TRACKING MARINE MAMMALS AROUND MARINE RENEWABLE ENERGY DEVICES USING ACTIVE SONAR

GORDON HASTIE

URN: 12D/328: 31 JULY 2013

This document was produced as part of the UK Department of Energy and Climate Change's offshore energy Strategic Environmental Assessment programme © Crown Copyright, all rights reserved.

SMRU Limited
New Technology Centre
North Haugh
ST ANDREWS
Fife KY16 9SR

www.smru.co.uk

Switch: +44 (0)1334 479100
Fax: +44 (0)1334 477878

Lead Scientist:	Gordon Hastie	
Scientific QA:	Carol Sparling	
Date:	Wednesday, 31 July 2013	

Report code: SMRUL-DEC-2012-002.v2

This report is to be cited as: Hastie, G.D. (2012). Tracking marine mammals around marine renewable energy devices using active sonar. SMRU Ltd report URN:12D/328 to the Department of Energy and Climate Change. September 2012 (unpublished).

Approved by:

Jared Wilson

Operations Manager

Photo credit (front page): R Shucksmith (www.rshucksmith.co.uk)

TABLE OF CONTENTS

TABLE OF FIGURES

1. NON TECHNICAL SUMMARY

1. Currently, there is a high level of uncertainty surrounding the environmental impacts of marine renewable energy devices on marine wildlife (particularly seals, whales, and dolphins). The principal concerns derive from the potential of physical injury to marine mammals through direct contact with moving parts of marine energy devices.

2. In recent years, there has been accelerated development of active sonar systems for the defence sector for sub-sea monitoring of potential security threats, and for fisheries research and management. This may provide a basis for monitoring close range interactions between marine mammals and energy devices.

3. In this report, we describe a program to develop a sonar system to provide a behavioural monitoring tool for marine mammals around marine energy devices that is accurate, user-friendly, and data efficient.

4. A 4-phase program involved collaborations between marine mammal specialists, marine renewable energy developers, and sonar engineers to develop a sonar system for the marine renewable industry. The overall approach was one of caution with key tests at each phase which had to be satisfied in order to progress to the subsequent phases

5. As part of Phase 1 of the project, a Request for Proposals (RFP) document was drafted and distributed to sonar manufacturers who were invited to provide a formal proposal for the development of a marine mammal sonar. A total of 5 proposals were received from sonar manufacturers and although all manufacturers offered solutions based on off-the-shelf systems, there appeared limited interest in investing internal R&D support to system development for this application; however, two manufacturers (BioSonics and Tritech) did provide a commitment to internal R&D to the project and these were included in subsequent testing.

6. It was important when developing the behavioural monitoring sonar that any observed behavioural responses could be attributed to the tidal turbine rather than to the sonar being used to measure it; there is the potential that low frequency components of the signals from sonar systems could be audible to animals and elicit behavioural reactions. Phase 2 of the project was therefore designed to measure potential behavioural responses by marine mammals to each sonar and interpret the significance of these.

7. The results of the behavioural response trials suggest that grey seals and harbour porpoises exhibit differing behavioural responses to the signals of each sonar system. Porpoises exhibited relatively subtle responses to the Tritech Gemini; in contrast, seals exhibited overt responses to the BioSonics DT-X by leaving the pool when the sonar was active.

8. In addition to the behavioural response trials, the range of audibility of the sonar signals was modelled to predict the ranges that different species would be likely to hear the signals in a tidal environment. Seals and harbour porpoises were predicted to be able to hear the

signals of the Tritech Gemini and BioSonics DT-X at ranges of approximately 60 and 4,000 metres respectively.

9. Given the results of the marine mammal behavioural response trials and the predicted ranges of audibility, there was a clear need to modify the acoustic properties of the BioSonics DT-X signal prior to any further development. Although signal modification was carried out, analysis of the modified signal suggested these were unsuccessful in sufficiently reducing the lower frequency components likely to be responsible for eliciting the observed responses; the decision was therefore made not to continue with development of this system.

10. Improvements to the Gemini system focused on the development of efficient classification algorithms to reduce data volumes and provide a probabilistic indication of the identity of individual targets; these included variables such as size, shape and swimming characteristics to determine valid marine mammal targets.

11. In order to develop classification algorithms sonar image data for some of the more abundant marine mammal species around the UK (grey and harbour seals, harbour porpoises, and bottlenose dolphins) were collected. Using this, a series of detection and classification developments were implemented in the Gemini software.

12. Results of the analysis of the software 'detection efficiency' suggest that there is a significant negative relationship between range and probability of detection; the probability of the software automatically detecting a seal was greater than 0.9 for ranges up to around 37 metres and dropped to below 0.1 at ranges greater than 56 metres. In the context of using this sonar as a behavioural monitoring tool, this appears to limit analysis of small marine mammal behaviour to ranges of approximately 40-50m.

13. To provide an assessment of the software 'classification capabilities', the classification probabilities for each of the confirmed targets and the unidentified targets were analysed. The majority of classification probabilities for confirmed seals were '*Probable*' and '*Potential*'. However, both the unidentified targets and confirmed debris also had a relatively high proportion of '*Potential*' and '*Probable*' classifications assigned to them. These results highlight the scope for behavioural monitoring using active sonar but also highlight the current limitations in terms of species ID.

14. To evaluate the long term reliability and detection capabilities of the sonar on an operational tidal turbine, a Gemini system was deployed on the SeaGen tidal turbine in Strangford Lough. A single Tritech Gemini sonar transducer was attached to a mounting plate and secured to the centre of the crossbeam of the turbine, facing south towards the seaward end the Narrows. Sonar images were collected on a total of 42 days between the 20th May and 29th July 2011. Only data collected during the flood tide (i.e. the sonar was facing the incoming tide) were used in analysis.

15. The data were then analysed post-hoc using the developed software to determine what proportion of targets were classified as marine mammals with a high probability and their proximity to the turbine. In addition, the temporal variation in the number of 'marine

mammal' targets were analysed in a General Additive Modelling framework to assess how 'time of day', 'tidal speed', and turbine operation (ON/OFF) influenced the number of marine mammals around the turbine.

16. The results of the deployment suggested that there were 109 'high probability marine mammals' in the data. A manual review of the data associated with these 'marine mammal' detections appeared to confirm that they were marine mammals with only 3 of the targets being obviously non-marine mammals. The detection rate of 'high probability marine mammals' was approximately 5.9 per day.

17. The ranges that 'marine mammals' were detected at Strangford Lough suggest that marine mammals do move in close proximity to the tidal turbine both when it was operational (minimum range=9.9m) and non-operational (minimum=8.4m).

18. The results of the modelling of 'marine mammal' detections with the temporal covariates suggested that the occurrence of 'marine mammals' changed with time of day. Detections generally decreased during early morning with a minimum at approximately 0500. In contrast, there was no significant variation in 'marine mammal' detections in relation to tidal speed and turbine operation (ON/OFF).

19. In terms of future sonar development work, the automated classification algorithms are currently highly conservative and the reduction of these to 'high probability marine mammals' requires post hoc analysis; this feature could either be incorporated into the existing software or an additional classification module could be developed to analyse the detection and track data. Furthermore, validation of marine mammal detections around a tidal turbine [through visual observations or by tagging seals with high resolution movement tags (e.g. Wilson et al., 2007b)] would be of clear benefit. In terms of measuring fine scale behaviour of animals around tidal turbines, the system developed here does not currently provide data on the depth of the targets and although there are deployment configurations (e.g. using more than one transducer in different orientations) that could address this to a certain extent, the development of a true 3D sonar system would be highly beneficial for measuring tracks of marine mammals around turbines.

2. INTRODUCTION

Currently, there is a high level of uncertainty surrounding the environmental impacts of marine renewable energy devices on marine wildlife (particularly seals, whales, and dolphins). This has the potential to curtail acceptance of new proposals, and can create barriers to commercial introduction of the technology. The principal environmental concerns derive from the potential of physical injury to marine mammals through direct contact with moving structures of marine energy devices.

Due to the infancy of the industry, there is very little direct monitoring of animal movements around tidal turbines; limited data exist from commercial demonstrator projects such as SeaGen in Strangford Lough (http://www.seageneration.co.uk/). However, interpretation of these data can be challenging due to legislative mitigation requirements to shut down the turbine when marine mammals are observed in close proximity to the turbine, and use of the data to make predictions about other tidal sites or species is limited. Recent studies have therefore focused on the development of theoretical frameworks to predict the risk of collisions by marine mammals with tidal energy devices (e.g. Wilson et al., 2007a); within these it is highlighted that marine mammals are likely to show behavioural responses to the presence of marine renewable devices. Despite this, with the paucity of empirical information to quantify responses, there is a clear need for research into the behaviour of animals around devices. However, measuring the underwater behaviour of marine mammals can be extremely challenging and there is a clear need for an efficient underwater monitoring system to detect and track animals around devices in order to safeguard against such injuries.

Available methods for measuring animal movements underwater are limited; animal borne instrumentation is a technology that is increasingly used to track individuals underwater and can provide data on 3D movements in very high resolution (e.g. Madsen et al., 2002; Tyack et al., 2011). However, when the focus of the study is the movements of animals around a particular location, the use of animal tags can be impractical due to the wide ranging and highly mobile nature of marine mammals, and the requirement for the animals to be in the vicinity of the location of interest. Furthermore, logistical challenges associated with catching wild animals and the financial costs involved can often limit sample sizes, and when coupled with high inter-individual variability in behaviour can result in low statistical power when measuring behavioural responses. Passive acoustic techniques are increasingly being used to locate and track cetaceans underwater (Clark et al., 1985; Freitag and Tyack, 1993; Janik et al., 2000; Jensen and Miller, 1999; Leaper et al., 1992); arrays of hydrophones (which could be relatively easily mounted on tidal devices) can be used to record vocalisations of free ranging animals and the differences in arrival times of each sound is used to calculate the location of the vocalising animal. Although this potentially works well for vocally predictable species (e.g. harbour porpoises), it is not suitable for those that produce little or no sound (e.g. seals, fish, or diving birds). Underwater video technology has been used to a limited extent to image animals underwater (e.g. Davis et al., 1999; Herzing, 1996; Ridoux et al., 1997; Simila and Ugarte, 1993) and record their behaviour; however, this has generally been relatively short range and has been carried out during daylight hours in waters with good visibility. In most tidal areas around the UK, low visibility due to suspended sediment or relatively long periods of darkness are likely to severely constrain the use of video.

In recent years, there has been accelerated development of active sonar systems for the defence sector for sub-sea monitoring of potential security threats, and for fisheries research and management. Many of the systems now on the commercial market have the capacity to build up an acoustic image of sub-sea moving objects in areas with low visibility prevent the use of video. For example, Nottestad et al (2002) used a 95kHz Simrad SA 950 multibeam sonar to measure the behaviour of fin whales (*Balaenoptera physalus*) foraging on herring schools, Similä (1997) used a Reson SeaBat 6012 to image killer whales feeding on herring, and Benoit-Bird & Au (2003b) used a Tournament Master Fishfinder NCC 5300 to integrate the behaviour of spinner dolphins (*Stenella longirostris*) and their prey. Furthermore, Benoit-Bird & Au (2003a) used a Kongsberg SM2000 to locate and track spinner dolphins in the water column in Hawaii. More recently, West Indian manatee behaviour was measured in waters with very poor visibility (due to turbidity and sediment load) using a range of side scan sonar systems (Gonzalez-Socoloske et al., 2009; Gonzalez-Socoloske and Olivera-Gomez, 2012).

Recent research showed that a new generation of imaging sonar systems have the capacity to produce acoustic images of marine mammals, and may provide a basis for monitoring close range interactions between marine mammals and energy devices (Hastie, 2008). An assessment of commercially available sonar systems concluded that a limited number of systems may be suitable for tracking marine mammals around marine energy devices. However, after the series of tests, it was clear that none of these systems were ideal, and there were currently a number of technical (either hardware or software) issues that limited their suitability for detecting and tracking marine mammals around energy devices (Hastie, 2008). Despite this, it was anticipated that such technical issues are likely to be relatively minor problems that could be remedied if technical R&D was committed from the sonar manufacturers involved.

Here we describe a program to develop a sonar system that would provide a behavioural monitoring tool for marine mammals around marine energy devices for monitoring around tidal energy turbines that is accurate, user-friendly, and data efficient.

PROJECT SCOPE

The 4-phase program involved collaborations between marine mammal specialists, marine renewable developers, and sonar engineers to develop a user-friendly sonar system for the marine renewable industry. The overall approach was one of caution, and to that end key tests were identified at each phase which had to be satisfied in order to progress to the subsequent phases (Figure 1).

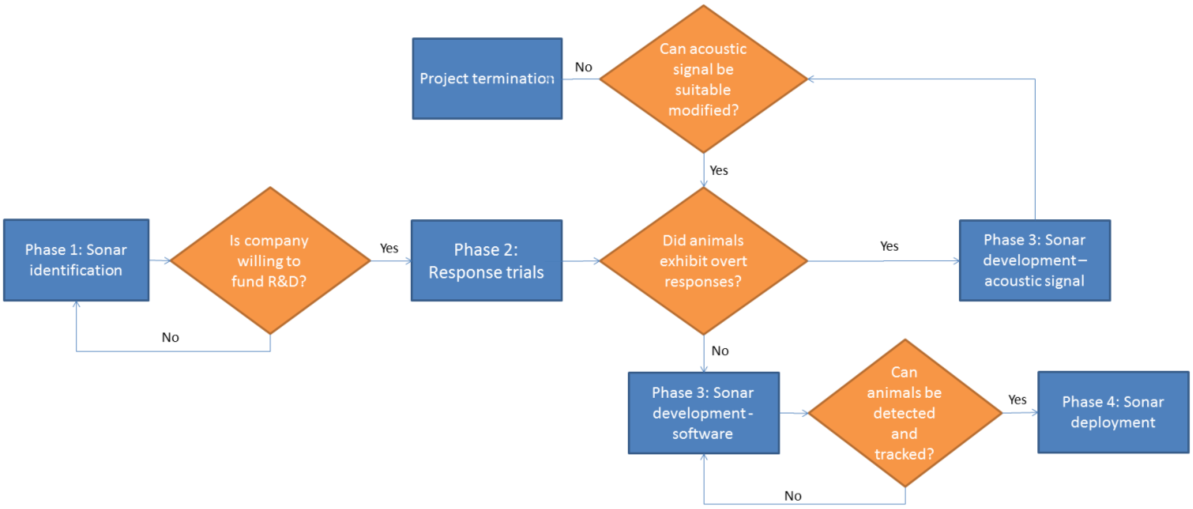


Figure 1: Schematic showing the phases of the program and the key tests which determined whether to proceed to the next phase.

Phase 1: Sonar identification

Initially, we carried out a data compilation phase to identify the requirements of a generic sonar monitoring system for the renewable energy industry and provide a shortlist of sonar systems that met these criteria. Suitable sonar manufacturers were then contacted and asked to formally commit to a period of R&D to develop a suitable system. A research collaboration was then initiated with manufacturers whose system met on-paper specifications and who expressed a willingness to collaborate and upgrade their system to suit the specific needs. This potentially included changing the hardware specifications (e.g. spatial coverage of scan, image resolution), or upgrading the software (e.g. automatic recognition and tracking of marine mammals) and user interface.

- Requirements to proceed to Phase 2: At least one sonar company expressed a willingness to develop a suitable system.

Phase 2: Marine mammal response tests

There was then a series of formal trials with captive seals at the Sea Mammal Research Unit captive seal research facility to test the system prior to any further development and subsequent field deployment on a marine renewable energy device. These trials were designed to provide a test of the reliability of the detection capabilities of the system in a controlled environment. Furthermore, many sonar systems have low frequency sound components which may be within the hearing range of marine mammals; monitoring with the sonar could be compromised if the animals were able to detect the presence of the sonar with the possibility that there could be either avoidance of, or attraction to, the sonar itself. Therefore, behavioural responses by seals to the sonar signals were also evaluated at this stage of the project. We also aimed to test the sonar systems on captive harbour porpoises at an equivalent facility in Denmark. This phase of the project was conducted in close collaboration with the device suppliers in the event that any hardware changes to the system were required for the proposed application. Evaluation included (a) the capacity of the sonar to detect and identify marine mammals at a series of ranges and (b) the capacity of marine mammals to detect the presence of the sonar.

- Requirements to proceed to Phase 3: 1) Developed sonar system should be able to detect marine mammals at a suitable range, and 2) seals and porpoises should not exhibit unacceptable (e.g. overt startle responses or approaching the sonar) behavioural responses to the developed sonar signals.

Phase 3: Sonar development

A period of development and upgrading was then initiated between the selected sonar manufacturer, SMRU Ltd and developers based on the findings in the previous phase.

- Requirements to proceed to Phase 4. Development to the required specifications was carried out by the sonar manufacturer.

Phase 4: Sonar testing and deployment

Once the sonar system was successfully upgraded, it was deployed at a marine energy device. This was designed to ensure that the upgraded system was robust enough to operate in a turbulent tidal environment, was user friendly, and met the renewable industry needs. This also allowed users of the sonar to provide feedback on the system functionality and ease of use. After the initial series of tests described above, the upgraded sonar was deployed on a marine energy device for a period of several months to evaluate the efficiency and reliability of the system over an extended period. This included tests of the capabilities for detection and tracking of marine mammals in a tidal environment.

3. PHASE ONE: SONAR IDENTIFICATION

As part of Phase 1 of the project, an active sonar inventory was compiled; the list details 228 systems from 39 sonar manufacturers and includes summary specifications for each system and full contact details (where available) for each manufacturer (Sections 10 and 11). Each system was given a system type and included single beam echosounders (119), multibeam bathymetry (17), multibeam imaging (44), single beam manual scanning (35), and towed multibeam (12). Fundamental transmission frequency, together with secondary or tertiary frequencies (in multi-frequency systems) was reported and ranged from 12 to 2,250 kHz. Source level was provided by manufacturers in 99 of the systems and ranged from 187 to 237 dB re 1 µPa at 1m. The software available for the sonar systems included automated target detection and tracking software in 24 systems; it should be highlighted that these were generally designed for vessel or port security rather than for marine wildlife tracking.

To assist in the development of a bespoke marine mammal detection sonar, a Request for Proposals (RFP) document was drafted (Section 12) and distributed to sonar manufacturers who were invited to provide a formal proposal for the development of a marine mammal sonar. The document detailed hardware and software specifications required for the sonar to detect marine mammals and potentially other marine wildlife (e.g. diving birds). The document included information on proposal format, deadline dates, proposal review process, and points of contact. A formal process involving a DECC project steering group was established to review the RFP responses.

A total of 5 proposals were received from sonar manufacturers (Qinetiq, Reson, Biosonics, Didson, and Kongsberg). Although all manufacturers offered solution based on off-the-shelf systems, there appeared limited interest in investing internal R&D support to system development for this application; however, BioSonics (http://www.biosonicsinc.com/) did provide a commitment to internal R&D to the project. It should be highlighted that since the RFP was distributed, correspondence has been maintained with a number of manufacturers to ensure that any new developments are represented in this program; the project was approached at a later date by another manufacturer [Tritech (http://www.tritech.co.uk/)] that expressed a willingness to provide the developments to their multibeam technology required for this application and their system was therefore included in subsequent testing.

In addition to the systems above, a further system (CodaOctopus Echoscope 2; http://www.codaoctopus.com/) was available for testing during the project and although the manufacturer did not commit to providing R&D for this study, this system was included in the review and behavioural response trials stages of the project.

BIOSONICS DT-X

HARDWARE DETAILS

The BioSonics DT-X is a split beam scientific echosounder; this consists of a 200 kHz transducer with a narrow (10^o cone) highly focused beam, which could potentially detect marine mammals up to around 100m. The system uses a PC controlled rotator to achieve a larger spatial coverage area and because the system uses a “split beam”, it is possible to locate targets in the vertical plane as well as the horizontal, effectively allowing 3D tracking of targets.

The underwater transducer sensor connects through a high speed digital signal cable to a surface mounted echosounder transmitter unit installed in an instrument compartment or sealed canister. A cable conduit is added to provide protection for the digital signal cables. The system requires 30 watts of 12 volts DC or 110-240 Volts AC and an Ethernet connection to the system control PC; Ethernet connection can be via fibre-optic or wireless system. The control PC can thus be located at a remote site and receive data through this Ethernet link, reducing the in-water power requirements.

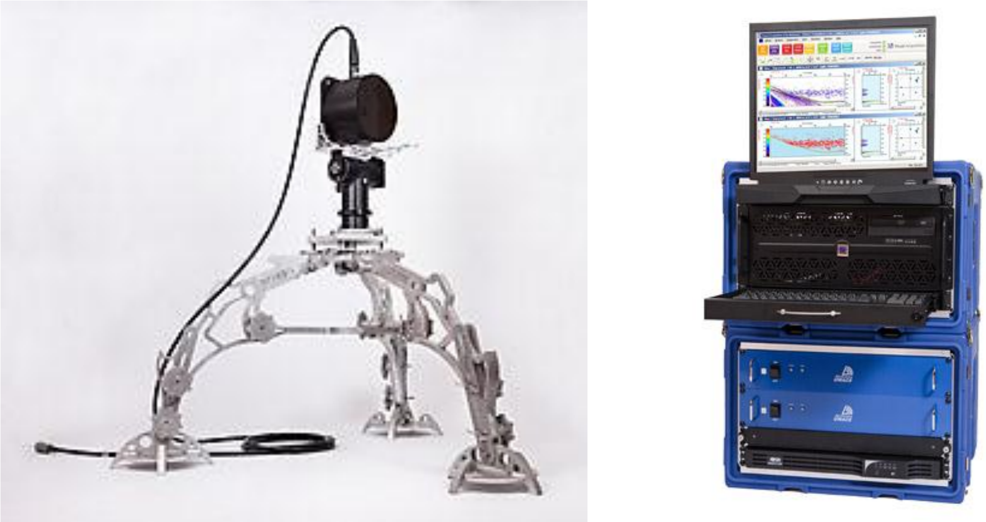


Figure 2: BioSonics DT-X hardware including the transducer (left) and topside communications, processing, and power unit (right) (image courtesy of BioSonics Inc.).

BioSonics provided a spectrum of the DT-X transmit signal (Figure 3); this shows the clear peak in source level (around 220 dB re1 µPa at 1m) at 200 kHz. Furthermore, measurements appear to show that source levels at lower frequencies are relatively high; at frequencies between 30 and 110 kHz, source levels range between 130 and 170 dB re1 µPa at 1m.

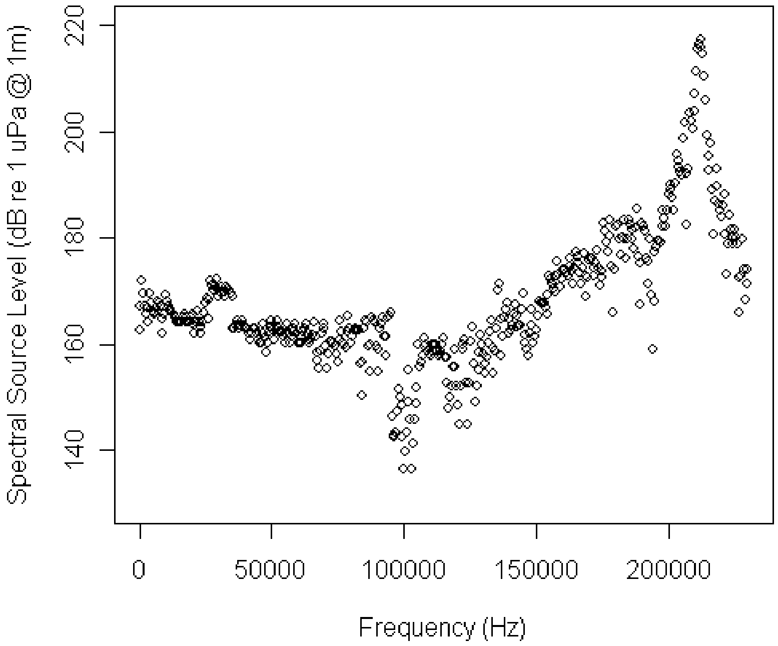


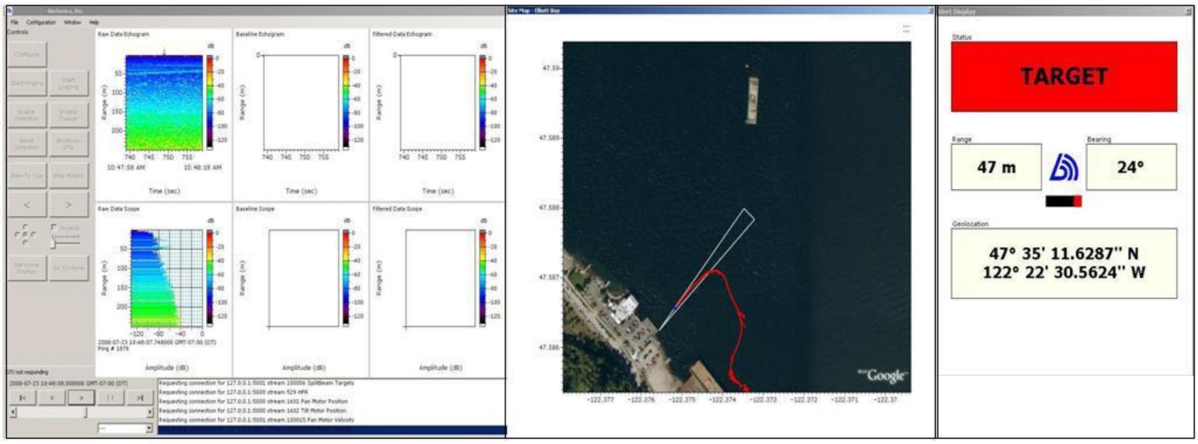
Figure 3: Spectrum of the transmit signal of the BioSonics DT-X; the signal exhibits a peak of around 220 dB re1 µPa at 1m at 200 kHz and ranges between approximately 130 and 170 dB re1 µPa at 1m at frequencies between 30 and 110 kHz (data courtesy of BioSonics Inc.).

EXISTING MARINE WILDLIFE TRACKING SYSTEM

BioSonics has an existing tracking system that was designed to detect and track marine wildlife including marine mammals. The system has relatively high instantaneous dynamic range (160 dB) and short operator-controlled pulse durations (0.1 to 1 ms) are implemented to optimize range resolution. The data stream is routed to analysis software, which extracts target tracks and sends them to a classifier algorithm. If water velocity data are available, net target velocity is also calculated. Real-time analysis is designed to allow determination of specific events, such as detection of a target of certain size within a specified range and moving closer. This determination is translated via BioSonics Target Tracking software into a signal to an operator, or to an automated response.

The tracking system uses two software suites; one which controls the real-time data collection functions in the embedded PC (LINUX operating system), and the other that provides the user interface and tracking processing (C++) (Figure 4). Raw acoustic data and processed results can be archived automatically with file names labelled with date/time. The tracking system also contains “watchdog” software, which monitors performance of the acoustic system and the file writing, and can re-boot the system if a system lockup occurs. The automated tracking system writes an alert message to file and could be expanded to send a signal or message out through USB or Ethernet to an operator or to the turbine control system.

Although this system had previously been used to detect seals, sea lions, killer whales, fish, and diving seabirds in several local research projects (BioSonics, pers. comm.), the efficiency of the detection and classification software had not been fully verified.



```
Requesting connection for 127.0.0.1:5001 stream 100006 SplitBeam Targets
Requesting connection for 127.0.0.1:5000 stream 529 HPR
Requesting connection for 127.0.0.1:5000 stream 1601 Pan Motor Position
Requesting connection for 127.0.0.1:5000 stream 1602 Tilt Motor Position
Requesting connection for 127.0.0.1:5001 stream 100015 Pan Motor Velocity
```

Status: TARGET

Range: 47 m

Bearing: 24°

Geolocation: 47° 35' 11.6287" N 122° 22' 30.5624" W

Figure 4: User interface of the BioSonics tracking system; the display includes a map of the target track and a series of acoustic plots (image courtesy of BioSonics Inc.).

TRITECH GEMINI

HARDWARE DETAILS

The Tritech Gemini is a 720kHz forward looking multibeam sonar (Figure 5) that is designed for detecting objects in the water column. It is a 2D system that allows detection and localisation of objects in the X-Y plane but does not provide information on the depth of the target. The image update rate of the sonar is between 7 and 30Hz which appeared adequate for marine mammal tracking, the angular range resolution is 0.5^o and the range resolution is 0.8 cm which is relatively high and potentially good for target/species discrimination. The horizontal and vertical swathe widths of the Gemini are 120^o and 20^o respectively and up to 4 heads can be synchronised by pinging in sequence.

For long term deployments, a titanium housed version of the system is available in the deep rated system (720id). Raw data files have relatively large data volumes at present (1 GB per 7 minutes of data) and it is clearly impractical to store long periods of data in a monitoring study. Achievable VDSL data rates (dependent on length and quality of twisted pair) are 50Mbps (cabling <500m), and 20Mbps (cabling 1km). Typical power consumption of the Gemini is 39 watts per unit.

A spectrum of the Gemini transmit signal (Figure 6) illustrates a clear peak in source level (around 198 dB re1 µPa at 1m) at 720 kHz with source levels at lower frequencies (between 30 and 110 kHz) ranging between 105 and 129 dB re1 µPa at 1m.

Figure 5: Tritech Gemini hardware including the transducer (right) and topside communications and power unit (left).

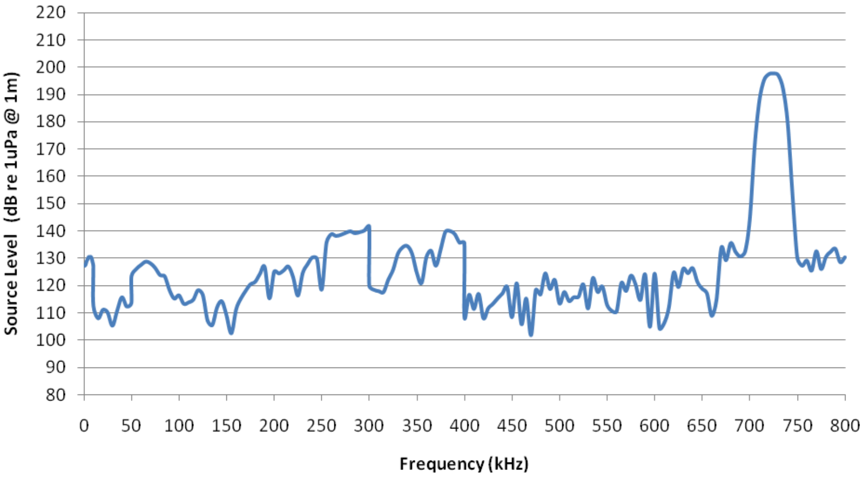


Figure 6: Spectrum of the transmit signal of the Gemini; the signal exhibits a peak of around 198 dB re1 µPa at 1m at 720 kHz and ranges between 105 and 129 dB re1 µPa at 1m at frequencies between 30 and 110 kHz (data courtesy of Tritech International).

EXISTING MOVEMENT DETECTION SYSTEM

Tritech Gemini software included a rudimentary system for detecting movement in a marine environment that performed basic detection of moving targets that could initiate automatic logging of sonar data. Targets were classified according to their size, range, target strength and persistence. Figure 7 provides a summary of the basic processing flow of movement detection in the movement software.

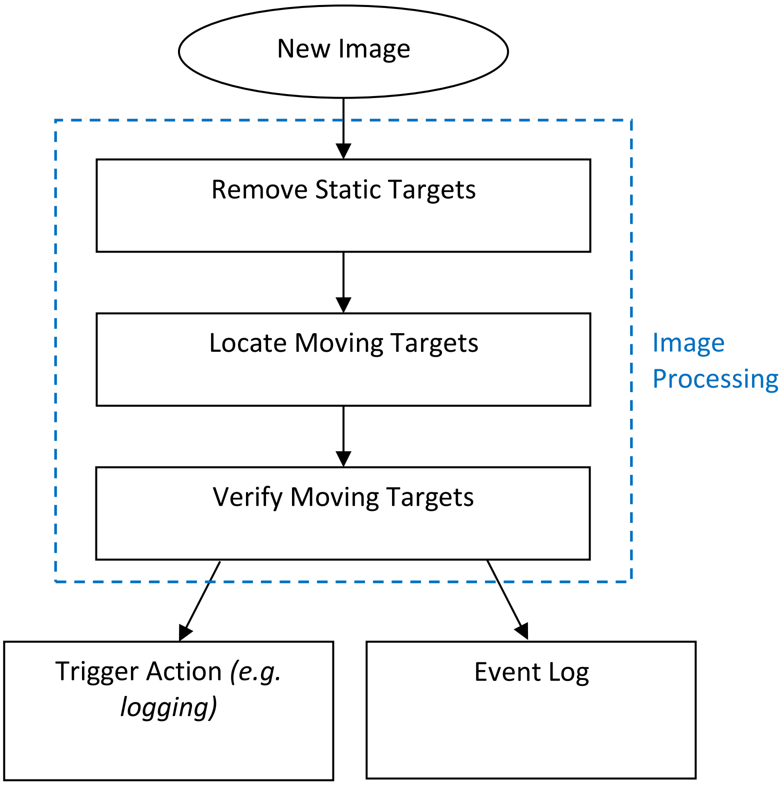


Figure 7 Movement Detection processing flow for the existing Tritech Gemini Movement Detection software (image courtesy of Tritech International).

