic range and frequency response, is known and documented.
2. Calibration of the entire system during operational conditions (e.g. against a known source or "Marine Mammal Replicate", calibrated to International Standards) so that the performance of the system at sea under its conditions of use is known and documented
3. Software and analysis to agreed standards (e.g. as provided by PAMGUARD) that would allow technically competent but inexperienced users to operate the system effectively and to make detections of known quality
4. Documented data acquisition and analysis procedures so that results and conclusions from different PAM activities can be archived into a common database and compared.
5. The recording of data that is not required for making an identification, but which would subsequently allow data to be interpreted, and hence enhance the value of the data, for instance by including measurements of the background noise levels.
6. The archiving of data in a common form where it may be used by a wide range of users, for instance by providing raw time histories at an adequately high sampling.
7. The data archived should at a minimum include recordings of marine mammal vocalisations during detection, along with sufficient information (species, distance etc.) to allow subsequent analysis, for instance to give estimates of the Source Level and variability.

Consideration of these requirements has led to the development of the architecture discussed in this report enabling the majority of the above functions to be achieved.

3 A test of feasibility for an unambiguous PAM system.

3.1 Current Issues

This section of the report provides some initial indications as to the feasibility of developing inexpensive and unambiguous PAM systems. The work was not intended to provide a practical working system, but to test under realistic conditions some of the electronic hardware, software and deployment features that might be required in a commercial system.

Two chief shortcomings of currently available purpose designed PAM systems were identified. These comprise:

Ambiguity. Simple PAM systems based on listening using a single hydrophone have no ability to locate a marine mammal, but only to make a detection. There are towed PAM systems available which use a streamer, or line of hydrophones, to detect the angle that the animal makes to the axis of the streamer. In most cases, the streamer will comprise only two hydrophones.

Systems based on lines of transducers are ambiguous, in that they can only detect the angle the animal makes to the streamer, but not whether the animal is on the left or the right of the array. Such systems are termed as displaying left-right ambiguity. In some cases where the animal continues to vocalise this ambiguity may be resolved by making small turns in the tow boat. The actual bearing of the animal can be detected by the change in apparent bearing of the vocalisations, which will be consistent with the turn on the side on which the animal is located but inconsistent on the other. However, where the tow boat is for instance a seismic source vessel towing seismic streamers, which relies on following a straight course, it may be impossible to make turns. In addition, the requirement to resolve bearing by this means adds a level of complexity to the use of the system, which may result in inexperienced users not being able to use it effectively, and which may detract from the performance achieved even in the hands of experienced users.

Data rate. Vocalisations and clicks may span a frequency range from a few Hertz up to 120 kHz or more. In order to resolve these frequencies, data must be recorded from the hydrophones at sampling rates of 300 ksamples/sec or more. In systems using multiple hydrophones, the data rate increases in proportion to the number of hydrophones deployed. However, the data must typically be passed from a remote underwater sensing array, to the support vessel on which the user is based. In an ideal system, raw data might be transmitted from the hydrophones to a processor on the vessel where the data can be analysed and archived. This is indeed how offshore seismic streamers work. However, in the case of seismics the data is transmitted at a much lower rate of about 400 samples/sec, which is much lower than is required for such a PAM system. For instance, where four hydrophones are deployed in a PAM system, the constant data rate that would have to be transmitted to the surface would be 1.2 Msamples/sec, or typically about 20 Mbytes/sec. This is beyond the bandwidth generally achievable by analogue wireless transmission systems or simple cable transmission.

Many currently available systems therefore operate on the basis of having a click detector adjacent to the array for making detections and locations at high frequencies, but associated with a lower frequency recording ability for vocalisations. This approach greatly reduces the data rate required, but reduces the flexibility of the processing, limits the ability of the system to locate the click, and also means that the clicks cannot be recorded and archived as fundamental data in a raw form.

3.2 Alternative approach

An alternative scheme can be formulated that would allow detection of clicks and vocalisations, archiving of raw data at high speed, and estimation of bearing. Conceptually, where

measurement hydrophones are organised on a plane in any other configuration than a line, it is possible to estimate the bearing of a source on that plane with a low or negligible ambiguity. For instance, a triangle of hydrophones will allow complete resolution of the angle of bearing of most sources in practice. In this sense, a triangle of hydrophones, or quartet in a two-by-two configuration, is preferable to a line array.

