

A review of the potential use of sonar to observe the underwater behaviour of diving birds near tidal energy devices





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ARCHIVE REPORT

Archive Report No. 051

**A review of the potential use of sonar to
observe the underwater behaviour of diving
birds near tidal energy devices**

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ARCHIVE REPORT

Summary

A review of the potential use of sonar to observe the underwater behaviour of diving birds near tidal energy devices

Archive Report No. 051
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Note: This report was originally completed in 2010 but not published, formally, at the time. It is being published in 2018 in recognition of the ongoing value of the research concerned but readers should note that the text has not been updated in the intervening period.

Background

With the need for novel and innovative approaches in mind, Scottish Natural Heritage (SNH), through funding from Marine Scotland, commissioned RPS to carry out a feasibility study into the potential use of sonar to observe the underwater behaviour of diving birds near tidal energy devices. SNH recognises the need to balance the meeting of renewable energy targets with the preservation of Scotland's seabird populations. Therefore it is keen to investigate the interaction between diving birds and tidal devices to identify and mitigate any potential negative impacts before large-scale commercial deployment begins.

Main outputs and findings

The report presents:

- A review of relevant and available sonar (and underwater video camera and strain gauge) technologies, considering benefits and limitations, availability, cost and methods of attachment.
- A summary of past examples from the scientific literature of the use of sonar to observe the underwater behaviour of diving birds.
- A summary of current trials in the use of sonar for biological monitoring near tidal devices.
- A description of the underwater conditions characterising high-energy tidal currents, waves, turbidity and air bubbles, and how these variables will affect the use of sonar.
- A review of scientific literature relating to the underwater behaviour of diving bird species occurring around the Pentland Firth and Orkney Islands, with an emphasis on dive depth, dive duration, dive profile and swimming speed, to aid in the potential classification of birds' sonar signatures.

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1. BACKGROUND

In March 2010, the Scottish Government and the Crown Estate announced their commitment to construct the world's first commercial tidal and wave power schemes around the Pentland Firth and Orkney Islands, with plans to award leases to developers by late summer. The aim is to harness energy from some of the UK's strongest tides and largest waves and generate up to 1.2GW of energy to power 750,000 homes. This development of Scotland's coastal waters will make a significant contribution towards a low carbon future, will increase the UK's energy security and promote economic growth in remote and rural areas.

However, such highly dynamic coastal regions have, by inference, powerful upwellings of nutrient-rich, productive waters supporting large numbers of foraging seabirds, many of which dive for their prey. As the behaviour of diving birds underwater is not well understood, there is concern that tidal energy devices in particular, which comprise large moving parts and are often invisible from the surface, will pose a potentially significant collision risk to diving birds foraging underwater. There is therefore an urgent need to investigate novel and innovative techniques to gain baseline data on the underwater behaviour of diving birds near tidal devices.

1.1 Project Brief

With this need for novel and innovative approaches in mind, Scottish Natural Heritage (SNH), with funding from Marine Scotland, commissioned RPS to carry out a feasibility study into the potential use of sonar to observe the underwater behaviour of diving birds near tidal energy devices. SNH recognises the need to balance the meeting of renewable energy targets with the preservation of Scotland's seabird populations. Therefore it is keen to investigate the interaction between diving birds and tidal devices to identify and mitigate any potential negative impacts before large-scale commercial deployment begins.

1.2 Report Outline

The aim of this feasibility study is to review the relevant sonar technology, put this into context with examples from the scientific literature and experiences from current trials, and to set this against the backdrop of the physical conditions of coastal regions and the diving behaviour of the seabirds that forage in such areas. This report includes:

- A review of relevant and available sonar (and underwater video camera and strain gauge) technologies, considering benefits and limitations, availability, cost and methods of attachment.
- A summary of past examples from the scientific literature of the use of sonar to observe the underwater behaviour of diving birds.
- A summary of current trials in the use of sonar for biological monitoring near tidal devices.
- A description of the underwater conditions characterising high-energy tidal currents, waves, turbidity and air bubbles, and how these variables will affect the use of sonar.
- A review of scientific literature relating to the underwater behaviour of diving bird species occurring around the Pentland Firth and Orkney Islands, with an emphasis on dive depth, dive duration, dive profile and swimming speed, to aid in the potential classification of birds' sonar signatures.

1.3 Why Sonar?

Sonar observation of the underwater behaviour of diving birds near tidal devices is a novel and innovative biological monitoring tool aimed at helping to solve the problems of sub-surface data collection. To date, bird surveys informing offshore renewable energy proposals have used trained ornithologists to carry out above-surface biological monitoring from the

land, boats and aircraft; whilst in academic studies, time-depth recorders have been fitted to diving birds to obtain underwater behavioural information. The advantage of the former technique is that an exact area of water can be targeted, although no underwater behaviour can be captured; whereas with the latter technique the opposite is true.

With sonar, however, both variables of a targeted location and a focus on underwater behaviour may be achieved in the same study. Sonar instrumentation in the vicinity of a tidal device will aim to collect data passively, under low light and high turbidity conditions, on any bird within range, and record dive depth, dive duration, dive profile and swim speed. Such data could help assemble an understanding of the interaction between diving birds and tidal devices and highlight any potential negative impacts the industry might have on seabird populations.

It is suggested that sonar should be used initially once tidal devices are at the prototype stage during testing at European Marine Energy Centre (EMEC) on Orkney. This would enable the early identification and mitigation of any potentially negative impacts. It is also suggested that sonar should be used once large-scale arrays are in place. This would allow monitoring to be continued on-site, among several devices and over an extended period of time.