- **Remove Static Targets**.
  Each sonar ping creates an image (or frame). Each pixel (picture element) is a cell that contains a sonar intensity value for a particular point (range and bearing) in the image. Static targets are identified by using a series of images that are accumulated to create an average frame. Images have their intensity values reduced, or faded, before being accumulated. Each accumulation frame is calculated using faded versions of both the previous average image and the current new image and the final displayed image is then calculated by subtracting a scaled version of this average frame from the new image.

- **Locate moving targets.**
  After removing static objects, each frame is searched for significant targets. A significant target is identified as a collection of high intensity samples using a Flood Fill process; this examines a high intensity sample's extended neighbourhood stopping when it reaches areas where intensity values drop below a pre-defined level. This identifies blocks that are potential targets.

- **Verify moving targets.**
  Flood Filled targets are checked for overlap with previous sonar images. If a target appears in more than one frame it is more likely to be a valid moving target; if no overlap is detected a target is identified as transient. The number of points (pixels) in the target that exceed a detection intensity threshold is required to be above a certain value to be classed as valid. The dimensions of the target should be within a valid user-defined size range. If all of the above tests pass the target is considered a valid moving target.

- **Actions performed when movement is detected.**
  The user can specify the action to be performed upon movement detection:
  - **Do nothing**.
  - **Start logging**: the software will automatically start logging and will continue until a user specified time after the last movement detected.
  - **Pause player**: stop playback of a log file to allow closer inspection of the sonar image.

CODAOCTOPUS ECHOSCOPE 2

HARDWARE DETAILS

The CodaOctopus Echoscope 2 is a 375kHz forward looking multibeam sonar that is designed for detecting objects in the water column (Figure 8). It is a fully 3D system that allows detection and localisation of objects in the X-Y-Z plane. The Echoscope 2 has 128 vertical beams and 128 horizontal beams that ensonify a volume of approximately 50^o x 50^o. The image update rate of the sonar is up to 12Hz which appeared adequate for marine mammal tracking (Hastie, 2007), and the range resolution is 3 cm. Internal motion sensors (attitude, pitch and roll sensors: accuracy <0.5°) enable the image data to be positioned accurately in 3D space.

Figure 8: CodaOctopus Echoscope 2 transducer (image courtesy of CodaOctopus).

The underwater transducer connects through an RS232 and ethernet cable to a surface mounted (or submerged) echosounder control unit; this is then connected to a PC via Ethernet. The control PC can therefore be located at a remote site and receive data through this Ethernet link, reducing the in-water power requirements. Typical power consumption by the Echoscope 2 is approximately 3-6A at 24Vdc.

EXISTING SOFTWARE

CodaOctopus Echoscope 2 software includes a comprehensive real time 3D display (e.g. Figure 9) and control software suite including information on viewing angle, transmit power, receive amplification. It provides the ability to position the users' viewpoint and centre of observed volume arbitrarily within 3D space, to generate movies of real time 3D data, and to create mosaics of sonar image data using external motion sensors. There is currently no target tracking capability in the software and no immediate plans to implement this by the manufacturer; this system is therefore limited as a basis for an automated marine mammal tracking system. However, as described above, this system was available for testing during the project and it was therefore included in the review and behavioural response trials stages of the project.

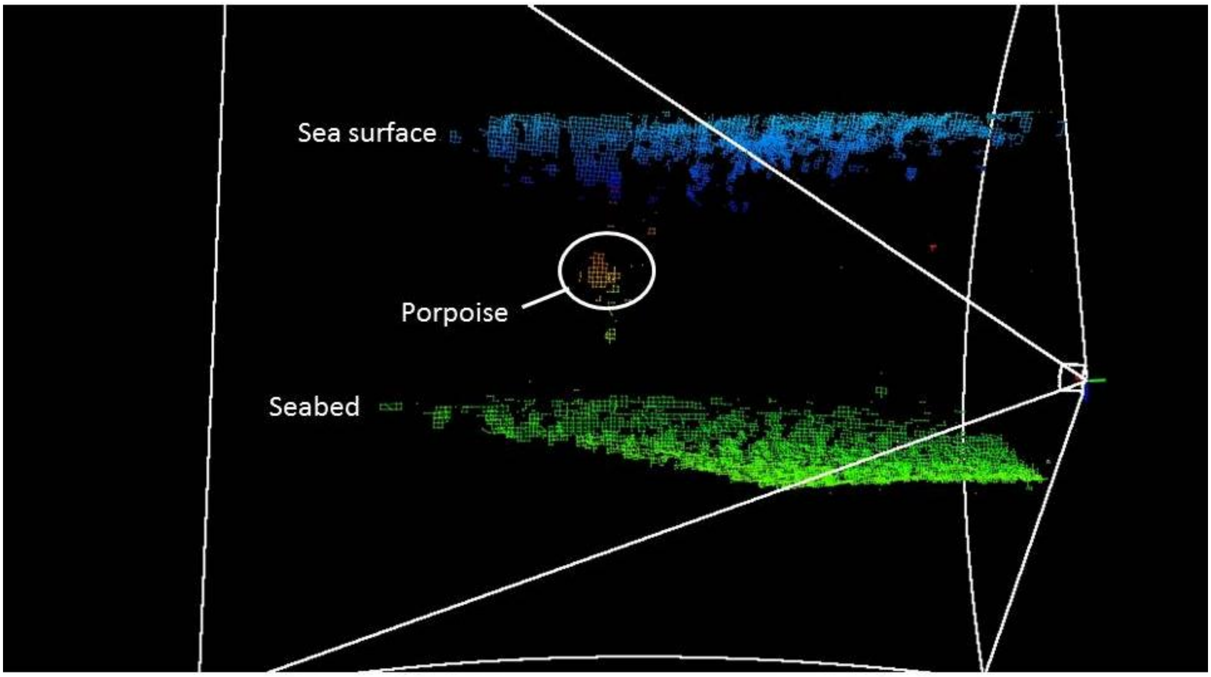


Figure 9: 3D image from the CodaOctopus Echoscope 2 showing the seabed, sea surface and a porpoise mid water.

4. PHASE TWO: MARINE MAMMAL RESPONSE TESTS

INTRODUCTION

Most marine mammals rely heavily on sound as a means of navigation, and for detecting prey, and the hearing and vocal ranges of many species (Richardson et al., 1991) overlap with the transmission frequencies of many commercial sonar systems (approximately 12 to 150 kHz). Therefore, there is a clear potential that the acoustic signals produced by sonar systems, could cause a range of negative impacts from auditory injury (Southall et al., 2007) or changes in behaviour (for review see Richardson et al., 1991) to interference of communication (e.g. Fristrup et al., 2003). Although interest in impacts of sonar has focused on relatively low frequency systems with fundamental transmission frequencies within the hearing ranges of marine mammals (Tyack et al., 2011), there is the potential that low frequency components of the signals from sonar systems with higher fundamental transmission frequencies could be audible to animals and elicit behavioural reactions.

This is particularly important when developing a monitoring tool which is designed to measure behavioural responses. I.e. it is important that any observed behavioural responses can be attributed to the tidal turbine rather than to the sonar being used to measure them. Furthermore, monitoring using sonar could be compromised if the animals are able to detect the presence of the sonar with the possibility that there could be attraction to it. To address this, we carried out a series of behavioural response tests with captive grey seals and harbour porpoises to assess whether there were overt behavioural reactions to the sonar systems and carried out a modelling exercise with the sound characteristics of the sonar and a tidal turbine to predict how far each system could be heard by different marine mammal species.

METHODS AND RESULTS

Behavioural response trials were carried out with grey seals at the Sea Mammal Research Unit (http://www.smru.st-andrews.ac.uk/) holding facility with 2 sonar systems (Biosonics DT-X and CodaOctopus Echoscope 2) and with harbour porpoises at the Fjord & Bælt Aquarium (http://www.fjord-baelt.dk/), Denmark with the Tritech Gemini and the CodaOctopus Echoscope 2. These two species were chosen as they represented both a low (grey seals) and high (harbour porpoises) frequency marine mammal hearing group, thus providing a range of hearing capabilities within which most species around the UK would fall. It should be noted that due to availability of experimental animals, it was not possible to test the Tritech Gemini with seals; furthermore, due to animal welfare issues, the BioSonics DT-X system could not be tested with harbour porpoises (due to high noise levels produced by this system). This was clearly not ideal for assessing behavioural responses by the different species; however, we did have access to a CodaOctopus Echoscope 2 for both species and although it was not one of the shortlisted systems in this project, it provided a useful comparison between species.

GREY SEALS: METHODS

A total of 4 experimental response trials were carried out with the sonar systems (a single experimental trial was carried out with each of the sonar systems with each of two grey seals). The seals used in the trials were housed temporarily in SMRU holding facility having been caught in the wild from local haul-out sites. Seals were released back into the wild after a maximum period of one year[2]. Descriptions of each of the grey seals used in the trials are presented in Table 1.

Table 1: Grey seals used in the sonar behavioural response trials at the SMRU holding facility; details include age class, sex, mass (where available), and the time each had been in captivity prior to the trials.

Seal	Age	Sex	Mass (kg)	Time in captivity
Gabi	Adult	F	NA	10 months
Hannah	Juvenile	F	NA	10 months
Therese	Juvenile	F	24.6 - 30.2	4 months
Ulrika	Juvenile	F	33.0 - 36.4	4 months

During each trial a single grey seal was permitted to swim freely throughout a large experimental pool. The dimensions of the pool were approximately 42m long x 6m wide x 2.5m deep (Figure 10). Aluminium mesh panels approximately 0.2m below the water surface covered the majority of the pool. However, four of the mesh panels were removed to allow the seal access to the surface in one of these four holes. A mobile crane was used to lower the sonar head into position approximately 1.5m below the surface in surfacing hole 1 at one end of the holding pool. The remaining surfacing holes were located at a range of distances from the sonar head (2 = 9m, 3 = 23m, and 4 = 36m).

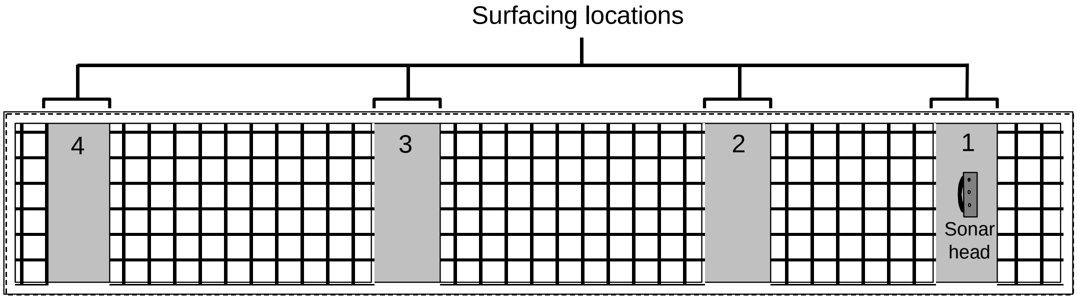


Figure 10: Equipment setup to evaluate behavioural responses of seals to the signals produced by the Echoscope 2 and the BioSonics DT-X in the SMRU holding seal facility. The figure shows a plan of the experimental pool (42m long x 6m wide). Aluminium mesh panels were placed approximately 0.2m under the water surface across the majority of the pool. Four of the mesh panels were removed, limiting each seal to surfacing in these holes (1-4) or hauling out on the side of the pool (5).

Two sonar systems were used for the seal behavioural response tests; both (BioSonics DT-X and CodaOctopus Echoscope 2) are described in detail in Section 3 (Phase one). Acoustic recordings of the CodaOctopus Echoscope 2 signals were made using a Reson 4034 hydrophone with an ETEC amplifier and an NI-PCI 6251 digital acquisition system to a laptop computer at sample rates up to 500 kHz. Post-hoc analyses of the recordings were carried out using the acoustic analysis software package Cool Edit Pro 2.0 to measure the sound characteristics of the signals produced. This sonar

---

[2] The study was conducted under Home Office licence numbers 60/2589 and 60/3303.

unit produced acoustic pulses approximately 90 µsec in duration, at a rate of 10 Hz. The results of the high frequency recordings showed that, despite the transmission frequency of this unit being 375 kHz, there were marked low frequency components of the signal down to 6 kHz (Figure 11). Maximum peak-to-peak source level measurements of the sonar signals were 205 dB re 1µPa at 1m at the sonars fundamental frequency (375kHz).

The sonars were controlled from a PC located in a laboratory adjacent to the experimental pool and the swimming and surfacing behaviour of the seals was recorded using a video camera located above the pool and was monitored visually by the sonar operator. To ensure that the seals did not respond to secondary external stimuli, no persons were visible to the seals throughout the trials, and noise was kept to a minimum. Furthermore, to help ensure that seals did not exhibit a protracted response to initial equipment set-up during the tests, we did not initiate each test for a period of 30 minutes after equipment set-up. It should also be noted that, although each had been used in sound reaction tests previously, the two seals used in the tests were initially naïve to the sonar signals.

Each experimental test consisted of a 90 minute observation period during which the sonar signals were turned on and off for alternating ten-minute periods; this period was designed to maximise the number of treatment periods (ON/OFF) whilst ensuring that, based on mean dives times [mean dive duration =5.3±1.8 minutes (Sparling and Fedak, 2004)], the probability of an animal surfacing within a period was high. A series of behaviour parameters were measured continuously throughout the trials and included the proportion of time spent at the surface in the pool and hauled out on the poolside, the locations of the seals when they were at the surface, and the occurrence of any behaviours at the surface that may have indicated a response (rapid swimming, splashing at the surface, hauling out at the side of the pool); these metrics were designed to provide a measure of potential avoidance or attraction to the device.

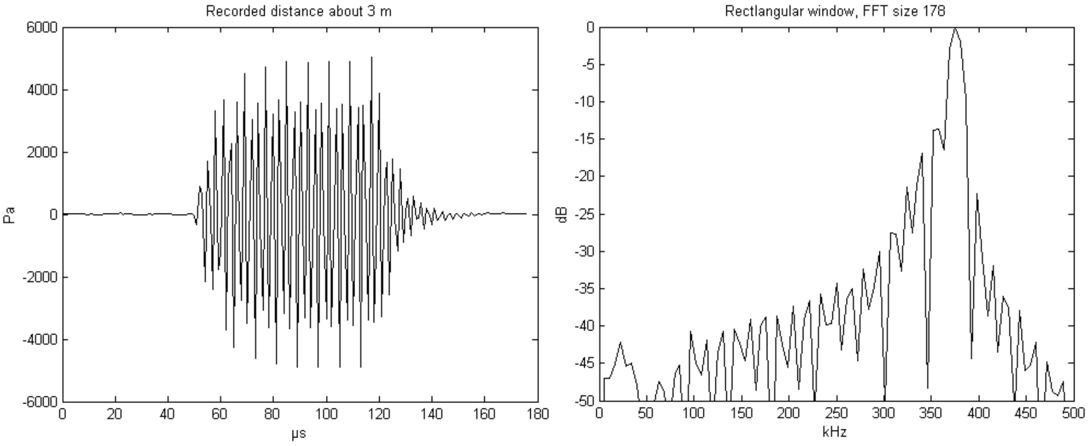


Figure 11: Waveform (left) and spectrum (right) of the CodaOctopus Echoscope 2 sonar signals. The SPL at the fundamental frequency of the signal (375 kHz) was estimated to be 195 dB re 1µPa at 1m.

The responses of the seals to the experiment were modelled as a multinomial Generalized Linear Model fitted using Generalized Estimating Equations (Liang and Zeger, 1986; Yan and Fine, 2004) to account for repeated measures on the same animals. The modelled response was the surfacing location of the animal within the pool, where positions 1 through 4 were progressively further from the sonar source, and position 5 (out of the pool) was deemed the most distant. The applied model was for an ordinal categorical response with the type of sonar and whether it was ON/OFF used as explanatory variables. The model consisted of a cumulative logit link function and multinomial error distribution fitted using GEEs. The treatment within each seal was used to define blocks, within which autocorrelation was accounted for (sequential 5-minute period in each trial). For example, block 1 consists of 5 minutes where animal 1 was observed with the sonar system CodaOctopus Echoscope 2 turned off and block 2 consists of minutes where animal 1 was observed with the sonar system CodaOctopus Echoscope 2 turned on. The ON/OFF alternates for the first 24 blocks of measurements for animal 1. Analysis was conducted in R (R Development Core Team 2011) using the package vgam (Yee, 2008; Yee and Wild, 1996) and SAS PROC GENMOD (SAS V9.2 SAS Institute, 2009).

GREY SEALS: RESULTS

Figure 12 presents the proportion of the 10 minute experimental blocks spent at each of the 4 pool positions (1-4 as given in Figure 10) and hauled out (position 5). Initial investigation of the data (Figure 12) suggests the CodaOctopus EchoScope 2 and Biosonics DT-X trials were associated with markedly different usage of the experimental pool; however, seals within each of the sonar trials appeared to exhibit similar patterns. The CodaOctopus Echoscope 2 was associated with a wide range of surfacing positions regardless whether it was active. Qualitatively there were longer periods at the surface for the inactive sonar phases (in grey) compared to the active sonar phases (blue). It should be noted that this difference between the systems was likely to be due to factors outwith this study such as differences in the locations of feeding stations in the pool for different individuals and previous experience in feeding trials using these stations.

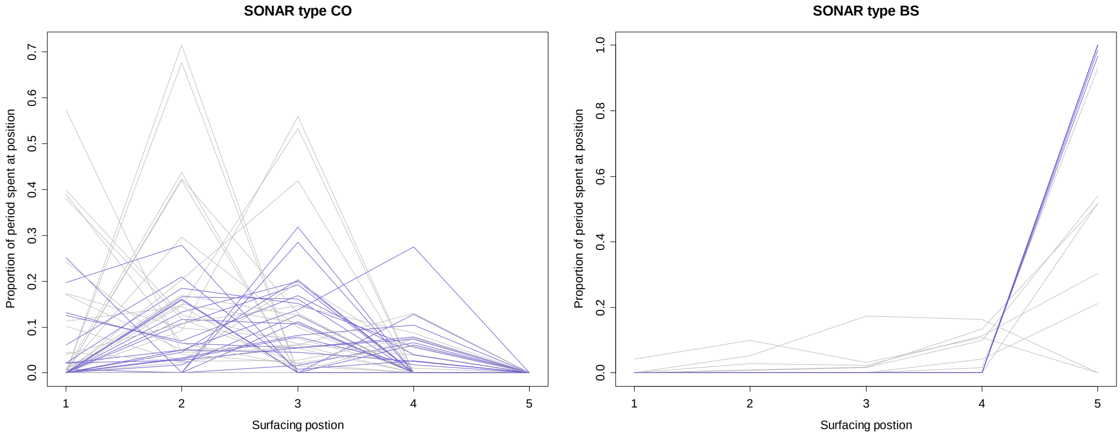


Figure 12:The proportion of time spent at the surface positions 1-5 for experimental blocks involving the CodaOctopus Echoscope 2 (left) and Biosonics DT-X (right). Grey lines indicate distributions when the sonar was inactive and blue lines indicate the distribution when the sonar was active. The remaining proportion of time for each distribution was spent submerged.

The Biosonics DT-X plot suggests broader usage of the pool positions when the sonar was inactive compared to active, when the subjects spent all their time hauled out (position 5). Qualitatively there appears to be a relative favouring of positions 4 and 5 in the Biosonics DT-X experiments compared to the CodaOctopus Echoscope 2 experiments, irrespective of whether it was active. The distribution of pool usage was modelled formally using a multinomial GLM fitted with GEEs and results suggest that the distribution of surfacing positions for the subjects differed significantly both across sonar system whether it was active or not (*p*-value=0.0246, Table 2,Figure 11, and Appendix 4).

Table 2: Significance of model terms for a multinomial GLM fitted with GEEs to the seals surfacing location.

Model term	df	χ^2 test statistic	*p*-value
Sonar ON/OFF	1	7.57	0.0059
Sonar system (Codaoctopus or Biosonics)	1	27.03	<0.0001
Interaction	1	5.05	0.0246

Results showed that for the Biosonics DT-X, the active phase had a predicted distribution that was significantly skewed towards the hauled-out position (5) compared to when the sonar was inactive. In other words, for the Biosonics DT-X, there is a clear shift by seals from surfacing in locations 3 & 4 to the hauled out position 5 when the sonar is active (Figure 13, top); seals were predicted to spend more time hauled out when the sonar was active. Results for the CodaOctopus Echoscope 2 suggested there is a relatively small shift from locations 1 & 2 to positions 3 & 4 when the sonar is active (Figure 13, bottom).

Given the results from the modelling suggested that the BioSonics DT-X resulted in seals leaving the pool, there is a possibility that responses from the ON periods influenced behaviour in the subsequent OFF periods; therefore a further investigation of the timing of the sonar activation and the seals haul out behaviour was carried out. This showed that in all but one of the times when the sonar was activated, the seals immediately left the pool (Figure 14). Furthermore, the periods when the seals were hauled out and the sonar was inactive appeared to be a protracted response from the preceding active period (Figure 14). It should also be noted that during the only time when the seal remained in the water in a sonar active period, it remained at the surface immediately behind the transducer where it can be assumed the noise levels were lowest. Furthermore, seals would regularly place their heads into the pool when hauled; a behaviour that it was assumed would allow the seal to monitor whether the sonar was active or not.

There are clear limitations to the interpretation of the findings presented here. Data was collected from only four animals and despite care in statistical estimation (we attempted to account for the gross auto-correlation by use of Generalized Estimating Equations (Liang & Zeger, 1986), which empirically adjust for correlation in the error variance), four animals cannot characterise a population well and generalisation from these results must be carried out with caution. Additionally the CodaOctopus Echoscope 2 treatment was applied to two individuals and the Biosonics DTX to another two, leading to a potential confounding between sonar system treatment and subjects. However, the subjects were randomly allocated to treatments and the operation of each sonar (ON/OFF) was alternated within individuals and when viewed alongside the marked patterns observed, the results are strongly suggestive of overt behavioural responses to the BioSonics DTX and subtle (but significant) responses to the CodaOctopus Echoscope 2.

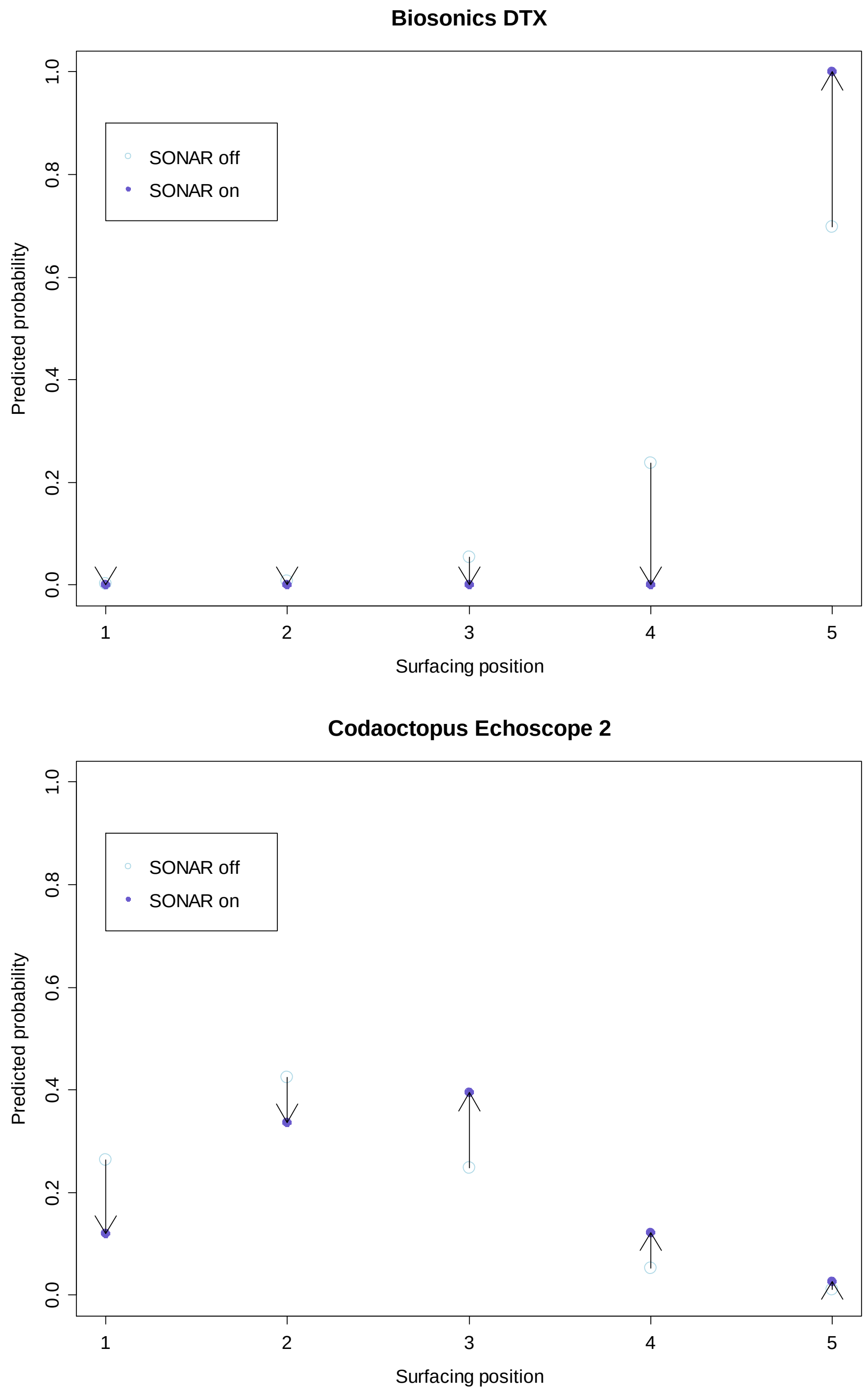


Figure 13: Changes in predicted probability of surfacing at particular locations when activating the sonar. The open dot indicates the probability when the sonar is inactive and the solid dot when the sonar is active.

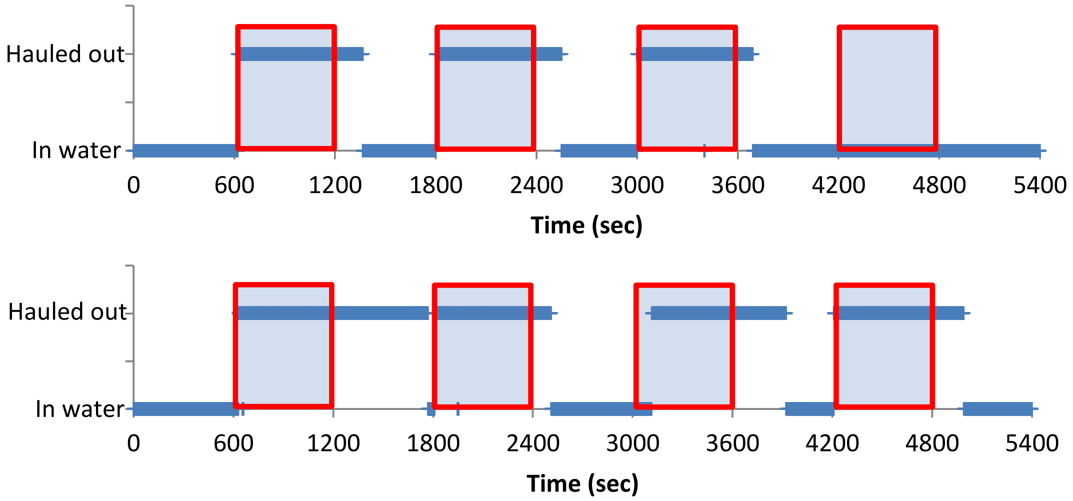


Figure 14: Haul out patterns by 2 grey seals at the SMRU holding facility. The figure shows the periods when each seal was hauled out and in the water in relation to sonar activity (red boxes indicate the sonar was active). The results support that both seals responded overtly to the timing of the sonar signals by leaving the water and hauling out at the side of the pool.

HARBOUR PORPOISES: METHODS

To understand whether harbour porpoises exhibit behavioural responses to the signals produced by the sonar systems, a series of behavioural response trials were carried out with four porpoises in the Fjord & Bælt Aquarium, Denmark. A total of three one-hour experimental tests were carried out with the CodaOctopus Echoscope 2 and two with the Tritech Gemini. Descriptions of each of the porpoises used in the trials is presented in Table 3.

Table 3: Harbour porpoises used in the sonar behavioural response trials at the Fjord and Bælt Aquarium.

Porpoise	Age (years)	Sex	Time in captivity (years)
Frigg-Amanda	3	F	3
Freja	14	F	13
Eilgil	14	M	13
Sif	7	F	6

During each trial the porpoises were permitted to swim freely throughout a large experimental pool (Figure 15). The sonar head was lowered into position approximately 1.5m below the surface from a pontoon at the side of the pool, and was controlled from a PC located in a laboratory adjacent to, and overlooking, the experimental pool.

The swimming and surfacing behaviour of the porpoises was recorded using a video camera located above the pool and was monitored visually by the sonar operator. To ensure that the porpoises did not respond to secondary external stimuli, no persons were visible to the porpoises throughout the trials, and noise was kept to a minimum. Furthermore, to help ensure that porpoises did not exhibit a protracted response to initial equipment set-up during the tests, we did not initiate each test for a period of 30 minutes after equipment set-up. It should also be noted that, although each porpoise had been used in sound reaction tests to a range of sound signals previously (including active sonar) the porpoises used in the tests were initially naïve to the sonar signals of each system.

Each experimental test consisted of a one-hour observation period during which the sonar signals were turned on and off for alternating five-minute periods; this period was designed to maximise the number of treatment periods (ON/OFF) whilst ensuring that, based on mean dives times [mean dive duration =1.6±0.7 minutes (Otani et al., 1998)], the probability of an animal surfacing within a period was high. A series of behaviour parameters were measured continuously throughout the trials and included the number of surfacing in each of three sub-areas of the pool and the occurrence of any overt behaviours at the surface that may have indicated a response (rapid swimming or splashing at the surface).

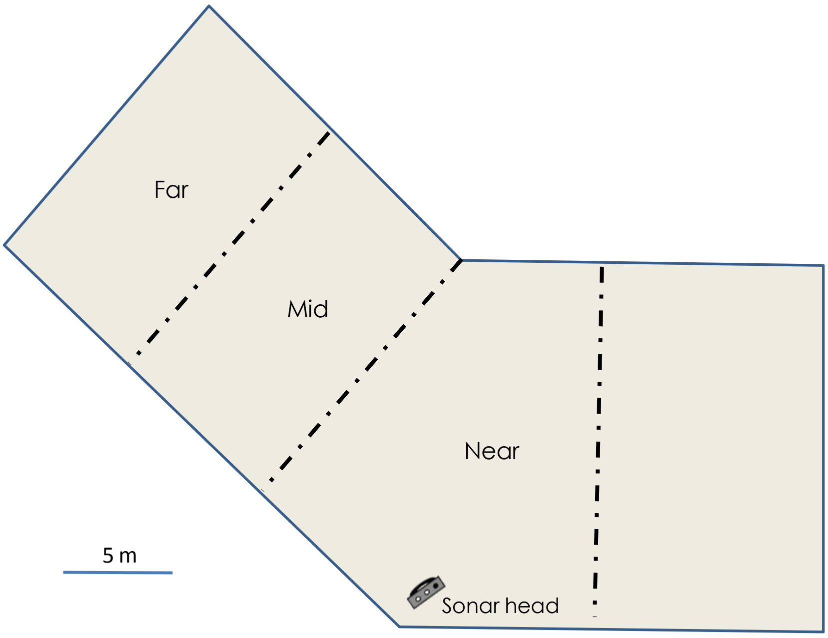


Figure 15: Equipment setup to evaluate behavioural responses of porpoises to the signals produced by the Echoscope 2 in the Fjord and Baelt captive porpoise facility. The figure shows a plan of the experimental pool. For analytical purposes, the pool was divided into sub areas, denoted as Near, Mid, and Far (from the sonar head). NB: The area of the pool to the right of the 'Near' area was not accessible to porpoises.

To assess whether sonar activity influenced the surfacing patterns of porpoises, data were analysed within a generalized linear modelling framework. The number of surfacings observed in the sub-areas of the pool during each five minute sample was the response variable. Predictor variables were selected for inclusion in the model using a stepwise procedure by first fitting each variable in to the null model. The term that resulted in the greatest improvement in the model fit was selected for inclusion at the next step and *P*-values were calculated using a chi-squared approximation. Models were created using the software package R version 2.8.1 (R Development Core Team 2011). The predictor variables tested in the modelling procedure were Trial number (1, 2, or 3), Pool Area (Near, Mid, and Far), Treatment number (sequential 5-minute period in each trial), Sonar Activity (ON/OFF), and Sonar system (CodaOctopus Echoscope 2 or Tritech Gemini). The number of porpoises in the pool (3 or 4) was included as an offset term in the model. The family specified in the model was *quasipoisson.*

HARBOUR PORPOISES: RESULTS

The results of the generalized linear models suggest that a number of interacting factors explain the variation in surfacing rates observed during the behavioural response trials for porpoises (Table 4). Examination of the model diagnostics suggests that the data can be considered as independent (Runs Test; Standard Normal = 0.6007, p-value = 0.5481) and normally distributed (Shapiro-Wilk normality test; W = 0.9854, p-value = 0.3238). Investigation of the diagnostics plots for the model suggests that approximately 9% of the data account for the majority of the influence in the model (Appendix 4).

