Project	AtlantOS – 633211
Deliverable number	D4.6
Deliverable title	Guidance on acoustic monitoring from marine autonomous vehicles
Description	A feasibility study presenting results from acoustic monitoring from marine autonomous vehicles in typical coastal ocean conditions (i.e. 50-100m depth) to investigate current capability in measuring marine noise levels and detection of vocalisation of marine mammals and to provide guidance on future use.
Work Package number	WP4
Work Package title	Interfaces with coastal ocean observing systems
Lead beneficiary	NERC
Lead authors	Dr Matthew Palmer (NOC)
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Submission data	
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Comments	

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Last updated: 02 October 2018

Stakeholder engagement <u>relating to this task</u>*

WHO are your most important stakeholders?	☐ Private company If yes, is it an SME ☐ or a large company ☐? ☐ National governmental body ☐ International organization ☐ NGO X others Please give the name(s) of the stakeholder(s): Marine and environmental research community Statutory marine monitoring agencies Marine robotics industry Defence industry Hydrographic industry
WHERE is/are the company(ies) or organization(s) from?	X Your own country ☐ Another country in the EU ☐ Another country outside the EU Please name the country(ies): Research : Global Monitoring: National Industrial: Global but predominantly US or European
Is this deliverable a success story? If yes, why? **If not, why?**	X Yes, because this case study provides a unique and highly valuable time series for use by the marine science community and provided a test case for emerging technologies. ☐ No, because …..
Will this deliverable be used? **If yes, who will use it?** **If not, why will it not be used?**	☐ Yes, by research communities interested in monitoring of marine noise identifying or locating marine mammals. ☐ No, because …..

NOTE: This information is being collected for the following purposes:

1. To make a list of all companies/organizations with which AtlantOS partners have had contact. This is important to demonstrate the extent of industry and public-sector collaboration in the obs community. Please note that we will only publish one aggregated list of companies and not mention specific partnerships.
2. To better report success stories from the AtlantOS community on how observing delivers concrete value to society.

*For ideas about relations with stakeholders you are invited to consult D10.5 Best Practices in Stakeholder Engagement, Data Dissemination and Exploitation.

Title: Guidance On Acoustic Monitoring From Marine Autonomous Vehicles

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1 Executive Summary

It is important to effectively measure and monitor natural sound in the marine environment to assess the abundance and location of marine fauna, particularly marine mammals. It is also important to monitor anthropogenic introduction of sound; such as from seismic and underwater drilling activites, largely due to its potential to cause harm to marine life. For this reason, marine noise is listed under the EU Marine Strategy Frame Directive as a potential source of pollution under Descriptor 11: Energy including Underwater Noise and industry spends considerable sums to avoid undertaking high-impact marine noise activities in the vicinity of marine mammals.

This report represents results from an experiment on the northwest European shelf seas targeted at investigating the effects of variable environmental conditions on acoustic monitoring of marine noise and detection of vocalisation signals from marine mammals. This brief review of current capabilities forms the final objective of AtlantOS WP4 task 4.2. The acoustic monitoring considered in this study is from a deployment of multiple marine autonomous platforms including submarine gliders and a surface Waveglider. This report outlines the capability of these new and emerging marine platforms in delivering long-term acoustic monitoring.

In total, nine autonomous vehicles were deployed in the Malin Sea, west of Scotland with a variety of acoustic sensors that collected a novel set of data characterising the acoustic environment over several 100kms scale: detailing background noise levels from different marine platforms and identifying marine mammal vocalisations and anthropogenic noise. This work highlights the capability of marine autonomous vehicles to provide increased coverage at reduced cost compared to traditional ship based or moored acoustic networks.

This work also identifies that the field of marine acoustic monitoring, particularly from autonomous vehicles, is still in development and considerable future effort is required before current ship, mooring and aerial based methodologies can be considered to be replaced by such methods. Recommendations for future work include;

- Instrumenting single vehicles with multiple array hydrophones for 3D location of a sound sources.
- Using multiple autonomous vehicles for automatic location, identification and tracking with a view to following targets, such as migrating whales.
- Increased investment into specialist skills to improve the quality of the data recorded and analysis of data.
- Characterisation of the acoustic signature of individual platforms to reduce inherent noise pollution/contamination of monitored signals.
- Improved efficiency or power availability to enhance autonomous vehicle endurance.
- Further development of through water communications and sound transmission to improve submarine geolocation.