While continuous data rates of the order indicated above may be difficult to provide, it may be possible to use high speed local processing to reduce the signal from the hydrophones to provide the bearing of a source. This has the benefit that it would only be necessary to pass the directional information to the tow vessel at a relatively low data rate. However, this can be associated with an ability to record or “grab” clicks at a high data rate locally, and to pass these to the tow vessel at lower rate. It therefore seemed likely that it would be possible to develop an inexpensive, unambiguous PAM system with high speed data capture ability.

The general architecture of a four-hydrophone system is shown in Figure 1. During operation, and in its quiescent state, a local processing system might continuously sample the data from the four hydrophones. The data from the hydrophones can be processed to form an image of the direction from which sound is arriving at the array. For instance, it is possible to form a cross correlation of the signal at the hydrophones, which may be mapped onto an angle of arrival domain. If there is a dominant direction of arrival (i.e. a click or vocalisation arriving from a particular direction) this will show up as a “hot spot” in the sound field. During this process a detection algorithm can also be run, say on the output of one hydrophone. This might be a PAMGUARD algorithm or other. In the event of a detection, the click or other noise that has triggered it can be locally grabbed from say one of the hydrophones, then transmitted at a lower rate to the tow vessel.

This greatly reduces the need to transmit data. For instance, whereas one second’s worth of raw data from four hydrophones will comprise at least 1.2 Msamples of data, or about 40 Mbits or so, the directional information from that data can be carried as a correlation of only 16 kbits.

This scheme can therefore provide both directional information and archiving of important raw data, while limiting the rate at which data has to be transferred to the surface. It requires local processing, but the processing is both simple in concept and well within the capability of currently available microprocessors. An additional advantage is that the data rate is low enough that it would be well within the capability of established data networks and equipment such as those based on the Ethernet protocol.

4 Experimental results.

This section presents a test which indicates that a simple prototype system incorporating a suitable array type and processing scheme is capable of removing the ambiguity of bearing from a PAM system, which may have a significant impact on the efficiency of some operations such as seismic operations. In addition, important data such as clicks may be grabbed at full sample rate, but transmitted to the surface at a reduced rate.

4.1 Initial airborne tests

The work presented is by no means exhaustive, but indicates that advances in the capability of PAM systems at a hardware level may be achievable at a reasonable cost. Since the local processing may easily be achieved via an easily available microprocessor, the prospect emerges of a system which can be reprogrammed as required to meet future requirements.

In the first case, initial development of the general principles of the system was undertaken using an array of microphones in air. This airborne system indicated that a moving sound source could be tracked using a simple transducer array, but also established the ability to pass data from the sensing elements to the remote user interface was critical.

4.2 Underwater tests

It was decided to test the general principle of operation experimentally. A prototype PAM system was constructed using four hydrophones in an oblong configuration. The geometry of the array is indicated in the photograph of Figure 2. The system used four hydrophones in a two-by-two formation as the sensing elements of the array; these were housed in "pods" on the end of hydrofoil section arms attached to a central fuselage. The hydrophones were set in two pairs which were 0.70 m apart. One pair was 2.4 m apart from the other pair axially. In the first instance, it was decided to use the greatest spacing, and hence the highest resolution of bearing, that might be operationally realistic. The system was consequently rather unwieldy. However, in the light of experimental results, it is believed that these spacings could be significantly reduced, to perhaps of the order of 0.5 m apart and 1 m from front to back hydrophone pairs respectively, which would produce a light and easily manhandleable system.

The reason for placing the hydrophones in pairs on either side of the fuselage was because when system was towed this would place them in the free water, away from the turbulent boundary flow around the cable and fuselage. By this means, flow noise could be minimised.

A line array of hydrophones can roll around its axis without changing the signal that it receives, and hence there is no reason to attempt to stabilise the array so that it cannot roll. However, in an array of this sort, it is necessary to keep the array upright in the water, so that the hydrophones stay in the horizontal plane. Consequently, the array was also provided with two stabilisation fins above and below. The upper fin was provided during towing tests with a small buoy. The lower fin was provided with a small weight and hydrofoil. Finally, to stop the array yawing in the water, a fin was attached to the rear of the fuselage. The system operation and towing performance at various speeds was assessed during tests off the North Devon coast in March 2006. The system was found to stay upright and to be extremely stable during tow.

4.3 Processing

In order to allow flexibility of the experimental system the data processing of the system was not, in fact, accomplished locally, but was performed on a laptop on dry land. The processing was, however, performed in a way which mimicked the behaviour of an eventual locally-processed array, with correlations etc. being performed on the hydrophones and the data being subsequently passed to a graphical output stage.