It is thought that sonar should not be used to assess baseline diving bird presence at a proposed development area as this can be done satisfactorily and at considerably less expense by using trained ornithologists and established above-surface monitoring techniques. Sonar is expensive and has a limited range, so the chances of accurately recording baseline diving bird presence across a development area are likely to be poor, unless a number of sonar instruments are used.

An optimal methodology for monitoring large-scale tidal arrays would be to use surface observers to establish pre-deployment diving bird presence and sonar to establish post-deployment diving bird interaction with the devices.

1.4 Recommendation for a Field Trial

This report is a feasibility study only. It presents the best options that sonar technology can currently offer to observe the underwater behaviour of diving birds near tidal energy devices. However, a field trial will be essential to test sonar equipment, attachment methods and overall performance under the challenging conditions of high energy waters. A trial will also be crucial to examine sonar outputs and assess their usefulness in documenting diving bird behaviour.

2. SONAR TECHNOLOGIES

2.1 Types of Sonar

Sonar offers a means of recording diving bird behaviour at ranges far in excess of that afforded by underwater video cameras. But since the wavelength of sound is much longer than that of light, image resolution is poorer. Sonar technology can be divided into two broad types: single-beam and multi-beam.

Single-beam sonar emits a narrow cone (e.g. 7°), so coverage is quite limited. This kind of sonar would therefore only record low frequencies of diving behaviour and would provide limited information on dive metrics (dive depth, dive duration, dive profile and swim speed). Wide-angle alternatives include multi-beam sonar, which can scan areas of >50° in both horizontal and vertical planes and produce detailed three-dimensional images.

2.2 Single-Beam Sonar

Single-beam sonar comprises a single transducer which emits and receives acoustic pulses. Pulses are emitted in a fan shape, at intervals, in a fixed direction. The fan shape is usually of a narrow beam-width (<20°) and is pointed perpendicular toward the direction of movement of the sonar system through the water. The system is usually mounted on the hull of a boat, or towed. Alternatively, mechanical scanning sonar systems comprise a transducer which rotates within an angle of 180° - 360°. Pulses are reflected off objects (e.g. the ocean floor, a school of fish) and received by the transducer. These acoustic reflections are recorded in a series of snapshots, thus single-beam sonar cannot provide continuous coverage or real-time imagery. The resolution of sonar output is determined by beam-width, sampling interval and sampling speed. When fitted together, 'snapshot' sonar outputs form an image of the ocean floor within the width of the beam. Single-beam systems are generally portable, inexpensive and easily deployed from small boats that can access shallow waters. Single-beam sonar provides much lower spatial resolution than multi-beam sonar, described below.

Single-beam transducers can be calibrated for several applications, including:

- mapping features of the ocean floor;
- measuring depth;
- monitoring benthic habitats; and
- locating fish.

The frequencies used in single-beam sonar typically range from 12 - 710kHz. Higher frequencies yield improved resolution but at the cost of reduced range. Higher frequencies (200kHz) are used in shallow waters (1-50m) whereas lower frequencies (12 - 50kHz) are used in deeper waters (<11,000m). Some transducers are available with dual frequencies (high and low).

The Super SeaKing DST, manufactured by Tritech, is an example of a single-beam mechanical scanning sonar currently in use for biological monitoring around the SeaGen tidal device in Strangford Lough in Northern Ireland (Section 4.1).

Single-beam sonar has a relatively narrow beam-width, so coverage is quite limited. This kind of sonar would therefore only record low frequencies of diving behaviour and would provide limited information on dive metrics (dive depth, dive duration, dive profile and swim speed).

2.3 Multi-Beam Sonar

Multi-beam sonar essentially comprises parallel arrays of single-beam sonar. Using the multiple returns it is possible to create a three-dimensional image without the need to move the sonar (as with single-beam). These sensors emit multiple beams that cover large overlapping swathes of the seafloor, enabling the output of continuous, real-time sonar imagery (unlike single-beam sonar). Different multi-beam sonar systems are available, but a typical system would have a field of view of around $50^{\circ} \times 50^{\circ}$, at which angle the width of 'image' obtained is approximately the same as the distance from the sonar (e.g. at 25m from the sonar the window of sonar returns will be approximately 25m x 25m). The effective range of multi-beam sonar will depend on conditions on site, but is unlikely to exceed 50m. Factors which may reduce the range will include turbidity and air bubbles in the water column forced downward by the mixing action of waves. These systems can be used in extremely deep waters (<11,000m). Multi-beam systems are often larger and less portable than single-beam sensors and produce very large data streams.

The Echoscope, manufactured by CodaOctopus, is an example of a multi-beam sonar device which successfully recorded diving bird behaviour during a trial in the Firth of Forth (Section 4.3).

As multi-beam sonar has a relatively wide beam-width it can scan areas of $>50^{\circ}$ in both horizontal and vertical planes and produce detailed three-dimensional images, and therefore potentially reveal detailed information on dive metrics (dive depth, dive duration, dive profile and swim speed).

2.4 Technical Terminology

The short glossary below describes some of the technical terminology referred to later in this study surrounding sonar equipment:

- frequency: the frequency of the sound emitted by sonar (usually expressed in Hz), where a higher frequency provides more detail, but travels less far, and a lower frequency travels further though loses detail;
- beam-width: the diameter along any specified line that is perpendicular to the beam axis and intersects it (usually expressed in degrees);
- ping rate: the frequency per unit time (e.g. per second) at which an acoustic pressure wave (the ping) is emitted; and
- beam spacing: set distance between individual beams.