2 Introduction to marine acoustics

Passive acoustic transducers are routinely used to monitor the acoustic signals from marine creatures and ships (Zimmer, 2011; Garrett, et al., 2016). However, standard passive acoustic monitoring has limitations, bed mounted transducer arrays are fixed to a location and ships towing transducers create noise and are expensive to operate (Greene, et al., 2014; Baumgartner & Fratantoni, 2008). Marine autonomous systems (MAS) offer a relatively cheap and flexible method of studying and monitoring the marine environment, and can be deployed on the surface, sub-surface and in the air (Stommel, 1989; Rudnick, Davis, Eriksen, Fratantoni, & Perry, 2004; Greene, et al., 2014; Koski, Abgrall, & Yazvenko, 2011). MAS are mobile and have a much smaller acoustic signature than traditional survey vessels, and can potentially operate uninterrupted for months at a time, even during inclement weather (Baumgartner & Fratantoni, 2008; Rudnick, Davis, Eriksen, Fratantoni, & Perry, 2004; Bingham, et al., 2012; Greene, et al., 2014). These capabilities allow MAS to collect sustained measurements over large areas, supplementing standard platforms and even replacing them for some tasks (e.g. regular transects by ship or fixed moorings). When used in collaborative networks of multiple platforms, MAS would be able to detect and locate acoustic sources and characterise the acoustic signals with higher temporal and spatial resolution than for single platforms in isolation.

This report presents acoustic data collected from multiple autonomous platforms collected during the MASSMO4 project, a pioneering multi-partner series of trials and demonstrator missions that aim to explore the UK seas using a fleet of innovative marine robots (http://projects.noc.ac.uk/massmo/). AtlantOS funding contributed to the participation of two early career researchers to expand the capability of this programme and provided further funding to coordinate marine acoustic expertise in the production of this report.

This study was conducted with the following aims: studying the effect of water properties and oceanographic features on acoustic transmission; detecting and tracking marine mammals and vessels; and generating time-evolving maps of natural and anthropogenic noise with respect to oceanographic properties. Oceanographic features in the Faroe-Shetland channel include shelf fronts, internal waves and different water masses (Sherwin, Turrell, & Dye, 1999; Hosegood, J., & van Haren, 2004; Hall, Huthnance, & Williams, 2011; Gallego, et al., 2018) and it is expected that these will have an effect on the acoustic environment. An experiment was also carried out to obtain a 'best composite picture' of an area, where ocean gliders worked together to provide a near-synoptic characterisation of a specified ocean volume.

3 Marine acoustics overview

The use of a listening tube to detect ships was reported by Leonardo da Vinci and similar methods were still in use during World War I, when towed hydrophone arrays started to be used to locate submarines (Urick, 1975) . Post World War II, fixed arrays of hydrophones were deployed on the deep ocean floor, primarily for submarine tracking (Urick, 1975). These deep ocean hydrophones greatly extended knowledge of ambient sound and its characteristics, including the effects of wind speed, tide and waves (Wenz, 1962; Urick, 1975). In the 1980's, ocean acoustic tomography was developed to measure water properties on a basin scale, using transmitted signals and an array of fixed hydrophones, and these methods were further developed to use passive acoustic signals (Munk & Wunsch, 1979; Gervaise, Vallez, Ioana, Stephan, & Simard, 2007; Dushaw, Worcester, Munk, Spindel, & Mercer, 2009). Acoustic measurements have also led to a greater understanding of marine creatures, their habitats and the effect of noise on their health (Hastie, Swift, Gordon, Slesser, & Turrell, 2003; Radford, Stanley, Tindle, Montgomery, & Jeffs, 2010; Merchant, et al., 2015; Casaretto, Picciulin, & Hawkins, 2016; de Soto & Kight, 2016; Stanley & Jeffs, 2016; Williams, et al., 2015).

The speed of sound in seawater is affected by temperature, pressure and salinity, but also by the presence of air bubbles (Urick, 1975; Coates, 1990). Sound intensity decreases with range from the source, due to spherical spreading, scattering and absorption by seawater (Urick, 1975; Coates, 1990; Francois & Garrison, Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions, 1982a; Francois & Garrison, Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption, 1982b). Interfaces between layers of different densities will cause the acoustic pulse to be reflected or refracted, depending on the angle of incidence and relative density of the layers (Urick, 1975; Coates, 1990). Objects in the water or waves along interfaces between layers can cause scattering. All these processes modify how sound is transmitted in the ocean, and can be related to oceanographic features such as stratified layers, fronts, surface waves and internal waves.