4.4 Transducers

Each pod contained a Reson Type TC4014 Broad Band Spherical Hydrophones, as illustrated in Figure 3. These hydrophones were chosen because they have a wide bandwidth (10Hz to 480 kHz) and are insensitive to electronic noise because they are provided with built-in preamplifiers. Each hydrophone was flexibly mounted to remove vibration transmission. The hydrophones were mounted within cages which were also provided with flow shields, which comprised a thin flexible plastic coated material stretched over the cage. This was to reduce the noise created by flow over the hydrophones.

The system was provided with a 200 metre cable to feed the signals from the hydrophones to the surface. Due to the difficulty of transmitting signals at high frequency along a long cable data was transmitted by current coupling, rather than voltage coupling. The fuselage of the array was consequently provided with a line amplifier to act as a driver to send signals to the surface. The signals arriving there were digitised and analysed using a laptop computer working in the National Instruments LabView domain.

4.5 Detection

Tests of detection performance were conducted in a flooded quarry at Chichester. The lake is approximately 1 km long and 600 metres wide. The experiment was mounted on buoys in the water, and a source moved around the array using a small boat at ranges from 50 metres to 600 metres from the array. For initial testing, a convenient impulsive source was created by lowering a metal pole into the water, and striking the end of the pole with a hammer. This created a short impulse with frequencies predominantly in the 1-10 kHz region. For later tests, a “marine mammal replicate” source unit was used, which generated a high frequency sweep from 2 kHz to 20 kHz at a rate of 5 sweeps per second. The transmitting element of the source was a small spherical hydrophone, with a Source Level of 190 dB re 1 uPa @ 1 metre. The unit is illustrated in Figure 4.

Figure 5 illustrates an early result from the system. The figure presents a record taken during a pole strike, for the case of the source to the port of the array. The figure is a “screen grab” which illustrates the appearance of the front screen of the system during an actual detection.

The upper part of the plot presents the voltage arriving from the four hydrophones over a period of one second; in fact, the differences in the responses of the four hydrophones are very small and mainly correspond to small differences in arrival time of an otherwise identical signal. This difference cannot easily be discerned on this timescale.

On the lower part of the screen, the system presents the correlation of the four hydrophones, mapped in terms of arrival angle of the sound; this quantity may be considered to be an estimate of the specular density of the sound field. It may be seen that the plot indicates a strong arrival from port of the array, which corresponds to the direction of the source.

Interestingly, it may be immediately seen that there is no ambiguity of the arrival direction, since the plot is not symmetric. This would not be the case for a line array, where the equivalent quantity would be symmetric about the axis of the array. The ability to resolve direction is unsurprising, as whereas line arrays will receive an identical signal for a given sound arriving from the same angle on one side or another, a signal arriving at a two-by-two array will arrive first at the hydrophones on one side or another and its direction may thus be identified. The result nonetheless confirms that the system is easily able to distinguish between arrivals from one side or another.

Figure 6 illustrates an identical result, but this time for a source to starboard of the array; Figure 7, which presents a result for a source to the starboard and forward of the array, yields similar conclusions.

It was generally found that this method of presenting the data (which was termed the “radar screen” approach) was difficult for non-experts to interpret, especially in the presence of noise.

Consequently, a more sophisticated system was developed and tested. The system did not differ in the array or the fundamental architecture and processing of the signals, but only in the way that the data was captured and displayed.

4.6 Data display

The system offered three main outputs. The first of these was auditory; the signal from one hydrophone was fed to the operator by an earpiece. This activity occurred constantly whether a detection was made or not, and enabled the operator to listen for a source of interest. The system was very simple in that the operator was provided with two controls only. First, a high pass filter allowed the noise from any breaking waves and boat engines to be largely removed from the processing. In general, it was found that filtering the sound to remove low frequency components improved the ability of the system and the operator to detect specific noise sources in windy conditions where there was a lot of wave noise. The detection threshold could also be set; when the detection level was exceeded the system would record a second's worth of data, plot the specular density of the sound field, locate the peak arrival angle, and plot it as a function of time on a rolling trace. The data was also stored for later analysis.

This is most easily understood by reference to a typical screen from the system. Figure 8 illustrates the output of this system seen by the operator during the use of the marine mammal simulator. Visually, the system offered two main pieces of information. It may be seen that the system presents on the lower part of the screen the specular density of the sound field, for the particular case of the most recent second's worth of data during which a detection has been made. In this case, it is mapped as a simple graph, of level versus angle from the axis of the array. It may be seen that there is a significant peak in the density, which shows that the majority of the noise is mapped as arriving from an angle of about 50 degrees from the axis. Significantly, it will again be noted that the system is unambiguous, that is, there is no equivalent peak at an angle of -50 degrees.