2.5 Methods of Attachment

Limitations of Fixing Sonar Equipment to Boats

Boat-mounted sonar equipment is not an advised methodology for documenting the underwater behaviour of diving birds because the presence of the boat influences behaviour and normal foraging patterns are disturbed. A field trial of boat-mounted sonar equipment among birds in the Firth of Forth was carried out by RPS (Figure 1 & Section 4.3) and although dives were successfully recorded, diving was determined by surface observers to be an evasion response to the boat. While boat-based observations traditionally used to inform offshore renewable energy developments represent an appropriate and reliable methodology for documenting species and numbers of seabirds, the use of boats to record detailed and natural foraging behaviour is not effective, since most species will respond to the boat.



Figure 1. Boat-mounted sonar equipment in the Firth of Forth. (RPS)

Benefits of Fixing Sonar Equipment to pontoons

Installing a sonar system on a static structure would entail automated running of the system, perhaps in tandem with a surface camera so that dive traces could be linked to video footage to add information on species and perhaps even age/sex. Power supply and downloading of the data would need to be considered. Fixed to a moored pontoon, the sonar equipment would move up and down with the tide. The equipment could encompass a bespoke design where the sonar would contain a gyroscope to remove much of the 'wobble' from the sonar image due to wave action. However, structures to which sonar equipment could be fixed are likely to have an influence on birds (either attracting or repelling) and consequently representative diving behaviour may not be captured. Only through trials could the extent of such effects be determined.

2.6 The Sonar Signature of Diving Birds

The sonar signature of diving birds detected by sonar will vary depending on size and acoustic reflectance. Larger birds will give stronger signatures simply due to their larger surface area, while acoustic reflectance depends on the amount of air trapped in the birds' plumage, so birds which carry more air underwater with them will also give stronger signatures. Also the bubble train trailing in birds' wake will leave a conspicuous streak on the resulting echogram.

2.7 Non-Sonar Options

Underwater video cameras are readily available, with many off-the-shelf options, such as those used for fish farms. These would have the advantage of simplicity, established technology and price over sonar systems. However, the main limitation associated with underwater video cameras is likely to be the restricted field of view, and hence bird detection range, resulting from one or more factors (e.g. low light levels due to depth, night-time, turbidity, etc.). Thus, while an underwater camera-based system may be able to provide species (or at least species group) identification, in practice sea conditions may limit images to a range of only 4-5m. Over these distances it would also be difficult to determine the extent to which interactions between underwater devices and birds could be recorded, since only a small volume of sea would be captured. Thus, underwater video cameras are considered by this study to be of limited value for observing the underwater behaviour of diving birds near tidal energy devices. No further consideration is provided in this report.

3. PAST EXAMPLES FROM THE LITERATURE IN THE USE OF SONAR TO OBSERVE DIVING BIRDS UNDERWATER

To date, the majority of research on diving behaviour in seabirds has been based on fitting data loggers to birds. The direction of the present study will be novel in that the data recording device, i.e. the sonar equipment, will be fixed underwater in anticipation that any birds present will be detected, i.e., sites will be selected for study as opposed to individual birds. Scientific literature on the use of sonar to observe diving birds underwater is extremely limited. One published and one unpublished study were found; these are summarised below:

3.1 Sonar Observations of Diving Northern Gannets (Brierley & Fernandes, 2001)

In July 1999, the Autonomous Underwater Vehicle (AUV) Autosub-1 was deployed from the offshore research vessel Scotia to investigate near-surface schooling herring in the North Sea. Autosub-1 is a 6.8 x 0.9m torpedo-shaped unmanned submersible vehicle. It is battery-powered and can conduct pre-programmed missions at speeds of up to 3 knots, to depths of 500m and with durations of over 24hr. During the study the AUV was deployed on missions which were on average 8hrs long; it was unattended, tens of kilometres away from Scotia, purposefully surveying transects geographically distinct from those being surveyed by the ship.

Autosub-1 was equipped with Simrad's EK-500 Scientific echosounder operating 38 and 120 kHz transducers generating conical 7° sampling beams. Acoustic surveys (pings) were collected every 1s during each deployment and data were logged over an ethernet to a local computer using the software package SonarData Echoview. The AUV was deployed on 12 missions with an upward-looking transducer. On these deployments, the AUV was programmed to cruise at depths of 20, 30, or 50m, or to remain at a fixed depth above the seabed (effectively undulating between 35 and 50m depth). The sea surface was always 'visible' acoustically.

Northern gannet *Morus bassanus* dives were clearly visible on echograms and could be attributed directly to gannets observed from Scotia. The birds were strong acoustic reflectors due to the air trapped in their plumage and lungs, and the bubble train trailing in their wake which leaves a conspicuous streak on the echogram. Dive depths were evaluated from the echograms as the difference between the range from Autosub-1 to the sea surface, and the closest approach of the dive trace to Autosub-1. With one or more echosounder transducers facing upwards along a total survey track of 330km, 19 gannet dive traces were evident on the echograms recorded.

Weather conditions deteriorated somewhat during the course of the two missions, causing the sea surface to become increasingly disturbed. Air bubbles mixed downwards by wave action partially obscured dive traces and lowered confidence in the ability to distinguish dives during these conditions; these data were not included.

