PAMGUARD: SEMIAUTOMATED, OPEN SOURCE SOFTWARE FOR REAL-TIME ACOUSTIC DETECTION AND LOCALISATION OF CETACEANS

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1 INTRODUCTION

Regulators in many regions require mitigation involving the real-time detection of marine mammals during activities emitting intense sound, such as seismic surveys, pile driving and military sonar exercises. Visual monitoring is the default method for detecting marine mammals. However, these animals are difficult to sight. Some make long dives and hence are unavailable to be seen at the surface for extended periods and sighting efficiency is also dramatically reduced by poor weather conditions. Visual detection is, of course, extremely limited at night, yet for economic reasons, operators may need to continue activities round-the-clock. Another consideration is that maintaining high levels of vigilance is demanding on observers. During visual surveys for example, teams of six or more observers will be used to provide effective coverage.

Fortunately, many marine mammal species produce loud distinctive vocalisations and for these, passive acoustic monitoring (PAM), whether conducted alone or in conjunction with visual effort, can greatly enhance the overall detection capability. Trials of a PAM system deployed from an oil industry guard vessel in the late 1990’s showed that PAM resulted in approximately 8 times more marine mammal detections than marine mammal observers on the bridge of the seismic vessel. As well as being used for mitigation exercises, PAM is being increasingly used in population monitoring (Leaper et al., 2000; Gordon and Tyack, 2001; Mellinger, 2002.; Mellinger et al., 2007; Thode, 2005). As well as being able to operate equally effectively at night and during inclement weather, PAM systems can also be largely automated, thus reducing the number of observers required.

Cetaceans produce an incredibly wide variety of vocalisation types, from low frequency (10 Hz) moans of blue whales to ultrasonic (150 kHz) echolocation clicks from harbour porpoise. Some marine mammals appear to vocalise for much of the time, whereas for others vocalisation may only occur at certain times during a dive cycle, be related to a certain behavioural state or be highly seasonal. Some marine mammals vocalise mostly close to the surface, others only at depth. Some species have not yet been recorded. PAM is therefore much more effective with some species than with others, and detection hardware and software which is optimal for one species may be entirely unsuitable for another.

As affordable computer power and the marine mammal research community’s interest in PAM have increased, new algorithms and techniques which enhance our ability to detect and track marine mammals have been developed. There is certainly still a role for the human observer in PAM detection, tracking and species identification. A good pair of headphones and the human ear are an obvious and important component of human assisted PAM, however, many PAM hardware configurations now contain several hydrophone sensors making it difficult to listen to all of them. More importantly, many marine mammals vocalise outside the range of human hearing, rendering our auditory senses useless for many species. Easy to use interactive displays which enable operators to visualise sound at any frequency, select sounds for localisation and assist with tracking and localisation are therefore an essential component of a modern PAM system.

There is no single PAM solution that will work for all cetacean species. In the past, a number of researchers have developed PAM applications designed to detect a particular signals type under certain conditions. However, it has often been the case that running one application for one species on a computer would preclude the operator from running a different application perhaps more suited to detecting a different species or it would be impossible to display data from both applications on the same map due to a lack of compatibility.

PAMGUARD is an attempt at providing standard software both to developers and to users of PAM systems. For developers of PAM systems, an Application Programming Interface (API) has been developed which contains standard classes for the efficient handling of many types of data, interfaces to acquisition hardware and to databases, and provides a GUI framework for data display. For the PAM operator, PAMGUARD provides a flexible and easy to use interface which provides a standard interface across different platforms with the flexibility to allow multiple detectors to be added, removed and configured according to the hardware configuration and species of interest.

Although primarily designed for real time operation in the field, PAMGUARD can equally well analyse archived data from files. When analysing archived data, GPS and other ancillary data (such as hydrophone depth) can be automatically merged with the acoustic data in order that detection locations are correctly geo-referenced.