It is rather easier to interpret this display. For instance, it is interesting to note that the specular density illustrates a small peak in the arrivals from an angle of about 140 degrees. The day on which the measurements were made was rather windy, and it is thought that this corresponded to small waves breaking on an adjacent stretch of beach. It is assumed that this created a high level of high frequency noise; it may also be that some shingle shifting was occurring. It may be seen that there are also arrivals from most other angles which may correspond to noise created by breaking waves at the water surface.

The upper part of the screen plots the location of the peak arrival angle of the sound, during periods that caused a detection to be made by the system, that is, it is a detection angle time history. The plot is a rolling plot, that is, it presents the bearing of a detection versus the time, but is continually updated so that only 1 minute of data is shown. If a detection is made, the system finds the peak in the specular density and plots it on the screen to indicate the angle of bearing of the source, otherwise, nothing is plotted.

The screen illustrates the last minute of data, during which a marine mammal replicate source was moved around the array, being dropped into the water and fired at three positions. The source was at about 100 metres from the array. It may be seen that the direction of the source is accurately located, at angles of about -100 degrees to the array, -30 degrees and +50 degrees. It may also be seen that the detection is unambiguous. There is one false detection, just over half way through the period, and at an apparent angle of about -160 degrees. It is probable that this was caused by a wave splash.

4.7 Summary

The system proved to be capable of unambiguously locating the direction of a source. The display was found to be readily understood; several other forms of display were tried, but it was

found that this form, which mirrors that used in some other PAM systems, was the most readily interpreted by an operator.

It is worthwhile considering the data load that would be placed on the network that might be used to transfer locally grabbed or processed data up to the surface via a cable or wireless link. The angular information defining the specular density comprised about 1000 points. During the one minute period, sixty such points would be transmitted, giving a steady data rate of 1k points/sec or 32 kbits/sec for 32 bit samples. During the period, there were also 20 detections. If the corresponding sound file were transferred from one hydrophone for analysis or archiving, this would add 20 seconds of data at 350 ksamples/sec, or a total of about 7 Msamples. If these were transmitted to the surface for operator scrutiny and storage, it would put an additional load of 116 ksamples/sec on the system, or about 3.7 Mbits/sec.

A further refinement is to transmit an audio feed from one of the hydrophones at a lower rate to the surface, so that the operator can listen in real time to background noise or vocalisations in the human audible range. Assuming a sample rate of say 44 ksamples/sec or 1.4 Mbits/sec (corresponding to the current standards for digital audio), the total load on the network would rise to just over 5 Mbits/sec. The total load is thus, for instance, well within the capability of currently available Ethernet systems.

In summary, the experimental results indicate that unambiguous PAM systems are readily achievable, given a suitable distribution of hydrophones within the array and the ability to process the data to resolve the angle of arrival of the sound at the array. Simple architectures may be found where the data could be processed locally, for instance to determine the specular density, and the resulting reduced data alone transmitted. Such a system architecture would enable continuous monitoring of noise, detection and location of marine mammal vocalisations and clicks, and archiving of this data as raw time histories at a high sample rate.

5 Conclusions

A simple prototype PAM system was constructed and tested. It was found that:

1. Unambiguous PAM systems are readily achievable, given a suitable distribution of hydrophones within the array and the ability to process the data to resolve the specular density of the sound field, that is, the spectrum of angle of arrival of the sound at the array.
2. However, this approach greatly increases the quantity of data that must be processed, to a point where it would be very difficult to transmit it in raw form by cable or wireless link to a distant vessel
3. Simple architectures may be found where the data could be processed locally, for instance to determine the specular density, and the resulting reduced data alone transmitted.
4. Such a system architecture greatly reduces data rate, and hence would simultaneously enable continuous monitoring of noise, detection and location of marine mammal vocalisations and clicks, and archiving of these as raw time histories at a high sample rate.

6 References

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2. Parvin, S J, Harland E and Nedwell J R. Lethal and physical injury of marine mammals, and requirements for Passive Acoustic Monitoring. Subacoustech Report No. 565R0211 December 2006.
3. Guidelines for minimizing acoustic disturbance to marine mammals from seismic surveys. Joint Nature Conservation Committee, Marine Advice, Dunnet House, 7 Thistle Place, Aberdeen AB10 1UZ. Available at http://www.jncc.gov.uk/pdf/Seismic_survey_guidelines_200404.pdf