Limitations with this sampling technique were that dive profiles, i.e. U- and V-shaped dives, could not be distinguished. The echosounder transducers had 7° beam angles. From a depth of 50m, they provided a circular sampling window 6.1m in diameter, but that window decreased in size as depth decreased (diameter = $2 \times \tan 3.5^\circ \times \text{range}$), being only 1.2m at 10m range. Only dives that passed directly down the centre of the echosounder beam were observed in full and, unless the descent and ascent components of the dive were spatially very close, it was unlikely that bubble trails from both would be detected. The AUV travelled typically at 1.2ms^{-1} and, at a range of 50m, would have been able to observe a fixed point in the water column above for only a little over 5s. Another implication of the conical acoustic sampling window was that deeper dives were more likely to pass out of the sampling beam and thus true depth would not be recorded.

3.2 Sonar Observations of Diving Common Guillemots (Fernandes, P., 1990s, Unpubl. Data)

This study employed a multi-beam, three-dimensional sonar with a range of 100m. The equipment was fixed to a pole beneath an offshore research vessel investigating near-surface schooling fish in the Clyde Sea. Among the echograms produced, occasional conspicuous streaks were noted and attributed to diving common guillemots (*Uria aalge*) foraging nearby. These sonar signatures were easily distinguished from the schooling fish and background interference of bubbles caused by wave action. This clarity was due to the birds diving deep, where interference was less, and because they acted as strong acoustic reflectors due to their large size (relative to the fish for which the sonar equipment was selected), the air trapped in their plumage and lungs, and the bubble train trailing in their wake.

Fernandes, P., Pers. Comm.

AUVs are available for hire and can be contracted from companies and research institutions, specifically, the oilfield services corporation Halliburton, the Scottish Association for Marine Science (SAMS) and the National Oceanography Centre (which owns the AUV Autosub-1 used in Brierley & Fernandes, 2001). However, the deployment of an AUV to use sonar to observe the underwater behaviour of diving birds would be excessive. AUVs are extremely expensive and available hire periods are few. The control of AUVs is also a very technically demanding field. In addition AUVs usually have relatively low top speeds which would render them unsuitable for deployment in the high flow rate locations targeted for tidal energy extraction.

Although the Brierley and Fernandes (2001) study successfully recorded the underwater foraging of northern gannets with the use of an AUV, Fernandes' (1990s, unpubl. data) study recorded the underwater foraging of common guillemots with equal success using sonar equipment mounted on a boat. In the present feasibility study, where the aim of research is to use sonar to observe the underwater behaviour of diving birds near tidal energy devices, fixed sonar equipment mounted on or among the devices themselves is much more appropriate.

When selecting sonar equipment, a balance must be reached between acuity and range. For the purpose of observing the underwater behaviour of diving birds near tidal devices, a high-frequency device would give the best acuity, but with a limited range. This would be suitable for the interaction of foraging birds with tidal devices, where a shorter range (approximately 50m) would be acceptable.

Deeper diving activity will produce a clearer echogram due to reduced interference from bubbles caused by wave action. Most diving bird species present around the Pentland Firth and Orkney Islands forage within this deeper range (Section 6).

4. CURRENT TRIALS IN THE USE OF SONAR FOR BIOLOGICAL MONITORING NEAR TIDAL DEVICES

The underwater application of sonar was initially prompted by the sinking of the SS Titanic in 1912, when the potential for depth sounding, underwater communications and echo ranging was first explored. In the century since, sonar technology has burgeoned, largely in the fields of defence, engineering and fisheries. With the advent of underwater renewable energy bringing a need for biological monitoring near tidal devices, the use of sonar in this field has just begun to develop. Trials using sonar to observe diving birds (and marine mammals) underwater are extremely few, indeed only three separate efforts were found in this study; these are summarised below:

4.1 Sonar Trials Led by SMRU for the SeaGen Tidal Energy Device at Strangford Lough

SeaGen is a 1.2MW tidal energy device installed in 2008 in the narrows of Strangford Lough in Northern Ireland, comprising two, unenclosed turbines each with a diameter of 16m. The SeaGen project represents the first ever effort to use sonar technology to carry out biological monitoring near tidal devices. The Sea Mammal Research Unit (SMRU) has deployed sonar at SeaGen to detect marine mammals, and diving birds have also been observed. Monitoring has supplied real-time underwater imagery of marine mammals passing through the narrows within the sonar equipment's 80m range. Sonar will continuously monitor the waters around the tidal energy device for a five-year trial period.

After testing various commercially-available sonar packages, SMRU selected the single-beam Super SeaKing DST (Digital Sonar Technology) mechanical scanning sonar, manufactured by Tritech, for its excellent results in terms of range and coverage.

Summarised Specifications for Tritech's Super SeaKing DST Mechanical Scanning Sonar

- Two frequency options: 250 - 350kHz and 620 - 720kHz;
- beamwidth: 20° x 3.0° for lower frequency option and 40° x 1.5° for higher frequency option;
- maximum range: 300m for lower frequency option and 100m for higher frequency option;
- minimum range: 0.4m;
- range resolution: 0.5 - 40cm depending on range;
- scan modes: various combinations of resolution and speed; and
- scanned sector: variable to 360°.

The sonar equipment was initially manned alongside a Marine Mammal Observer (MMO) on the tidal energy device itself to provide calibration between what was detected above water by the trained observer and what was detected below water by sonar. The MMO and the sonar operator had the capacity to shut down the tidal device if a marine mammal was detected within a set distance. This 'shut down limit' was initially 200m, but was later reduced to 50m based on the sonar data indicating no negative impacts from the tidal device on marine mammals. The sonar equipment later became operated remotely from the MMO, and eventually the MMO was removed altogether as sonar proved to provide sufficiently conservative mitigation. Sonar also provides mitigation through the night. SMRU hopes, eventually, to completely remove the shut-down protocol as monitoring so far has shown marine mammals to be capable of detecting and avoiding the tidal device. It is hoped that removal of the shut-down protocol will reveal further sonar data indicating no negative impacts on marine mammals near the operating device.