The vision for the PAMGUARD initiative is to create an integrated real-time PAM software infrastructure that is open source, platform independent and freely available to all PAM users for the benefit of the marine environment. Being open source ensures long term viability, encourages its acceptance and fosters a community of programmers to contribute to the code. Cross platform compatibility is achieved by the choice of Java as the programming language and the open-source aspect of software development is facilitated through the project’s presence on SourceForge, where a community of developers provides extra resources. Open development means that the software is free and access to the code is straightforward and assured, speeding up innovations and improving the performance and maintainability of the code.

PAMGUARD has been designed to utilise data from multiple sensors in any configuration. Structurally, PAMGUARD is highly modular following the principle of minimal coupling. This autonomous structure facilitates the development of modules to perform specific functions by different programming teams.

Currently PAMGUARD software replicates and extends the important capabilities of real-time acoustic monitoring and detection software that preceded it, in particular the IFAW software suite (www.ifaw.org/sotw) and Ishmael (Mellinger, 2001) and retains much of their look and feel. It also incorporates new routines for calculating 3D locations described in Thode (2005).

2 THE PAMGUARD API

Implementation of a PAM algorithm into a framework which can be used for practical applications requires not only the algorithm itself, but also a data handling system which will get data into it and to handle data coming out of the algorithm. A developer who has expertise in detection and classification algorithm development may not be expert in (and probably doesn’t want to be expert

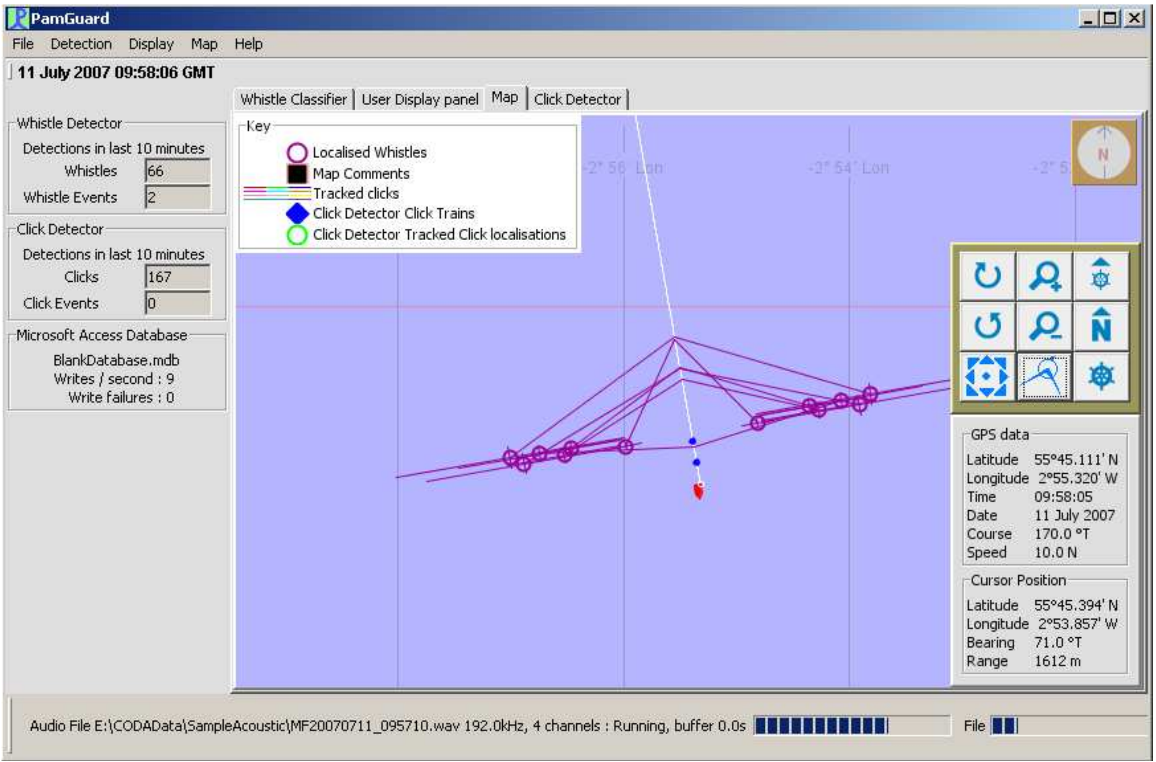

Figure 1. The PAMGUARD Graphical User Interface. The map shows the ships position (red), track (white) and hydrophone locations (blue) as well as an overlay of located dolphin whistles (with a left/right ambiguity). Smaller side panels summarise recent detection information. Other 'tabs' in the main display allow access to more detailed information from other detectors.