Table 4: Summary of the stepwise generalized linear models describing the influence of sonar activity on surfacing rates of porpoises. Variables were selected for inclusion in the model using a stepwise procedure by first fitting each variable in to the null model. The term that resulted in the greatest improvement in the model fit was selected for inclusion at the next step. *P*-values were calculated using a chi-squared approximation.

Term	LR	df	*P* (Chisq)
System	36.41	1	<0.0001
Pool area	62.61	2	<0.0001
Sonar activity	0.99	1	0.32
Trial	39.09	2	<0.0001
Treatment	0.01	1	0.91
System:Pool area	103.36	2	<0.0001
Pool area:Sonar activity	63.53	2	<0.0001
Trial:Treatment	16.94	2	0.0002
Sonar activity:Trial	6.79	2	0.03
System:Sonar activity	6.77	1	0.009

The results suggest that the porpoises changed their surfacing patterns in response to the signals of each of the sonar. The model predicts that there were different responses to each of the systems; this can be seen in the interaction between System and Sonar activity. Overall, when the sonar was off, the distribution of porpoise surfacings in the pool was spatially stratified with the lowest number of surfacings in the near area and the highest number of surfacings in the far area during the CodaOctopus trials; this pattern was reversed in the Tritech Gemini trials. It is not thought that this pattern was associated with the sonar trials but is probably a function of other experimental trials carried out prior to the sonar trials and their associated feeding locations.

The model predicted that porpoises decreased their surfacing rate in all three of the pool areas in response to the CodaOctopus Echoscope 2 and in the Near and Mid areas of the pool in response to the Tritech Gemini; there was a predicted increase in surfacings in the far area of the pool in response to the Tritech Gemini (Figure 16).

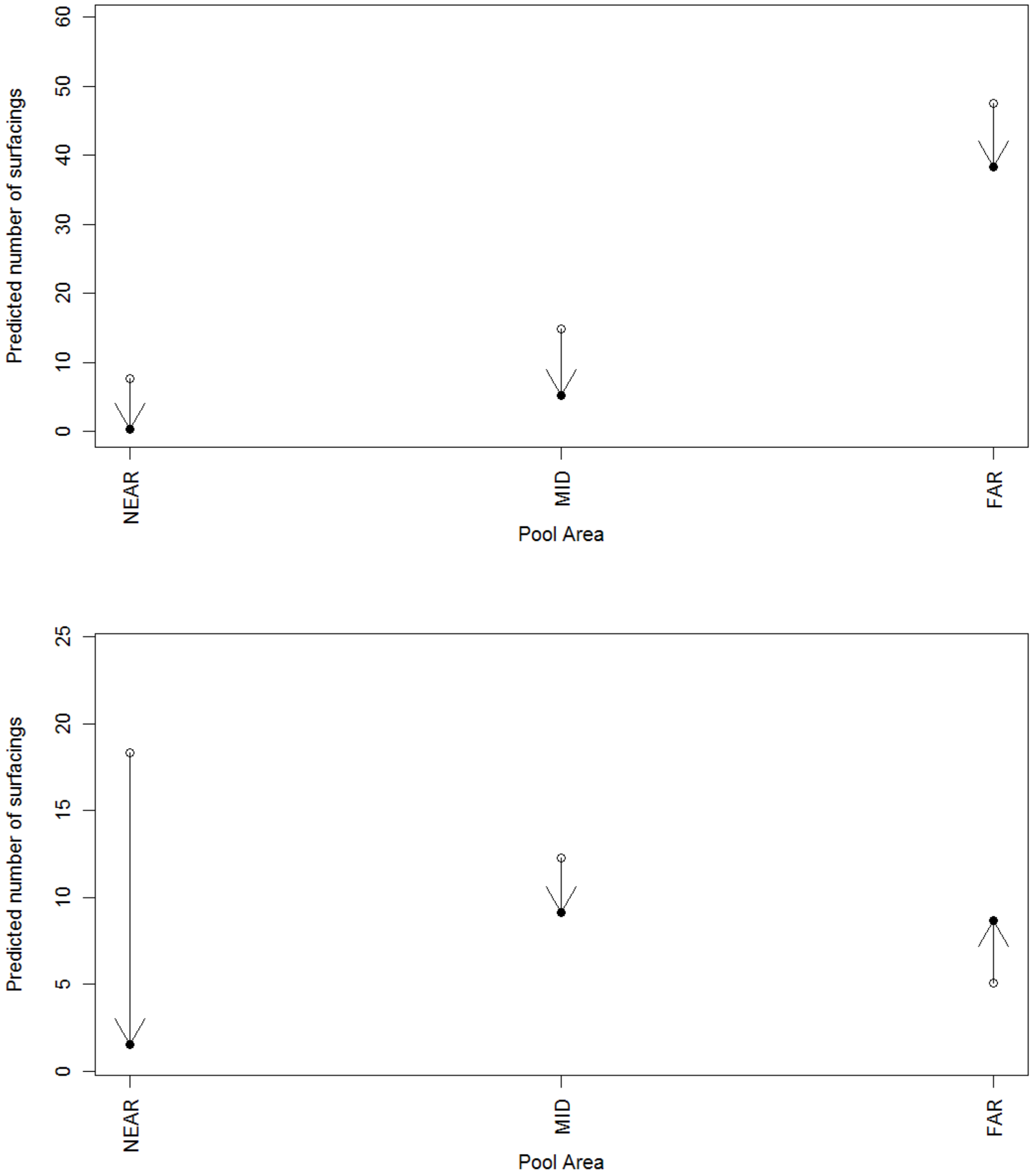


Figure 16: The predicted change in the number of harbour porpoise surfacings in response to the operation of each of the sonar systems. The figure shows the surfacing patterns in response to the CodaOctopus Echoscope 2 (top) and the Tritech Gemini (bottom) and illustrates that in general surfacings were reduced in response to each of the system although there was a slight increase in surfacings in the far area in response to the Gemini. The open dots indicate the predicted number of surfacings when the sonar is inactive and the solid dots when the sonar is active.

SONAR AUDIBILITY ON A TIDAL TURBINE

In addition to the behavioural response trials described above, it is important to view the sonar signals in the context of marine mammal hearing and the ambient noise conditions at tidal locations. Although behavioural responses by wild animals to sound are traditionally challenging to predict (responses may vary depending on individual traits of exposed animals and the context in which they are exposed), it is possible to make broad generalisations based on the perceived level of sound by different species. The predicted perception of the sonar signals was therefore modelled to predict the ranges that different species would be likely to detect the signals in a tidal environment.

An important concept in understanding the way an animal perceives sound is that of the auditory threshold (also called hearing threshold) (Johnson, 1967). The hearing threshold is the average sound pressure level that is just audible to a subject under quiet conditions. When the hearing threshold is plotted as a function of frequency it is called an audiogram. To give an example, the harbour porpoise hearing threshold at 500 Hz is about 90 dB re 1 µPa, while its hearing threshold at 50 kHz is about 35 dB re 1 µPa (e.g. Kastelein et al., 2002). This would mean that a sound with a sound pressure level of 100 dB re 1 µPa and a frequency of 500 Hz would be barely audible to the porpoise; however, the same sound pressure level at a frequency of 50 kHz would be perceived as relatively loud.

In the context of sonar signals, the sound pressure level must firstly be above both ambient noise and the noise created by the operating turbine to be perceived by the marine mammal. Secondly, the hearing threshold at the relevant frequencies must be sensitive enough to allow perception of the sonar signal; the sound pressure level in dB by which the sonar signal exceeds the hearing threshold at a given frequency of interest can be termed the “sensation level” (Yost, 2000). Although this is a reasonable approximation, one should note that perceived loudness is also influenced by other factors such as bandwidth and stimulus duration. For the purposes of this study, composite audiograms for grey/harbour seals (*Phoca vitulina*) (Götz and Janik, 2010) and harbour porpoises were constructed.

A basic propagation model (Equation 1) was used to predict received levels of each sonar and the turbine noise (in third octave bands) at a series of ranges from the turbine.

Equation 1

$$RL=SL-15 \times \log(R) - \alpha R$$

Where:
RL=Received sound pressure level
SL=Source sound pressure level
R=Range in metres
α=Frequency dependent absorption coefficient (Jensen et al., 1994)

As described above, detection of a sonar signal relies on the sound being above the turbine noise; sonar noise was therefore overlaid by the predicted received levels of turbine noise at each of the ranges and was weighted by the composite audiograms to predict sensation levels for each sonar system at a series of ranges from the turbine. Turbine noise data was based on sound recordings of SeaGen in Strangford Lough; recordings (18 bit, 500 kHz sampling rate) were made by deploying a hydrophone from an anti-heave buoy allowed to drift with the tide past SeaGen on the 3rd and 4th November 2009 (Kongsberg_Maritime_Ltd, 2010). The source level of SeaGen was then back-calculated using the field measurements and a series of sound propagation models (Götz, 2011). It should be noted that although the CodaOctopus Echoscope 2 was not part of the development program it was used as a comparison for the sonar systems between species; as such, sensation levels have also been plotted for this system.

Predictions suggest that both seals and harbour porpoises would be able to hear the signals of the Tritech Gemini at 60m and the CodaOctopus Echoscope 2 and BioSonics DT-X at approximately 3,000 and 4,000 metres respectively (Figure 17 and Figure 18).

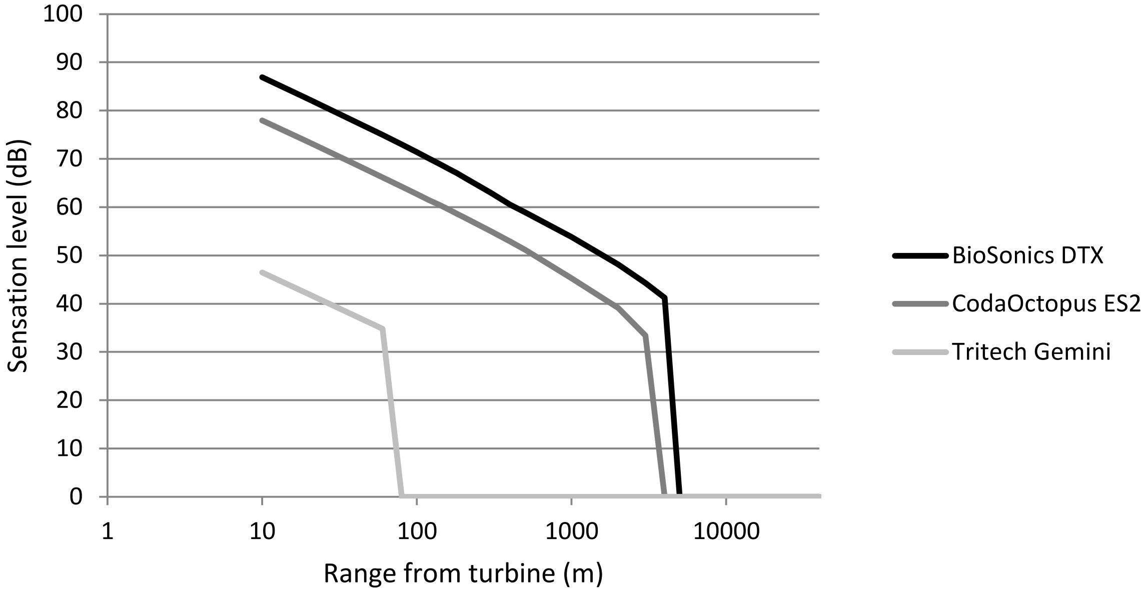


Figure 17: Graph of the maximum "sensation" levels for seals to the acoustic pulses of the BioSonics DT-X, CodaOctopus Echoscope 2, and the Tritech Gemini.

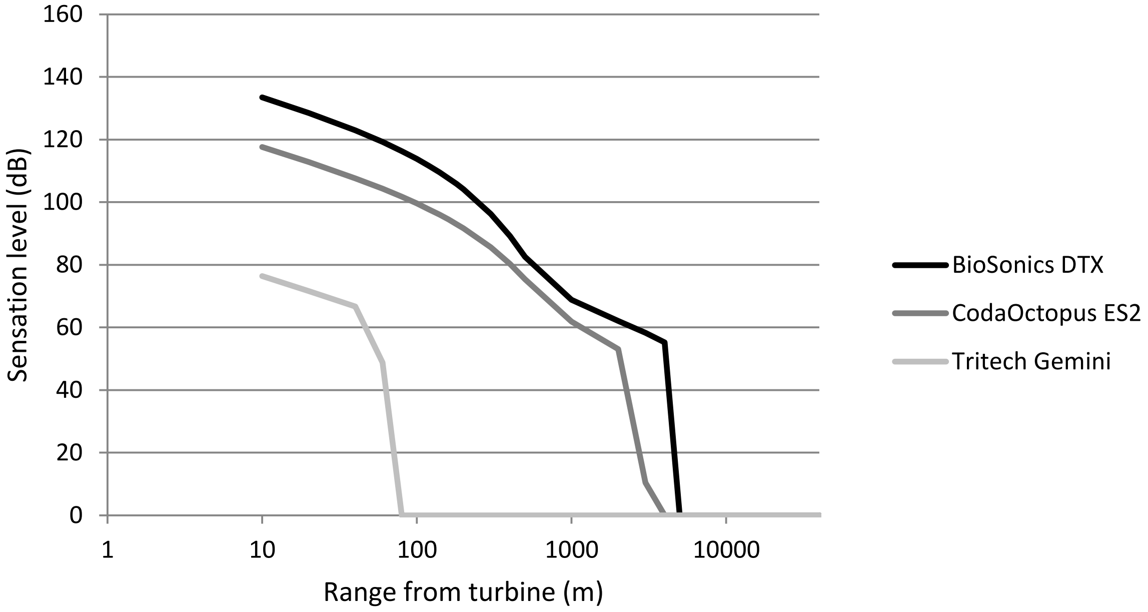


Figure 18: Graph of the maximum "sensation" levels for harbour porpoises to the acoustic pulses of the BioSonics DT-X, CodaOcotpus Echoscope 2, and the Tritech Gemini.

DISCUSSION

This phase has provided a detailed account of the behavioural responses by grey seals and harbour porpoises to the sonar signals of three sonar systems within a captive environment and the predicted audibility ranges at a tidal turbine location. The results of the behavioural response trials suggest that both grey seals and harbour porpoises exhibit behavioural responses to the signals of all of the sonar systems. However, the apparent magnitude of these responses appeared to be different between sonar systems. For example, both seals and porpoises exhibited relatively subtle responses to the CodaOctopus Echoscope 2; there were changes in the patterns of surfacing by both seals and porpoises in response to the sonar. Furthermore, the seals tended to surface further from the sonar head when it was active. In contrast, responses to the BioSonics DT-X were far more overt; seals spent significantly longer out of the pool when the sonar was active. Furthermore, when the timing of the seals hauling out was viewed against sonar activity, it was clear that this was a response to the sonar activation.

The analysis of the behaviour of animals in response to an external stimulus is traditionally an extremely challenging field of study, and there are potential limitations with using captive animals to understand behavioural responses of wild animals. For example, although direct, controlled studies can be carried out with captive animals, there may be differences in the response thresholds of captive and wild animals; wild animals may react more acutely to the introduction of a novel sound stimulus. Furthermore, all individuals had been used in sound reaction tests previously and their responses during the current study may represent a more muted response than would have occurred in wild animals. Alternatively, as an animal's behavioural state will make it more or less likely to exhibit a response; animals that are engaged in some non-essential activity (such as those in our study) might be expected to exhibit a greater behavioural change than animals highly motivated to perform an important activity, such as feeding or mating (in the wild). However, these caveats are likely to be reduced in our study by the fact that the animals used in the tests were temporarily captive (having been caught in the wild) and naïve to the sonar signals making it likely that the shorter term-startle type responses would have provided a good measure of whether animals will react to the signals in the wild.

These results suggest that seals and porpoises can hear the sonar signals of all the sonar systems tested and respond to them by either moving away from the sonar head or increasing their dive durations (seals) or decreasing their surfacing rates (porpoises). One of the most important facets of the sonar for use as a behavioural monitoring tool is that it should not lead to attraction to, or avoidance of the area that is ensonified (e.g. Harris, 2001). For example, during a series of tests to evaluate the impacts of intense underwater sounds, harbour seals exhibited strong avoidance behaviour, swimming rapidly away from the sound source (Thompson et al., 1998). This is extremely important in the context of a sonar unit being mounted on a tidal turbine in a narrow tidal channel. Firstly, it is important that the signals from the sonar do not lead to the avoidance of an area that is potentially an important route to offshore foraging areas, and secondly, it is important that the signals do not lead to the attraction to an area where the risks of direct physical injury are potentially heightened.

Although the results of the behavioural response trials are based on a relatively small sample size, they are supported by the audibility and behavioural response predictions; once the ambient and turbine noise conditions at a tidal site have been accounted for, harbour seals and harbour porpoises were predicted to be able to hear the signals of the Tritech Gemini and BioSonics DT-X at ranges of approximately 60 and 4,000 metres respectively. Behavioural avoidance responses by grey seals have been shown at sensation levels of 59–79 dB (Götz and Janik, 2010). Using this level for each species, it suggests that at a tidal site, the Tritech Gemini is unlikely to elicit behavioural avoidance responses by seals but porpoises may exhibit responses up to 40m. In contrast, these sensation levels for the BioSonics DT-X are exceeded out to ranges of 2,000m for harbour porpoises and 400m for seals suggesting that behavioural avoidance responses are a risk out to these ranges for this system.

It is important to highlight that the propagation of sound in shallow seawater is typically highly complex and the relatively simple propagation model used here is unlikely to capture this complexity; these predictions should therefore be viewed with this in mind. Further, an important caveat in this process relates to the noise data used in the audibility predictions; specifically, the ambient noise data and turbine acoustics characteristics used in this phase were recorded at SeaGen in Strangford Lough, and may not be directly transferable to other locations or tidal turbines. For example, if ambient noise at another location is significantly less than the values used here, it is likely that each sonar system would be audible to greater ranges than predicted here. However, until further empirical data become available, our predictions would seem valid.

This study provided the basis for taking the Tritech Gemini to the next stage of development and testing prior to deployment on a tidal turbine. The results suggest the sonar unit could successfully be deployed on a turbine to detect and track animals with a relatively low risk that the signals would significantly attract or exclude them from the immediate area around the turbine. However, this should be carried out with caution as in relatively quiet ambient conditions, it is likely that marine mammals would be able to hear the sonar at several tens of metres. In contrast, given the high source levels of the BioSonics DT-X and overt behavioural responses, there are clear risks with deploying this on tidal turbines to measure behaviour of marine mammals without significant signal modification to reduce the noise levels.

5. PHASE THREE: SONAR DEVELOPMENT AND TESTING

DEVELOPMENT AIMS

BIOSONICS DT-X DEVELOPMENT

Given the results of the marine mammal behavioural response trials and the predicted ranges of audibility, there was a clear need to modify the acoustic properties of the signal prior to any further development.

The initial aim for improvement of the transmit signal was suppression of energy below 200kHz from the transducer. The transmit signal of the BioSonics DT-X transducers had a rectangular pulse envelope (Figure 19) and the assumption was that the lower frequency components were artefacts of the square transmit pulse envelope. A tapered envelope was therefore developed and integrated into the DT-X echosounder using a new 204 kHz transducer.

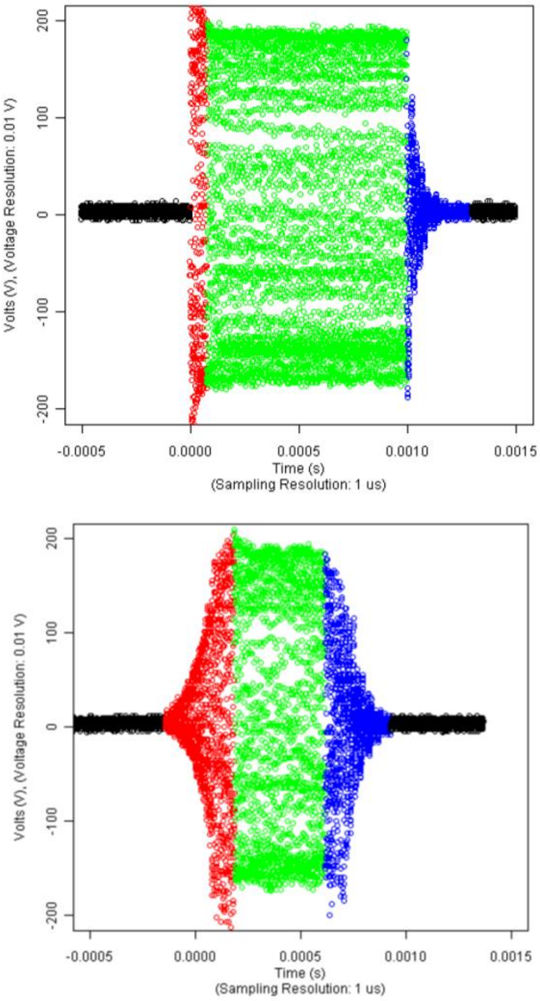


Figure 19: Original (top) and modified (bottom) waveform of the BioSonics DT-X transmit signal showing the rectangular pulse envelope (pulse duration = 1ms) (image courtesy of BioSonics Inc.).

Although initial spectral analyses suggested that this was relatively successful with broadband SPLs below 200 kHz being reduced (particularly in frequencies above 150kHz), there was a clear narrow band increases in SPL at around 100 kHz (Figure 20). With only a single new transducer tested, it was unclear whether this narrow band increase was a transducer specific artefact; it may therefore have been desirable to test a number of different transducers and carry out further behaviour response tests with the modified signals. However, given there was little obvious reduction in the energy at most frequencies within the regions of high sensitivity in some species hearing (particularly odontocete cetaceans) further tests would be unlikely to have been successful. The decision was therefore made to stop further collaborative development of this system.

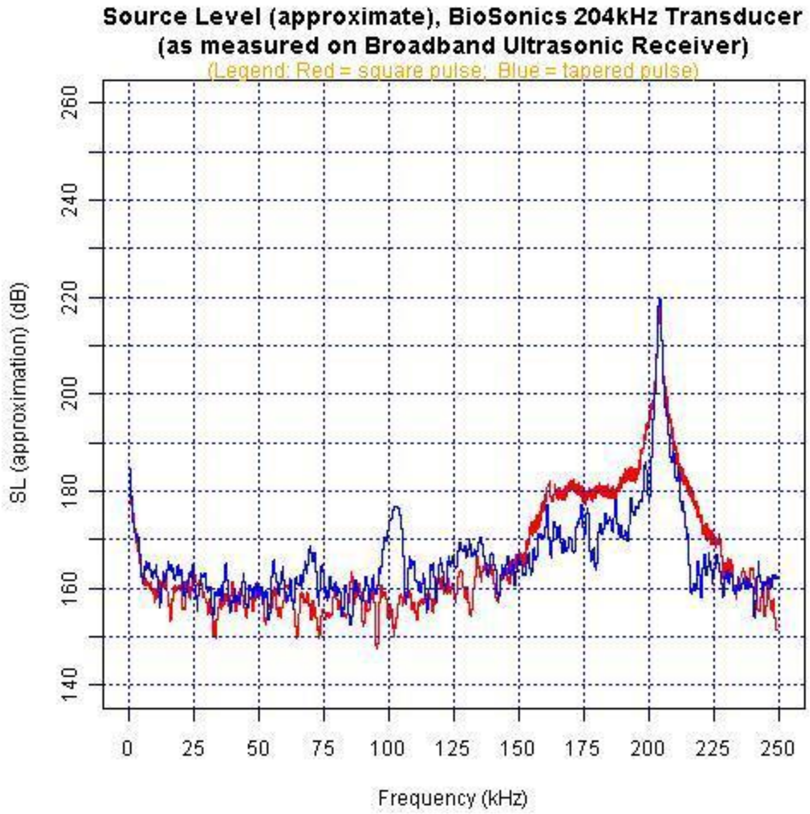


Figure 20: Spectrum of the BioSonics DT-X transmit pulse showing the original square pulse (red) and the new tapered pulse (blue) (data courtesy of BioSonics Inc.).

TRITECH GEMINI DEVELOPMENT

Although there was a functional movement detection module in the Gemini software, this had not been validated with marine mammals and it was clear that in a tidal environment, there are likely to be a high number of moving targets detected that are not marine mammals. Improvements to the Gemini system therefore focused on the development of efficient classification algorithms to reduce data volumes and provide a probabilistic determination of the identity of individual targets; these included variables such as size, shape and swimming characteristics to determine valid marine mammal targets. Specifically, the aim was to include target tracking and swimming path analysis, a proximity alert with a user configurable tidal turbine layout, and classification of targets based on size, shape and swimming characteristics.

MARINE MAMMAL DATA COLLECTION

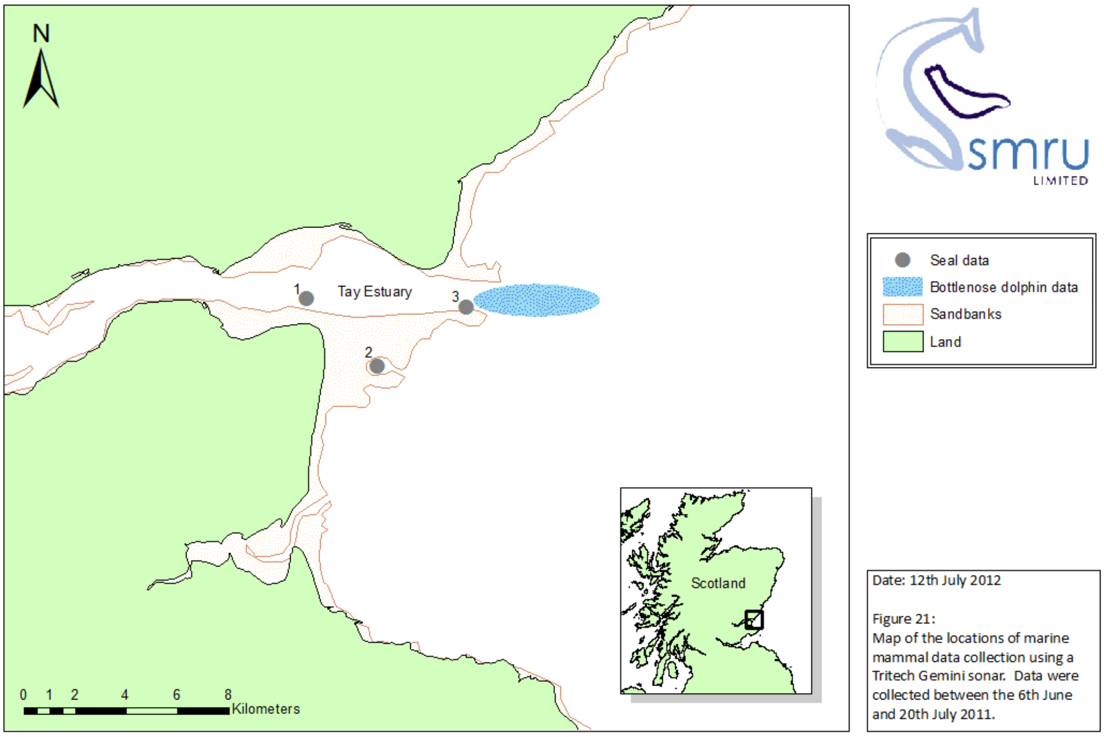
In order to develop classification algorithms, sonar image data of marine mammals was required. We therefore collected image data for some of the most common marine mammal species around the UK (grey and harbour seals, harbour porpoises, and bottlenose dolphins). A Tritech Gemini was mounted on a pole and deployed from the stern of a 7.5m aluminium vessel (for the majority of data collection) and data were stored to a laptop located in the cabin of the boat (Figure 21).

Figure 21: Vessel used for the majority of the marine mammal data collection; a Tritech Gemini was mounted on a pole and deployed from the stern of the vessel. Photo courtesy of Marine Revolution (http://www.marinerevolution.com/)

GREY SEALS

Grey seal data on were collected between the 6th and 20th June 2011 in waters adjacent to a haul out site close to St Andrews where up to 1,000 seals regularly haul out (around 100 were present on the data collection days) (Figure 22). The boat was anchored approximately 200 metres offshore and seals were imaged as they passed between the haul out and the open sea. The water was relatively shallow (3-5 metres) with a sandy seabed and tidal currents were relatively slow (1-2 knots).

Grey seals were successfully imaged up to ranges of between 2 and 70 metres from the boat appearing as distinct targets that could be visually tracked moving around the frame (Figure 23); this allowed rudimentary swimming behaviour of individuals to be recorded. The image resolution at close range (Figure 24) appeared sufficient to allow a crude determination of the identity of the marine mammal (e.g. seal species) and could be used to measure the size of the animal and monitor fine scale behaviour of individuals; furthermore, an acoustic “shadow” was frequently visible beyond the seal providing a mechanism to estimate the swimming depth of the seal (Figure 24).



Date: 12th July 2012

Figure 21:
Map of the locations of marine mammal data collection using a Tritech Gemini sonar. Data were collected between the 6th June and 20th July 2011.

Figure 22: Map showing the locations of the marine mammal data collection using the Tritech Gemini. Data for algorithm development included bottlenose dolphin data (blue polygon) from the mouth of the Tay Estuary, harbour seal data (grey point #1) from within the Tay Estuary and grey seal data (grey point #2) from a haul out to the south of the Tay Estuary. Data for software validation included grey seal data (grey point #3) collected from the mouth of Tay Estuary.

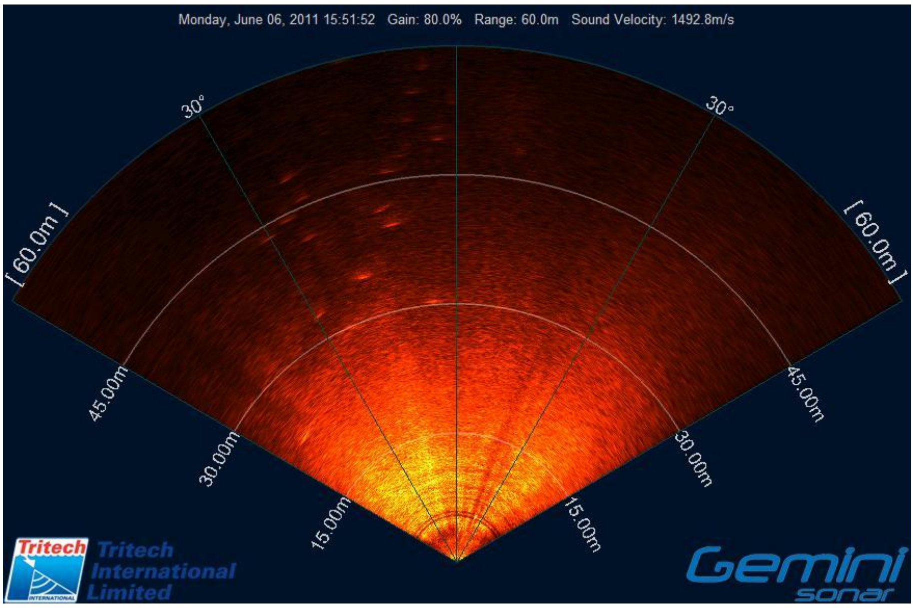


Figure 23: Sonar image of grey seals at a haul out close to St Andrews. Individual seals can be seen in the image at ranges between 20 and 60 metres.

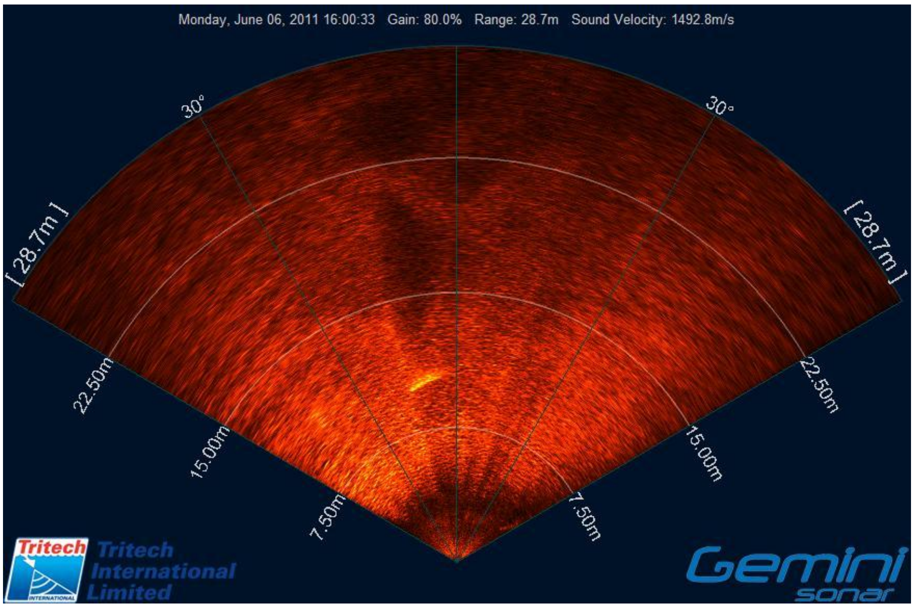


Figure 24: Sonar image of a grey seal at relatively close range (10 metres). In this image the seal was actively swimming to the left of the frame and an acoustic "shadow" can be seen extending away from the seal at ranges between 12 and 20 metres; this information can be used to estimate the depth of the seal.