The constant seismic activity of the earth produces low frequency sound, although the main sources of ambient sound in the range 1-50 kHz are wind waves breaking and rain, from the creation and collapse of bubbles (Wenz, 1962; Urick, 1975; Ma, Nystuen, & Lien, 2005). Acoustic signals can also result from earthquakes, volcanic activity, icebergs, lighting strikes and hydrothermal vents (Arnold, Bass, & Atchley, 1984; Crone, Wilcock, Barclay, & Parsons, 2006; Chadwick Jr., Cashman, Embley, Matsumoto, & Dziak, 2008; MacAyeal, Okal, Aster, & Bassis, 2008).

Many sea creatures produce sound as communication, navigation or as the result of feeding behaviour (Wenz, 1962; Radford, Stanley, Tindle, Montgomery, & Jeffs, 2010; Casaretto, Picciulin, & Hawkins, 2016). Passive acoustics are an improvement on tradition visual observation methods, as measurements of sub-surface targets can be collected automatically and are less effected by weather conditions (Hastie, Swift, Gordon, Slesser, & Turrell, 2003; Mellinger, Stafford, Moore, Dziak, & Matsumoto, 2007; Marques, et al., 2013; Merchant, et al., 2015). Understanding how creatures respond to the ambient acoustic environment is important to their conservation, in particular to avoid indirect effects from shipping noise on behaviour and direct effects from collisions (Blue & Gerstein, 2005; de Soto & Kight, 2016; Stanley & Jeffs, 2016).

Anthropogenic sound sources can come for many sources including shipping, geophysical surveys and pile driving (Williams, et al., 2015). Noise in the 10 Hz to 10 kHz range is regulated under the Marine Strategy Framework Directive in the EU with a view to reducing the exposure of marine ecosystems (Garrett, et al., 2016; Merchant, Faulkner, & Martinez, Marine Noise Budgets in Practice, 2017). In regard to take acoustic measurements, flow round the ship and hydrophone, cable strumming, waves splashing on hydrophone cable, transducer electrical noise can all contribute to noise that can mask the signals of interest (Urick, 1975). Autonomous vehicles, being much smaller and quieter than conventional vessels, have the potential to collect high quality sound measurements with less effect of noise sources and therefore be able to monitor the ambient sound in the sea more effectively.

4 Mission Details

During MASSMO4 two types of experiment were carried out using acoustics. Active transmission and reception of pingers, and passive recording of natural and anthropogenic signals. A map giving an overview of the MAS deployments can be seen in Figure 1. The MAS platforms deployed with acoustic instruments mounted are listed in Table 1, with the instrument specifications listed in Table 2. Coded acoustic pingers, coded receivers and hydrophones were deployed on multiple vehicles in the MASSMO4 fleet. The hydrophones measured in the frequency range to detect the pinger signals.

During the deployment period vehicles were piloted to be in close proximity to each other, with aim of receiving signals from the other platforms (e.g. by converging on a waypoint). Lists of observations and periods where these signals should detectable are given in section 5.6. Pinger detection is dependent on range between the source and receiver, depth, wind speed and current speed (in descending order of importance), with only a slight effect of glider orientation (Oliver, et al., 2017). The maximum pinger detection range in the marine environment estimated at about 500-800 m, depending on wind speed, and signals can be detected at 1.3 km (Oliver, et al., 2017; Vemco, 2018). However, when the transmitter and receiver are greater than 0.6 km the detection efficiency of the coded pulses drops significantly (Oliver, et al., 2017). Oliver et al. (Factors affecting detection efficiency of mobile telemetry Slocum gliders, 2017) recommend that to improve understanding of the effect of a stratified water column on acoustic detection efficiency, more data should be collected in highly stratified waters.