in) other details such as how sound cards are controlled or how to code SQL (Structured Query Language) statements to write detections to a database. The PAMGUARD API has been written so that algorithm developers are largely insulated from these other areas. For example, simply by subscribing their module to the sound acquisition module, they will receive packets of raw audio data, without having to know anything about sound card control. To write to the database, the developer can make very minor additions to a standard class in the PAMGUARD API, none of which require any knowledge of SQL.

2.1 PAMGUARD MODULES

PAMGUARD consists of a number of modules, each of which performs some sort of data handling task. Individual modules may do anything from acquiring sound data, to managing a database or searching for a particular sound type. Generally every module will acquire data either from another module, or through some external interface (such as a sound card, GPS or depth sensor readout). The output of a module may be a display, more data or both. A single module may have multiple output data streams. For instance, the sound acquisition module primarily outputs raw audio data to other PAMGUARD modules, but also outputs data providing a record of when sound acquisition was started and stopped which can be stored in the database. The PAMGUARD API provides the programmer with a flexible interface whereby the displays, data, control menus and other features of each module, and of new ones, are easily incorporated into a single overall data management and GUI framework.

PAMGUARD currently contains 29 plug-in modules which can be selected and configured by the user. Module details can be viewed on the PAMGUARD web site at www.pamguard.org. It is generally possible to create multiple instances of a given module type. For instance, the operator may wish to incorporate two click detectors, each optimised for a different species, or have two

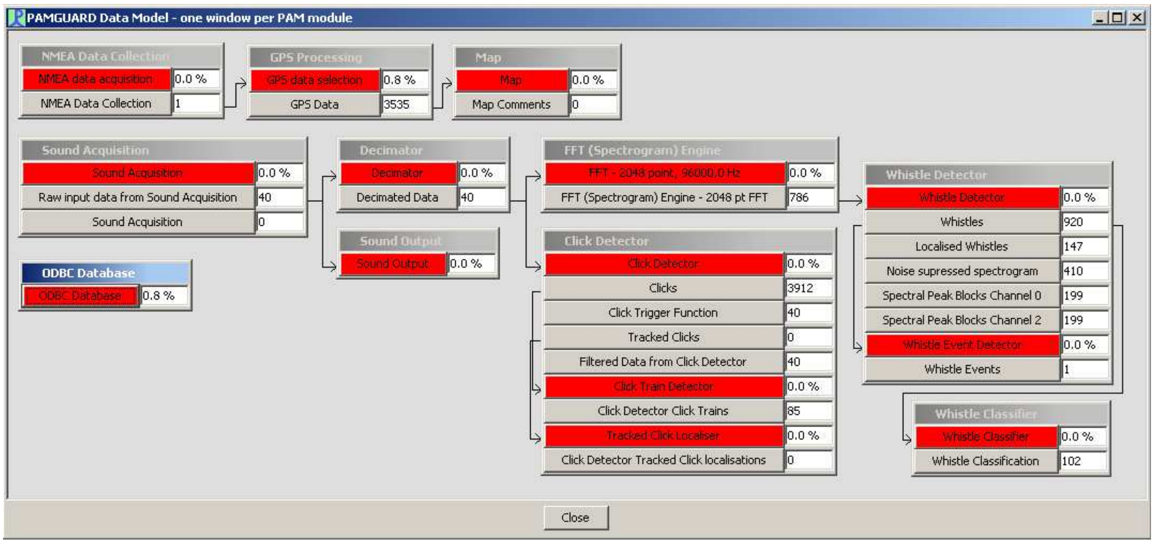

Figure 2. The PAMGUARD model viewer. Each module is represented by one window. Processes within each module are shown in red and output data streams in grey. The arrows show the data flow between the different modules. Numbers to the right of each process show the percentage of processor CPU being used by each process and the numbers to the right of each data stream show the number of data unit's in that stream. Clicking with the mouse on a process or data stream will display additional data or configuration options. Menu commands allow the operator to add, remove and configure the different modules.

sound acquisition modules, one acquiring low frequency data and one high frequency data. For certain module types (e.g. GPS acquisition), the user may be restricted to having a single instance.