HARBOUR SEALS

Data on harbour seals were collected in the Tay Estuary on the 17th June 2011; the boat was allowed to drift with the incoming tide with the view to imaging seals as they swam between their haul out sites in the Tay and the open sea. The water depth varied between 10 and 30 metres during the drifts and tidal currents were relatively slow (2-3 knots). However, sample sizes for harbour seals were relatively limited with only a single seal passing during the data collection; this was imaged at a range of 22m from the vessel (Figure 25).

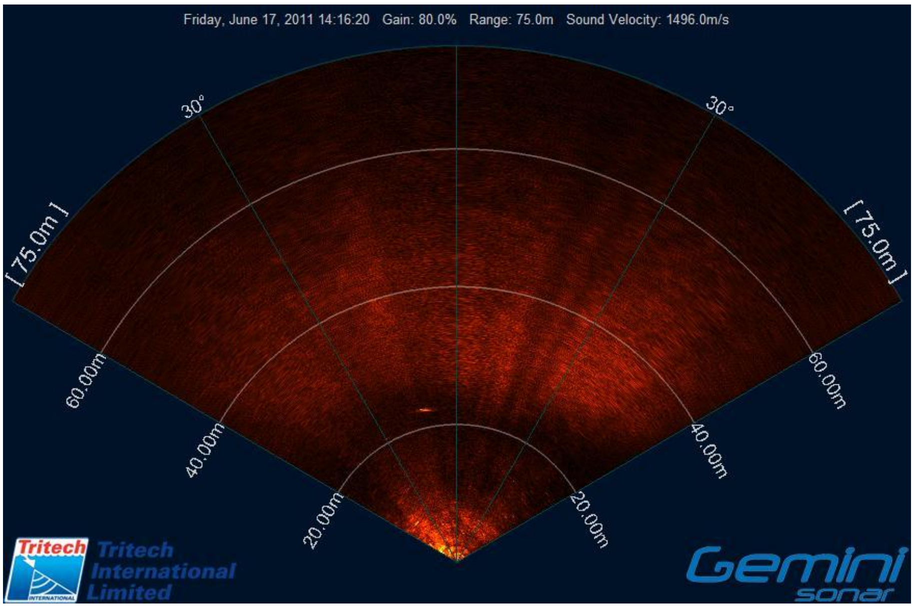


Figure 25: Sonar image of a harbour seal in the Firth of Tay; the seal can be seen in the image at a range of 22m and an angle of -15° from the transducer as it swam to the left of the frame.

HARBOUR PORPOISES

Captive harbour porpoises were imaged at the Fjord and Bælt Aquarium in Kerteminde, Denmark on the 13th May 2011 and free ranging porpoises were imaged at the Little Bælt in Denmark on the 14th May 2011 from a modified sailing vessel carrying out wildlife tours. Free ranging porpoises were imaged up to ranges of between 45 and 50 metres (Figure 26). Although there was generally a high degree of acoustic clutter in the captive environment, the image resolution at close range (Figure 27) appeared sufficient to allow a crude determination of the identity of the marine mammal (e.g. cetacean species) and appeared sufficient to measure the size of the animal and monitor fine scale behaviour of individuals.

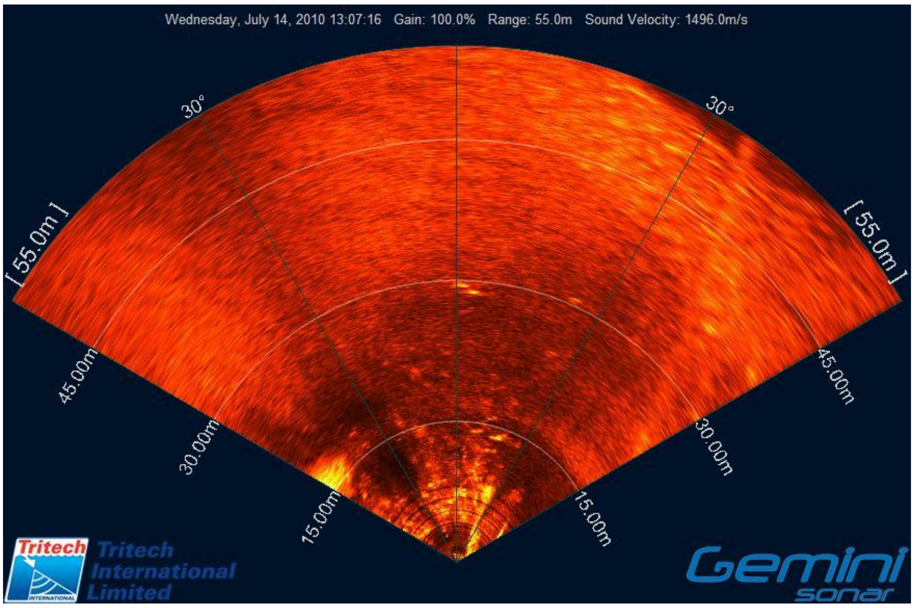


Figure 26: Sonar image of a two harbour porpoises in the Little Bælt, Denmark; the porpoises can be seen in the image at a range of 29m and an angle of 5° from the transducer as they swam to the right of the frame.

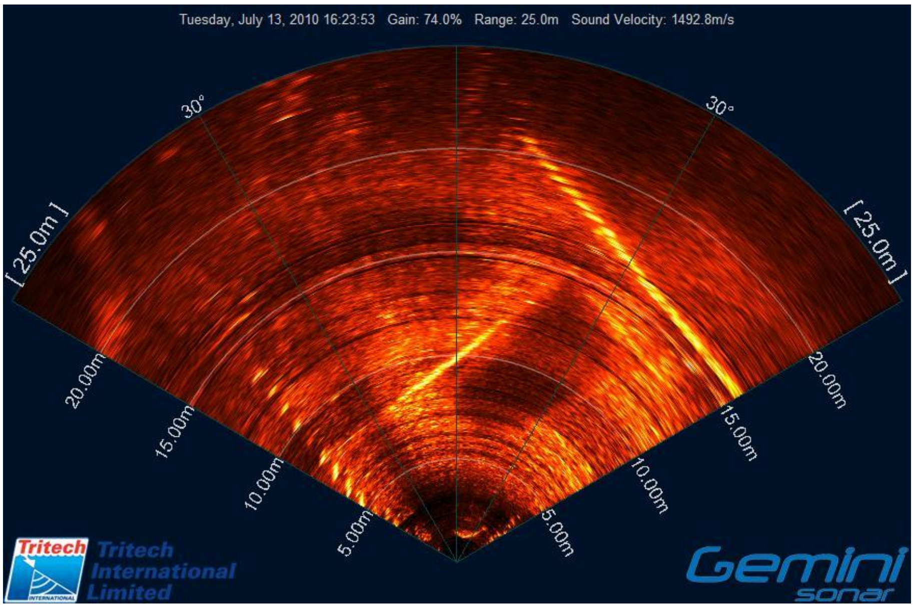


Figure 27: Sonar image of a harbour porpoise in the Fjord and Bælt Aquarium, Denmark. In this image the walls of the pool can be seen as high intensity lines and the porpoise was actively swimming to the left of the frame at very close range (2 metres).

BOTTLENOSE DOLPHINS

Bottlenose dolphins were imaged in the Tay Estuary between the 17th and 20th July 2011. The water depth varied between 10 and 40 metres and tidal currents were relatively slow (2-3 knots). The aluminium boat was maneuvered at speeds of approximately 2-3 knots. Dolphins were detected at ranges of between 2 and 60 metres from the boat as distinct elongated targets that could be visually tracked moving around the frame (Figure 28 and Figure 29); this allowed rudimentary swimming behaviour of individuals to be recorded. The image resolution at close range (Figure 30) appeared sufficient to allow a crude determination of the identity of the marine mammal (e.g. cetacean species) and appeared sufficient to measure the size of the animal and measure fine scale behaviour of individuals.

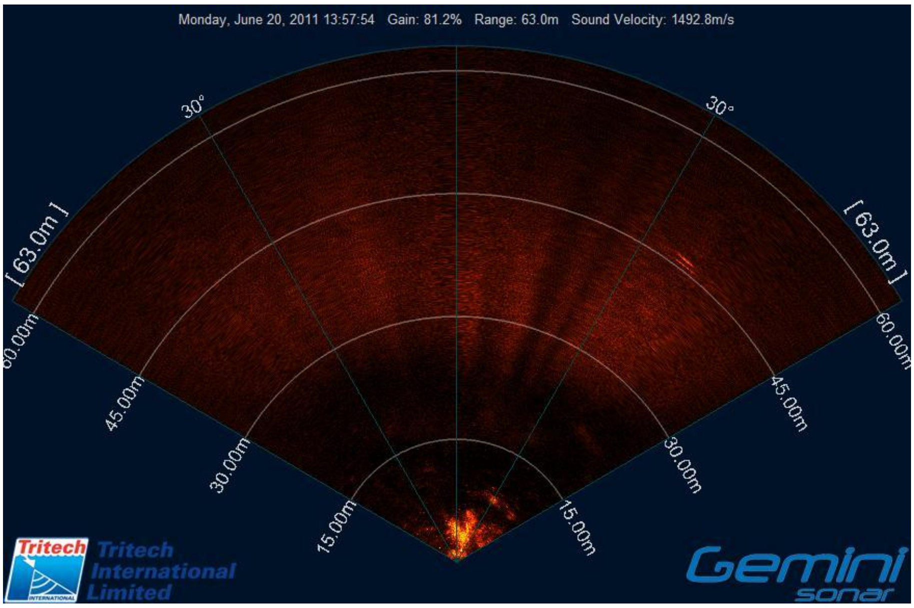


Figure 28: Sonar image of a two bottlenose dolphins in the Tay Estuary; the dolphins can be seen in the image at a range of 46m and an angle of 40° from the transducer.

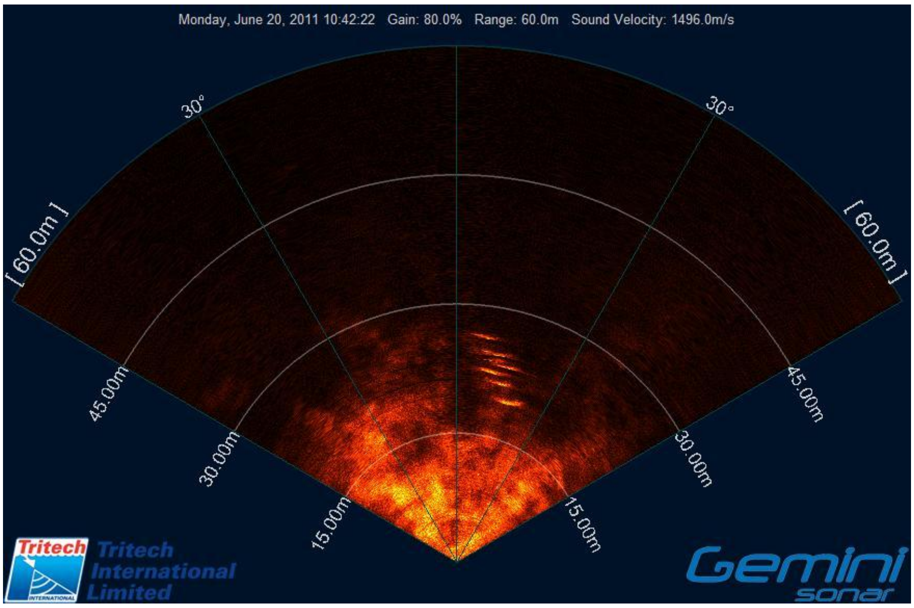


Figure 29: Sonar image of a seven bottlenose dolphins in the Tay Estuary; the dolphins can be seen in the image swimming to the right of the frame at a range of between 20 and 30m and an angle of 10° from the transducer.

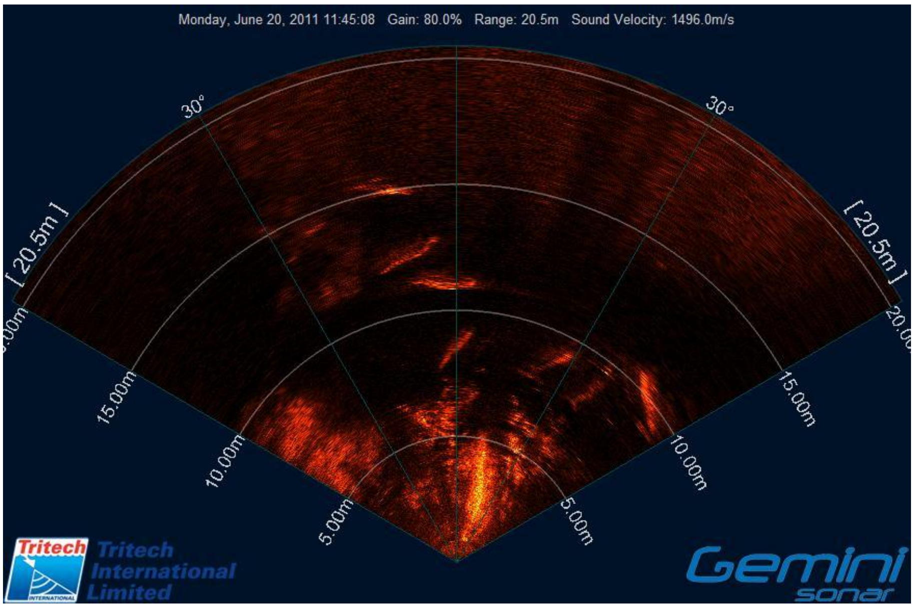


Figure 30: Sonar image of at least eight bottlenose dolphins in the Tay Estuary; the dolphins can be seen in the image at close range swimming at different angles; the high intensity object between 0 and 5 metres is the hull of the boat.

Although the primary purpose of the marine mammal data collection was to collect data for algorithm development, it should be noted that no behavioural responses (e.g. startle response or rapid movement towards or away from the sonar) to the signals were observed for any of the species.

MARINE MAMMAL CALIBRATION TESTS

To validate the efficiency of the sonar at detecting marine mammals, the sonar image data on grey seals were compared to visual observations. A series of photographs of seals at the surface were taken throughout the data collection and these data were analysed post hoc; seals that were present in the photographs were compared manually to the sonar images at the corresponding time and the data were summarised in terms of the number of seals that were matched in the photographs and the sonar images (blue), the number that were manually observed in the sonar images but were not present in the photographs (green), and the number that were present in the photographs but were not in the sonar images (red) (Figure 31 and Figure 32).

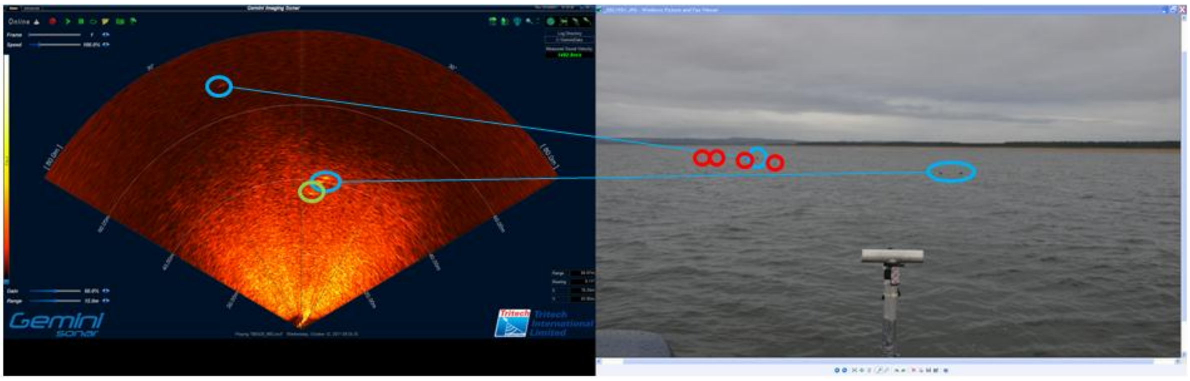


Figure 31: Photograph and sonar image from calibration number 5 where 3 seals were matched in the 2 images (blue circles), 1 seal was imaged by the sonar that did not appear in the photo (green circle), and 4 seals appeared in the photo but not on the sonar image (red circles).

Results of this initial calibration showed that seals could be readily imaged at ranges up to 70 metres from the transducer. In all calibration photographs (10 in total), a proportion of seals that could be seen in the photographs could be matched to targets in the sonar images; this ranged from 1 to 3 seals being matched. However, in 4 of the calibration photographs, seals were present in the photographs but did not appear in the sonar images; this ranged from 1 to 4 seals. In contrast, in 8 of the calibrations, a number of seals could be seen in the sonar images but were not present in the photographs; this ranged from 3 to 9 seals. When expressed as proportions of the total seals assumed to be present (‘seals matched’ + ‘seals missed by sonar’ + ‘seals missed in photos’), the mean proportion of seals not imaged by the sonar was 0.19 (se=0.9) (Figure 32). However, it should be highlighted that all the seals that were seen at the surface but not imaged by the sonar appeared to be at relatively high ranges (greater than 60m) from the boat and when only data within this range are presented, no seals appear to have been missed by the sonar (Figure 33).

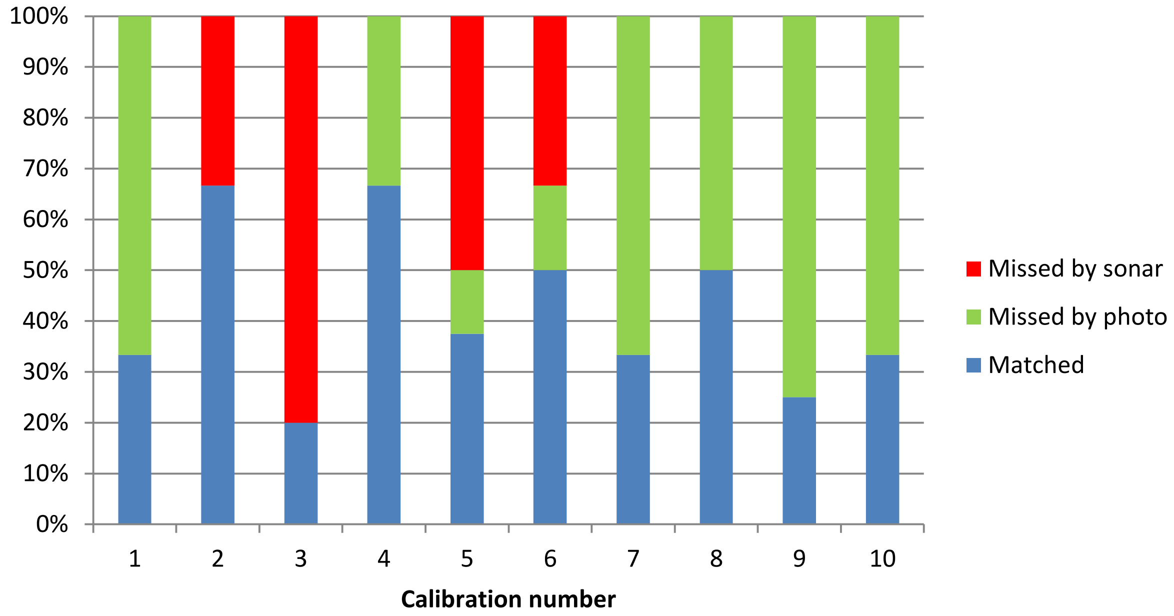


Figure 32: Results of the Gemini calibrations; the graph shows the proportion of seals that were matched in the photographs and the sonar images (blue), the proportion that were imaged by the sonar but were not present in the photographs (green), and the proportion that were present in the photographs but were not imaged by the sonar (red).

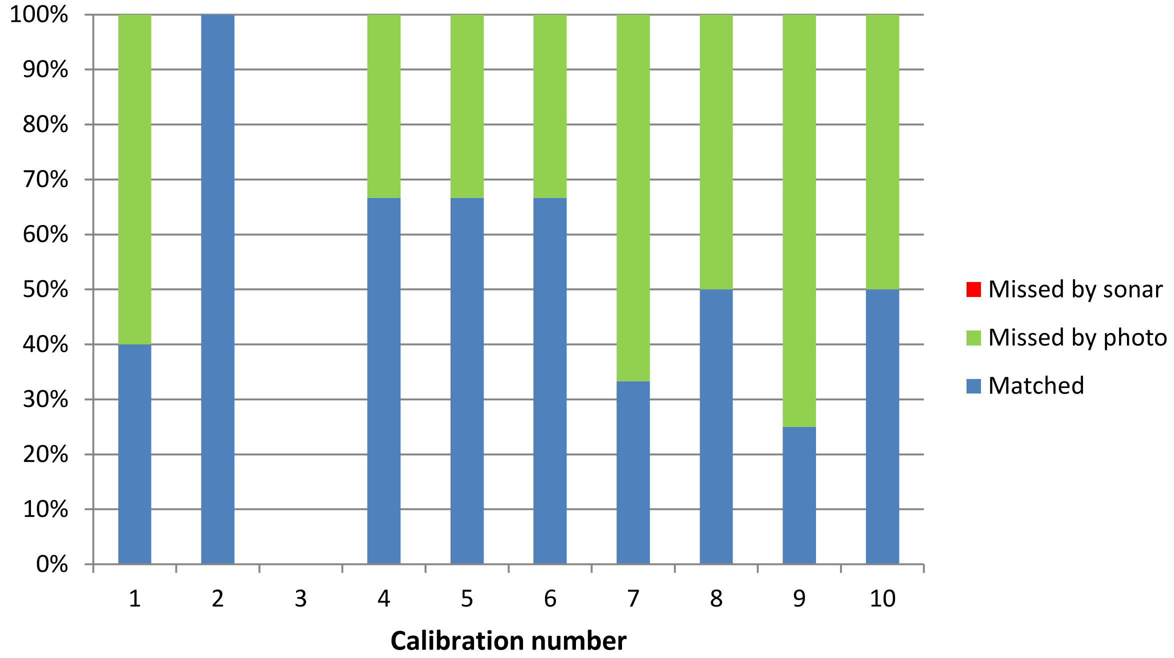


Figure 33: Results of the Gemini calibrations for seals within 60m of the sonar; the graph shows the proportion of seals that were matched in the photographs and the sonar images (blue), the proportion that were imaged by the sonar but were not present in the photographs (green), and the proportion that were present in the photographs but were not imaged by the sonar (red). It should be noted that no seals were present at ranges of less than 60m in calibration 3.

These calibration results suggest that the Tritech Gemini is relatively efficient at detecting grey seals at ranges up to 60m; however, at ranges beyond this, the detection probability appeared to decrease significantly. To some extent, this is governed by the inherent sonar capabilities but will also depend on a number of extrinsic factors including the size and target strengths of the marine mammals being imaged, the environmental conditions, and behaviour of the animals. In particular, the high frequency nature of the system (720 kHz) means that the acoustic signal exhibits rapid loss due to absorption (Urick, 1983); for example, the loss in dBs per km for a 720 kHz signal is approximately 600 times higher than the loss for a 100kHz signal. Effective range could in theory be increased by an increase in sonar source level; however, this has an inherent trade-off with likely increases in the potential for behavioural responses (Section 4; Phase two). Nevertheless, the results do provide a level of confidence that the sonar can efficiently detect small marine mammals and allow tracking of individuals at ranges up to 60m. Furthermore, the fact that the sonar detected seals which were not visible at the surface highlights the usefulness of this system for monitoring and measuring the behaviour of animals not available to be observed by visual means from the surface.

SOFTWARE DEVELOPMENT

Using the marine mammal data, a series of detection and classification developments were implemented in the Gemini 'SeaTec' software. As a first step, a 'Flood Fill' algorithm was developed to look specifically for shape and intensity patterns exhibited by marine mammals. These data suggest that marine mammals exhibit a shape and pattern of intensity values that are either roughly circular with a high intensity areas (probably the lungs) in the centre (when the animal is head on to the sonar), or ellipsoidal with the high intensity area closer to one end (when the animal is side on to the sonar) (Figure 34).

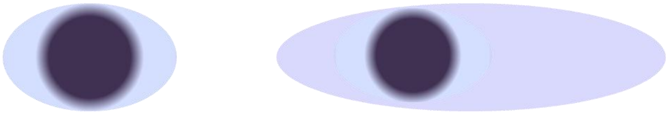


Figure 34: Intensity pattern of marine mammals. The figure shows the typical intensity patterns when the animal is head on to the sonar (left) and side on to the sonar (right).

Early identification of targets is important to generate sufficient information for classification. However, increasing the range capabilities of the sonar introduces issues with data volume; the larger the range of a sonar system the more information is generated and communicated from the head to the processing unit. In order to ensure that data communication remains at acceptable rates, range compression is therefore applied. In practice, this means that not all data is returned from the sonar head thereby reducing the volume of data to be communicated. However, this leads to an inherent trade-off between early identification and target information available for classification. The ideal classification mask for a marine mammal was therefore adapted to take account for range compression. The result is a mask that empirically searches for particular patterns of sonar image data with neighbouring high, medium and low intensities. The values used to define whether targets were marine mammals included:

- Targets within user specified animal size bounds.
- Targets that consisted of more than one range line.
- Targets that contained a group of high intensity cells situated in adjacent cells.
- Targets that contained a group of lower intensity cells that neighbour the high intensity cells.

Qualification of intensity samples (i.e. high or low) were determined by analysing the local maximum, minimum and average sample values. This relative approach was necessary because targets at greater distances inherently return less intense values compared to those closer targets.

Furthermore, it was clear from the marine mammal data collected that potential targets could be lost for short periods probably due to localised hydrodynamic conditions or variations in its orientation to the sonar (particularly at greater ranges; due to range compression). Tracking the target path and providing each target a persistence allowance allowed a target to have a very faint (or no) return in a single frame without being eliminated entirely. If the target was lost for a single frame but subsequently appeared again on the same path it was still considered. A secondary benefit of tracking the path of a target is in noise elimination; if a target does not persist or move it is not evaluated further.

The second stage of development was to incorporate swimming behaviour through path analysis into the classification algorithms. This utilised a combination of the marine mammal data described above and the tidal current data collected during the initial stages of phase 4, as described in Section 6 below. As tidal areas are dynamic environments, there are likely to be a large number of mobile targets that move passively with the tide. Therefore, information such as speed, direction and the change in path was used as a basis used of classifying the target according to its propulsion. As a first step to this, the X-Y tracks for targets were used to calculate the target's speed and direction. The movement of the tide was then incorporated into this to estimate a net velocity (relative to the water). Tide generally moves in a predictable direction in relation to the sonar head, the direction depending on flood or ebb. The speed, however, varies considerably depending on high, low or slack tides. Tidal speed is therefore estimated locally using small moving targets that appear to be moving with the tide (in the same direction); these targets are assumed to be debris. A target's path was then used to calculate a classification probability that a detected target was moving under its own propulsion (either: tidal or self/other).

The combination of all the stages of algorithm development described above (size of the targets, new flood fill mask, the tide weighted velocity, and the tracked path allowed for a simple classification based on the probability that each target is a marine mammal. Using this approach, each target is monitored and allocated a progressively refined probability that it was a marine mammal. In real time, this is visualised using a simple traffic light alarm system; for example, when a mobile target is detected, it is initially classed as '*Possible*' and displayed within a green box if it matches the user defined size and is within a predetermined range. If the '*Possible'* target persists for a predetermined period and is moving in a direction not consistent with tidal drift it is reclassified as '*Potential*', and displayed as an amber box. If a '*Potential'* target's path subsequently varies significantly from the tidal direction, or has large direction changes it is labelled '*Probable*', with a red box. It is important to highlight that the probability progression has the scope to operate in both directions with these detection algorithms. I.e. a target can progress from '*Potential*' to '*Possible*' as well as '*Possible*' to '*Potential*'. Although the simple User Interface visualises the probability with the traffic light system, all technical information associated with each target is available in an extended User Interface.

Furthermore, when valid marine mammal targets are detected (at least one of the detections is '*Probable*', detections are logged to text (*.txt) files in the log data folder. By default, there is one detection file per day, with the filename being automatically generated from the current date. For example, a detection log file generated on the 18th of September 2011 would be named: **MD_20110918.txt**. Detection log files are only generated if movement detection is enabled, and events occur in that day. All detections in the detection log file have a series of information associated with them; this includes the following:

- Time (e.g. 10:59:58);
- Target ID (Sequential number identifying the target track);
- Certainty (Probability that detection is a marine mammal based on the above classifications);
- Range (in metres);
- Bearing (in degrees);
- X (location of target in the X plane in metres);
- Y (location of target in the X plane in metres);
- Mean size X and Y (target size in the X and Y planes in metres);
- File (Raw image file name);
- Speed (speed of the target in ms^{-1});
- Min, Max, and Mean velocity (mean velocity in X and Y planes accounting for tidal speed);

SOFTWARE VALIDATION TESTS

To test the efficiency of the developed software at detecting, classifying and tracking marine mammals, a new series of grey seal data were collected at a haul out close to the Tay Estuary (a different location to the one used for algorithm development) on the 12th October 2011; this was analysed by the developed software (SeaTec; Framework version 2.08, Application version 1.15.05, Gemini DLL version 1.07.52). This marine mammal software calibration data included approximately 3 hours of image data of grey seals. On average, there were 5.6 (SD=4.6; max=14; min=1) individual seals in each of the 5 minute image files. In addition, sonar image data of a series of items of marine debris that were similar in size to small marine mammals and are likely to represent of targets that would be encountered in tidal areas were collected and tested with the SeaTec software. Debris included a semi-submerged wooden plank (1.5m x 0.4m x 0.1m), a large matt of weed, a large piece of air filled plastic debris, and a floating boat fender with weed hanging below it.

The SeaTec software was used in a post hoc analysis of the seal and debris data and the marine mammal detection parameters were set to the parameters that most efficiently detected seals in the software development phase of the project. The SeaTec software stored a series of individual detections that were combined into tracks of targets based on the spatial and temporal characteristics of the detections. Individual detections were also assigned a nominal probability that it was a marine mammal based on the underlying classification algorithms; as described above, the probabilities were ‘*Possible*’, ‘*Potential*’, and ‘*Probable*’ marine mammal. Targets were also be assigned a ‘*Group*’, ‘*Large*’ or ‘*Small*’ level if the target characteristics did not meet the criteria during the classification process.

The calibration produced a detection text file that contained a total of 6,233 detections (371 tracks); for the purposes of software appraisal individual tracks (and its associated detections) were confirmed as seals (2,931 detections; 115 tracks), an item of confirmed debris (1,658; 36 tracks), or an unidentified target (1,643 detections; 220 tracks) through visual inspection of the raw image data. The detections of all seals are shown in Figure 35.

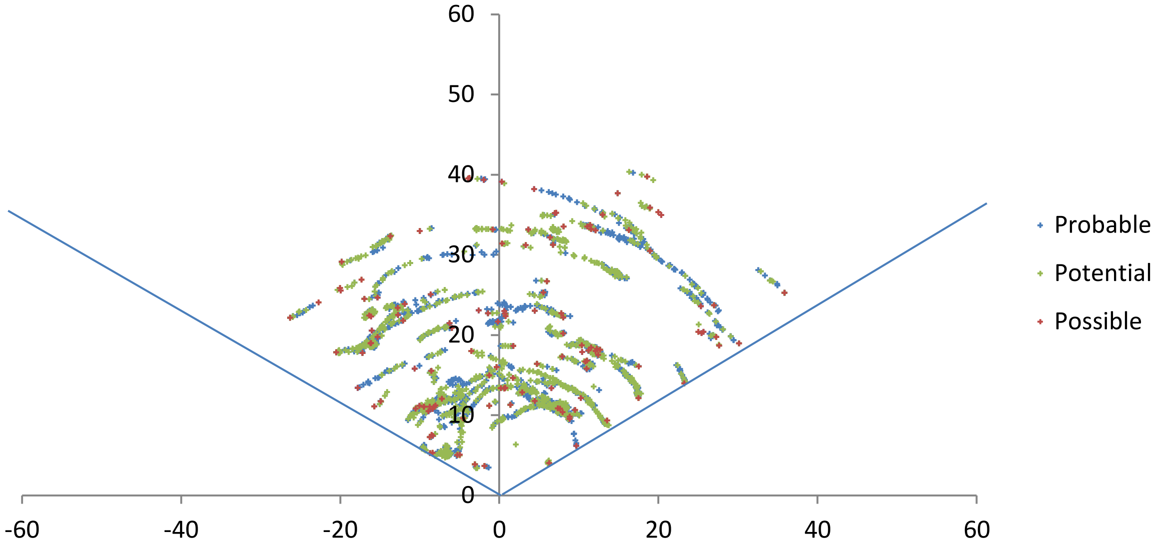


Figure 35: The X-Y locations of all detections that were visually confirmed as seals; the detections are colour coded to illustrate the software assessment of the detections being *Possible*, *Potential*, and *Probable* marine mammals. The axes are in metres and the diagonal lines represent to the spatial limits of the Gemini.

There appeared to be marked variation in the ranges that each of the target types were automatically detected and tracked by the SeaTec software with seals being consistently the furthest detected targets (maximum = 56m) (Table 5). However, it should be highlighted that seals were generally visible in the raw image data at ranges up to 70-80 metres; there was therefore a clear range limitation in the automated detection and classification process. To empirically assess this limitation, mean range of each seal was visually measured in the raw image data and an analysis of whether each seal was detected by the software was carried out. This was carried out by fitting a binomial relationship to the data in a Generalised Linear Modelling framework; models were created using the software package R version 2.8.1 (R Development Core Team 2011). The predictor variable in modelling procedure was mean range of the seal from the sonar in metres and the response term was whether the seal was automatically detected (Yes=1, No=0); the family specified in the model was *binomial.* The results of the modelling suggest that there was a significant negative relationship between range and probability of detection ($\chi^2 = 59.9$, df = 1, $P<0.0001$); the probability of the software automatically detecting a seal was greater than 0.95 for ranges up to around 33 metres, 0.5 at approximately 47m and dropped to below 0.05 at ranges greater than 59 metres (Figure 36).