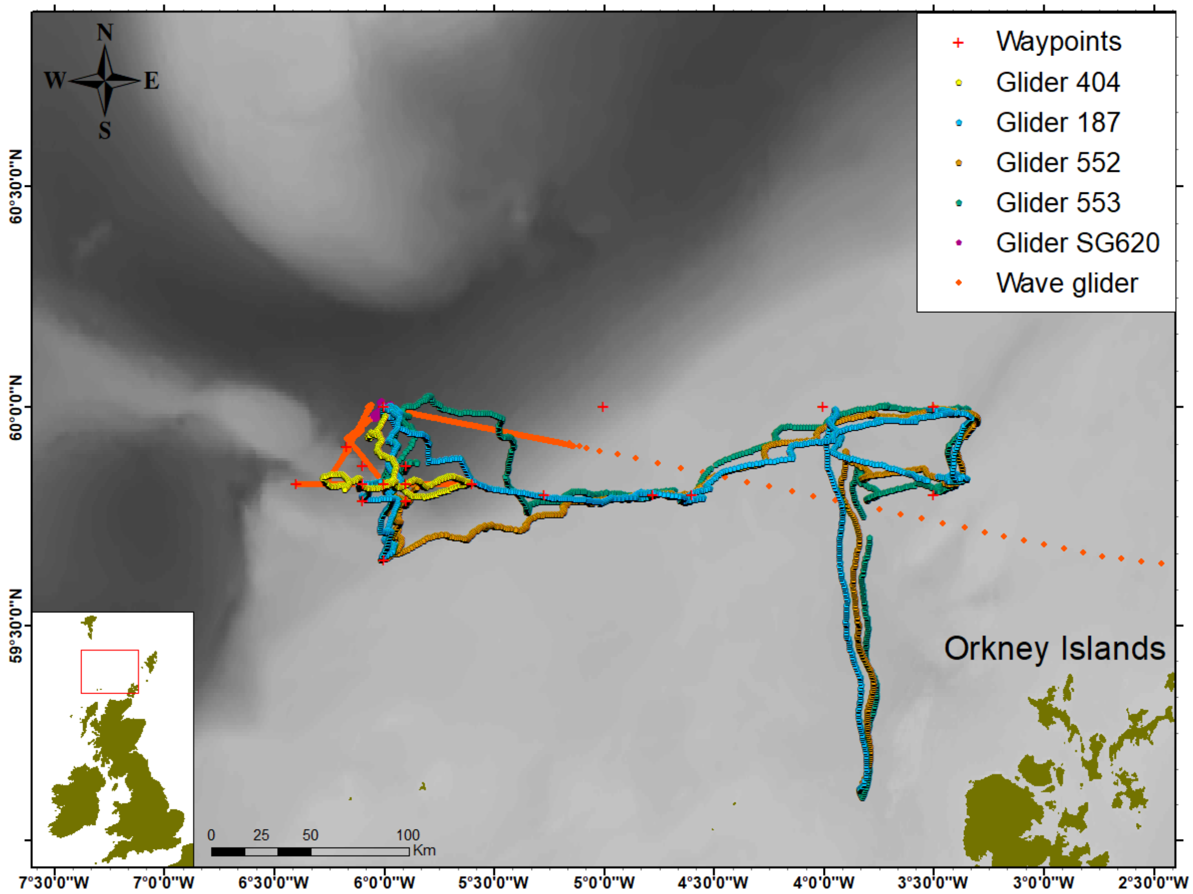

Figure 1: Map of the MASSO4 deployment area, north of Scotland (UK), showing an overview of the waypoints and selected autonomous systems. The individual tracks are separated for clarity in the sections below.

Table 1: Autonomous vehicle mounted acoustic equipment deployed during MASSMO4. The specifications of the acoustic instruments are listed in Table 2. (n.b. Glider SG613 failed to log any acoustic data.)

Unit no.		Model	Deployed	Recovered	Period, days	PAM	Pinger	Coded receiver
552	⬟	Slocum	19/05/2017	06/06/2017	18		Vemco V16TP	
553	⬟	Slocum	19/05/2017	06/06/2017	18		Vemco V16TP	
404	⬟	Slocum	01/06/2017	06/06/2017	5	RS Aqua RS ORCA	Vemco V16TP	
187	⬟	Slocum	19/05/2017	06/06/2017	18	JASCO AMAR G3	Vemco V16TP	
SG613	[1]	Seaglider	02/06/2017	06/06/2017	4	HTI-92-WB		
SG620	⬟	Seaglider	02/06/2017	06/06/2017	4	HTI-92-WB		
SV3-026	●	Waveglider	01/06/2017	06/06/2017	5			Vemco VR2C
Gordon	[1,2]	AutoNaut	22/05/2017	26/05/2017	4	Seiche towed		
Thomas	[1]	C-Enduro	25/05/2017	05/06/2017	12	Seiche towed		Vemco VR2C

[1] Not shown on Figure 1. [2] See Figure 15.

Table 2: Acoustic instruments deployed on the MAS listed in Table 1.

Name	Type	Sample rate, kHz	Acoustic freq., kHz	Acoustic press., dB	Ping rate	Maximum range, m
Vemco V16TP	Acoustic pinger		69	156	every 30 s	500-800
Vemco VR2C	Acoustic receiver		69			
Seiche	Towed PAM array	300	0.01 - 200			
HTI-92-WB	PAM hydrophone	125	0.005 - 60			
JASCO AMAR G3	PAM hydrophone	128	0.005-64			
RS Aqua RS ORCA	PAM hydrophone	384	0.01 to 150			

5 Results

All the PAM systems, apart from the one on Seaglider 613, returned data. This section gives a first look at the data and the features within. To analyse the hydrophone data different software were used: PAMGuard, Raven and the MATLAB signal processing toolbox (Sea Mammal Research Unit, University of St Andrews, 2018; Cornell Lab of Ornithology, 2018).