Figures

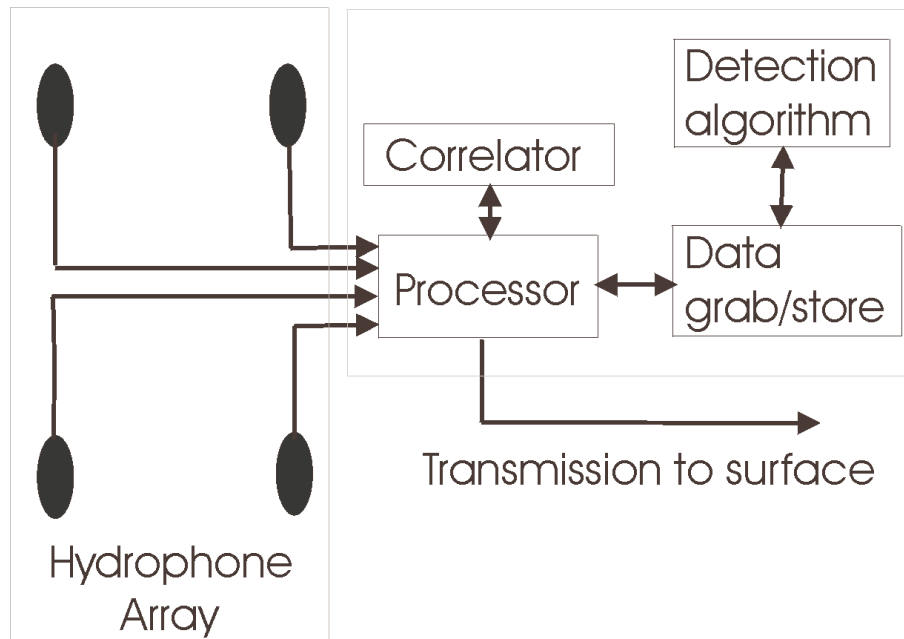


Figure 1. An architecture for a PAM system with local processing

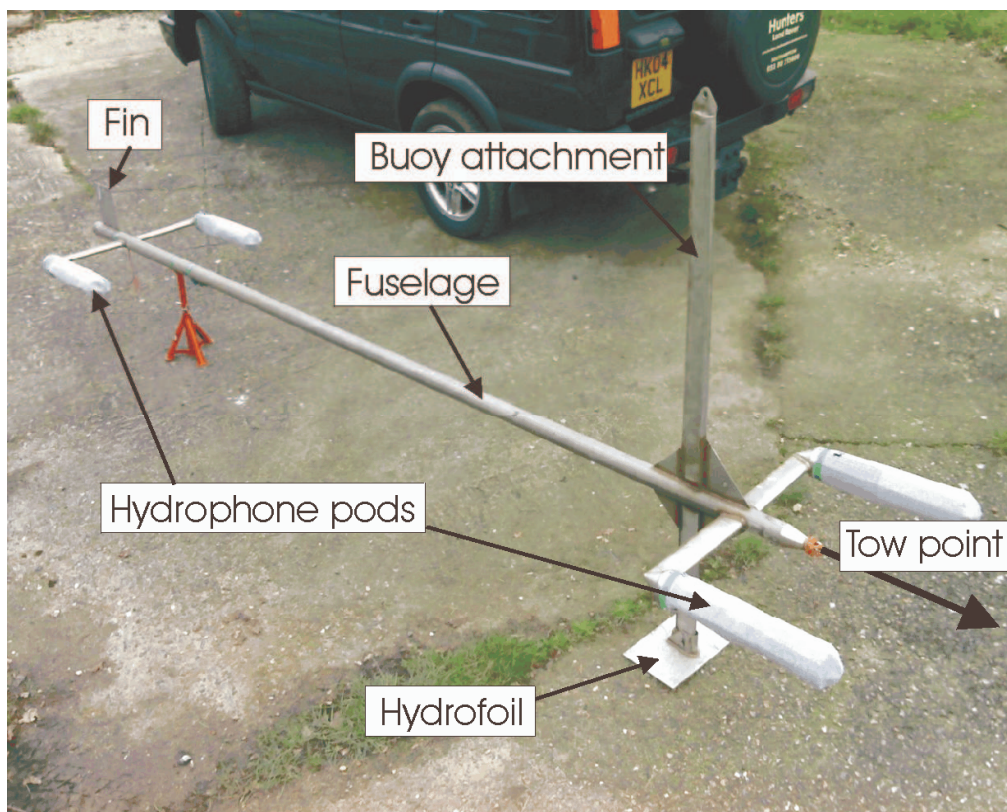


Figure 2. A photograph of the experimental PAM system