Table 5: Summary of the ranges of the detections made by the SeaTec software for each of the identified targets (seals, buoy, plastic, weed, wood and wood/weed) and the unidentified targets; the seals had markedly higher detection ranges than the other targets.

	Detection range (m)		
Target	Mean (SD)	Maximum	Minimum
Seal	22.0 (8.9)	56.0	4.0
Unidentified	2.6 (1.3)	8.8	0.6
Buoy	8.7 (2.2)	12.0	2.1
Plastic	8.0 (2.8)	13.6	2.5
Weed	12.6 (4.5)	20.2	3.6
Wood	6.3 (0.5)	7.1	4.4
Wood/weed	9.4 (4.3)	17.7	1.4

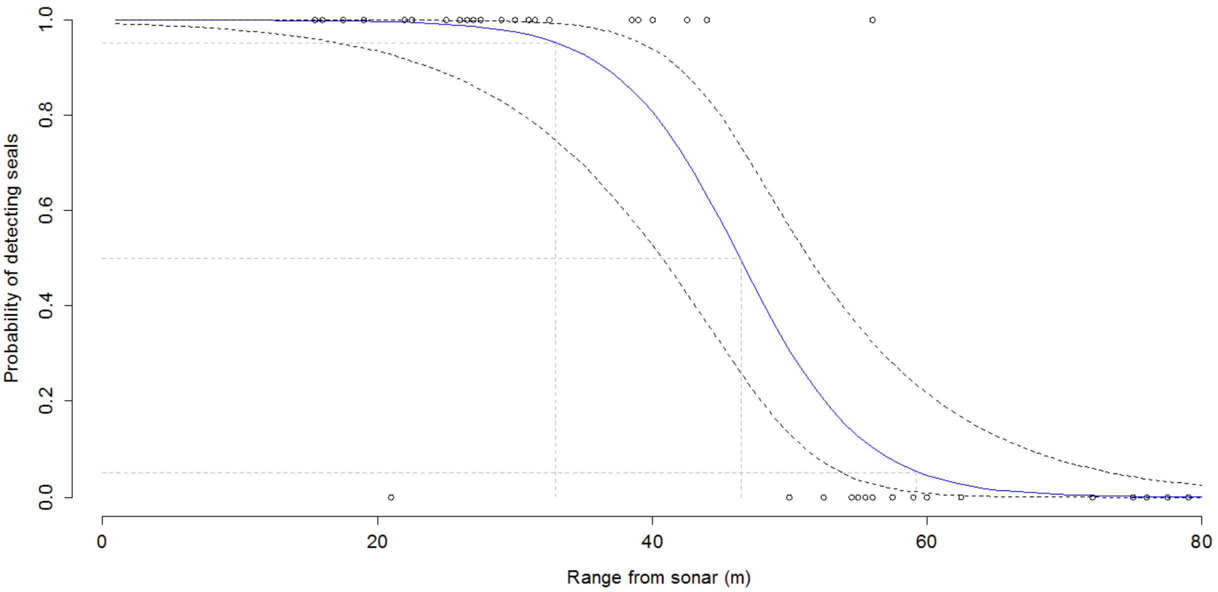


Figure 36: The probability (± se) of the Gemini software automatically detecting seals; the figure shows the relationship between range (m) and probability for the best fit binomial model. The probability was greater than 0.9 for ranges up to around 37 metres, 0.5 at around 47m and dropped to below 0.1 at ranges greater than 56 metres. The grey dashed lines represent the associated ranges with a 0.95, 0.5, and 0.05 probability of detection.

In terms of classifying targets as 'marine mammals' a single '*Probable*' classification leads to the classification of the target as a marine mammal and the subsequent saving of track information (described above). This is clearly a highly conservative approach to classification and is likely to lead to a high number of false positives. In order to refine this, the classification probabilities for each of the confirmed targets and the unidentified targets were further analysed. The majority of classifications for unidentified targets and confirmed debris were '*Potential*' (although they also had a relatively high proportion of '*Probable*' classifications assigned to them) (Figure 37); in contrast, the majority of classification probabilities for confirmed seals were '*Probable*' with only a small proportion being classified as '*Possible*' and none being classified as '*Group*', or '*Small*' (although they also had a relatively high proportion of and '*Potential*' classifications assigned to them). This suggests that the distribution of classification may present a reasonable means of identifying 'high probability marine mammals' [e.g. where the proportion of '*Probable*' classifications is greater than 0.33 (based on lower quartile (Figure 37)) and the sum of proportion of '*Possible*', '*Probable*' and '*Potential*' is greater than 0.95]. Although this potentially reduces the number of false positives (other targets classified as marine mammals), false negatives and positives remain in the data; based on the levels chosen here, 65% of the seals in the calibration trials would have been correctly identified as marine mammals and only 6% of the other targets would have been identified as marine mammals. It is clear that the distribution of classifications used to identify 'high probability marine mammals' could be modified depending on the aims of the application; for example, real time mitigation may tolerate a higher number of false positives in order to ensure that all marine mammals are identified and risk is effectively reduced, whereas long term behavioural monitoring may require lower numbers of false positives to reduce post hoc data validation.

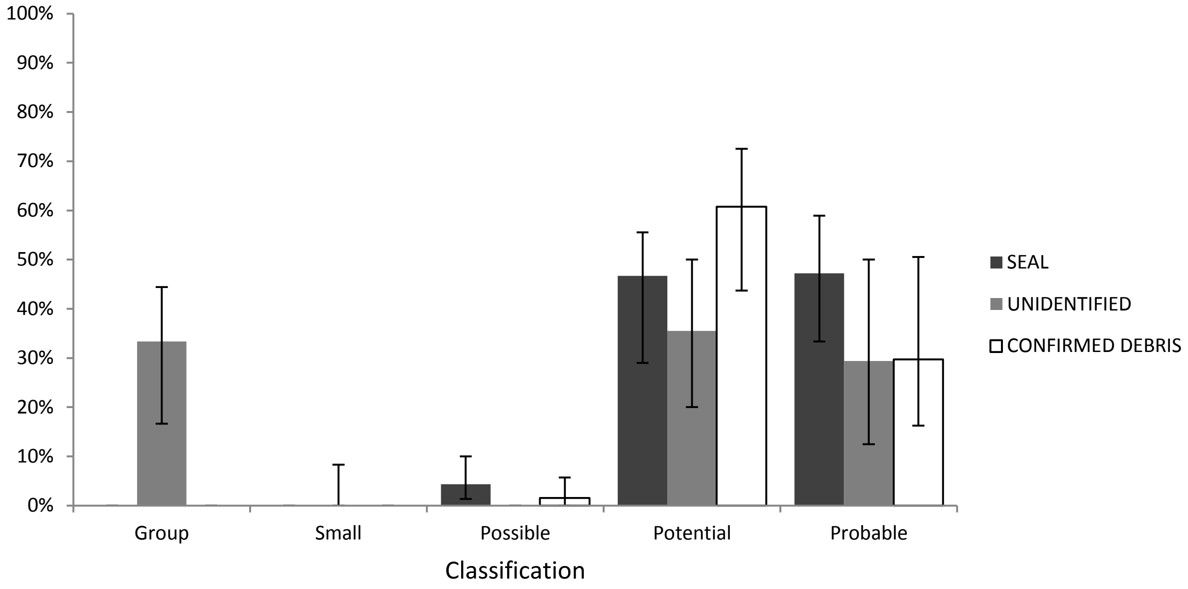


Figure 37: Distribution of the classification probabilities for each of the target groups (seals, unidentified targets, and confirmed debris). The graph shows the median proportion (± IQ ranges) of detection classifications within each track.

MANUAL TARGET CLASSIFICATION BY USERS

To evaluate the capabilities of users to manually classify species by viewing the sonar data, a series of sonar data with known marine mammal species and confirmed items of debris were reviewed by a number of users (all marine mammal scientists) who were asked to make a critical evaluation of the species in the data. A total of 12 data files collected using the Tritech Gemini were played independently to 4 marine mammal scientists and each was asked to make an assessment of the target ID in each of the files. The files consisted of confirmed grey seals, bottlenose dolphins, harbour porpoises, and a range of items of debris (weed, floating wood, buoys). All targets were in ranges of between 25 and 45m.

Each user viewed the data and made a judgment of the ID of each target based on its size, shape, and movement. Each was asked to identify whether they considered each target to be an item of debris, a marine animal, or was unidentifiable; if the target was identified as a marine animal, each was asked to provide an identification to the level of taxonomy that they were confident could be assigned to the target.

The results of these trials showed that items of debris were correctly classified in all cases. Similarly, marine mammals were successfully differentiated from debris in all but one case (where a harbour porpoise was classified as an item of debris). Bottlenose dolphins were correctly classified down to order level (i.e. cetaceans) in between 50 and 100% of the trials and were not classified to species in any of the trials. However, grey seals were correctly classed to order in only 33 to 67% of trials and harbour porpoises were correctly classed to order in 50% of trials; interestingly, the harbour porpoises were correctly identified to species in all cases when they were identified correctly to order level (Figure 38).

These results suggest that visual discrimination of small marine mammals from items of debris is relatively good for the data collected using the Tritech Gemini; furthermore, some of the users were relatively good at discriminating between cetaceans and pinnipeds. However, users appeared to have less confidence when classifying to species level with only 2 users correctly identifying harbour porpoises to species level and one user incorrectly classifying a grey seal as a harbour seal. These results suggest that users of the system should be able make a reliable post hoc assessment of the targets to at least marine mammal level and in most cases to a seal or cetacean level.

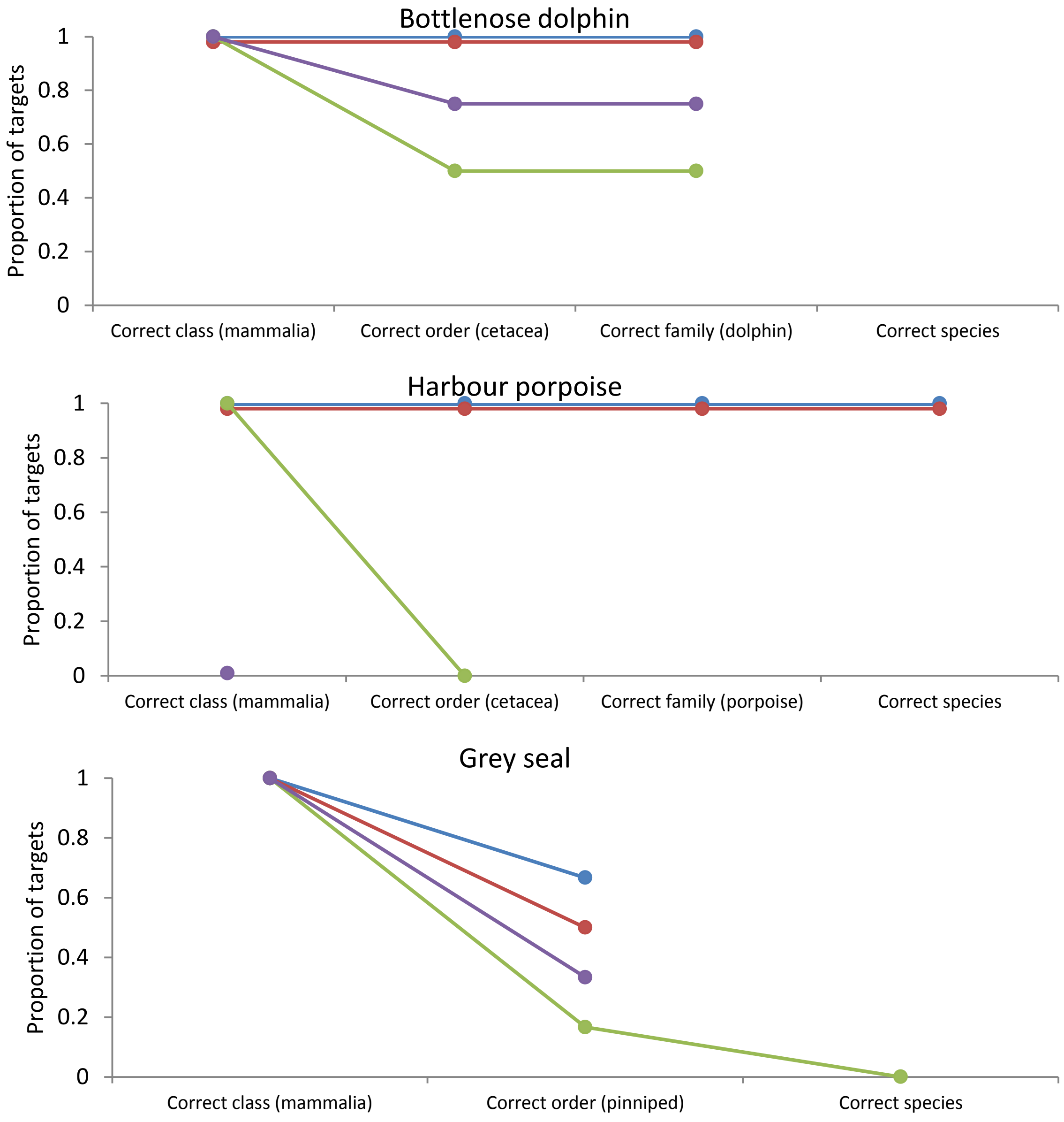


Figure 38: Results of the visual target ID assessment; the graph shows the proportion of targets that were correctly identified to a series of levels by each of the 4 users for bottlenose dolphins (top), harbour porpoises (mid), and grey seals (bottom). Each user is denoted by a line of a different colour. If there is no data point, this indicates that the user was not confident at classifying the target to this level of classification.

DISCUSSION

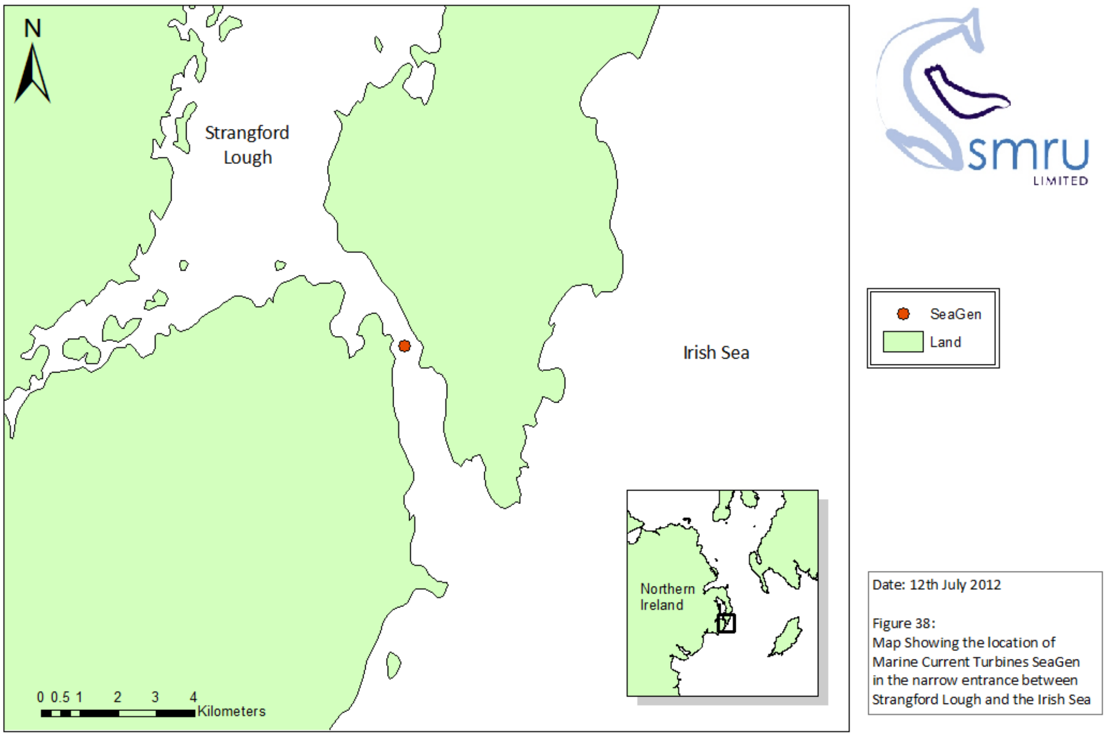
Overall, these results suggest that the SeaTec software is highly effective system for automatically detecting small marine mammals out to ranges of at least 40 metres. Beyond this range, the detection probability appeared to decrease markedly. However, it should be highlighted that these tests were on a single, relatively small, marine mammal species in a shallow, acoustically cluttered environment. Furthermore, although efforts were made to ensure the sonar transducer did not move during the calibration trials, it was deployed from a boat and automatic detection ranges and probabilities may have been compromised by transducer movement; it would seem reasonable to assume that stable deployments in deeper environments, automatic detection ranges would be greater.

In terms of automated classification, the results of the comparisons between confirmed debris, unidentified targets, and seals suggest that, although the seals generally had '*Probable*' as their highest classification category, there was marked variation around this and it was clear that other targets were frequently given a high probability of being marine mammals. With respect to using this system as a behavioural monitoring tool, the summary detection files provided an efficient means for storing and data. Furthermore, the ability to make automated recordings of raw image data when detections allow the data to be relatively easily interrogated post hoc. However, the relatively poor discriminatory capabilities of the software mean that a certain level of post hoc analysis/visual confirmation of targets may be required to effectively differentiate marine mammals from other debris. Furthermore, the results have implications for the use of the sonar as a real time mitigation system. Specifically, the effective detection capabilities out to 40 metres mean that control measures could be effectively implemented when marine mammals are within this range; however, the relatively poor differentiation from other marine debris means that it would likely function as a highly precautionary real time mitigation tool and would be likely to lead to control measures being implemented as a result of debris and marine mammals.

6. PHASE 4: LONG TERM TIDAL TURBINE DEPLOYMENT

The primary aim of this project stage was to evaluate the long term reliability and detection capabilities of the sonar on an operational tidal turbine. Data permitting, a secondary aim was to evaluate the frequency of encounters between marine mammals and the tidal turbine, and to measure potential behavioural responses to turbine operation.

We deployed a Tritech Gemini sonar system on the SeaGen tidal turbine (http://www.seageneration.co.uk/); a 1.2MW commercial demonstrator tidal energy convertor that is located in the narrow entrance to Strangford Lough, Northern Ireland (Figure 39). Installation of SeaGen began in April 2008 and was completed in June 2008 with operation starting in July 2008. The turbine consists of a central tower (diameter = 3m, height above sea bed = 41m), with a control room at the top and a crossbeam that can be raised and lowered for rotor maintenance. Two turbines are mounted on the cross beam, either side of the single monopile structure; the rotors (diameter = 16m) have a maximum tip speed of 12ms^{-1} (Figure 40). The entrance to Strangford Lough is approximately 750 metres wide at the turbine location and SeaGen is located approximately 400m from shore. Maximum currents speed during spring flood tides in this area are 7.8 knots (4ms^{-1}) and ebb flows at 7.2 knots (3.7 ms^{-1}); current speeds on a neap tide are considerably reduced and peak flows were recorded around 1.5 ms^{-1}.



Date: 12th July 2012

Figure 38:
Map Showing the location of Marine Current Turbines SeaGen in the narrow entrance between Strangford Lough and the Irish Sea

Figure 39: Map showing the location of SeaGen (Marine Current Turbines) in the narrow channel between Strangford Lough and the Irish Sea.

Strangford Lough has a number of marine mammal species that have the potential to interact with the tidal turbine. The most common marine mammals occurring in Strangford Lough are harbour seals. These are a qualifying feature of the Strangford Lough Special Area of Conservation (SAC) designation, although they are not the primarily reason for the site selection. A recent survey of seal numbers in Strangford Lough counted 272 harbour seals within the Lough and the narrow entrance to the Lough (SMRULtd, 2010a). Evidence from telemetry studies suggested that individual tagged harbour seals transited the narrows a mean number of around 0.36 times per day (SMRULtd, 2010b); this equates to a total of approximately 62 seal transits per day. Grey seals and harbour porpoises have also been recorded in relatively low numbers. Furthermore, a number of fish species and seabirds are likely to present around the turbine.

In response to uncertainties about impacts on environmental sensitivities, an Environmental Monitoring Programme (EMP) and associated suite of mitigation measures were established. The aim was to ensure that significant impacts on the features of the designated sites did not occur, while allowing any changes in the environment to be monitored; this aimed to provide a means of adapting the management of the turbine on the basis of actual data derived from the monitoring programme. Data collection began, pre installation, in April 2005 and as part of this, an active sonar monitoring system (two Tritech SuperSeaking transducers) was installed to provide a means detecting marine mammals underwater and mitigating physical interactions by initiating precautionary shutdown of the turbine.

METHODS

SONAR HARDWARE

A single Tritech Gemini sonar transducer was attached to a mounting plate, secured to the centre of the crossbeam of the turbine, and electrolytically isolated from the turbine using rubber matting between the head and the mounting plate (Figure 40). The depth of the transducer when the crossbeam was lowered was approximately 11.5m below MLWS and was close to the middle of the water column (seabed = 23.9m below MLWS). Data transmission from the sonar heads was incorporated into custom built cables within the turbines existing systems cabling. The sonar provided approximately 120^{o} horizontal coverage x 20^{o} vertical coverage in front of the turbine (Figure 41). This provided full water column coverage at approximately 68 metres from the turbine, at a range likely to be towards the limits of this system at detecting marine mammals. A laptop computer located in the turbine control room was used to record the sonar data in real time using the Gemini software.

Figure 40: Image showing the turbine with the cross arm raised out of the water (left). The mounting location of the sonar transducer on the centre of the crossbeam is shown on the right.

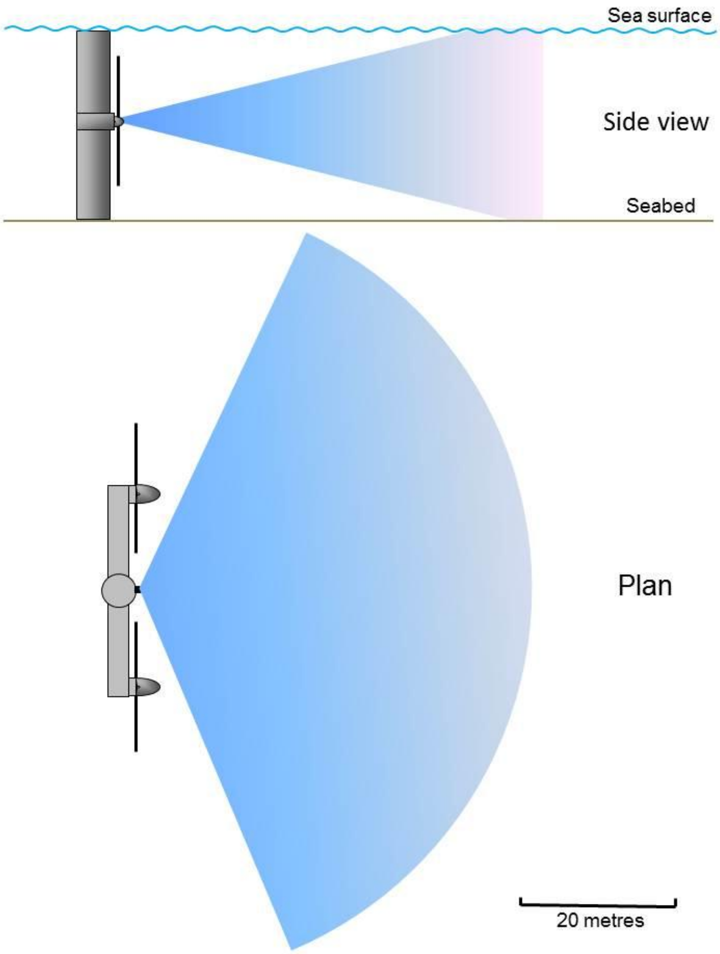


Figure 41: The approximate ensonification coverage achieved with the sonar. The figure shows the horizontal (top) and vertical (bottom) coverage around the turbine.

DATA COLLECTION AND ANALYSIS

The pre-development movement detection software was used to record data when mobile targets were detected; the size parameters for detection were set at a conservative level to maximise the number of mobile targets that were saved. Log files and associated txt files with target information were saved for post hoc analysis. The following settings were used for data collection: Gain = 87.2%, Range=50m. Data collection was monitored via a wireless LAN connection to the turbine using a remote desktop application and data were backed up manually every 14-21 days. It was originally planned to deploy the sonar for a period of 5 months; however, equipment availability and SeaGen operational constraints limited sonar data collection to a total of 42 days between the 20th May and 29th July 2011 equating to 6.07 Tb of data. Only data collected during the flood tide (i.e. the sonar was facing the incoming tide) were used in analysis. These data were then analysed post-hoc using the developed SeaTec software to determine what proportion of the targets were classified as marine mammals with a high probability and how these behaved around the turbine. As described in Section 5 (Phase 3), the SeaTec software employs a highly conservative approach to classifying marine mammals (where a single '*Probable*' classification is enough to classify the target as a marine mammal) and it is therefore likely that the majority of these targets will not be marine mammals. We therefore used the distribution of probabilities that were associated with known marine mammals (grey seals) [proportion of '*Probable*' classifications was greater than 0.33 and the sum of the proportions of all marine mammal classifications ('*Possible*', '*Potential*', and *'Probable*') was greater than 0.95 (Figure 37)] to further classify high probability 'marine mammals' in the data from SeaGen. The data were therefore summarised in terms of the number of 'marine mammals', and the number of 'other' targets. The tracks of all targets were plotted in X-Y coordinates around the turbine to assess the frequency and proximity of 'marine mammals' and 'other' targets to the turbine.

In addition, the temporal variation in the number of 'marine mammals' were analysed in a General Additive Modelling Framework (Hastie and Tibshirani, 1990) to assess how 'time of day', 'tidal speed', and 'turbine operation' influenced the number of marine mammals around the turbine. These data are essentially relative animal abundances collected over time, which are likely to be nonlinearly related to the model temporal covariates. For this reason, Generalized Additive Models [GAMs] were used to model mean number of 'marine mammal' targets. GAMs with quasi-poisson errors and a log-link were fitted. The data comprised of observations collected close together in time, and consecutive observations are likely to be correlated beyond the underlying processes. While a part of this correlation in the data might be explained by including temporal information in a model, this approach is unlikely to explain the correlation in full and will most likely result in some residual auto-correlation which violates a key assumption of many statistical modelling methods. For this reason, Generalized Estimating Equations (GEEs) were used to account for any residual auto-correlation and adjust GAM standard errors and *p*-values accordingly.

RESULTS

From a hardware perspective, the sonar transducer operated continually throughout the deployment period without any significant issues and fouling by marine life was not observed on the equipment. However, the transducer that was fitted on SeaGen had an aluminium housing and there was evidence of an accelerated rate of corrosion on the housing components. The rate of corrosion was markedly higher compared to typical corrosion rates observed on sonar equipment. Although the heavily tidal environment may have contributed to the rate of corrosion, it is unlikely that this was the fundamental factor underlying the corrosion. When the Gemini housing was inspected there were iron deposits on the housings, which would suggest chemical corrosion due to metal mismatch around the sonar mountings resulting in the housing acting as an anode to the mild steel (Tritech pers. comm.).

Sonar images from 42 days between the 20th May and 29th July 2011 were post processed using the SeaTec software; this provided a total 441 hours of data. The total number of detections that the software detected and where at least one of the classifications was '*Probable*' was 9,142; this equates to a detection encounter rate of 20.7 targets.hr^{-1}. However, when these targets were refined and only those considered as being high probability marine mammals (targets where the proportion of '*Probable*' classifications was greater than 0.33 and the sum of the proportions of all marine mammal classifications ('*Possible*', '*Potential*', and *'Probable*') was greater than 0.95), the number of 'marine mammals' (e.g. Figure 42) that were detected and tracked was 109; this equates to an encounter rate of 0.25 'marine mammals'.hr^{-1} (approx. 5.9 per day).

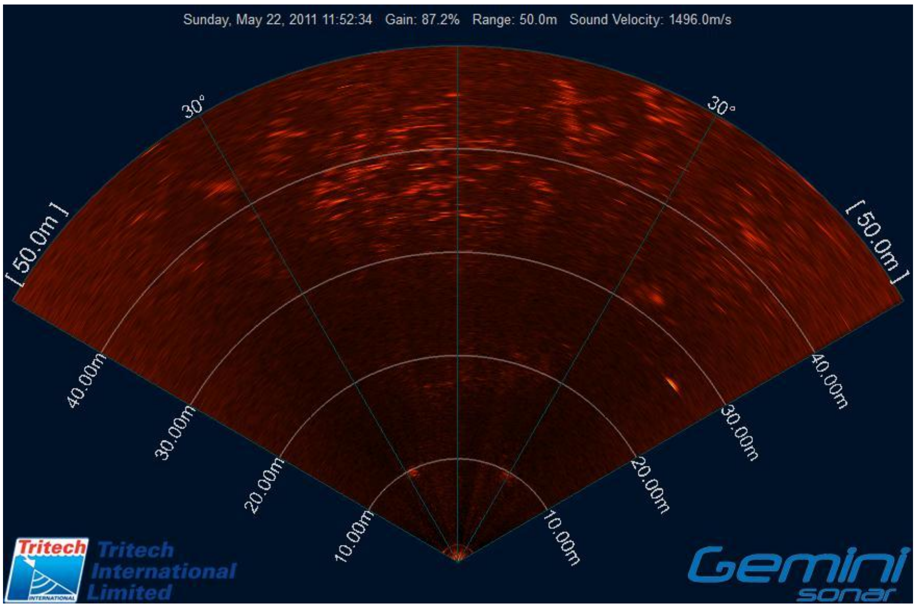


Figure 42: Sonar image of a detection that was classified as being a high probability marine mammal (as described in the text); the 'marine mammal' can be seen at a range of approximately 27 metres at an angle of 50 degrees to the right of centre.

The X-Y plots of all the detections illustrated that mobile targets were frequently detected relatively close to the turbine. The mean range from the turbine of 'all targets' was 21.5m (SD = 11.4m, max = 49.9m, min = 0.86m) with the mean range being similar when the turbine was operational (22.3 (SD=11.4)) compared to when it was not operational (21.3m (SD=11.4)). The mean range from the turbine of the 'marine mammals' was 31.5m (SD = 9.8m, max = 49.3m, min = 8.4m) with the mean range being lower (27.2m (SD=9.4) when the turbine was operational compared to when it was not operational (31.9m (SD=9.7)); however, this relationship was not significant (GLM: χ^2 =0.14, df=1, *P*=0.71).

The mean speed (not accounting for tidal speed) of 'all targets' was 3.38ms^{-1} (SD = 3.24ms^{-1}) and the mean speed of the 'marine mammals' was 2.63ms^{-1} (SD = 2.02ms^{-1}). When the tidal current was accounted for, the mean net velocity of 'all targets' was 1.09ms^{-1} (SD = 1.07ms^{-1}) and the mean net velocity of the 'marine mammals' was 1.25ms^{-1} (SD = 1.31ms^{-1}).

The results for the temporal modelling of the 'marine mammal' targets suggests that the time of day was a significant predictor of the occurrence of 'marine mammals' (Table 6); detections appeared to peak between midday and midnight and a minimum at approximately 0500 (Figure 45). In contrast, there was not any significant variation in the occurrence of 'marine mammal' detections in relation to tidal speed or turbine operation (ON/OFF).

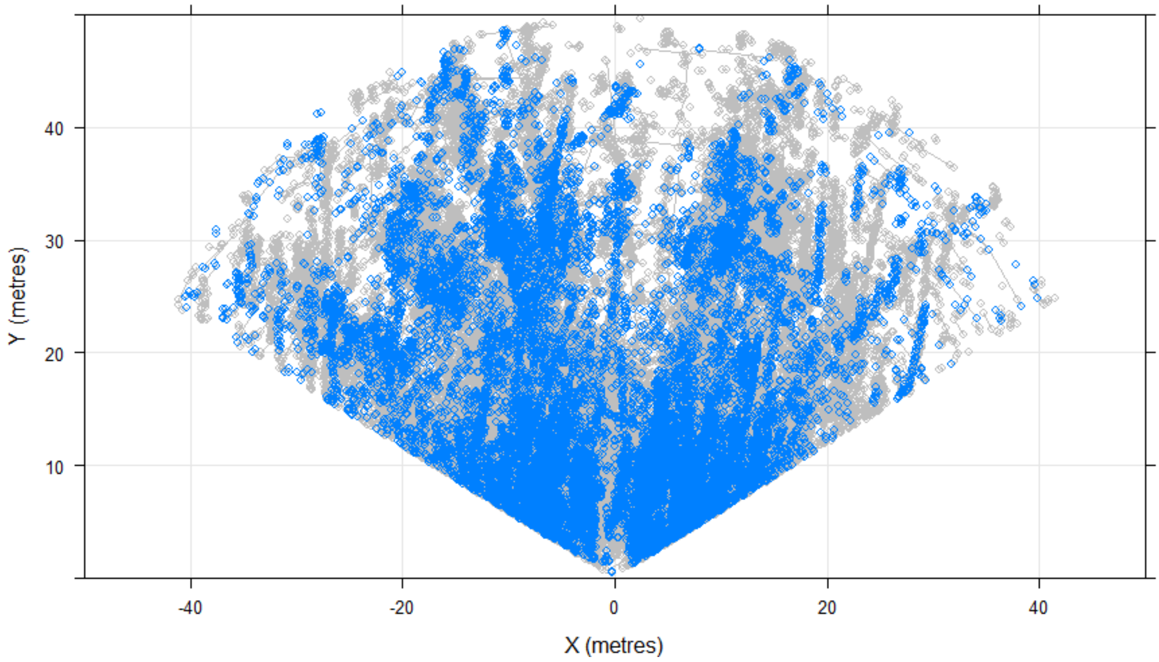


Figure 43: X-Y plot of the tracks of all targets around SeaGen between the 20th May and 29th July 2011; the plot shows the X-Y location of all detections made by the SeaTec software when the turbine was operating (blue) and not operating (grey).