2.2 DATA HANDLING

Even a relatively simple PAM configuration will be handling many gigabytes of data per hour. Data may take many forms. There will generally be raw audio data coming from some kind of input device (such as a sound card, or audio file). There will also be ancillary data such as GPS positions and hydrophone depth information as well as the output from the various detection and localisation modules. In the loosely coupled programming framework used by PAMGUARD, each module that requires data from another module subscribes to the output data of that module and is notified each time new data become available. Having multiple modules subscribe to the same data increases overall program efficiency performance since, for example, the same spectrogram data can easily be used for displays and as input to a detector.

In some cases, the arrival of new data will be a regular and frequent occurrence (for instance the arrival of new raw audio data). In other cases the arrival of new data may be very intermittent (for example the output of a detector searching for a particular type of sound). Some data may be used and discarded immediately. Other data may need to be held in memory for a considerable time. For example, several hours of GPS track may be held in memory to allow re-drawing on the map, as might detection data. Raw data on the other hand may be held for just a few seconds and discarded once it has been scanned for interesting sounds. A feature of the loose coupling employed between the various PAMGUARD modules is that individual modules cannot know in advance for how long their data are likely to be required since this will depend on specific PAMGARUD set-ups. The data managers within each module must therefore regularly query each subscribing module to determine how long data are required for before discarding it.

2.3 GRAPHICS

Any PAMGUARD module can create it's own graphics display panels which will be incorporated into the overall PAMGUARD Graphic User Interface (GUI). This gives the module programmer ultimate control over what is displayed. However, it is more often desirable to incorporate the output of a detector onto existing standard displays such as the PAMGUARD map or a scrolling spectrogram. The PAMGUARD API therefore incorporates a system of graphic overlays, whereby a module's output data can be added to existing displays.

2.4 THE PAMGUARD USER INTERFACE

The PAMGUARD user interface (Figure 1) performs two main tasks:

1. It enables the operator to add and remove modules and configure them for a particular cetacean monitoring task.
2. It enables the user to interact with the detection process, confirming detections, selecting sounds for localisation and interpreting results displayed on the map and spectrogram displays.

The PAMGUARD GUI provides simple tools which clearly show the user how different modules relate to one another in the PAMGUARD data model. Figure 2 shows the data model view in which relationships and data flow are clearly displayed. The display also provides information on how much processor time each module is using.

3 TESTS AND FIELD TRIALS

Several field trials to test various aspects of PAMGUARD have been completed. Feedback from operators who are familiar with other PAM software and have used PAMGUARD either in the field or for offline analysis has generally been positive and has been essential for developing a useful and usable product.

In addition to improving software functionality and usability it is important to measure and quantify the efficiency with which species of interest can be detected at different ranges and weather conditions. The most substantial trails so far were completed in conjunction with the CODA offshore cetacean survey in the NE Atlantic in Summer 2007. This provided an opportunity to test PAMGUARD detections and localisations against data collected concurrently by large teams of visual observers. Three vessels were used to survey waters between the shelf break and the 200 mile EEZ to the west of the British Isles and continental Europe.

3.1 METHODS

3.1.1 VISUAL SURVEY

During daylight hours, one pair of observers (the trackers) searched far ahead of the survey vessel with 7x50 and 25x100 binoculars. The second pair of observers (the primary platform) observed with the naked eye out to a distance of approximately 500 m. The aim of the trackers was to locate and track groups of animals before the primary observers could see them allowing the use of dual platform mark recapture line transect survey methods (Borchers *et al.*, 1998).