Tritech (Aberdeen) Pers. Comm.

Tritech have recently developed the Gemini 720i multi-beam imaging sonar which will be deployed for trials on the SeaGen tidal device in autumn 2010. Once the system has been fully tested and calibrated, it will replace the Super SeaKing, possibly by spring 2011.

4.2 Sonar Trials by SMRU on Marine Mammal Detection

SMRU published a series of reports on active sonar trials carried out to establish the capacity for detection of marine mammals by different devices as well as any behavioural responses to sonar. Although not focussed on birds, knowledge gained during these trials provides a valuable platform to inform future bird-targeted studies (Hastie, 2008a, Hastie, 2008b, Hastie & Janik, 2007).

In a trial with captive grey seals it appeared the animals were able to detect the presence of sonar and responded to these (Hastie, 2008a). However, these experiments were undertaken in a non-natural environment, and while they do show that an effect of the sonar itself could be expected, "live" trialling would be required to try and establish the magnitude of any effect¹.

In a second trial SMRU concluded that although it was unlikely that identification of individual species would be possible using information available from active sonar, it may be possible to allocate sonar contacts to one of three main groups of marine animals based on a combination of size, speed, and numbers of sonar contacts made.

A series of formal field tests of the Tritech Super SeaKing, the CodaOctopus Echoscope 2, and the Didson sonar were carried out at Strangford Lough to determine whether small marine animals could be reliably detected in tidally active conditions. A porpoise carcass was used as a dummy.

In the majority of these tests, independent users were able to identify the porpoise in the sonar images. Each system suffered from a certain degree of error with users failing to identify the porpoise a number of times, and marine debris being misidentified as the porpoise in some of the tests. Based on the results from this study it appeared the Tritech Super SeaKing was the most efficient system for detecting small marine mammals².

4.3 Sonar Trials Led by RPS in the Firth of Forth

In contrast to the application of sonar technology for biological monitoring at Strangford Lough, which has largely focussed on the detection and observation of marine mammals, RPS has focussed research efforts on diving birds. To investigate the potential use of sonar to observe the underwater behaviour of diving birds, RPS, in a feasibility study funded by the Welsh Assembly Government (WAG), carried out a one-day field trial of boat-mounted sonar among birds in the Firth of Forth in January 2010.

Careful consideration of several 'off-the-shelf' sonar packages eventually led to the selection of the CodaOctopus Echoscope for its high resolution and three-dimensional facility.

¹ An update to these findings, including field trial, is presented in Hastie (2013).

² In a separate, later trial the Tritech Super SeaKing was deployed on the SeaGen tidal turbine in Strangford Lough. Results showed that small marine mammals (and other mobile targets) could be detected in a tidally turbulent water column in real time using high frequency imaging sonar (Hastie, 2013). However, SMRU concluded that the sonar used would require significantly more development to produce a reliable and efficient mitigation tool.

Summarised Specifications for CodaOctopus' Echoscope

- Frequency: 375kHz;
- beamwidth: 50° x 50°;
- maximum range: 150m;
- minimum range: 1m;
- range resolution: 3cm;
- ping rate: >12Hz;
- number of beams: 128 x 128 (16,384 in total); and
- beam spacing: 0.39°.

The trial established that the Echoscope was capable of supplying real-time, high-resolution, three-dimensional sonar imagery of diving bird behaviour (Figures 2 and 3). The two first-winter razorbills *Alca torda* recorded were diving within 45 -50m range of the sonar equipment. The birds were strong acoustic reflectors due to the air trapped in their plumage and lungs. In addition, whilst diving the birds left a trail of bubbles in their wake which gave a conspicuous streak on echograms (Figure 3). These promising results indicated that it is possible to capture diving bird behaviour using multi-beam sonar, including data on dive depth, dive duration, dive profile and swim speed.