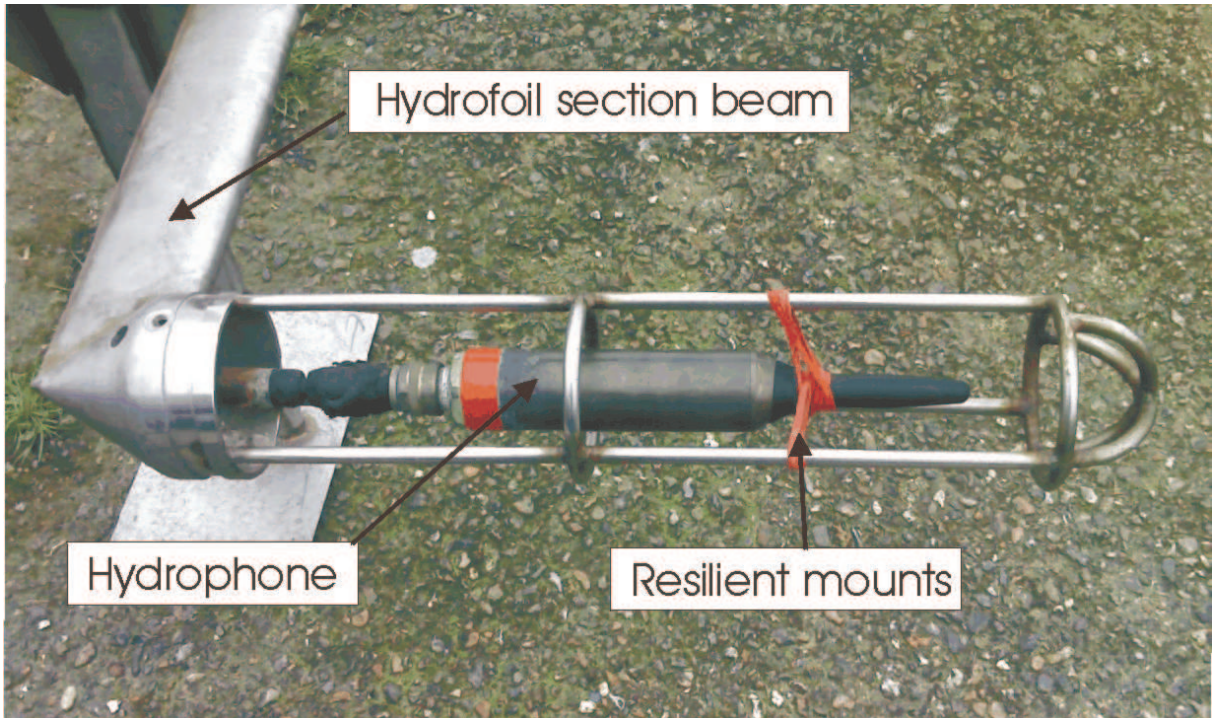


Figure 3. An photograph of the hydrophone pods with the flow cover removed

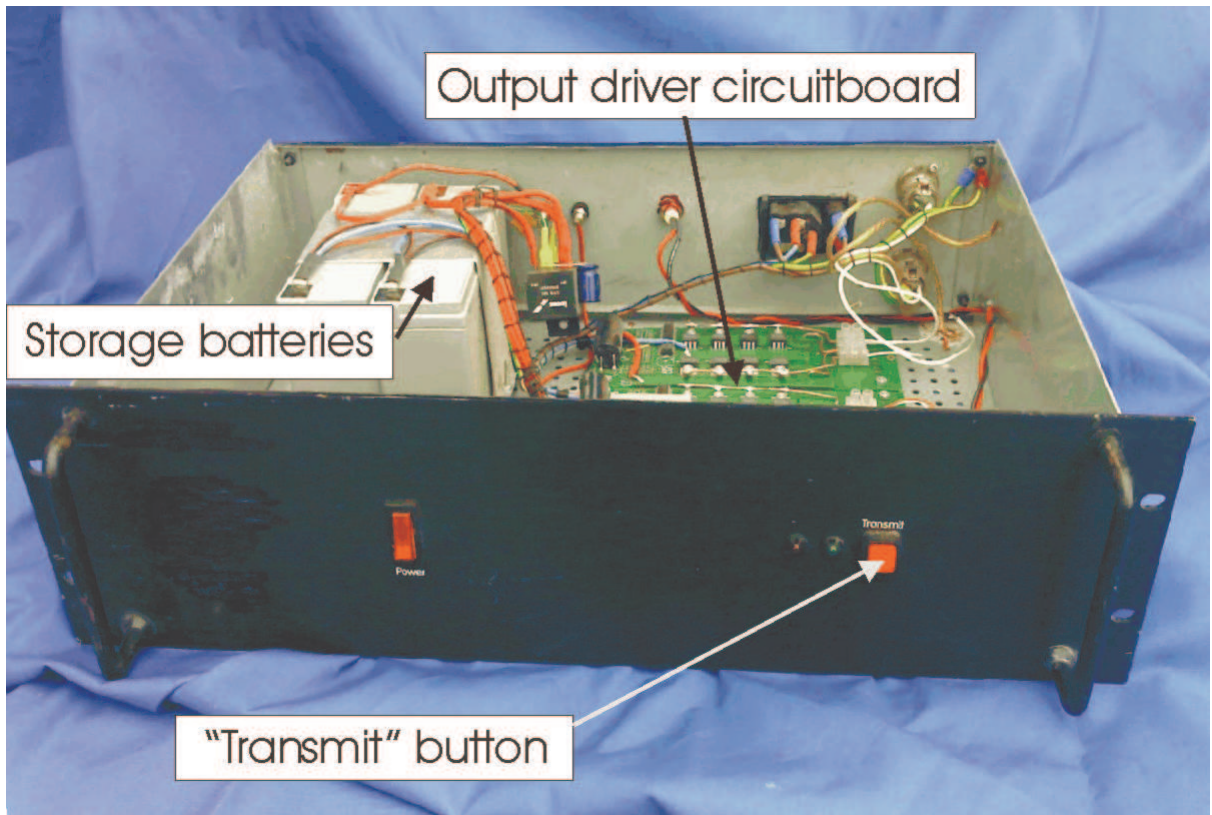


Figure 4. A photograph of the marine mammal replicate source.