3.1.2 ACOUSTIC MONITORING

Each vessel towed a four element linear hydrophone array consisting of two pairs of hydrophone elements at 200m and 400m astern of the survey vessel with an inter pair spacing of 3m. Data from all four channels were recorded to hard disk at a sample rate of 192 kHz using an RME Fireface soundcard.

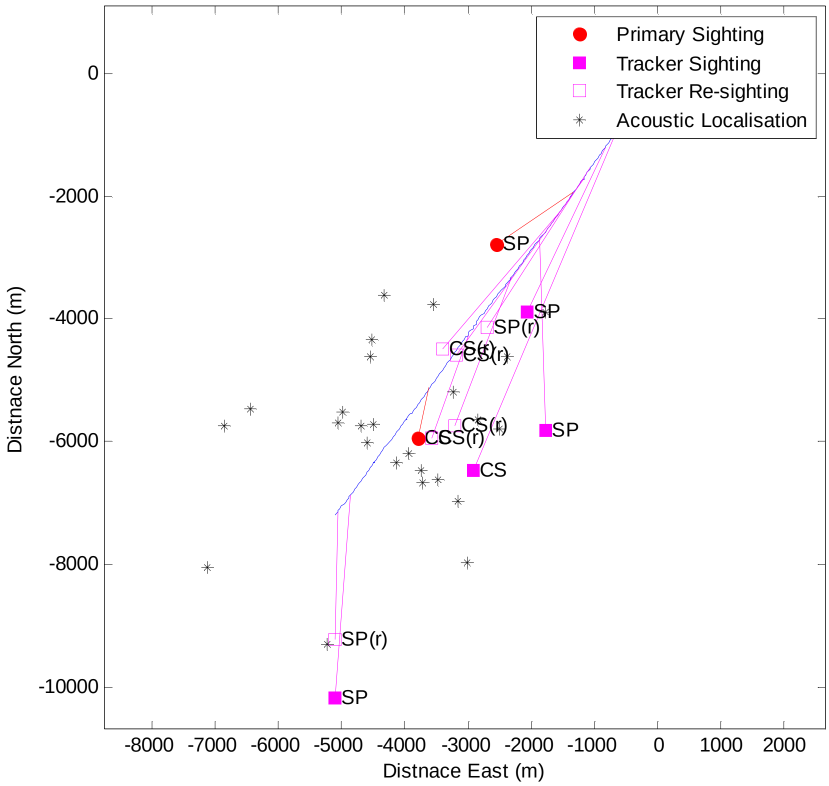

Figure 3. A typical encounter with a group of sperm whales and common or striped dolphins during a joint visual and acoustic survey showing the vessel track (heading south west), visual tracker and primary platform sightings and re-sightings and acoustic localisations from PAMGUARD. Sperm whales do not vocalise when they are near the surface and available to be sighted so that perfect correspondence between visual and acoustic locations would not be expected. Note that because a linear array was used here there is a left-right ambiguity in the acoustic data, and acoustic points are plotted on both sides of the vessel track-line. In this case the true locations are likely all to port.

Although PAMGUARD software was run online during the survey, here we concern ourselves solely with offline analysis of the acoustic data recorded at sea. A series of acoustic datasets, each approximately two hours long, were identified, each of which encompassed the sighting time of one or more sperm whales. Control data sets with no sightings were also selected. These were then analysed by a single acoustic analyst who was given a short training in the use of PAMGUARD and had no knowledge of what each dataset was likely to contain. Analysis was conducted with PAMGUARD configured so that acoustic data from files were analysed and played back to the operator in real time. The ship's GPS position was taken from a database of locations collected during the cruise and time aligned with the acoustic data. Thus, PAMGUARD looked and behaved exactly as they would have done during real time operation at sea. The operator viewed the displays and listened on headphones as they would have done at sea, making single "passes" through the blocks of data.