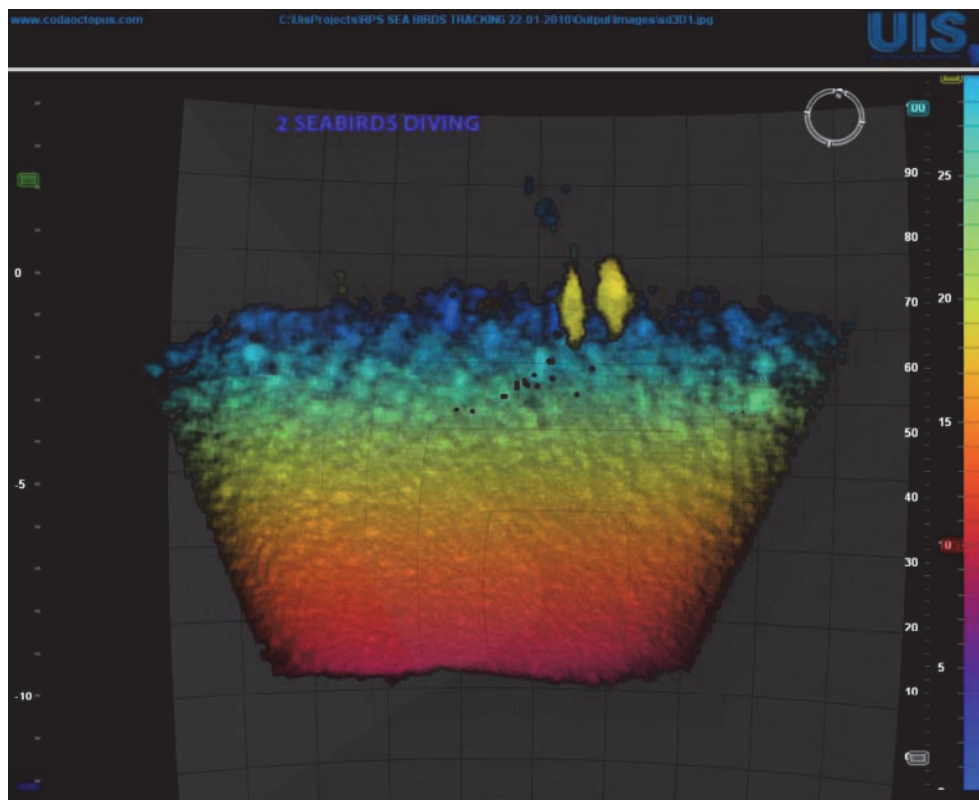


Figure 2. Echogram showing the side-on sonar signatures of two razorbills at the beginning of a dive. It should be noted that the approximate 'size' indicated by these images is considerably larger than the birds themselves, due to diffraction of the sound signals and the presence of air bubbles around the birds. (Sonar imagery recorded by CodaOctopus' Echoscope) (Image included courtesy of funding provided by the Welsh Assembly Government).

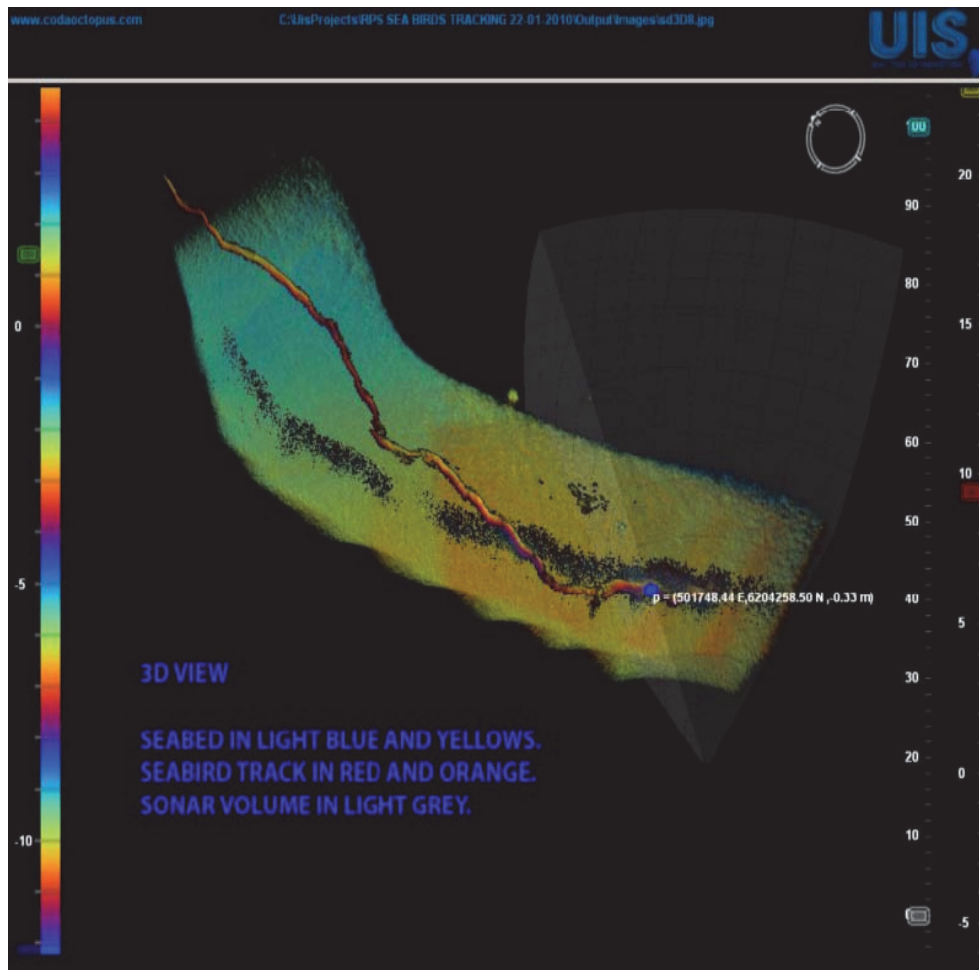


Figure 3. Echogram showing the partially side-on dive trace of a razorbill. The bird is located at the right-hand end of the trace, with the bubble train leaving a conspicuous path. (Sonar imagery recorded by CodaOctopus' Echoscope. Image included courtesy of funding provided by the Welsh Assembly Government).

However, the trial verified the concern that boat-mounted sonar would not capture normal foraging as the boat would influence behaviour. Most individuals approached on the water were disturbed by the boat and flushed well outside the maximum range of the sonar. Moreover, the razorbill dives that were recorded were determined by surface observers to be an evasion response to the boat and not normal foraging behaviour. Thus, sonar-equipped boats would be unsuitable for monitoring diving bird activity near tidal devices. Fixed equipment, mounted on a tidal device or a moored pontoon, would reduce such effects and be more likely to enable typical foraging behaviour to be recorded.

Once the sonar signatures of seabirds have been isolated, it would be valuable to add species, and even age/sex information, to echograms. The above trial highlighted the merit of linking surface observations by trained ornithologists with underwater sonar imagery to provide contextual information. A possible means to gather such observations remotely could be through the use of linked video cameras on the surface. Trials would be necessary to determine how feasible such a combined video/sonar system would be to operate and the quality of data obtained.