- MAS detected a range of natural and anthropogenic sound signals
- At various times during the study the different MAS and ships were in close proximity to each other, allowing acoustic detection
- These acoustic events are sections of the data with potential for further analysis

5.1 Glider Pancake (404)

Glider 404 was equipped with a Vemco V16TP coded acoustic pinger (69 kHz) and a RS-ORCA passive acoustic recorder sampling at 384 kHz, with a hydrophone frequency range of 0.01-150 kHz. The track of glider 404 can be seen in Figure 2, with the tracks of a nearby research vessel and gliders 187 and 553. Glider 404 passes within the expected range of acoustic detection of these vessels and their instruments. The breadth of signals picked up by glider 404 is shown in Figure 3, with the following features seen: pilot whales or dolphin whistles, sperm whale clicks, unknown low 2500 Hz whistles, the Vemco pinger, low frequency seismic shots, glider self-noise and ship noise.

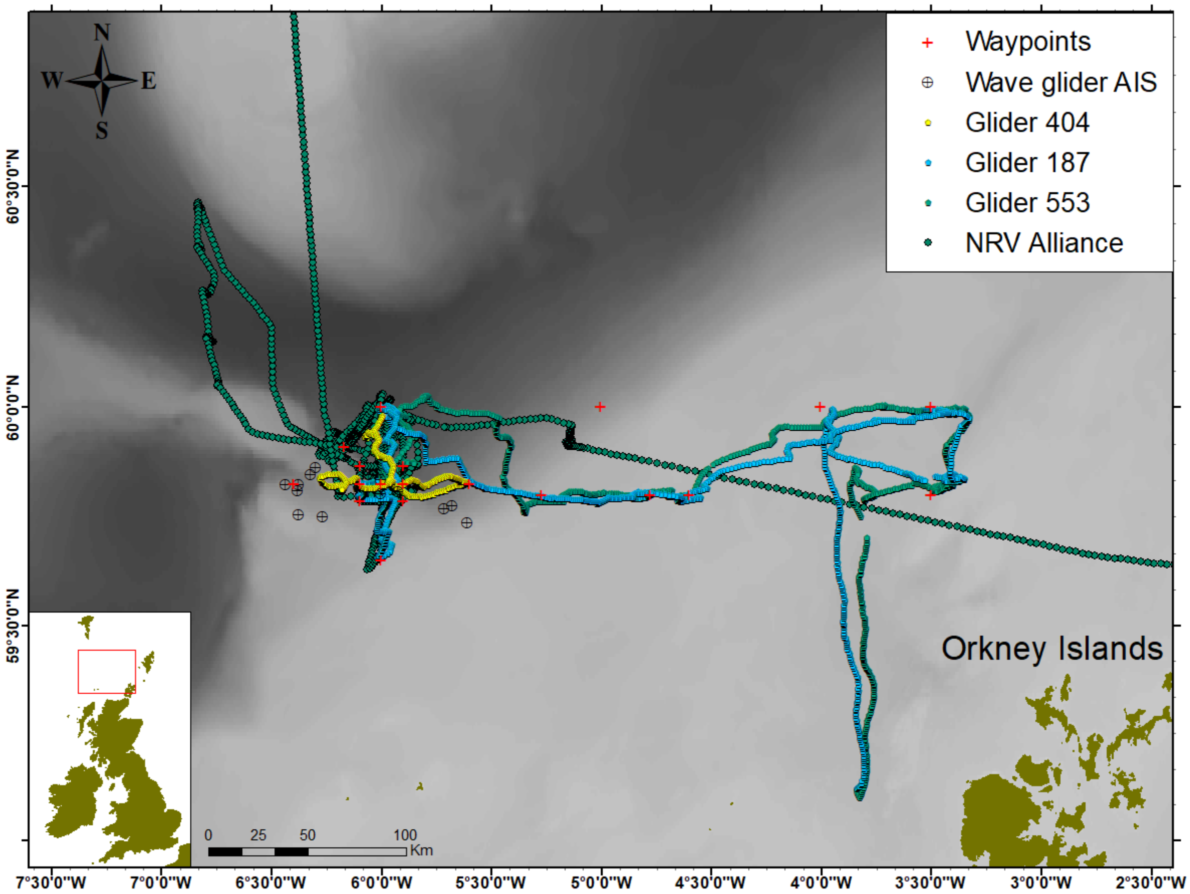

Figure 2: Map of glider Pancake's (404) track in relation to the research ship and gliders 187 and 553. The wave glider AIS shows the positions of passing vessels.