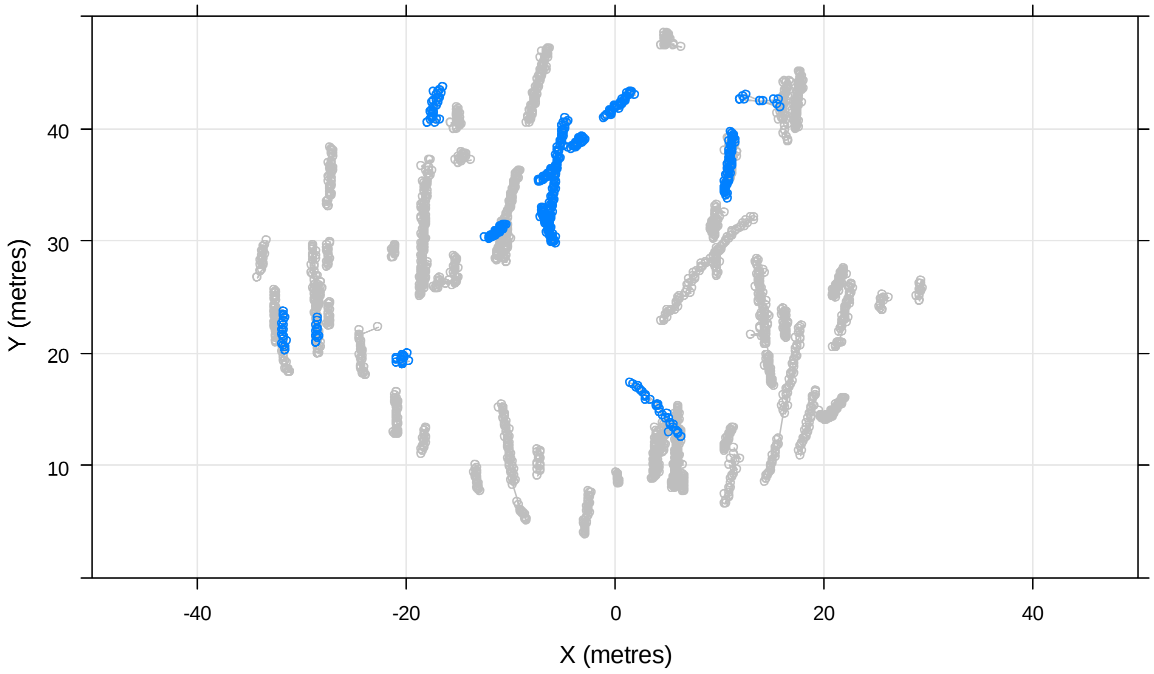


Figure 44: X-Y plot of the tracks of 'marine mammals' around SeaGen between the 20th May and 29th July 2011; the plot shows the X-Y location of all detections for tracks with a high probability of being a marine mammal when the turbine was operating (blue) and not operating (grey).

Table 6: Significance of model terms for a GLM fitted with GEEs to the occurrence of detections of 'marine mammals' around the tidal turbine at Strangford Lough.

Model term	df	Chi-sq test statistic	*p*-value
Time of day (hrs)	4	14.56	0.006
Tidal speed (ms^{-1})	4	2.58	0.631
Turbine operation (ON/OFF)	1	0.13	0.723

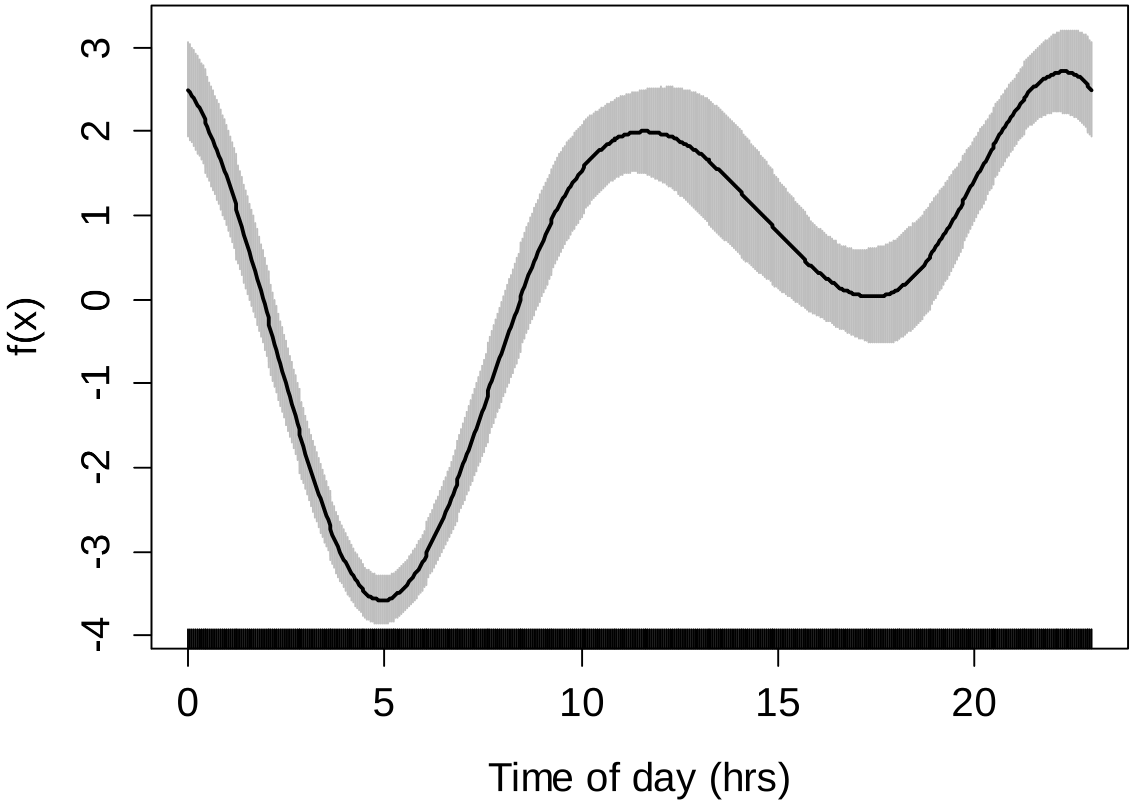


Figure 45: Generalized additive model functions of 'marine mammal' detections from the tidal turbine in Strangford Lough in relation to time of day. The function is scaled to the model mean.

In addition to marine mammals being detected by the sonar, it is interesting to note that a number of other marine wildlife species were regularly detected; these included diving birds (Figure 46) and fish (Figure 47). At present, no analyses of detection probability or behaviour has been carried out on these other species

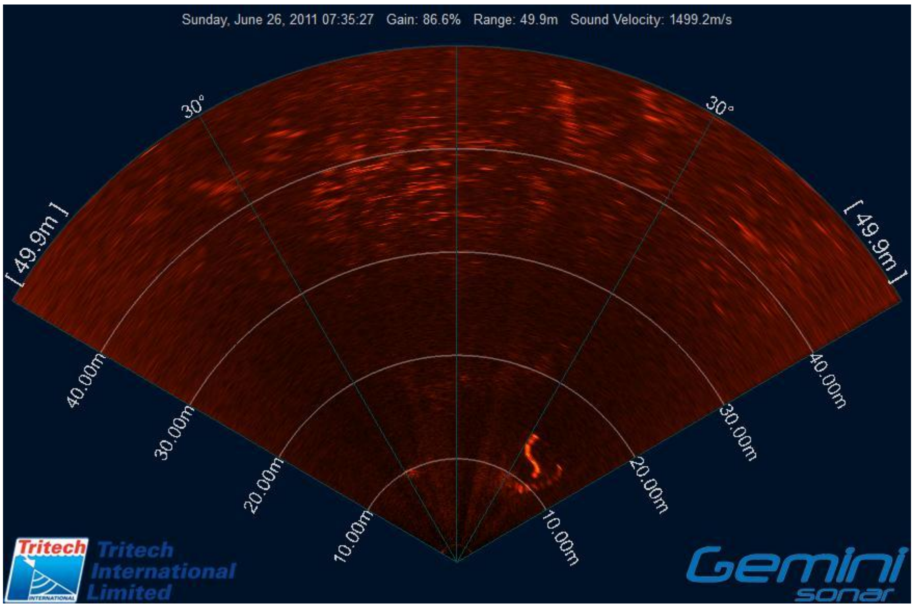


Figure 46: Sonar image of targets that were assumed to be diving birds close to the Strangford Lough tidal turbine; these were relatively small (≈0.25m in length), highly mobile targets that had distinctive trails of turbulence or bubbles streaming behind them. Two birds can be seen at ranges of approximately 15m at angles of 30 and 45 degrees to the right of centre.

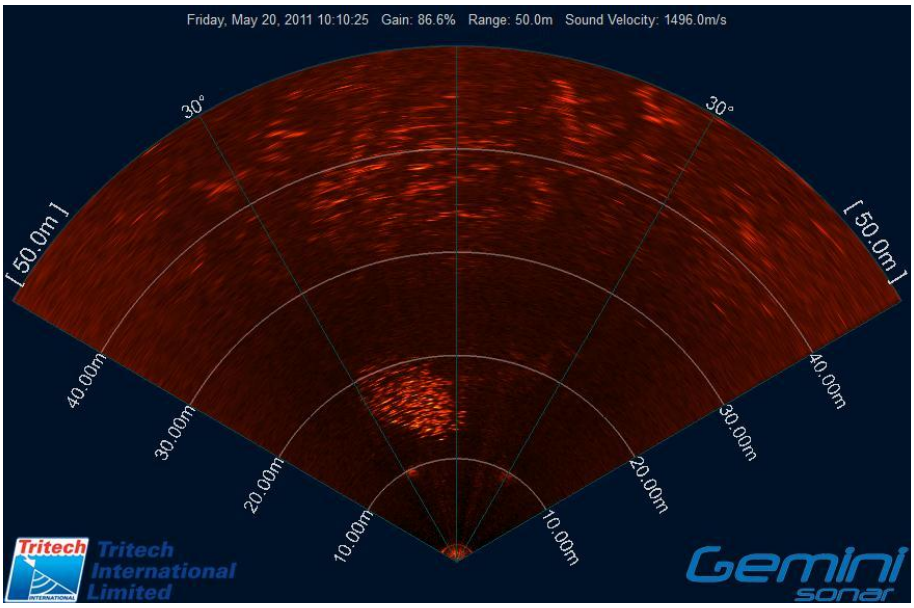


Figure 47: Sonar image of targets that were assumed to be fish close to the Strangford Lough tidal turbine; these were relatively small (0.2 - 0.3m in length) highly mobile targets exhibiting distinctive schooling behaviour. The school can be seen at ranges of between 10 and 20m and at angles of between 0 and 30 degrees to the left of centre.

DISCUSSION

The results of this phase of the program illustrate that high frequency imaging sonar can be used long term (over periods of several months) to detect small marine mammals (and other mobile targets) at a marine renewable energy site. In terms of practical operation, the system was successfully integrated into the turbine communications system and could be monitored remotely. As the system was installed post turbine installation, data had to be stored on a PC on the turbine and had to be collected manually; however, fibre optic cabling to a PC based ashore would potentially provide a more practical alternative for future deployments of the Gemini. From a hardware perspective, the system operated continually throughout the deployment period without any significant issues and fouling by marine life was not observed on the equipment. However, there was an accelerated rate of corrosion on the underwater housing components; given this, the manufacturer has recommended that titanium is used as the housing material for long term sonar deployments in these types of environments. Although this will not eliminate corrosion, it should result in considerable improvements.

Sonar images from 42 days between the 20th May and 29th July 2011 (a total of 441 hours of data) were post processed using the SeaTec software. Although post processing of the data was straightforward it was a relatively time consuming process, taking approximately 10 days PC time to fully process this data. The total number of detections that the software detected and where at least one of the classifications was '*Probable*' was 9,142; this equates to a detection encounter rate of 20.7 targets.hr^{-1}. Given marine mammal abundance in the area (SMRULtd, 2010a), it is clear that only a proportion of these targets are marine mammals and confirms that in its current configuration, the software is highly conservative. Although this is not a significant issue for behavioural research or long term monitoring (where post processing of data can be carried out), it is clearly a potential issue for certain applications (e.g. real time mitigation). Nevertheless, to maximise monitoring efficiency (and reduce data volumes) it is recommended that further work on the classification is carried out; this could either be incorporated into the Gemini SeaTec software or into the post processing during behavioural analysis. As a first attempt at this, we carried out a post hoc classification of 'high probability marine mammals' based on the distribution of classifications from each track. The results of this suggested that there were 109 high probability marine mammals in the data; this represents less than 0.01% of the targets that had at least one "*Probable*" classification associated with it. A manual review of the data associated with these 'marine mammal' detections appeared to confirm that they were marine mammals (e.g. Figure 42) with only 3 of the targets being obviously non-marine mammals (2 appeared to be large matts of weed and one appeared to be entrained air/turbulence).

The detection rate of 'high probability marine mammals' was 0.25 'marine mammals'.hr^{-1} which equates to 5.9 per day. Predictions from harbour seal telemetry data in Strangford Lough predicted an annual estimate of approximately 1200-1300 transits past the operating turbine within 25m of its centre (SMRULtd, 2010b); this equates to approximately 3.3-3.6 transits/day. Given the sonar had an effective detection range of around 40-50m, i.e. double the range used to estimate close transits from telemetry data, the sonar 'marine mammal' detection rates (5.9/day) and the telemetry predictions (3.3-3.6 seals per day) appear remarkably consistent.

An important consideration when using sonar in tidal environments is the effect that highly heterogeneous water characteristics or wind generated clutter near the surface can have on the imaging capabilities of sonar. For example, wind generated white caps on the surface are a very good acoustic reflector and the surface return clutter from the white caps can significantly corrupt the quality of the acoustic data to such an extent that it makes it unreliable for small target detection (Kozak, 2006). Furthermore, density variations in the water column can cause the path of the sound to follow a distorted or curved path; thermoclines are the most frequent cause of this distortion, but this effect can also be experienced wherever water masses of differing salinity occur together (Kozak, 2006). Despite this, the ranges that ‘marine mammals’ were detected at Strangford (max: 49.9m) was consistent with the data collected on marine mammals during the software calibration phase of the program (max: 56.0m) suggesting that there are no significant acoustic interference from the turbine or hydrographic limitations to detecting marine mammals at tidal sites. Furthermore, the data suggest that marine mammals do move in close proximity to the tidal turbine both when it was operational (minimum range=9.9m) and non-operational (minimum=8.4m).

Although the number of ‘marine mammals’ represent a relatively small sample size, these results have clear implications for the risk of physical interactions by marine mammals with moving rotors on the turbine. It is worth noting that the orientation of the sonar in this study did not effectively monitor the turbine rotors, thus precluding the measurement of potential close range evasion behaviour by animals; this is a clear limitation of this study that should be addressed in future studies. However, consideration of how rotor movement in the frame may affect automated detection and classification should be made and accounted for; this could potentially be achieved through software development to allow a user to identify areas in the sonar image where predictable movement (e.g. rotors) is likely to occur. Furthermore, data analyses presented here were limited to upstream targets only. Ideally marine mammal targets would have been tracked on both the upstream and downstream sides of the turbine; however, equipment and logistical constraints limited the deployment to a single sonar head. Although this should be addressed in future studies of marine mammal behaviour, it should be noted that tidal mixing downstream of the turbine pile appeared to create significant turbulence immediately downstream of the pile which may have implications for imaging marine mammals downstream in this area (Figure 48).

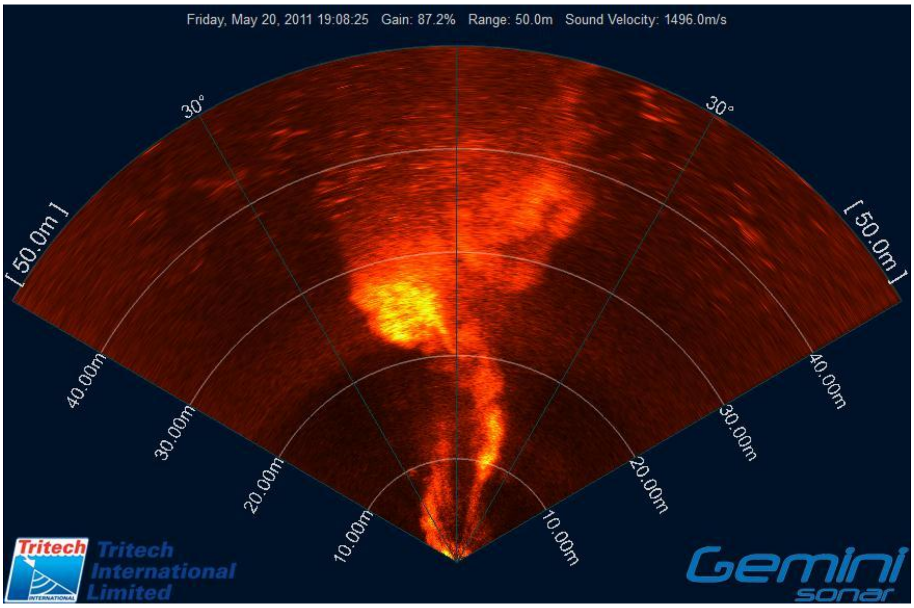


Figure 48: Sonar image of the area downstream of the Strangford Lough tidal turbine. Tidal mixing and/or entrained air at the surface can be seen immediately downstream of the pile which may have implications for imaging marine mammals in this area.

The results of the modelling of ‘marine mammal’ detections with the temporal covariates suggested that there were significant differences in the occurrence of ‘marine mammals’ with time of day.

Detections generally decreased during early morning with minimum at approximately 0500. The temporal pattern in detections is similar to transits of tagged seals which peak around midnight and drop during early morning (SMRULtd, 2010b). In contrast, there was no significant variation in ‘marine mammal’ detections in relation to tidal speed and turbine operation (ON/OFF). It should be highlighted that the operational data represent a relatively small proportion of the total data and the data collection only cover a period of approximately 2 months so these results should be interpreted in a broader context with caution.

The behavioural data that are produced as part of the track processing (XY location, speed, net velocity, angle of movement) provided a useful set of metrics for measuring the behaviour of marine mammals around tidal turbines; although analyses of tracks were relatively crude in this current study, these type of data do provide a basis for analysing fine scale movements of individual marine mammals in relation to the presence of tidal turbines. Furthermore, it provides a mechanism for assessing changes in movements in relation to turbine activity (e.g. operating vs. not operating). However, it should be highlighted that although the data allow plotting and analysis of tracks in the XY plane, analysis of movement is somewhat limited without information on the depth of the animals; this is a key limitation that should be considered during any future development of sonar systems for this application.

In summary, this phase of the program provides the basis for evaluating the practical effectiveness of sonar as a monitoring tool for the marine renewable industry. It is clear that small marine mammals can be reliably detected and tracked with the developed sonar system. However, it also confirms that the developed software employs a highly precautionary approach to classifying marine mammals and although it is not a significant issue for monitoring and behavioural research, this approach does make post hoc analysis relatively time-consuming if long term monitoring is to be achieved.

7. PRACTICAL APPLICATION OF SONAR AS A BEHAVIOURAL MONITORING TOOL

Uncertainty about the risk to marine mammals posed by marine renewable energy devices has the potential to curtail the development of the industry beyond a few small scale demonstration devices. In light of this uncertainty Statutory Nature Conservation Agencies are likely to be highly precautionary in the advice they provide to regulators wherever there is even a small possibility of an impact which could be considered a 'likely significant effect' (LSE) on a population protected under the EU Habitats Directive. The Habitats Directive legislation is unusual in that case law dictates that a plan or project cannot be consented unless the possibility of a Likely Significant Effect can be ruled out beyond reasonable scientific doubt. Giving consent to a plan or project where a LSE cannot be ruled out can put governments in breach of the Habitats Directive, even if no negative impact ensues. The highly mobile and wide ranging nature of marine mammal species means that it is highly unlikely that areas which have potential for marine energy will not also be used by protected marine mammals.

Until projects can provide data demonstrating that marine mammals can take appropriate avoidance action around operational devices, or more efficient, cost effective mitigation solutions are developed, uncertainty about the impacts will continue. A clear pathway to understanding the true impacts is to deploy devices in areas used by marine mammals alongside a comprehensive monitoring or behavioural research scheme which allows for any impacts to be quickly detected. The practical application of sonar at the appropriate stage of this pathway is therefore of key importance in reducing uncertainty.

BEHAVIOURAL RESEARCH:

To measure the behaviour of marine mammals around tidal energy devices, any sonar needs to meet a number of important specifications. Firstly, it needs to be reliable in terms of detection; the sonar developed in this program had a detection probability greater than 0.95 up to ranges of 37 metres. Secondly, it needs to provide relevant behavioural information and although this will clearly vary depending on the research question being asked, the Gemini provides data that could be used to address a number of questions relevant to movements around turbines (e.g. swimming speed, swimming direction, proximity to the turbine, and X-Y tracks). Thirdly, it is important that the sonar being used to measure behaviour does not elicit a behavioural response itself; from this perspective the Gemini could successfully be deployed on a turbine to detect and track animals with a relatively low risk that the signals would significantly attract or exclude them from the immediate area around the turbine. However, deployment of other systems without a thorough review of sound characteristics should be carried out with caution.

Although this work has illustrated the potential value of using active sonar to monitor the fine scale behaviour of marine mammals around tidal turbines, it is important to highlight the fundamental limitations associated with the Gemini. Specifically, the system does not currently provide information on the depth of targets; at present this may prove prohibitive for certain research questions or deployment scenarios. However, in order to gain depth information, it may be possible to design sonar configurations with multiple transducers mounted in different orientations; for example, 2 systems mounted together with one in the horizontal and one in the vertical plane would potentially allow simultaneous detection of a marine mammal on both systems thus providing X-Y-Z tracks of marine mammals around turbines. This is likely to require additional development to integrate tracking data from multiple systems.

Furthermore, the vertical swathe of the system is approximately 20 degrees (although we were able to routinely image marine mammals outside this) which means that careful consideration of the deployment location is required. In the Strangford Lough deployment, as the transducer was mounted on the turbine, the vertical coverage close to the turbine was relatively low. In order to fully cover the rotors of a turbine, it is likely that the transducer would need to be mounted away from the turbine. For example, to provide coverage of a set of rotors with a diameter of 15 metres, the Gemini would have to be mounted approximately 42m from the turbine; this has obvious logistical challenges associated with it.

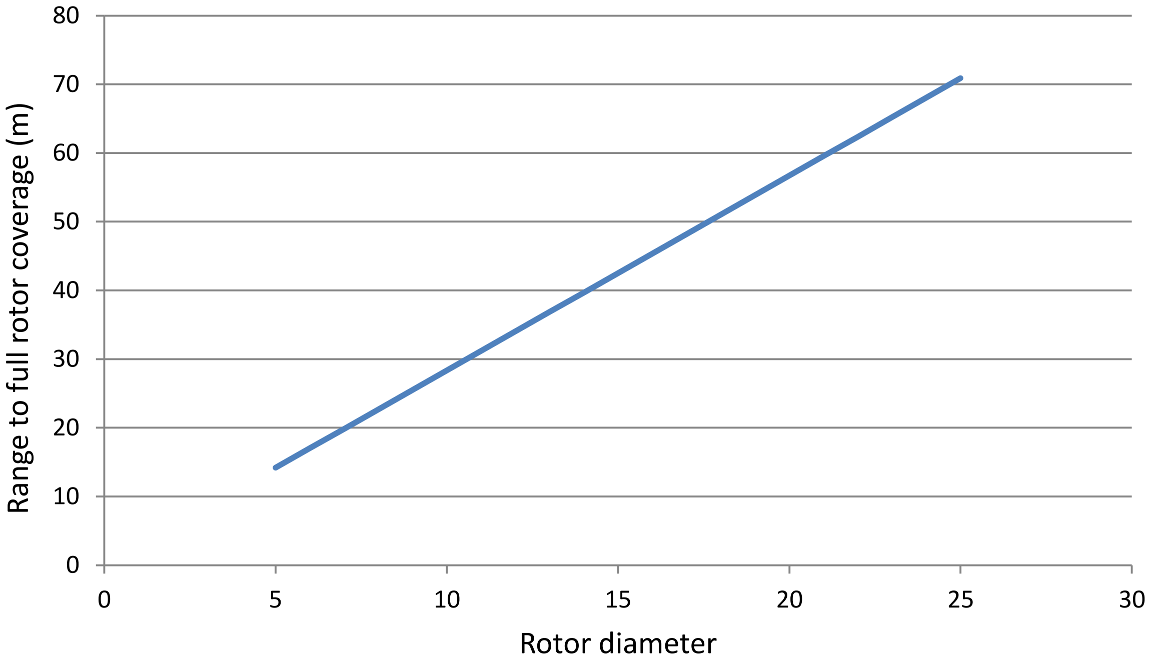


Figure 49: Relationship between the rotor size of a tidal turbine and the range from the turbine that the Tritech Gemini would need to be located to achieve full rotor coverage. For example, to achieve full rotor sonar coverage of a 15m diameter set of rotors, the Gemini would need to be located at approximately 42 metres from the turbine.

Furthermore, the automated classification algorithms in the developed software were highly conservative and although this can be overcome during post hoc analyses (or by integration into the existing software), species identification remains challenging. Complementary tools should be considered to assist in species discrimination and tracking. Specifically, the use of Passive Acoustic Monitoring (PAM) has been used extensively for the detection and classification of those species that are highly vocal (Clark et al., 1985; Freitag and Tyack, 1993; Janik et al., 2000; Jensen and Miller, 1999; Leaper et al., 1992) and the combination of active and passive acoustic data would potentially allow a more robust discrimination of marine mammal species. However, it is important to highlight that the combination of these systems has potential difficulties in terms of interference between active sonar signals and automated passive acoustic detection systems and further work would be required to assess the significance of this potential interference.

It is important to note that the resolution of the sonar developed here (or indeed any sonar) is unlikely to be able to determine with certainty whether a physical interaction (collision) occurs between a marine mammal and the rotors. However, additional tools such as video, or strain gauges or accelerometers mounted on the rotors potentially provide a valuable partner technology and should be considered alongside sonar to determine collisions with marine mammals. These, together with systematic monitoring of marine wildlife populations for evidence of physical injury or mortality (e.g. through necropsies of dead animals) should help reduce uncertainty surrounding the potential risks associated with tidal turbines.

In addition to monitoring behaviour around turbines once they have been installed, given a suitable static platform, it is likely that sonar could be used as a means of collecting data on marine mammal movements prior to turbine installation; this would effectively provide information on marine mammal behaviour prior to installation and potentially provide encounter rate information required for collision risk predictions.

ENVIRONMENTAL MONITORING PROGRAMS (EMP):

The overall goal of an Environmental Monitoring Program is generally to provide feedback about the actual environmental impacts of a project. Monitoring results help judge the success of mitigation measures in protecting the environment. They are also used to ensure compliance with environmental standards, and to facilitate any required project design or operational changes.

From a tidal energy perspective, sonar has the potential to provide a critical behavioural monitoring tool for fine scale interactions between marine mammals and tidal devices. It is anticipated that the sonar developed in this program could now provide a very useful component in a suite of best-practice methods for environmental monitoring and to ensure regulators have sufficient information on which to base permitting decisions in the future. To ensure that it was useful as a monitoring tool, several data management requirements (in addition to those described for behavioural research) were detailed for the system. Firstly, given the timescales usually associated with reporting, it was important that the data were stored in an easily accessible, efficient manner to allow rapid interrogation and analyses. Secondly, for post hoc review and environmental auditing purposes, it was important that raw data associated with the processed track data could be stored and linked easily to the processed data.

From a risk characterisation perspective, the sonar behavioural data provide the basis for informing risk assessments or parameterising formal collision risk models. For example, collision rate is a function of the encounter rate and the probabilities of avoidance and evasion. The latter parameters (avoidance and evasion) have not currently been measured; therefore current models have restricted modelling effort to predicting encounter only (Wilson et al., 2007a). Wilson et al (2007a) demonstrate the sensitivity of avoidance behaviour in collision risk models and highlight the importance of assessing the magnitude of avoidance behaviour by monitoring biological interactions with prototype tidal turbines operating at sea.

REAL-TIME MITIGATION:

Mitigation in the form of a control measure to reduce the potential risk of injury to marine mammals has been discussed extensively in relation to tidal energy. This could take the form of rotor shutdown, rotor speed reduction, or the activation of an alerting or aversive sound designed to signal the presence of the turbine to a marine mammal. For example, in Strangford Lough, since the commissioning of SeaGen there has been a regulatory requirement to shut down the rotors when marine mammals were detected within a risk zone around the turbine. Although active sonar is used currently, it is relies on 24-hour a day manual monitoring during operation and is thus clearly not commercially feasible in the long term or for scaling up from single devices to arrays. Should this mitigation approach be required in other deployments there is a clear need for an automated system such as the one developed in this study.

In order to provide effective mitigation, it is critical that there is sufficient time between initial detection and the appropriate control measure. The automated detection algorithms in this system were effective (probability of detecting grey seals = 0.5) to approximately 47 metres. Mean speed of 'marine mammals' from the Strangford data collection was 2.63ms^{-1} providing an effective mitigation time of approximately 18 seconds; i.e. the mitigation process (e.g. shut down of the turbine) from marine mammal detection to control measure would need to occur within this time.

From a turbine operational perspective, it is clear that using the current conservative approach taken by the software to classifying marine mammals (a single '*Probable*' event leading to the classification of a marine mammal) is likely to lead to a high number of mitigation events; however, using the approach of determining the distribution of classification probabilities within each target to identify 'high probability marine mammals' would potentially result in a far more useful mitigation tool. Furthermore, as described above, the use of complementary tools (e.g. PAM) could potentially reduce the uncertainty in target identification in certain cases.

In common with behavioural research and monitoring, a further important consideration for mitigation is the horizontal and vertical coverage of the sonar system being used. The system used in this study has 120 x 20 degree coverage (Figure 41); this means that although coverage is relatively extensive, there are certain "blind spots" where there is no coverage. For example, from a vertical perspective, a 20 degree angle would only provide full rotor coverage (of 15m diameter rotors) at a range of 42 metres or greater (Figure 49).

CONCLUSIONS AND FUTURE WORK

In conclusion, this report has described the development of a sonar system to provide a tool for monitoring behaviour of marine mammals; the 4-phase program involved collaborations between marine mammal specialists, marine renewable developers, and sonar engineers to develop a user-friendly sonar system for the marine renewable industry.

With respect the sonar system (Tritech Gemini) developed in the program, analysis of the software 'detection efficiency' suggest that there is a significant negative relationship between range and probability of detection; the probability of the software automatically detecting a seal was greater than 0.9 for ranges up to around 37 metres and dropped to below 0.1 at ranges greater than 56 metres. However, it is important to highlight that the detection ranges at sites with different hydrographic conditions may vary; although the detection ranges of 'marine mammals' at Strangford (max: 50m) were consistent with the calibration phase of the program (max: 56m) suggesting that there are no significant acoustic interference at this tidal site, it is clear that hydrographic conditions and levels of turbulence should be reviewed when considering sonar at new tidal sites.

Results of a 2 month deployment on a tidal turbine illustrated that there were high numbers of mobile targets and 109 high probability 'marine mammals'; the detection rate of high probability 'marine mammals' was approx. 5.9 per day. However, it is important to highlight that although detection capabilities were validated with visual observations close to a seal haul out, marine mammal detections at the tidal turbine were not validated with any secondary observations; future work could focus on using visual observations or by tagging seals with high resolution movement tags (e.g. Wilson et al., 2007b) to validate detection capabilities in tidal environments.

From a risk assessment perspective, the ranges that 'marine mammals' were detected at Strangford Lough suggest that marine mammals do move in close proximity to the tidal turbine both when it was operational (minimum range=9.9m) and non-operational (minimum=8.4m). Furthermore, modelling of 'marine mammal' detections with the temporal covariates suggested that the occurrence of 'marine mammals' changed with time of day. Detections generally decreased during early morning with a minimum at approximately 0500. In contrast, there was no significant variation in 'marine mammal' detections in relation to turbine operation (ON/OFF) or tidal speed.