Acoustic detections and tracks of sperm whales were then compared to the sightings data to compare visual and acoustic detection and localisation data. Sperm whales mostly vocalise during long foraging dives. They typically start vocalising a few minutes after leaving the surface and cease vocalising as they begin their ascent (Gordon *et al.*, 1992; Watwood *et al.*, 2006) consequently we would not expect to hear individuals while they are visible at the surface

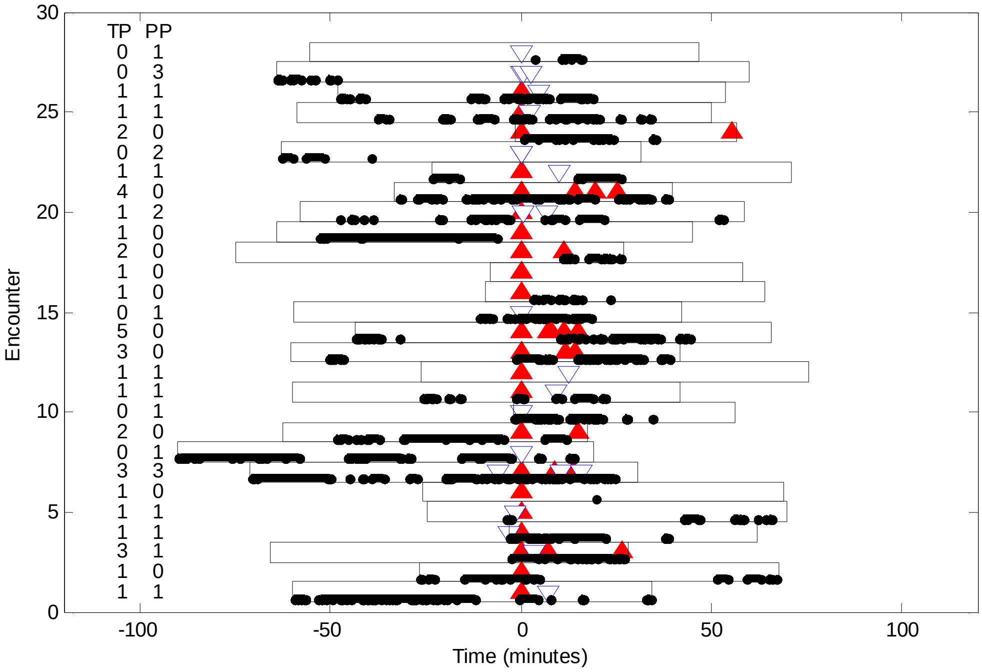

Figure 4. Visual and acoustic encounters with sperm whales during the CODA survey. Open rectangles represent periods of acoustic monitoring for each encounter. Solid red upward pointing triangles represent the times of tracker platform sightings and blue open downward pointing triangles the times of primary platform sightings. The solid lines represent times at which the acoustic operator was tracking one or more animals. Numbers to the left are the numbers of tracker and primary sightings in each encounter. Plots are aligned on the time of the first tracker platform sighting (or the first primary sighting if there were no tracker sightings) .

3.2 RESULTS AND DISCUSSION

The newly trained operator was quickly sufficiently proficient with PAMGUARD to be able to run and supervise the program in real time as it made detections of sperm whale click trains and plotted locations, even in situations where large groups were encountered and several whales were being tracked concurrently.

In all, 28 encounters with sperm whales were analysed. Each encounter containing between zero and five sightings from the tracker platform (mean = 1.36) and between zero and three sightings from the primary platform (mean = 0.82). Figure 3 shows a plot of visual and acoustic data from a typical sperm whale encounter. Figure 4 shows the times of primary and tracker sightings for each event along with times for which the acoustic system was being monitored and the times for which the operator was tracking one or more individual whales using operator assisted tracking.

No acoustic detections were made during two visual encounters (7 % of the total). One of these was a single tracker observation of a ‘diving sperm whale’ some 3.7 km ahead of the vessel. Fin whales were later spotted by both primary and tracker platforms when the vessel passed close to that location some minutes late. Thus, we cannot rule out the possibility of a misidentification of a distant animal by the tracker. On the other occasion, sperm whales were seen by both platforms at ranges varying between 1.5 and 3.2km. In this instance, misclassification seems less likely.