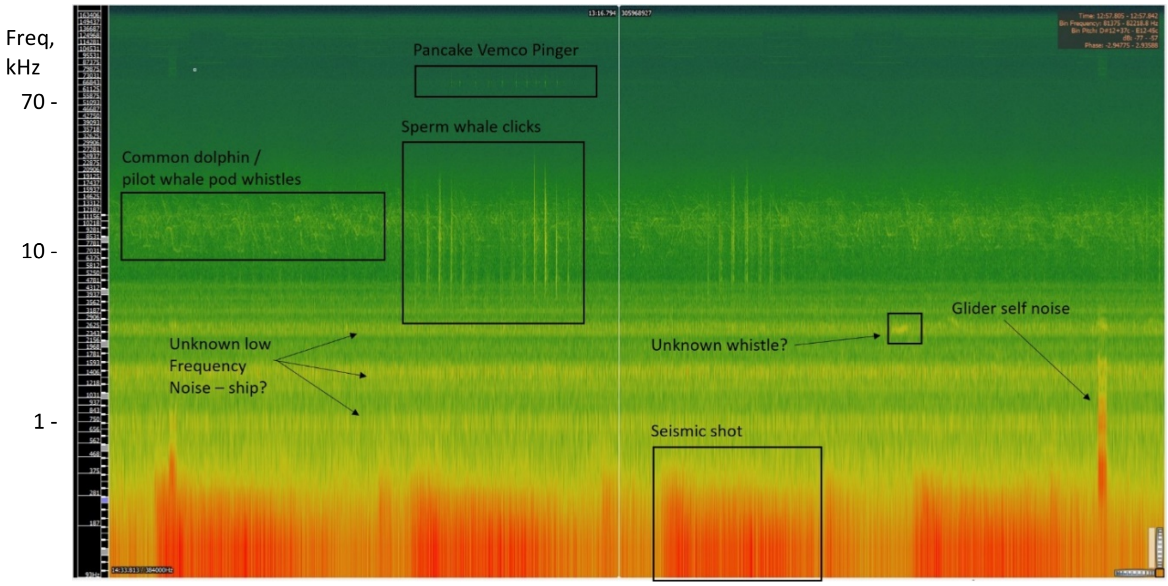

Figure 3: Spectrogram showing the range of acoustic features detected by the hydrophone on glider Pancake (404).

5.1.1 Marine life

Sperm whale clicks and pilot whale or dolphin whistles were detected as well as an unknown low whistle. This unknown longer low 2.5 kHz whistle could be a marine mammal, but it is hard to say what species.

Freq,
kHz

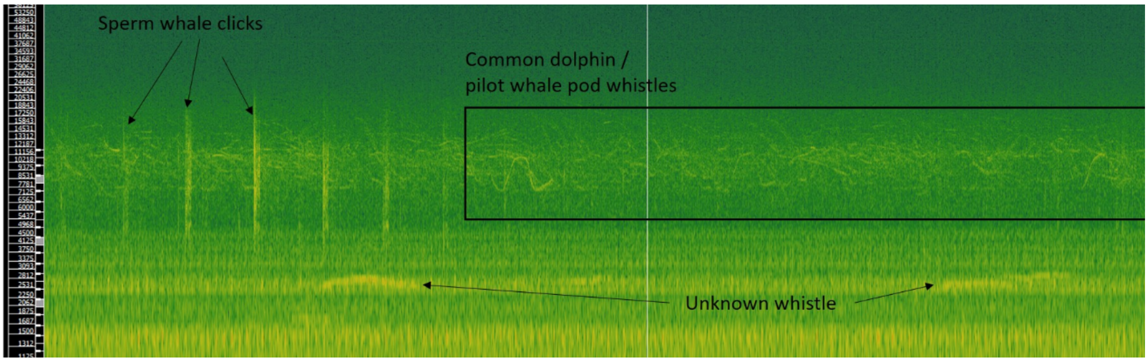

Figure 4: Spectrogram showing marine mammals detected by the hydrophone on glider Pancake (404).

5.1.2 Anthropogenic signals

Low frequency seismic shots could be clearly detected in the acoustic data (Figure 5). The bands of low frequency noise are probably due to ships in the location. Gilder self-noise and the Vemco pinger signal were also detected.