Although the developed sonar is potentially an extremely useful tool for monitoring the movements of marine mammals around tidal turbines, there are a number of limitations that would benefit from further work. Specifically, it is clear that the classification algorithms are extremely conservative and the reduction of these to high probability 'marine mammals' requires a certain amount of post hoc analysis; this feature could either be incorporated into the existing software or an additional classification module could be developed to analyse the detection and track data. More fundamentally, the system does not currently produce data on the depth of the targets and although there deployment configurations (e.g. using more than one transducer in different orientations) that could address this to a certain extent, the development of a true 3D sonar system would be highly beneficial for measuring tracks of marine mammals around turbines.

Finally, it is evident that a number of sonar manufacturers have recently expressed interest in the development of their systems for tidal energy. Although this is clearly positive for the tidal energy industry and will potentially lead to a far greater understanding of the potential impacts of tidal energy on marine mammals, there are a number of important findings made in this current study that are of general importance to the use of sonar for behavioural monitoring that should be highlighted. For example, the results of behavioural response trials suggest that marine mammals can exhibit overt responses certain sonar systems (even when the sonar fundamental frequencies are well above their hearing ranges), highlighting the importance of a thorough review of sound characteristics of systems prior to deployment for monitoring or mitigation. Furthermore, it is clear that tidal environments are extremely aggressive environments for subsea electronics and hardware clearly needs to be robust to operate over long periods. The dynamic nature of tidal areas also led to the sonar detecting extremely high numbers of mobile targets that were not marine mammals; this highlighted the importance of efficient detection and classification algorithms that should be fully appraised prior to monitoring.

8. ACKNOWLEDGEMENTS

This study was only possible through substantial research and development input, loan of equipment, and advice from all the sonar manufacturers; in particular, thanks must go to Malcolm Johnston and Pauline Jepp at Tritech International Ltd, Stephen Auld from CodaOctopus Products Ltd, and Tim Acker, James Dawson and Eric Munday from BioSonics Inc. Special thanks to Jenny Norris at EMEC and Ian Boyd at the Sea Mammal Research Unit for their invaluable input and support at the inception of this work and for providing advice on monitoring needs throughout the project. In addition, thanks to David Ainsworth from Marine Current Turbines for his help and encouragement in running turbine deployment component of the project. Behavioural response trials and acoustic recordings were carried out at the Sea Mammal Research Unit with help and advice from Simon Moss, Thomas Götz, Evelyn Philpott, Vincent Janik, and Dave Thompson, and at the Fjord and Bælt Aquarium with the help of Magnus Wahlberg. Marine mammal data in St Andrews Bay and Strangford Lough were collected with assistance from Andy Murray, Carol Sparling, Silvana Neves, and Julian Dale.

9. REFERENCES

Benoit-Bird, K. J., and W. Au. 2003a. Hawaiian spinner dolphins aggregate midwater food resources through cooperative foraging. Journal of the Acoustical Society of America 114: 2300.

Benoit-Bird, K. J., and W. L. Au. 2003b. Prey dynamics affect foraging by a pelagic predator (*Stenella longirostris*) over a range of spatial and temporal scales. Behav. Ecol. Sociobiol. 53: 364-373.

Clark, C. W., W. T. Ellison, and K. Beeman. 1985. Progress Report on the Analysis of the Spring 1985 Acoustic Data Regarding Migrating Bowhead Whales, *Balaena mysticetus*, near Point Barrow, Alaska. Reports of the International Whaling Commission 36: 587-597.

Davis, R. W. et al. 1999. Hunting behaviour of a marine mammal beneath the Antarctic fast ice. Science 283: 993-996.

Freitag, L. E., and P. L. Tyack. 1993. Passive acoustic localisation of the Atlantic bottlenose dolphin using whistles and echolocation clicks. Journal of the Acoustical Society of America 93: 2197-2205.

Fristrup, K. M., L. T. Hatch, and C. W. Clark. 2003. Variation in humpback whale song (*Megaptera novaeangliae*) song length in relation to low-frequency sound broadcasts. The Journal of the Acoustical Society of America. 113: 3411-3424.

Gonzalez-Socoloske, D., L. D. Olievera-Gomez, and R. E. Ford. 2009. Detection of free-ranging West Indian manatees *Trichechus manatus* using side-scan sonar. End Spec Res 8: 249-257.

Gonzalez-Socoloske, D., and L. D. Olivera-Gomez. 2012. Gentle Giants in Dark Waters: Using Side-Scan Sonar for Manatee Research. The Open Remote Sensing Journal 5: 1-14.

Götz, T. 2011. The impact of SeaGen operational noise on marine mammals and fish at Strangford Lough, Northern Ireland. SMRU Ltd Report to Marine Current Turbines.

Götz, T., and V. M. Janik. 2010. Aversiveness of sounds in phocid seals: psycho-physiolgical factors, learning processes and motivation. Journal of Experimental Biology 213: 1536-1548.

Harris, R. E., Miller, Gary W. and Richardson, W. John. 2001. Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. Mar. Mam. Sci. 17: 795-812.

Hastie, G. D. 2007. Using active sonar to detect large marine animals around the Seagen system: Results from preliminary testing phase. SMRU Ltd Report to Marine Current Turbines.

Hastie, G. D. 2008. Using active sonar to detect marine animals around marine energy devices: sonar efficiency at a tidal turbine location, SMRU Ltd Report, St Andrews.

Hastie, T. J., and R. J. Tibshirani. 1990. Generalised Additive Models. Chapman and Hall, London.

Herzing, D. L. 1996. Vocalizations and associated underwater behavior of free-ranging Atlantic spotted dolphins, *Stenella frontalis* and bottlenose dolphins, *Tursiops truncatus*. Aquat. Mamm. 22: 61-79.

Janik, V. M., S. M. Van Parijs, and P. M. Thompson. 2000. A two-dimensional acoustic localization system for marine mammals. Mar. Mam. Sci. 16: 437-447.

Jensen, F., W. Kuperman, B. Porter, and H. Schmidt. 1994. Computational Ocean Acoustics. Springer-Verlag, New York.

Jensen, M. E., and L. M. Miller. 1999. Echolocation signals of the bat *Eptesicus serotinus* recorded using a vertical microphone array: Effect of flight altitude on searching signals. Behavioural Ecology and Sociobiology 47: 60-69.

Johnson, C. S. 1967. Sound detection thresholds in marine mammals. In: W. N. Tavolga (ed.) Marine bio-acoustics No. 2. p 247-260. Pergamon, Oxford, U.K.

Kastelein, R. A., P. Bunskoek, M. Hagedoorn, W. L. W. Au, and D. de Haan. 2002. Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals. Journal of the Acoustical Soceity of America 112: 334-344.

Kongsberg_Maritime_Ltd. 2010. Operational Underwater Noise, SeaGen Unit. Report to Marine Current Turbines Ltd: 16 pp.

Kozak, G. 2006. Side Scan Sonar Target Comparative Techniques for Port Security and MCM Q-Route Requirements. Report to L-3 Communications Klein Associates, Inc.

Leaper, R., O. Chappell, and J. C. D. Gordon. 1992. The development of practical techniques for surveying sperm whale populations acoustically. Reports of the International Whaling Commission 42: 549-560.

Liang, K. Y., and S. L. Zeger. 1986. Longitudinal data analysis using generalized linear models. Biometrika 73: 13-22.

Madsen, P. T. et al. 2002. Sperm whale sound production studied with ultrasound time/depth-recording tags. J. Exp. Biol. 205: 1899-1906.

Nottestad, L., A. Ferno, S. Mackinson, T. Pitcher, and O. A. Misund. 2002. How whales influence herring school dynamics in a cold-front area of the Norwegian Sea. Ices Journal of Marine Science 59: 393-400.

Otani, S. et al. 1998. Diving behavior and performance of harbor porpoises, Phocoena phocoena, in Funka Bay, Hokkaido, Japan. Marine Mammal Science. April 14: 209-220.

Richardson, W. J. et al. 1991. Effects of noise on marine mammals. MMS Study 90-0093

NTIS PB91-168914, LGL Ecological Research Association Inc., TX, for US Dept. Interior.

Ridoux, V. et al. 1997. A video sonar as a new tool to study marine mammals in the wild: Measurements of dolphin swimming speed. Mar. Mam. Sci. 13: 196-206.

Similä, T. 1997. Sonar observations of killer whales (*Orcinus orca*) feeding on herring schools. Aquat. Mamm. 23: 119-126.

Simila, T., and F. Ugarte. 1993. Surface and underwater observations of cooperatively feeding killer whales in northern Norway. Can. J. Zool. 71: 1494-1499.

SMRULtd. 2010a. Seals in Northern Ireland: Helicopter surveys carried out in 2010. SMRU Ltd Rerport to Marine Current Turbines.

SMRULtd. 2010b. Strangford Lough Seal Telemetry. SMRU Ltd Report to Marine Current Turbines.

Southall, B. L. et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquat. Mamm. 33: 411-521.

Sparling, C. E., and M. A. Fedak. 2004. Metabolic rates of captive grey seals during voluntary diving. J. Exp. Biol 207: 1615-1624.

Thompson, D., M. Sjoberg, M. E. Bryant, P. Lovell, and A. Bjorge. 1998. Behavioural and physiological responses of harbour (*Phoca vitulina)* and grey (*Halichoerus grypus*) seals to seismic surveys. Report to European Commission of BROMMAD project. MAS2 C7940098.

Tyack, P. L. et al. 2011. Beaked whales respond to simulated and actual Navy sonar. PlosOne 6: e17009. doi:17010.11371/journal.pone.0017009.

Urick, R. J. 1983. Principles of underwater sound. 3rd ed. McGraw-Hill: NewYork.423pages.

Wilson, B., R. S. Batty, F. Daunt, and C. Carter. 2007a. Collision risks between marine renewable energy devices and mammals, fish, and diving birds. Report to the Scottish Executive. Scottish Association for Marine Science, Oban, Scotland, PA37 1QA.

Wilson, R. P. et al. 2007b. All at sea with animal tracks; methodological and analytical solutions for the resolution of movement. Deep Sea Research Part II Topical Studies in Oceanography 54: 193-210.

Yan, J. H., and J. P. Fine. 2004. Estimating Equations for Association Structures. Statistics in Medicine 23: 859-880.

Yee, T. W. 2008. The VGAM Package. R News 28-39.

Yee, T. W., and C. J. Wild. 1996. Vector generalized additive models. Journal of the Royal Statistical Society, Series B, Methodological 58: 481-493.

Yost, W. A. 2000. Fundamentals of hearing: An introduction. 4th ed. Academic Press, New York.

10. APPENDIX 1: SONAR MANUFACTURERS

Sonar manufacturers, contact person (where available) and details.

Manufacturer	**Website**	**Email**	**Contact person**	**Contact phone**
Arstech	http://www.arstech.de/index.html	arsTECH@t-online.de	Klaus Kremer	+49 4231 6774331
Atlas Elektronic	http://www.atlas-elektronik.com/index.php?id=448&L=1	jens.krueger@atlas-elektronik.com	Jens Krueger	+49 421 457 02
Biosonics	http://www.biosonicsinc.com/index.html	emunday@biosonicsinc.com	Eric Munday	+1 206 782 2211
Blueview Technologies	http://www.blueviewtech.com/	info@blueviewtech.com	Warren Fox	+1 206 545 7260
Chelsea Technologies Group	http://www.chelsea.co.uk/	sales@chelsea.co.uk		+44 20 8481 9000
C-Max	http://www.cmaxsonar.com/	sales@cmaxsonar.com	Peter Robinson	+44 1305 853005
CodaOctopus	http://www.codaoctopus.com/	sales@codaoctopus.com	Gareth Simpson	+44 131 553 1380
C-Tech	http://www.c-techltd.com/	ctl.admin@c-techltd.com		+1 613 933 7970
Didson	http://www.soundmetrics.com/	mgs@macartney.com	Mike Sawkins	+44 1420 478382
Eagle	http://www.eaglenav.com/			+1 800 324 1354
Echopilot	http://www.echopilot.com/home.aspx	info@echopilot.com		+44 1425 476211
Edgetech	http://www.edgetech.com/indexmarine.html	morris@edgetech.com	Rob Morris	+1 508 356 9712
Farsounder	http://www.farsounder.com/	info@farsounder.com		+1 401 784 6700
Furuno	http://www.furuno.com/	sales@furuno.co.uk		+44 2392 441000
Garmin	http://www.garmin.com/garmin/cms/site/us	sales.europe@garmin.com		+44 23 8052 4000
Hummingbird	http://www.humminbird.com/	cservice@johnsonoutdoors.com		+1 800 633 1468
Imagenex	http://www.imagenex.com/	imagenex@npsnet.com		+1 604 944 8248
Interphase	http://www.interphase-tech.com/main.htm	comments@interphase-tech.com		+1 888 777 6627
JRC	http://www.jrc.co.jp/eng/index.html	ovs-contact@jrc.co.jp		+1 206 654 5644
Klein Associates	http://www.l-3klein.com/index.html	Klein.mail@L-3com.com		+1 603 893 6131
Knudsen	http://www.knudsenengineering.com/	info@knudsenengineering.com	Judith Knudsen	+1 613 267 1165
Kongsberg	http://www.km.kongsberg.com/	km.waterlooville.uk@kongsberg.com	Mike Topp	+44 023 9224 7800
Lockheed Martin	http://www.lockheedmartin.com/index.html	carolyn.nelson@lmco.com	Carolyn Nelson	+1 613 599 3270
Lowrance	http://www.lowrance.com/Products/Marine/	info@lowrance.com		+1 800 324 1356
Northstar	http://www.northstarnav.com/en/	sales.tulsa@navico.com		+1 800 628 4487
Odom	http://www.odomhydrographic.com/	email@odomhydrographic.com		+1 225 769 3051
QinetiQ	http://www.qinetiq.com/			+44 8700 100 942
Raymarine	http://www.raymarine.co.uk/	info@raymarine.com		+44 23 9269 3611
Reson	http://www.reson.com/sw7542.asp	sales@reson.co.uk	John Fraser	+44 1224 709 900
Seiwa	http://www.seiwa-marine.com/	info@seiwa-marine.com		+852 2795 2008
Manufacturer	Website	Email	Contact person	Contact phone
Simrad	http://www.simrad.com/	contact@simrad.com		+47 3303 4000
SI-TEX	http://www.si-tex.com/	custsvc@kodenamerica.com		+1 727 576 5734
Sonardyne	http://www.sonardyne.co.uk/index.html	sales@sonardyne.com		+44 1252 872288
Teledyne Benthos	http://www.benthos.com/	klightbown@teledyne.com		+1 508 563 1000
Tritech	http://www.tritech.co.uk/	info@tritech.co.uk	Malcolm Johnston	+44 1224 744111
Valeport	http://www.valeport.co.uk/	sales@valeport.co.uk	Kevin Edwards	+44 1803 869292
Vexilar	http://www.vexilar.com/		Tom Zenanko	+1 952 884 5291
Westminster	http://www.wg-plc.com/international/	c.cantell@wi-ltd.com	Chris Cantell	+44 1295 756300

11. APPENDIX 2: SONAR SPECIFICATIONS

Sonar specifications of currently available commercial sonar and echosounder systems. Details (where available) include transmission frequencies (kHz), source level [dB re1 µPa at 1m (unless otherwise defined)], Sonar type (MI=Multibeam Imaging, ES=Echosounder, TM=Towed Multibeam, MS=Manual Scanning, MB=Multibeam Bathymetry), Cone angle (degrees), Number of transmission beams, and the Horizontal and Vertical swathe coverage (degrees).

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Arstech	DDS	60	226			MI		360	360	50
Atlas Elektronik	HSS-1000/T LF	100				MI		300	360	30
Atlas Elektronik	HSS-1000 LF	100				MI		300	90	24
Atlas Elektronik	HSS-100 VHF	420				MI		256	20	15
Atlas Elektronik	HSS-100 HF	200				MI		256	60	15
Atlas Elektronik	HSS-100 LF	100				MI		256	90	30
Biosonics	DT-X	200		420		ES	10	1		
Blueview Technologies	P900E-20	900				MI			45	20
Blueview Technologies	P450-15	450				MI			50	15
Blueview Technologies	DF900-2250	2250		900		MI			45	20
Chelsea Technologies Group	CTG0703	175	187			ES		1		
Chelsea Technologies Group	CTG1226	175	187			ES		1		
Chelsea Technologies Group	CTG1356	305	232	100		MI			2	60
C-Max	CM2-EDF	780	217	325		TM			0	50
C-Max	CM2-HF	325	217			TM			0	40
C-Max	CM2-DF	325	217	100		TM			0	40
CodaOctopus	Echoscope 2	375	205			MI		16384	50	50
C-Tech	CSDS-85	80				MI			360	24
Didson	Long range	1100		700		MI		48	29	14
Didson	Standard	1800		1100		MI		48	29	14
Eagle	Fishmark 500C	200	187 W RMS			ES	60	1		
Eagle	Seafinder 500C DF	200	500 W RMS	50		ES	60	2		
Eagle	Seafinder 480 DF	200	500 W RMS	50		ES	60	2		
Eagle	Seafinder 640C DF	200	500 W RMS	50		ES	60	2		

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Eagle	Fisheasy 320C	200	100 W RMS			ES	60	1		
Eagle	Fisheasy 245 DS	200	1500 W P2P	83		ES	60	2		
Eagle	Fishmark 640C	200	187 W RMS			ES	60	1		
Eagle	Fishmark 480	200	187 W RMS			ES	60	1		
Eagle	Fishmark 320	200	187 W RMS			ES	60	1		
Echopilot	FLS Bronze	200				MS		1	1	90
Echopilot	FLS Platinum	200				MS		1	1	90
Echopilot	FLS Silver 2	200				MS		1	1	90
Echopilot	FLS Gold 2	200				MS		1	1	90
Edgetech	2400	410		120	75	TM			1	70
Edgetech	4300-MPX	410		270		TM			180	1
Edgetech	4100	500		100		TM			180	1
Edgetech	4200-FS	410		120		TM			180	1
Farsounder	FS-3	60				MI			90	45
Farsounder	FS-3DT	60				MI			90	45
Furuno	FCV-291	200	1000 W	88	50	ES		2		
Furuno	FCV-620	200	600 W	50		ES		2		
Furuno	FCV-30	38	4000 W			ES		1		
Furuno	FCV-1200L/LM	200	1000 W	107	88	ES		2		
Furuno	FCV-1100L	200	1000 W	107	88	ES		2		
Furuno	FCV-292	200	1000 W	88	50	ES		2		
Furuno	CSH-5L	68			55	MI		360 26		
Furuno	CSH-7	70		55		MI			360	18
Furuno	CSH-73	180				MI			180	11

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Furuno	FCV-293	200	1000 W	50		ES		2		
Furuno	LS-4100	200	300 W	50		ES		2		
Furuno	CSH-83	107		75		MI			360	12
Furuno	CSH-84	107		81		MI			360	12
Furuno	FCV-667	200	1000 W	88	50	ES		2		
Furuno	FSV-30	27		21		MI			360	10
Furuno	CSH-23/24	45				MI			360	13
Furuno	LS-6100	200	300 W	50		ES		2		
Furuno	FCV-585	200	600 W	50		ES		2		
Furuno	FSV-24	24				MI			360	10
Furuno	CSH-23F/24F	32		24		MI			360	13
Garmin	Fishfinder 90	200	100W RMS			ES	45	2		
Garmin	Fishfinder 340C	200	500W RMS			ES	45	2		
Garmin	Fishfinder 300C	200	150W RMS	80		ES	45	2		
Garmin	Fishfinder 160C	200	150W RMS			ES	45	2		
Garmin	Fishfinder 400C	200	400W RMS	80		ES	45	2		
Garmin	Fishfinder 140	200	100W RMS			ES	45	2		
Hummingbird	575	455	250W RMS	200	83	ES	90	4		
Hummingbird	110 Fishin' buddy	200	125W RMS			ES	34	1		
Hummingbird	PirahnhaMAX 240	455	200W RMS	200		ES	35	2		
Hummingbird	737	455	500W RMS	200		83	ES	90 4		
Hummingbird	RF15	125				ES	90	1		
Hummingbird	323	200	300W RMS	83		ES	20	2		
Hummingbird	717	200	300W RMS	83		ES	20	2		

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Hummingbird	525	200	200W RMS			ES	20	1		
Hummingbird	PirahnhaMAX 230 Portable	200	100W RMS	83		ES	20	2		
Hummingbird	130 Fishin' buddy	455	125W RMS	200		ES	34	2		
Hummingbird	PirahnhaMAX 210 Portable	200	100W RMS			ES	20	1		
Hummingbird	PirahnhaMAX 220	200	200W RMS	83		ES	20	2		
Hummingbird	120 Fishin' buddy	455	125W RMS	200		ES	34	2		
Hummingbird	535	200	250W RMS			ES	20	1		
Hummingbird	565	200	200W RMS	83		ES	20	2		
Hummingbird	727	200	500W RMS	83		ES	20	2		
Hummingbird	777c2 CHO	200	500W RMS	83		ES	20	2		
Hummingbird	PirahnhaMAX 215 Portable	200	100W RMS	83		ES	20	2		
Hummingbird	585c	200	300W RMS			ES	20	1		
Hummingbird	565 portable	200	250W RMS	83		ES	20	2		
Hummingbird	343c	200	300W RMS	83		ES	20	2		
Hummingbird	717 CHO	200	300W RMS	83		ES	20	2		
Hummingbird	727 CHO	200	500W RMS	83		ES	20	2		
Hummingbird	747c	200	500W RMS	83		ES	20	2		
Hummingbird	747c CHO	200	500W RMS	83		ES	20	2		
Hummingbird	777c2	200	500W RMS	83		ES	20	2		

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Hummingbird	Matrix 12	200	250W RMS			ES	20	1		
Hummingbird	141c	200	150W RMS			ES	20	1		
Hummingbird	140c Fishin' buddy	455	125W RMS	200		ES	34	2		
Hummingbird	Matrix 47 3D	455	1000W RMS	83		ES	53	6		
Hummingbird	Matrix 97	200	500W RMS	83		ES	20	2		
Hummingbird	PirahnhaMAX 210	200	100W RMS			ES	20	1		
Hummingbird	PirahnhaMAX 215	200	100W RMS	83		ES	20	2		
Imagenex	Delta T	260				MI		480	120	20
Imagenex	852	850		675		MS		1	2	22
Imagenex	Sportscan	330				TM			2	60
Imagenex	881L	1000		675	310	MS		1	360	40
Interphase	Color Twinscope	233				MS		1	90	12
Interphase	PC 180	200				MS		1	90	12
Interphase	PV View	200				MS		1	90	12
Interphase	Iscan V90	200				MS		1	12	90
Interphase	Iscan 180	200				MS		1	180	12
Interphase	Seascout	200				MS		1	90	12
Interphase	Probe	200				MS		1	12	90
JRC	FF50	200	600W RMS	50		ES		2		
JRC	JFV-250	200	1000 W	75	70	ES		2		
JRC	JFS-3721	90		28		MS		1	360	60
JRC	JFC-130	200	1000 W	75	70	ES		2		
JRC	JFE680	200		50		ES		2		

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
JRC	JFE380	200		50		ES		2		
JRC	JFS-3381	45		28		MS		1	360	60
JRC	JFS-80	55				MS		1	360	60
JRC	JFS-3380	45		28		MS		1	360	60
Klein Associates	System 3000	445		132		TM				40
Klein Associates	System 5000	455				TM		10	1	90
Knudsen	1600 series	210		24		ES		1		
Knudsen	CHIRP 3260	210		3		ES		2		
Knudsen	CHIRP 3200	210		3		ES		2		
Kongsberg	2105	675				MS		1	360	3
Kongsberg	2123	675				MS		1	360	22
Kongsberg	SP60	30		20		MI			360	60
Kongsberg	SP70	30		20		MI			360	60
Kongsberg	SP90	30		20		MI			360	60
Kongsberg	SH80	122				MI			360	90
Kongsberg	SM2000	200				MI		128	180	20
Kongsberg	MS1000	675				MS		1	360	22
Kongsberg	2303	675				MS		1	360	30
Kongsberg	MS2104	330				MS		1	360	20
Kongsberg	MS1007					ES				
Kongsberg	2305	675				MS		1	360	30
Kongsberg	2101	675				MS		1	360	22
Kongsberg	2102	330				MS		1	360	40

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Kongsberg	2124	675				MS		1	360	22
Kongsberg	2302	675				MS		1	360	30
Kongsberg	2702	675				MS		1	360	22
Kongsberg	EM3000	300				MI			130	2
Kongsberg	2701	675				MS		1	360	22
Kongsberg	M^3	500				MI		256	140	30
L-3 ELAC NAUTIK GMBH	1185	180				MB		126	153	2
L-3 ELAC NAUTIK GMBH	1050	50				MB		126	153	2
L-3 ELAC NAUTIK GMBH	1055	50				MB		126	153	2
L-3 ELAC NAUTIK GMBH	1180	180				MB		126	153	2
L-3 ELAC NAUTIK GMBH	3012	12				MB		205	140	2
L-3 ELAC NAUTIK GMBH	2120	20				MB		149	150	1
L-3 ELAC NAUTIK GMBH	1055D	180		50		MB		126	153	2
L-3 ELAC NAUTIK GMBH	1050D	180		50		MB		126	153	2
Lockheed Martin	IDS					MI			360	
Lowrance	X52	200	188 W RMS			ES	20	1		
Lowrance	X96	200				ES	20	1		
Lowrance	X59 DF	200	300 W RMS			ES	20	1		
Lowrance	M68C s/Map	200				ES	20	1		
Lowrance	LMS 522C	200				ES	20	1		
Lowrance	X125	200				ES	20	1		
Lowrance	X126 DF	200		50		ES	20	2		
Lowrance	X135	200				ES	20	1		
Lowrance	X136 DF	200		50		ES	20	2		

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Lowrance	X510C	200				ES	20	1		
Lowrance	X515C DF	200		50		ES	20	2		
Lowrance	X67C	200	100 W RMS			ES	20	1		
Northstar	Explorer 443sp	200	150 W RMS			ES	14	1		
Northstar	Explorer 467	200		50		ES	14	2		
Northstar	Explorer 457	200		50		ES	14	2		
Northstar	Explorer 438	200				ES	14	1		
Northstar	Explorer 443d	200	250 W RMS	83		ES	14	2		
Northstar	Explorer 443df	200	250 W RMS	83		ES	14	2		
Northstar	Explorer 443s	200	150 W RMS			ES	14	1		
Northstar	8000i	200	1000 W RMS	50		ES	14	2		
Northstar	491	200	1000 W RMS	50		ES	14	2		
Odom	Echotrac MK3-E	1000		50	24	ES		2		
Odom	Echotrac CV100	750		100		ES		2		
Odom	Echotrac CVM	340		50		ES		2		
Odom	Echotrac CV300	1000		50	24	ES		2		
Odom	Echotrac CV200	1000		50	24	ES		2		
Odom	Echoscan	200	225			MI			3	90
Odom	Echotrac MK3-P	1000		50	24	ES		2		
QinetiQ	Cerberus	100				MI			360	
Raymarine	DS400x - DS600x	200	500 W RMS	50		ES	20	2		
Raymarine	DSM30	200	600 W RMS	50		ES	20	2		
Raymarine	E-Series	200	1000 W RMS	50			ES	20 2		
Raymarine	DSM300	200	1000 W RMS	50		ES	20	2		

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
Reson	Seabat 8111	100				MB	101	150 6		
Reson	Seabat 7012	400				MI		256	130	1
Reson	Seabat 7125	400				MB		512	128	1
Reson	Seabat 7128	400				MI		256	128	27
Reson	Seabat 9001	455				MB		60	90	2
Reson	Seabat 8160	50				MB		126	128	6
Reson	Seabat 8150	24		12		MB		234	150	4
Reson	Seabat 8128	455				MI		240	120	17
Reson	Seabat 8125	455				MB		240	120	1
Reson	Seabat 8124	200				MB		80	120	2
Reson	Seabat 8101	240				MB		101	150	2
Reson	Seabat 7150	14		12		MB		880	150	1
Seiwa	BBFF	200	1000 W RMS	50		ES	20	2		
Simrad	ES-60 Split beam	200	1000 W RMS	120	70	ES		2		
Simrad	ES-60 Single beam	200	1000 W RMS	120	70	ES		1		
Simrad	EC-1080	200		150	80	ES				
Simrad	EC-2035	200		50		ES				
Simrad	EK-60	200		120	70	ES				
Simrad	EC-8100	200		50		ES				
SI-TEX	CVS-210	200	1000 W RMS	50		ES		2		
SI-TEX	CVS118 Mk2	200	300 W RMS	50		ES		2		
SI-TEX	CVS-106LMk-2	200	300 W RMS	50		ES		2		

Manufacturer	Model name	Primary frequency	Source level	Secondary frequency	Tertiary frequency	Sonar type	Cone angle	Number of beams	Horizontal coverage	Vertical coverage
SI-TEX	Profish 3	200	200 W RMS			ES		1		
SI-TEX	CVS-106L-120	120	300 W RMS			ES		1		
SI-TEX	CVS-841	200	1000 W RMS	50	38	ES		2		
SI-TEX	Profish 2	120	300 W RMS			ES	40	2		
SI-TEX	CVS-833/833C	200	600 W RMS	50		ES		2		
Sonardyne	Sentinel IDS	70	206			MI		256	360	11
Teledyne Benthos	C3D	200		100		TM			1	20
Teledyne Benthos	1624	390		110		TM			0	50
Tritech	MiniKing	675				MS		1	360	40
Tritech	Super Seaking DFS	675		325		MS		1	360	40
Tritech	SeaPrince	675				MS		1	360	30
Tritech	Micron	950		650		MS		1	360	38
Tritech	Diver Surveillance	100				MS		1	360	15
Tritech	Gemini	720				MI		256	120	25
Valeport	Midas Surveyor	210		33		ES		2		
Vexilar	The Edge 2 & 3	400	200 W RMS	107		ES	10			
Westminster	WG 2000	200	210			MI			180	

12. APPENDIX 3: REQUEST FOR PROPOSALS DOCUMENT

Marine Mammal Detection Sonar for the Marine Renewable Energy Industry

Request for Proposals

13 July 2008

Statement of Purpose

In recognition of the need to understand the underwater behaviour of marine wildlife around Marine Renewable Energy Devices, the UK Governments Department of Business, Enterprise, and Regulatory Reform has provided funding to SMRU Ltd and EMEC (Appendix 1) to identify active sonar technology that could be used as a robust and reliable monitoring and mitigation tool.

SMRU Ltd and EMEC therefore seek to coordinate the delivery of a bespoke active sonar system(s) that, subject to successful testing, will be purchased and formally recommended for wildlife monitoring around future marine energy devices.

A suitable sonar system will have the capability of automatically detecting and tracking marine wildlife (primarily marine mammals but also basking sharks and diving birds) in close proximity to individual marine renewable energy devices and should meet the specifications detailed in Appendix 2.

Background

Currently, there is a high level of uncertainty surrounding the environmental impacts of marine renewable energy devices on marine wildlife. This has the potential to curtail acceptance of new proposals, and can create barriers to early commercial introduction of the technology. The principal environmental concerns derive from the potential of physical injury to marine mammals through direct contact with moving structures of marine energy devices. In order to safeguard against such injuries, an underwater monitoring system is clearly required to detect and track marine animals (primarily marine mammals but also basking sharks and diving birds) around devices. This would be a critical component in developing a suite of best-practice methods for environmental monitoring and mitigation and to ensure Competent Authorities have sufficient information on which to base permitting decisions including European Protected Species licensing and Appropriate Assessments of plans or projects.

In recent years, there has been accelerated development of active sonar systems for sub-sea monitoring, and for fisheries research and management. Many of the systems now on the commercial market have the capacity to build up an acoustic image of sub-sea moving objects, where low visibility prevents the use of visual cameras. A recent assessment of commercially available sonar systems by SMRU Ltd concluded that sonar has the potential for tracking marine mammals around marine energy devices. However, it was apparent that none of the available systems were ideal, and a bespoke system that meets a number of technical specifications is clearly required for the marine renewables industry.

Scope of Work

A period of development or upgrading of existing systems (if required) will be carried out through a collaboration between a sonar developer and SMRU Ltd and EMEC. Throughout this period, SMRU Ltd can act as a liaison point for the company and will provide information necessary for the system development. For example, this may include information on the swimming behaviour of UK marine wildlife (integral to developing software algorithms that will identify marine animals and differentiate them from other objects in the water column), or details of the hearing ranges of marine mammals (many sonar systems have “side-lobes” including low frequency sound components which may be within the hearing range of marine mammals).

There will then be a series of formal trials with captive seals at the Sea Mammal Research Unit’s captive seal research facility to test the developed system prior to purchase and deployment for field tests on a marine renewable energy device at EMEC to establish the performance in a highly turbulent, high energy tidal stream typical of future commercial deployment sites. These will allow us to test the reliability of the detection and tracking capabilities of the system in controlled environments. We also plan to test the sonar on captive porpoises at an equivalent facility. This phase of the project will continue to be conducted in close collaboration with the sonar manufacturer in the event that any changes to the system are required for the proposed application.

After the initial series of tests described above, the developed sonar system will be purchased and deployed on a marine energy device for a period of 5 months to evaluate the efficiency and reliability of the system over an extended period. This will include tests of the capabilities for detection and tracking of marine animals in a tidal environment, and will be calibrated using visual observations of animals at the surface. Subject to successful testing, the most efficient and reliable system(s) will be formally recommended by SMRU Ltd and EMEC as suitable for use on future marine renewable energy devices.