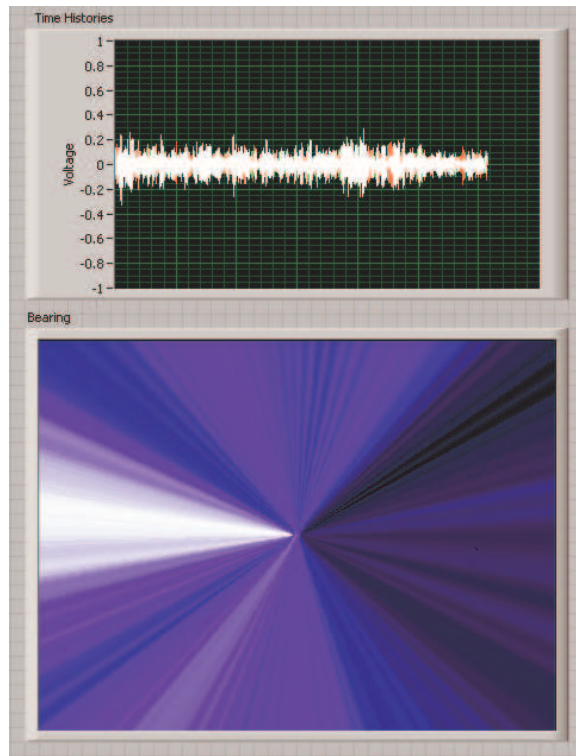


Figure 5. A PAM record for a source immediately to port of the array.

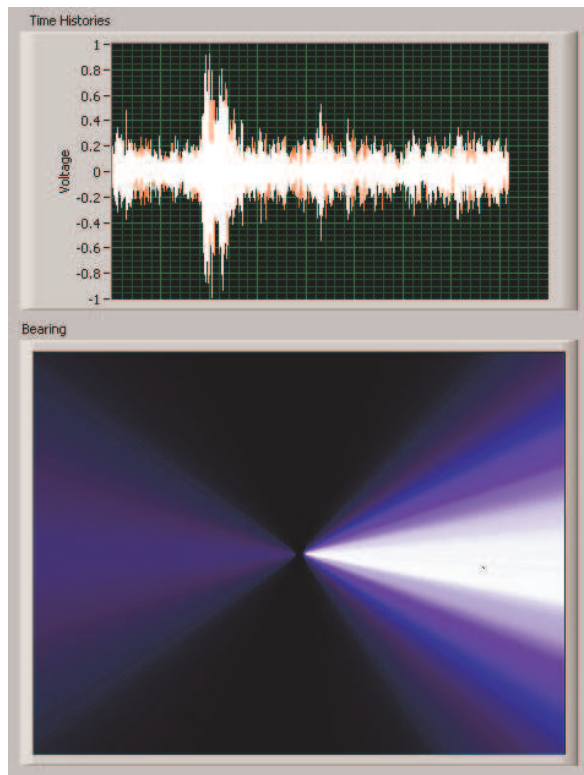


Figure 6. A PAM record for a source immediately to starboard of the array.