The unknown high frequency pings centred at 167.25 kHz (Figure 5) comprise 25 to 27 pings that spread out with time, though the change in transmission interval is not linear and lots of reverberation apparent. The pings are regular, with the inter-pulse interval and amplitude identical, suggests an echo sounder or other anthropogenic source. The short duty cycle indicates the pulses are interrogating about 120m to 190m of water. This could be an ADCP or a turbidity measuring device, and the change in interval in the pulse train and the short continuous wave pulse supports this hypothesis. It is not a side-scan sonar, as they would typically have a wideband chirp for a pulse form. The frequency of this signal does not match any of the acoustic transducers deployed on the autonomous systems or the Research vessel.

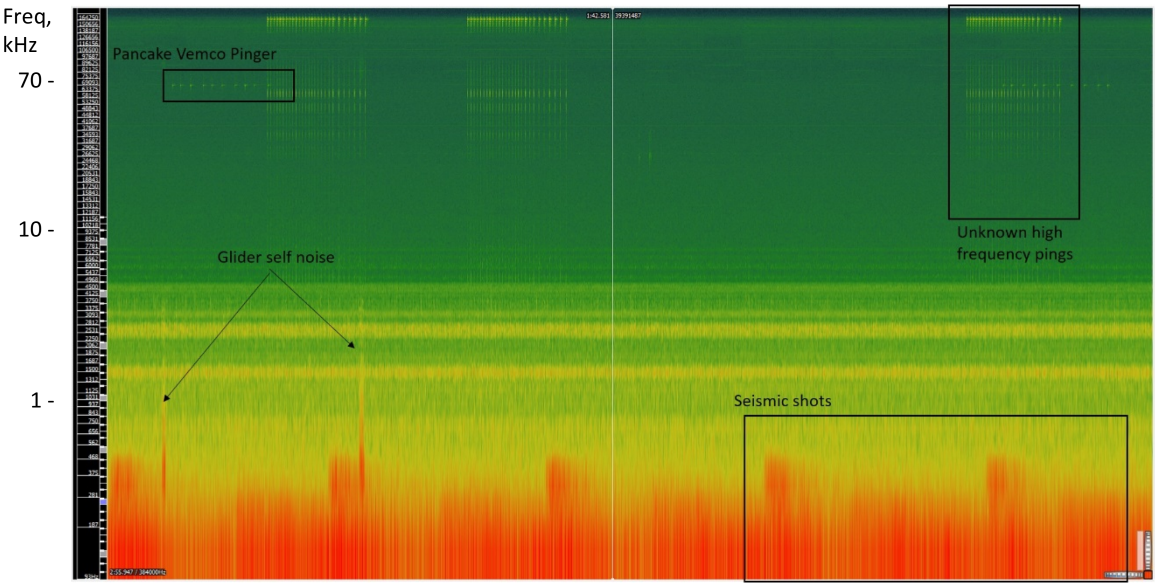

Figure 5: Spectrogram showing anthropogenic acoustic features detected by the hydrophone on glider Pancake (404).

Specific frequencies can be extracted from the spectrograms and these signals used to attempt to identify the source (Figure 6 and Figure 7). For example, the Research vessel carried out CTD stations in the area of the glider waypoints, while running an Acoustic Doppler Current Profiler (ADCP) at 75 kHz, and glider 404 detected a regular signal at this frequency (Figure 7). The data from glider 404 also showed strong repeated signals at 90 and 100 kHz at the start of the record (Figure 7), most likely the echosounders on Research vessel (FWC sounder 100 kHz). Using multiple receivers at know locations it should be possible to roughly track Research vessel from its acoustic signature and, therefore, other ships in a similar manner.