Sperm whales were generally heard before they were seen by either platform (**Figure 5**) although on a few occasions the tracker platform did spot whales before they were heard. This is to be expected for several reasons. The visual trackers were searching several km ahead of the vessel

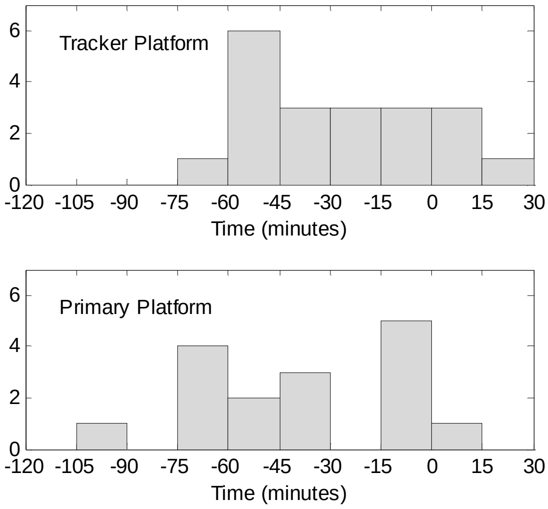

Figure 5. Time differences between first acoustic detection and first sighting by the tracker and primary observers. Negative times indicate that animals were heard before they were seen and positive numbers indicate that they were seen before being heard.

with high powered binoculars. Foraging sperm whales are silent for about 18 minutes in a typical 54 minute dive cycle (Watwood *et al.*, 2006). Finally, groups of sperm whales typically spend periods of several hours per day resting and socialising near the surface. During these periods they produce more complex vocalisations that do not propagate well and are rarely heard during towed hydrophone surveys.

Figure 4 shows that whales were often heard at the same time that they were seen even though whales rarely vocalise at the surface. This is because whales were encountered in large assemblages within which diving behaviour was not synchronised so that some individuals could be seen at the surface while others were still vocalising underwater. Hence, in most encounters, it has not been possible to match particular acoustic tracks to individual sighted animals. Most groups of whales were heard before they were seen confirming that acoustic detection is generally more efficient for this species even when such large visual effort is expended in good sightings conditions. There were a few occasions on which whales were seen but not heard. One of these may have been a visual misclassification however it is entirely to be expected that some sighted whales groups will not be detected acoustically. In good conditions observers equipped with powerful binoculars will detect some sperm whales at ranges of tens of kilometres beyond the acoustic range expected using hydrophones towed from noisy vessels. Other data on the proportion of groups that were heard and not seen are not yet available.

4 SUMMARY

In its current stage of development PAMGUARD provides a powerful, flexible and easy to use program for real time acoustic detection and localisation of cetacean vocalisations that combines the functionality of several previous software products and, in many cases, extends them. Thus PAMGUARD is well positioned to provide the standard tool for PAM during mitigation operations and towed hydrophone surveys. The emphasis of development so far has been mainly on cetacean detection but the software is sufficiently flexible to be used for many other acoustic detection and localisation tasks.

Perhaps of most fundamental importance is the programming environment that PAMGUARD offers to developers of new algorithms. The PAMGUARD API largely insulates algorithm developers from data handling tasks, making PAMGUARD an efficient development platform. It is this that promises to ensure PAMGUARD’s future as a viable and evolving product as programmers choose it as an efficient environment in which to develop new PAM functionality.

To date, PAMGUARD has primarily been developed to handle acoustic data. Many mitigation and survey applications combine both visual and acoustic data. The PAMGUARD API has been designed in such a way that it can be easily extended to handle visual data in the future. Clearly having both visual and acoustic data together within the same piece of software should greatly assist in the smooth running of both mitigation and survey applications.

Results from field trials indicate that PAMGUARD can provide useful real time information on the locations of whales in the vicinity of a moving vessel. However, not all whales vocalise all of the time, so PAM cannot be considered as a 100% effective method for detecting cetaceans.

5 ACKNOWLEDGEMENTS

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