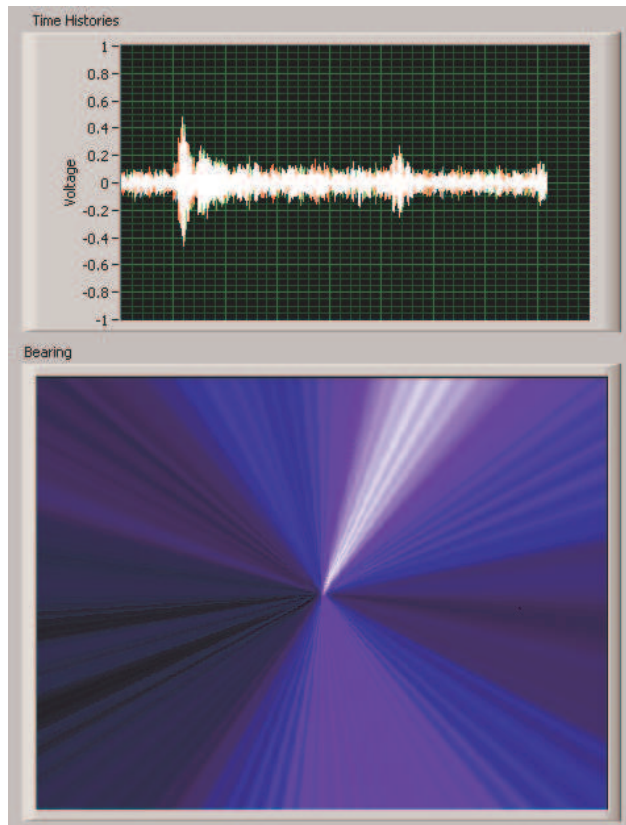


Figure 7. A PAM record for a source to starboard of, and forward of, the array.

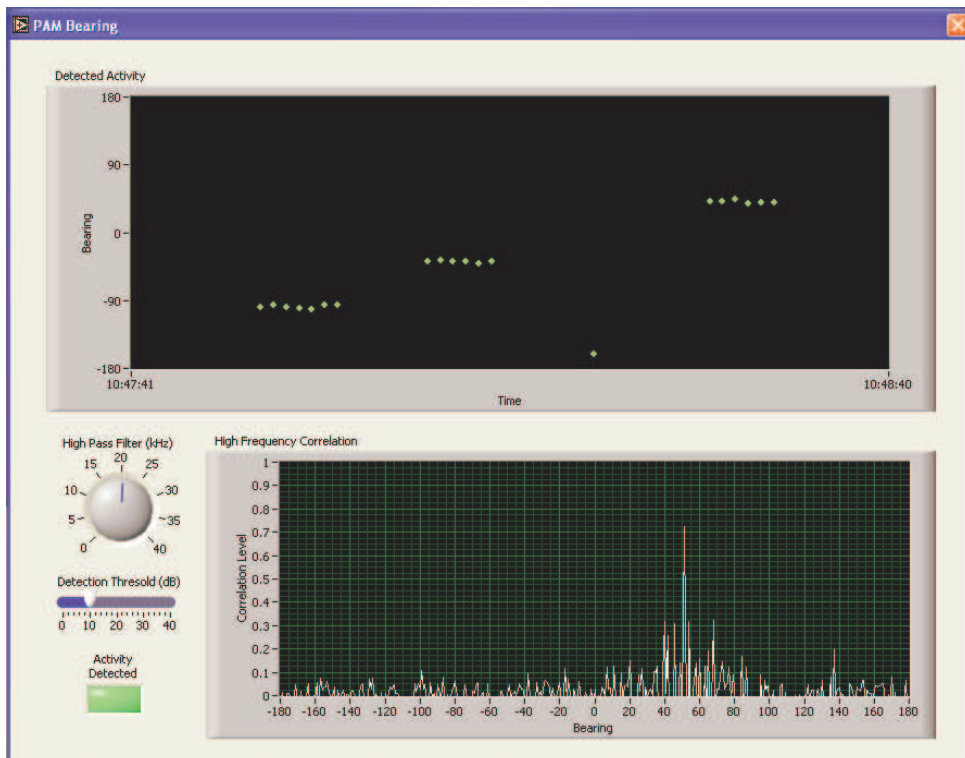


Figure 8. A PAM record for a later system, during the use of the marine mammal simulator.

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