It would be useful if automated detection software could be developed to classify the sonar signatures of seabirds. This could be achieved by combining desktop research into the underwater behaviour of locally occurring diving bird species (Section 6), with sonar

recordings collected during field trials, to define parameters and calibrate the software. Such software would isolate seabirds from categories such as marine mammals or debris and would help sift the large amount of sonar imagery produced by continuous monitoring, and ideally classify sonar signatures to species or species group level.

5. UNDERWATER CONDITIONS AFFECTING THE DETECTION CAPACITY OF SONAR

During a series of preliminary studies, SMRU identified a limited number of sonar systems as being potentially suitable to provide real-time sub-surface imagery of seals, cetaceans, and elasmobranchs in the proximity of underwater marine energy devices (Hastie, 2008b)³.

A series of formal field tests of these systems was then carried out to determine whether marine animals could be reliably detected with these systems. These showed that small marine mammal species could be reliably detected at ranges of 30m. However, these initial tests were carried out in good weather conditions, and in relatively shallow water (<10m) with little tidal movement. It remains to be seen how suitable these systems are in poorer weather and higher sea states.

The highly turbulent water characteristics in tidally active environments are likely to have significant impacts on the imaging capabilities of sonar. High winds can also cause turbulence. For example, wind-generated white caps on the surface are a very good acoustic reflector, and the surface return clutter from white caps can significantly degrade the quality of data to such an extent that small target detection becomes unreliable (Kozak, 2006).

During their study, Brierley & Fernandes (2001) found that deteriorating weather conditions, which caused the sea surface to become increasingly disturbed, affected the detection capacity of their sonar system. Air bubbles mixed downwards by wave action partially obscured dive traces and lowered confidence in the ability to distinguish dives during these conditions.

Furthermore, a non-iso density water column can cause the ray path for the outgoing transmit pulse as well as the returning target echoes to follow a distorted or curved path. Thermoclines are the most frequent cause of this ray path distortion, but this effect can also be experienced wherever mixing of water masses of differing salinity (i.e. tidal mixing) occurs (Kozak, 2006).

Sonar efficiency-reducing factors such as air bubble patterns through wave action, tidal mixing, the occurrence of white caps and thermoclines are weather-dependent, and spatially and temporally variable. Combined, these issues create a difficult environment in which to successfully and efficiently use sonar technology to detect seabird and marine mammal activity around tidal devices, particularly in the upper layers of the water column. Sonar-based monitoring at proposed development areas in the Pentland Firth and the Orkney Islands is likely to encounter all of these issues. However, it is considered that most diving bird species regularly occurring in the study area forage to depths below the most dynamic upper layers. Therefore these issues would probably not significantly affect the ability of sonar to record diving birds. Development and refinement of existing technologies may be able to further mitigate for these problems to an extent.

³ See also Hastie (2013).

6. UNDERWATER BEHAVIOUR OF DIVING BIRDS

Once diving bird activity has been captured by sonar and the signatures isolated on echograms, it would be valuable if the dive trace could then be interpreted to species or species group level. This study has summarised a literature review of the underwater behaviour of diving bird species occurring around the Pentland Firth and Orkney Islands which are capable of diving to depths at which they might encounter tidal energy devices. Table 1 provides an overview of the underwater behaviour of these diving bird species with an emphasis on dive depth, dive duration, dive profile and swim speed.

These species will occur in various numbers around the Pentland Firth and Orkney Islands and at varying times of year. For example, where sonar might detect the large numbers of locally breeding guillemots during the summer months, the occasional activity of great northern divers might be recorded during the winter months and in early spring. In addition to behaviour such as dive depth and dive profile, whether species are surface or plunge-divers, or whether they are wing- or foot-propelled, might also be useful diagnostic behaviour appearing on echograms. The information below should be a useful starting point to identify which species are likely to be detected, and what depth ranges, durations and shapes their dive traces might encompass.

Table 1. The underwater behaviour of diving bird species occurring around the Pentland Firth and Orkney Islands to aid in the potential classification of birds' sonar signatures.

Family and Species	Dive Depth	Dive Duration/Dive Profile/Swim Speed
<i>Sulidae</i>		
Northern gannet <i>Morus bassanus</i>	Mean dive depth of 5m (maximum 22m) off Shetland/Orkney (Garthe <i>et al.</i> 2000); and mean dive depth of 20m (maximum 34m) in the North Sea (Brierley & Fernandes, 2001).	Plunge-diver, wing-propelled; dive duration of 1 - 8s off Shetland (Garthe <i>et al.</i> 1999); dive duration of 8 - 38s off Shetland/Orkney (Garthe <i>et al.</i> 2000); can perform extended, deep, U-shaped dives as well as rapid, shallow V-shaped dives in Shetland/Orkney (Garthe <i>et al.</i> 2000); and Brierley and Fernandes (2001) suggest gannets can swim beyond the initial plunge-dive to retrieve prey.
<i>Procellariidae</i>		
Northern fulmar <i>Fulmarus glacialis</i>	Generally a surface-feeding species, but will occasionally dive to 3m (Hudson & Furness 1988; Hobson & Welch, 1992); maximum dive depth of 3m (Garthe & Furness, 2001); and maximum dive depth of 4m (Snow & Perrins, 1998).	Surface-diver, wing-propelled; and maximum dive duration of 8s (Garthe & Furness, 2001).
Manx shearwater <i>Puffinus puffinus</i>	Plunge-dives from a height of 1 -2m; research on this species is not yet available however closely-related species may be used as surrogates: wedge-tailed shearwaters <i>Puffinus pacificus</i> exhibit a mean dive depth of 14m (maximum 66m) (Burger, 2001); Audubon's shearwaters <i>P. lherminieri</i> exhibit a mean dive depth of 15m (maximum 35m) (Burger, 2001); and black-vented shearwaters <i>P. opisthomelas</i> exhibit a mean dive depth of 21m (maximum 52m) (Keitt <i>et al.</i> 2000).	Plunge-diver, wing-propelled; and closely related Audubon's shearwater exhibits a maximum dive duration of 20s (Snow & Perrins, 1998).