Requirements for Proposal Preparation

Response to this request for proposals should be in the form of a summary proposal (max 5 pages) detailing a sonar system for detecting and tracking marine animals around marine renewable energy devices. The report should be provided under the following headings:

***Company profile*:** Should include details of the company expertise in providing sonar solutions for bespoke applications such as this. Information on previous applications relevant to this one would also be useful.

***System details and operation*:** Details of how the proposed sonar system is expected to operate and meet the aims of the application should be included. This should also include a consideration of generic attachment procedures to marine renewable devices.

***Technical details*:** This should include hardware and software specifications relevant to this application.

***Estimated financial cost*:** The estimated financial cost of a single sonar system including installation and maintenance if required.

***Estimated delivery date*:** The earliest date when a system could be guaranteed to be delivered for testing and evaluation.

Evaluation Process

Proposals will be formally evaluated by a steering group with representation from the UK government, marine renewable developers, and marine wildlife experts. They will be scored in terms of company expertise, the period required to produce the system, estimated financial cost of the system, and whether the proposed system meets the minimum desired specifications (Appendix 2).

Outcome of Evaluation Process

Based on the proposal appraisal, successful companies will be invited to collaborate with SMRU Ltd and EMEC. This process will involve the purchase of a system for testing and further evaluation. SMRU Ltd will provide summary information on marine mammal biology (i.e. body sizes, swimming speeds, school sizes) for species around the coast of the UK. Subject to commercial confidentiality, EMEC will provide information on marine renewable energy devices and environmental conditions at energy sites. Provision of a proposal in response to this invitation will be taken as commitment by the organisation to a collaboration that may involve requirements for internal investment in R&D.

Critical dates

Deadline for proposal submission: 1700 (GMT) 4th July 2008. We will confirm receipt of proposals. It is expected that the evaluation of proposals will be carried out within 4 weeks of the submission date. Proposals should be submitted electronically to Fiona Skillbeck (fas@smru.co.uk)

Points of contact

- Dr Gordon Hastie (SMRU Ltd): Liaison point for information on desired sonar specifications and provision of marine wildlife data. gdh@smru.co.uk
- Dr Jennifer Norris (EMEC): Liaison point for information on marine renewable energy devices and environmental conditions at energy sites. jenny.norris@emec.org.uk

Commercial in Confidence

A proposal and all information contained within it will be released to the steering group on the understanding that it is Commercial-in-Confidence and will remain so regardless of the outcome of the steering groups' decision.

Appendix 1: Institutions

SMRU Ltd

SMRU Ltd is a wholly owned subsidiary of the University of St Andrews and is associated with their Sea Mammal Research Unit. SMRU Ltd specialise in providing high quality services and advice to government and industry on marine environmental issues and has considerable experience with developing frameworks for the environmental assessment of the effects of anthropogenic activities on marine mammals. Furthermore, SMRU Ltd has provided advice to government on the UK’s marine mammal populations through the Strategic Environmental Assessment process for offshore oil & gas and marine renewables development. Together, SMRU Ltd and the Sea Mammal Research Unit are experienced in the development of bespoke data collection and analytical frameworks for assessing the impacts of marine developments on wildlife, and can carry out all aspects of work from design and data collection (e.g. seal tagging and sighting/passive acoustic cetacean surveys), to analysis and interpretation.

www.smru.co.uk

European Marine Energy Centre (EMEC) Ltd

The European Marine Energy Centre (EMEC) Ltd is a private limited company, established by UK and European funding to provide grid-connected open sea testing facilities for developers of wave and tidal energy devices. The centre was formally opened in 2004, and has seen the deployment of Ocean Power Delivery's Pelamis at the wave site, and Open Hydro's Open Centre turbine at the tidal site, with imminent deployment of additional devices at both sites. EMEC occupies a unique position within the wave and tidal energy industries. Having links with a range of different wave and tidal energy device developers, as well as academic institutions and regulatory bodies, the nature of EMEC's business means that it is independent of any particular device type and any particular academic institution. This has created a key role in the independent monitoring of potential device impacts on the receiving environment, which is particularly important in the developing marine energy industries, where such impacts are as yet unknown. EMEC aims to ensure that different devices tested at its sites are monitored in a consistent way, using the best available methods.

www.emec.org.uk

Appendix 2: Desired specifications

Frequency

- Fundamental transmission frequency should be 200 kHz or above.
- Given the short pulsed nature of most sonar signals, it is anticipated that the bandwidth of signals may be broad. To reduce potential impacts of the signals, lower frequency components should be kept to a minimum and should be no greater than 90 dB re 1µPa @ 1m (RMS) at 110 kHz.

It is critical that the acoustic signals produced by the sonar do not have adverse effects on marine wildlife. These can range in severity from direct physiological damage to more subtle behavioural responses. Therefore, the transmission frequency of the sonar should be well above the hearing range of those species common around the coast of the UK. In particular, the harbour porpoise has the highest frequency hearing with the greatest sensitivity between approximately 30 and 110 kHz.

Automatic detection and classification

- Sonar system should have the capability for automatic detection, classification, and tracking of marine animals. Although the system will primarily be designed to detect marine mammals, it is envisaged that the detection of other marine wildlife (in particular, diving birds) would provide a valuable feature. It would therefore be useful to provide an assessment of the ranges that other marine wildlife could be detected.

  It is critical for efficient monitoring and mitigation that marine animals can be automatically differentiated from other underwater targets (e.g. marine debris). We anticipate that features of the target (target strength, speed, depth changes, number of targets, movement in relation to tidal direction etc) could be used to identify marine mammals from other targets (including other wildlife species). Throughout the development process, SMRU Ltd can provide summary information on marine mammal body sizes, swimming speeds, school sizes etc for species around the coast of the UK.

User interface

- As the system will potentially be used by a range of different operators, the user interface must be straightforward to set up and use.

- Many of the energy devices will be located at distances up to several hundreds of metres from the shore. It is likely therefore, that sonar systems deployed on operational devices will need to be interrogated and controlled remotely (e.g. across a wireless LAN or over the internet). This should be considered during system design.

Mitigation feedback process

- Although the requirements for individual feedback processes are likely to be specific to the location of energy devices, their potential risk to wildlife, and the device design, it is hoped that as a minimum, the sonar system should have the facility to **automatically alert a user** (visually and audibly) of the presence of a marine mammal or similar object.

- In the future, the system may be required to link directly into turbine operational control and allow automatic shutdown of turbines in the event of marine mammal detection. Although it is understood that this is likely to require a bespoke application in collaboration with individual device developers, the description of the sonar system should identify whether this is likely to be *Possible*.

Range

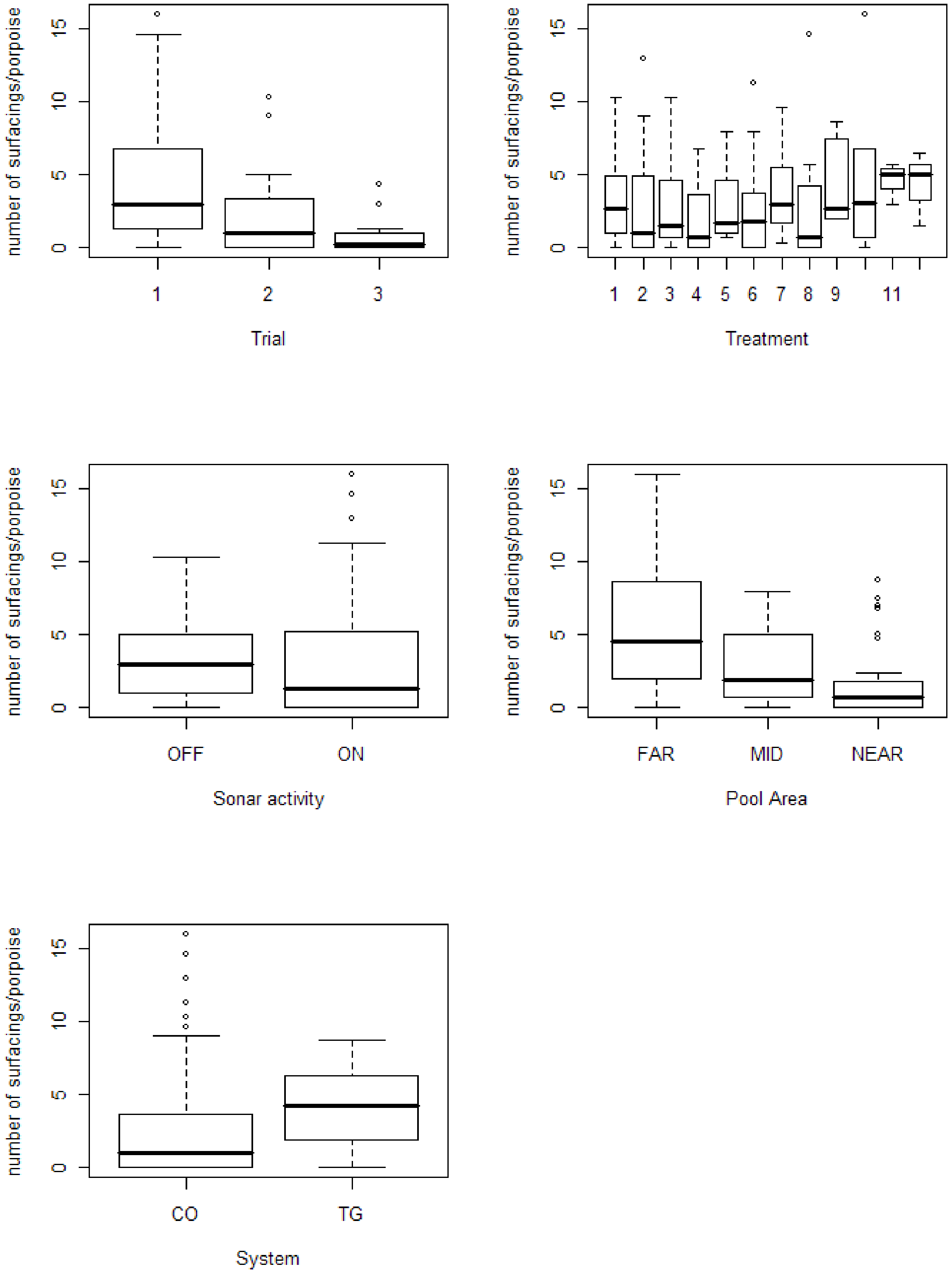
- The effective range of sonar to detect marine mammals in particular should be sufficient for automatic detection and classification whilst allowing sufficient time for potential turbine shutdown (experience to date indicates approx 17 seconds). Although the period required for detection and classification will be system specific, it is estimated that with a peak sustained swimming speeds of $6ms^{-1}$ (harbour porpoise) in strong tidal currents (around $4.6\ ms^{-1}$), this will be around 200m.

Spatial coverage

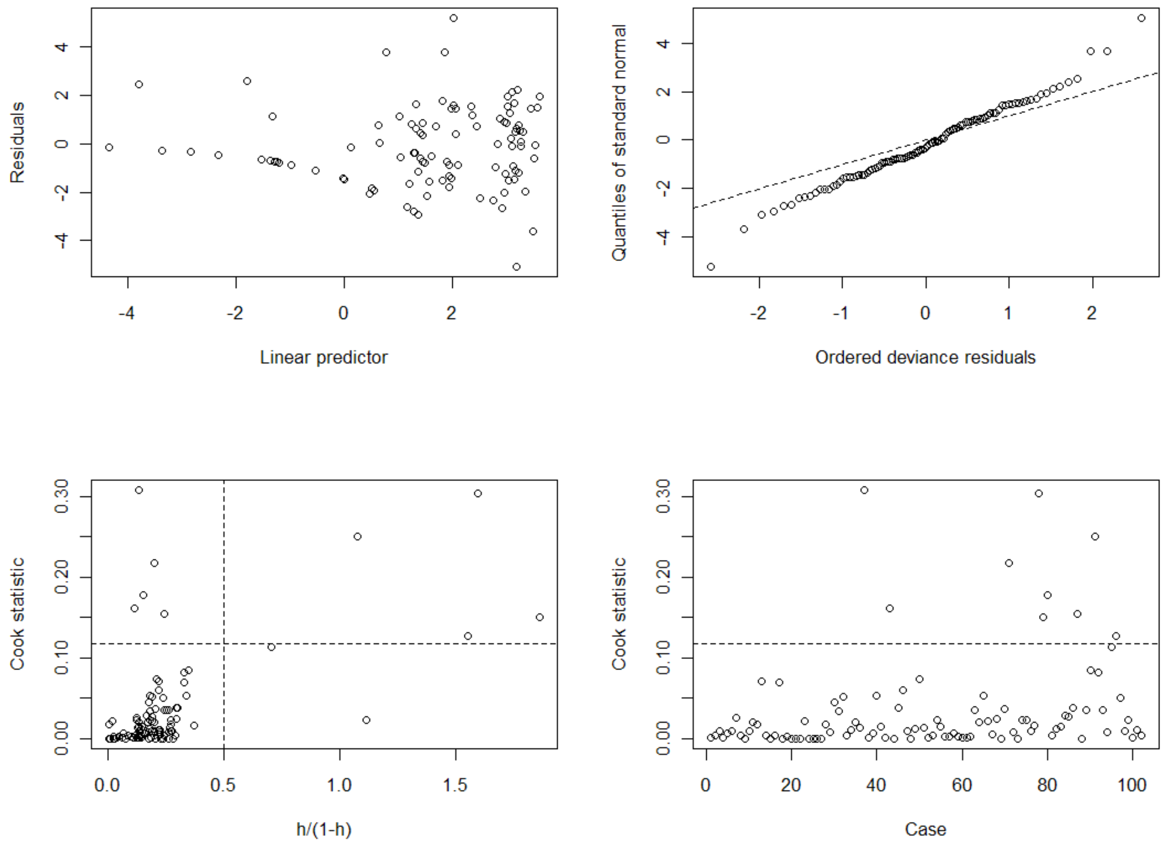
- Marine renewable devices are likely to be deployed in a range of water depths and required spatial coverage is likely to vary depending on location and device design. However, a generic sonar system design is likely to have a minimum spatial coverage of **45^o horizontal** and **30^o vertical**. The system should provide this coverage on both the upstream and downstream sides of the device.

- It is important to note that energy devices are likely to be located in strong, potentially turbulent, tidal conditions. This will need to be considered during system design.

13. APPENDIX 4: MODEL OUTPUTS FROM BEHAVIOURAL RESPONSE TRIALS



Summary of the predictor variables associated with porpoise behavioural response trials; these included the trial, treatment, sonar activity, pool area, and the sonar system.



Diagnostics plots from the porpoise surfacing model. The plots include the jack-knife deviance residuals against the fitted values (top left) and a normal QQ plot of the standardized deviance residuals (top right; the dotted line is the expected line if the standardized residuals are normally distributed, i.e. it is the line with intercept 0 and slope 1). The bottom two panels are plots of the Cook statistics. On the left is a plot of the Cook statistics against the standardized leverages; points above the horizontal line represent points with high influence on the model. Points to the right of the vertical line have high leverage compared to the variance of the raw residual at that point.

Link-scale parameter estimates and inferential statistics for a multinomial GLM fitted with GEEs to the seal's surfacing locations. The model consists of only the interaction term and the Codaoctopus ON serves as the baseline for comparison.

SONAR activity	SONAR system	Estimate (link scale)	Std error	95% confidence interval		Z test statistic	*p*-value
				Lower	Upper		
OFF	Biosonics	4.4058	0.8583	2.7236	6.088	5.13	<0.0001
OFF	Codaoctopus	-0.9715	0.3872	-1.7305	-0.2126	-2.51	0.0121
ON	Biosonics	29.2769	0.5642	28.1711	30.3827	51.89	<0.0001
ON	Codaoctopus	*(Baseline)*					

14. APPENDIX 5: TRITECH GEMINI SPECIFICATION SHEET

Tritech INTERNATIONAL

innovative underwater technology

www.tritech.co.uk

Gemini 720i

MULTIBEAM IMAGING SONAR

Benefits

- Provides crisp, clear, wide angle field of view in low visibility environments
- Real-time imagery increases target acquisition and aids in navigation
- Easier interpretation of sonar imagery and identification of targets at a longer range
- Lightweight, compact, robust design for ease of vehicle mounting
- Flexible interfacing for ROVs/ AUVs

Features

- 720kHz operating frequency
- 120° field of view
- Integrated velocimeter for accurate ranging
- Weighs only 1.2kg in water
- Interfaced with either Ethernet or VDSL
- Display data via Tritech's SeaNet Pro or Gemini's standalone software
- Software Development Kit available

Applications

- ROV / AUV navigation
- Search & Rescue
- Obstacle avoidance
- Target recognition
- Salvage operations
- Subsea monitoring & inspection

Gemini 720i sets new standards for multibeam imaging sonars. It offers a compact real-time high frequency imaging solution, which is suitable even for very small ROVs and AUVs. The sonar head weighs just over 1kg in water and is designed to be easily installed onto a variety of underwater vehicles and platforms.

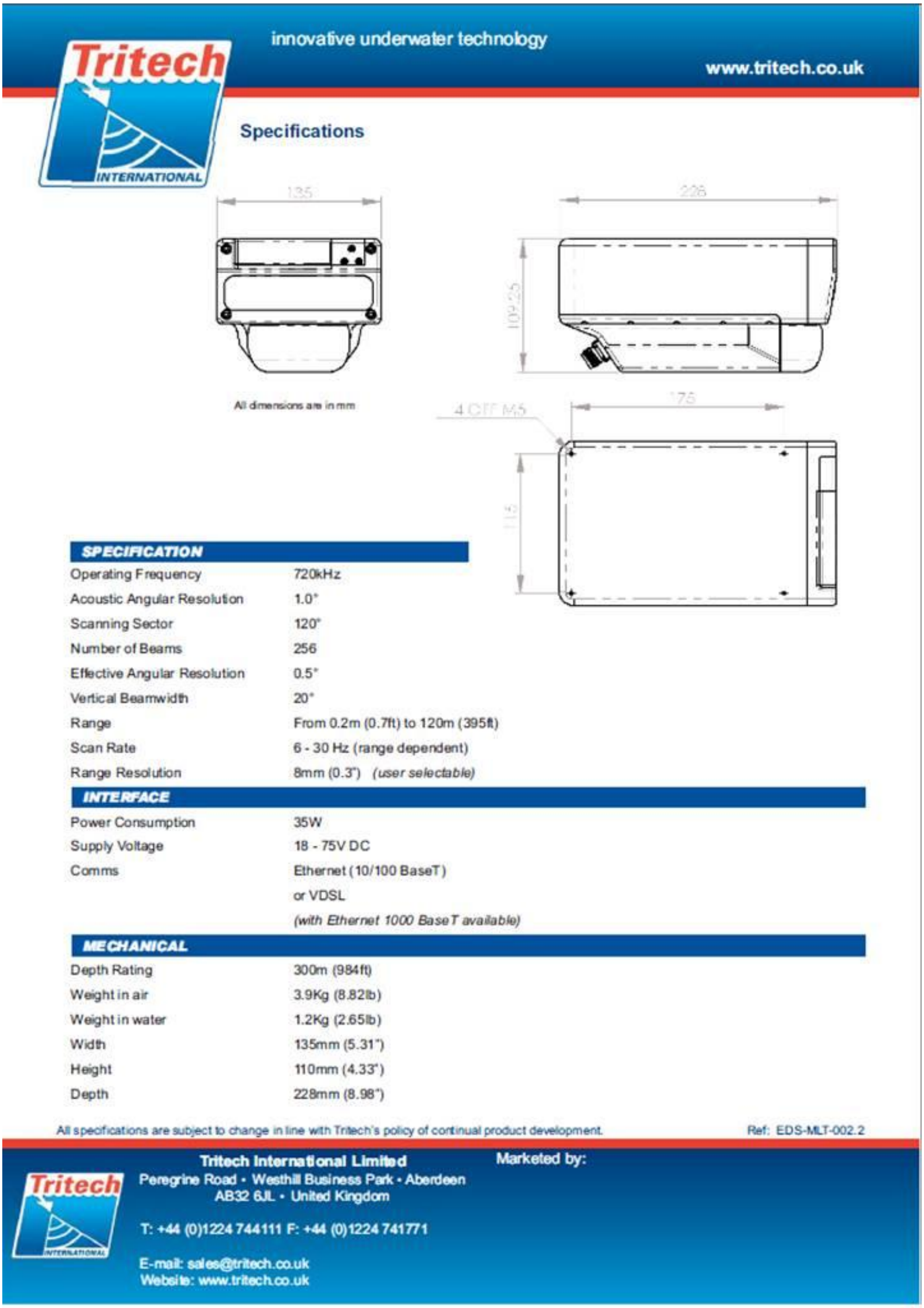
With a 720kHz operating frequency, and state of the art processing electronics, Gemini 720i produces images of superb clarity with the added benefit of real-time imaging. An integrated sound velocity sensor assists in providing the sharpest image possible, with accurate ranging.

Gemini 720i Sonar

Gemini 720i sonar image of a pipeline mattress

Gemini 720i sonar image of a mooring block

the finest range of high technology subsea products in the world



Tritech INTERNATIONAL

innovative underwater technology

www.tritech.co.uk

Specifications

All dimensions are in mm

SPECIFICATION	
Operating Frequency	720kHz
Acoustic Angular Resolution	1.0°
Scanning Sector	120°
Number of Beams	256
Effective Angular Resolution	0.5°
Vertical Beamwidth	20°
Range	From 0.2m (0.7ft) to 120m (395ft)
Scan Rate	6 - 30 Hz (range dependent)
Range Resolution	8mm (0.3") *(user selectable)*
INTERFACE	
Power Consumption	35W
Supply Voltage	18 - 75V DC
Comms	Ethernet (10/100 BaseT) or VDSL *(with Ethernet 1000 BaseT available)*
MECHANICAL	
Depth Rating	300m (984ft)
Weight in air	3.9Kg (8.82lb)
Weight in water	1.2Kg (2.65lb)
Width	135mm (5.31")
Height	110mm (4.33")
Depth	228mm (8.98")

All specifications are subject to change in line with Tritech's policy of continual product development.

Ref: EDS-MLT-002.2

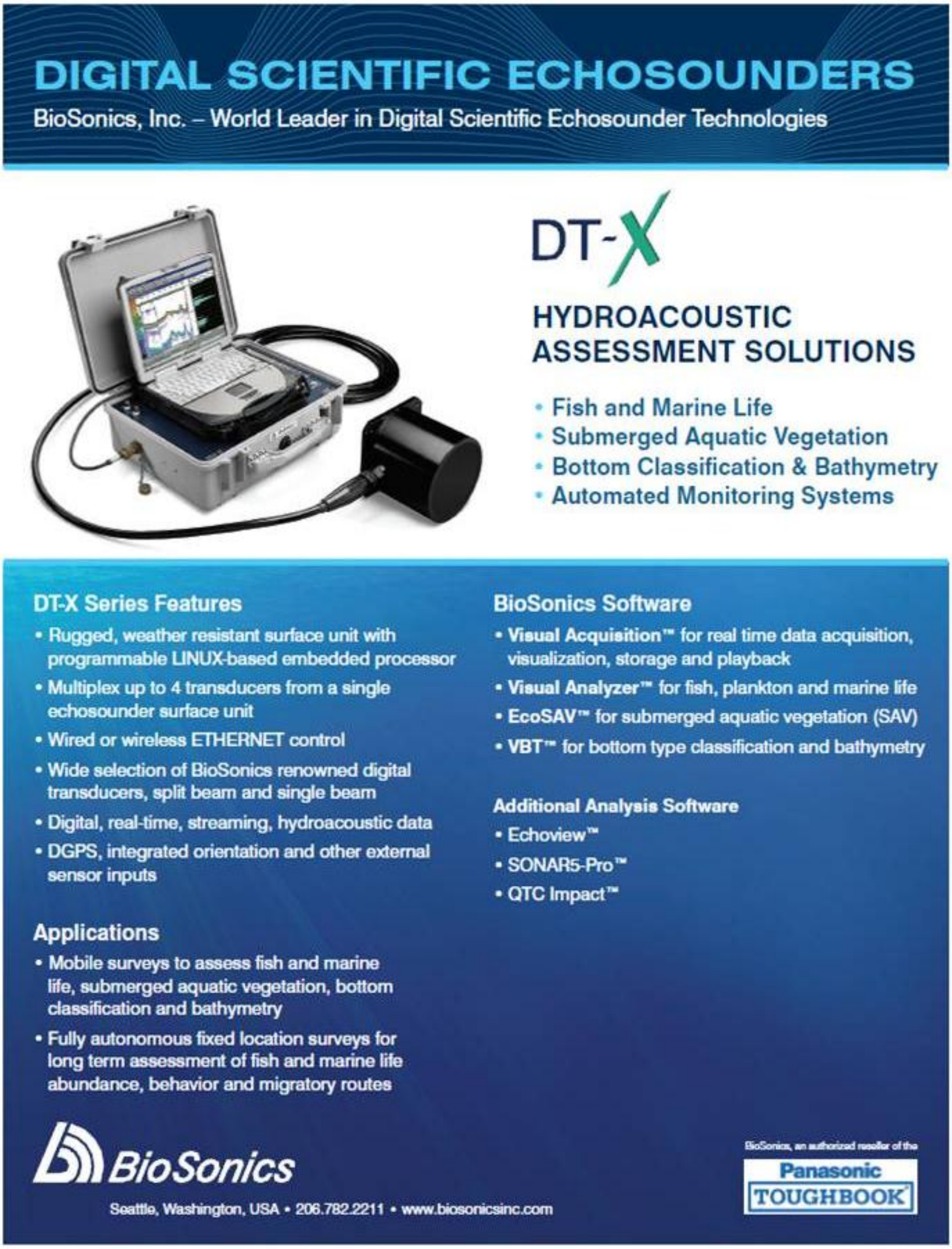
Tritech International Limited
Peregrine Road • Westhill Business Park • Aberdeen
AB32 6JL • United Kingdom

T: +44 (0)1224 744111 F: +44 (0)1224 741771

E-mail: sales@tritech.co.uk
Website: www.tritech.co.uk

Marketed by:

15. APPENDIX 6: BIOSONICS DT-X SPECIFICATIONS SHEET



DIGITAL SCIENTIFIC ECHOSOUNDERS

BioSonics, Inc. – World Leader in Digital Scientific Echosounder Technologies

DT-X

HYDROACOUSTIC ASSESSMENT SOLUTIONS

- Fish and Marine Life
- Submerged Aquatic Vegetation
- Bottom Classification & Bathymetry
- Automated Monitoring Systems

DT-X Series Features

- Rugged, weather resistant surface unit with programmable LINUX-based embedded processor
- Multiplex up to 4 transducers from a single echosounder surface unit
- Wired or wireless ETHERNET control
- Wide selection of BioSonics renowned digital transducers, split beam and single beam
- Digital, real-time, streaming, hydroacoustic data
- DGPS, integrated orientation and other external sensor inputs

Applications

- Mobile surveys to assess fish and marine life, submerged aquatic vegetation, bottom classification and bathymetry
- Fully autonomous fixed location surveys for long term assessment of fish and marine life abundance, behavior and migratory routes

BioSonics Software

- **Visual Acquisition™** for real time data acquisition, visualization, storage and playback
- **Visual Analyzer™** for fish, plankton and marine life
- **EcoSAV™** for submerged aquatic vegetation (SAV)
- **VBT™** for bottom type classification and bathymetry

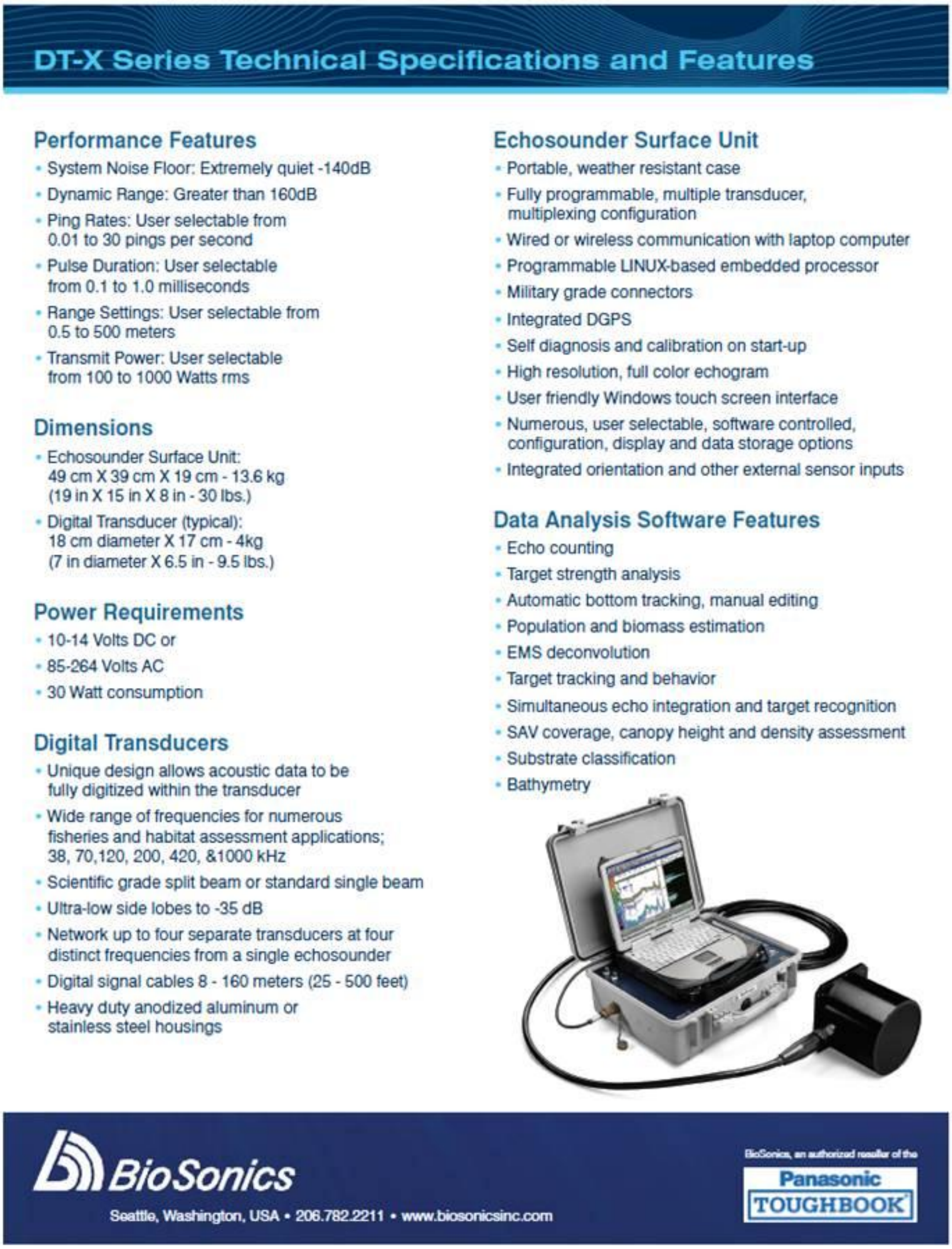
Additional Analysis Software

- Echoview™
- SONAR5-Pro™
- QTC Impact™

BioSonics

Seattle, Washington, USA • 206.782.2211 • www.biosonicsinc.com

BioSonics, an authorized reseller of the Panasonic TOUGHBOOK



DT-X Series Technical Specifications and Features

Performance Features

- System Noise Floor: Extremely quiet -140dB
- Dynamic Range: Greater than 160dB
- Ping Rates: User selectable from 0.01 to 30 pings per second
- Pulse Duration: User selectable from 0.1 to 1.0 milliseconds
- Range Settings: User selectable from 0.5 to 500 meters
- Transmit Power: User selectable from 100 to 1000 Watts rms

Dimensions

- Echosounder Surface Unit:
  49 cm X 39 cm X 19 cm - 13.6 kg
  (19 in X 15 in X 8 in - 30 lbs.)
- Digital Transducer (typical):
  18 cm diameter X 17 cm - 4kg
  (7 in diameter X 6.5 in - 9.5 lbs.)

Power Requirements

- 10-14 Volts DC or
- 85-264 Volts AC
- 30 Watt consumption

Digital Transducers

- Unique design allows acoustic data to be fully digitized within the transducer
- Wide range of frequencies for numerous fisheries and habitat assessment applications; 38, 70,120, 200, 420, &1000 kHz
- Scientific grade split beam or standard single beam
- Ultra-low side lobes to -35 dB
- Network up to four separate transducers at four distinct frequencies from a single echosounder
- Digital signal cables 8 - 160 meters (25 - 500 feet)
- Heavy duty anodized aluminum or stainless steel housings

Echosounder Surface Unit

- Portable, weather resistant case
- Fully programmable, multiple transducer, multiplexing configuration
- Wired or wireless communication with laptop computer
- Programmable LINUX-based embedded processor
- Military grade connectors
- Integrated DGPS
- Self diagnosis and calibration on start-up
- High resolution, full color echogram
- User friendly Windows touch screen interface
- Numerous, user selectable, software controlled, configuration, display and data storage options
- Integrated orientation and other external sensor inputs

Data Analysis Software Features

- Echo counting
- Target strength analysis
- Automatic bottom tracking, manual editing
- Population and biomass estimation
- EMS deconvolution
- Target tracking and behavior
- Simultaneous echo integration and target recognition
- SAV coverage, canopy height and density assessment
- Substrate classification
- Bathymetry

BioSonics

Seattle, Washington, USA • 206.782.2211 • www.biosonicsinc.com

BioSonics, an authorized reseller of the Panasonic TOUGHBOOK