Sooty shearwater <i>Puffinus griseus</i>	Maximum dive depth of 67m (Weimerskirch & Sagar 1996); and maximum dive depth of 68m (Shaffer <i>et al.</i> 2006).	Plunge-diver, wing-propelled.
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Alcidae

Common guillemot <i>Uria aalge</i>	Mean dive depth of 10m (maximum 37m) off Norway, with 50% of dives less than 6m and 90% of dives less than 22m (Tremblay <i>et al.</i> 2003); maximum dive depth of 50m off Norway (Barrett & Furness 1990); maximum dive depth of 53m off Scotland (Daunt <i>et al.</i> 2003); maximum dive depth of 138m off Newfoundland (Burger & Simpson 1986); and incidental catches in stationary gill nets on the seafloor off Newfoundland, 80% of birds were caught in nets set at <50m, however some were caught in nets set at 180m (Piatt & Nettleship 1985).	Surface-diver, wing-propelled; and U-shaped dive profile with mean bottom dive duration of 19s and an overall mean dive duration of 39s (maximum 119s), off Norway (Tremblay <i>et al.</i> 2003).
Razorbill <i>Alca torda</i>	Median dive depth of 25 - 30m off Norway (Barrett & Furness, 1990); dive depth of >35m (maximum 41m) off Iceland (Dall'Antonia <i>et al.</i> 2001); more than 50% of dive depths were <15m and dives rarely exceeded 40m (maximum 43m) in the Baltic Sea (Benvenuti <i>et al.</i> 2001); and incidental catches in stationary gill nets on the seafloor off Newfoundland reveal the species is capable of diving <120m (Piatt & Nettleship 1985).	Surface-diver, wing-propelled.
Atlantic Puffin <i>Fratercula arctica</i>	Median dive depth of 25m - 30m off Norway (Barrett & Furness, 1990); incidental catches in stationary gill nets on the sea floor off Newfoundland, birds were regularly caught in nets set at <40m, however some were caught in nets set at <60m (Piatt & Nettleship, 1985); and maximum dive depth of 68m off Newfoundland (Burger & Simpson, 1986).	Surface-diver, wing-propelled.
Black guillemot <i>Cepphus grylle</i>		Surface-diver, wing-propelled; mean dive duration of 45s (Snow & Perrins, 1998); and maximum dive duration of 50 - 60s, during which birds can travel 75m or more underwater (Snow & Perrins, 1998).

Phalacrocoracidae

Great cormorant <i>Phalacrocorax carbo</i>	Mean dive depth of 6m (maximum 32m) (Grémillet <i>et al.</i> 1999).	Surface-diver, foot-propelled; and mean dive duration of 40s (maximum 152s) off France (Grémillet <i>et al.</i> 1999).
European shag <i>Phalacrocorax aristotelis</i>	Maximum dive depth of 26m off Scotland (Daunt <i>et al.</i> 2003); mean dive depth of 33 - 35m (maximum 43m) off Scotland, birds spent 55% of time between 25 - 34m (Wanless <i>et al.</i> 1991a); and dive depth of 10 - 43m off Scotland (Watanuki <i>et al.</i> 2005).	Surface-diver, foot-propelled; birds descend and ascend almost vertically relative to the sea surface (Wanless <i>et al.</i> 1991b); mean underwater swim speed of 1.7 - 1.9ms ⁻¹ (Wanless <i>et al.</i> 1991a); and dive duration of >97s (Watanuki <i>et al.</i> 2005).

Seaducks

Common eider <i>Somateria mollissima</i>	Capable of diving to depths of 42m (Guillemette <i>et al.</i> 1993).	Surface-diver, foot- and wing-propelled; and powerful divers capable of exploiting prey in strong tidal currents of velocity > 1.5ms ⁻¹ (Heath <i>et al.</i> 2006)
Greater scaup <i>Aythya marila</i>	Usually dive to depths of 1m - 5m, but capable of diving >10m (Forrester <i>et al.</i>	

	2007).	
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Gaviidae

Red-throated diver <i>Gavia stellata</i>	Maximum dive depth of 21m (Palmer, 1962); and incidental catches in stationary gill nets in the Baltic Sea reveal the species is capable of diving >20m (Dagys & Zydalis, 2002).	Surface-diver, foot-propelled.
Black-throated diver <i>Gavia arctica</i>	Capable of diving to depths of 3m - 6m (Snow & Perrins, 1998); and incidental catches in stationary gill nets in the Baltic Sea reveal the species is capable of diving >20m (Dagys & Zydalis, 2002).	Surface-diver, foot-propelled; and mean dive duration of 45s (maximum 2mins) (Snow & Perrins, 1998).
Great northern diver <i>Gavia immer</i>	Incidental catches in stationary gill nets in Lake Superior reveal the species is capable of diving >60m (Schorger, 1947).	Surface-diver, foot-propelled.

Podicipedidae

Great-crested grebe <i>Podiceps cristatus</i>	Dive depth of >30m (Cramp & Simmons, 1977).	Surface-diver, foot-propelled.
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