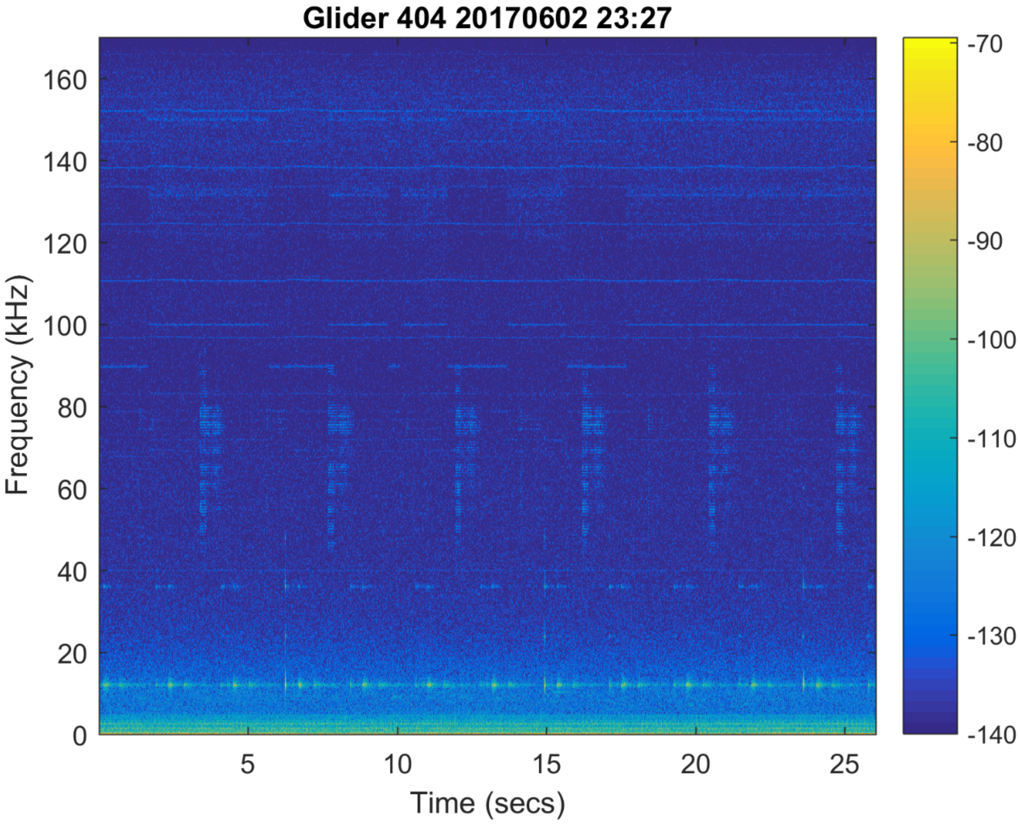

Figure 6: Spectrogram showing various sources of anthropogenic noise, including possible sonars at 75, 90 and 100 kHz (shown in Figure 7).

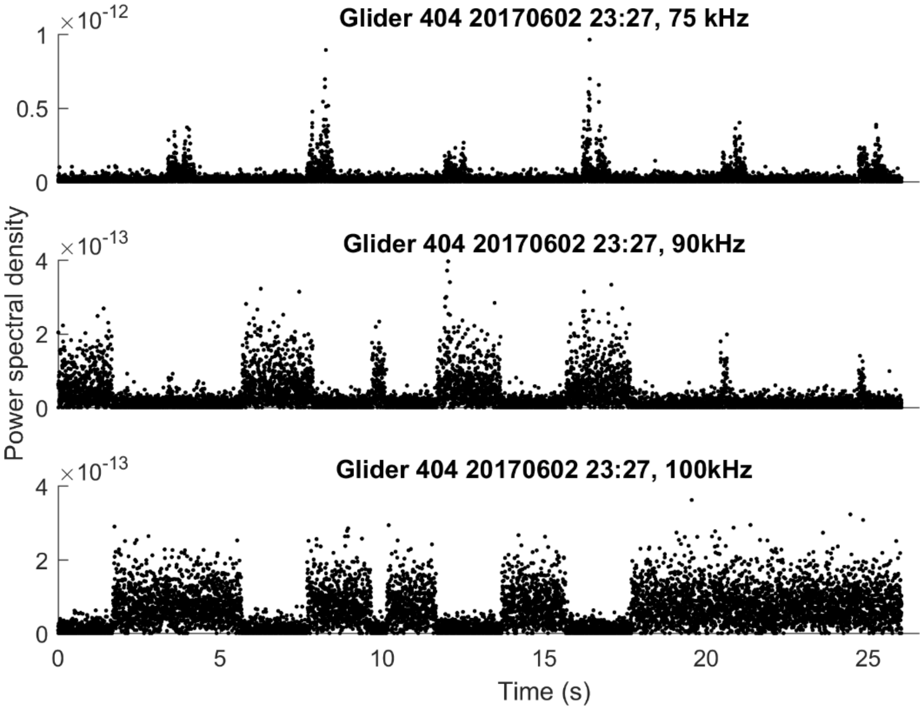

Figure 7: Example time series' of regular pulses at 75, 90 and 100 kHz, probably from sonars.

5.2 Glider Melonhead (sg620)

The UEA glider Melonhead (sg620) performed virtual mooring dives around WP2 (60°N, 6°W) from 02/06/2017 08:47 to 05/06/2017 16:18 (Figure 8). All the dives were to 1000m, except for a few mid-depth 30 minute loiter tests. Melonhead was equipped with an integrated PAM unit (HTI-92-WB hydrophone, EOS WISPR V1.1 digital signal processing board), recording continuously, with a sampling frequency of 125 kHz. The acoustic recordings were manually analysed and sounds were identified from anthropogenic and biological sources.

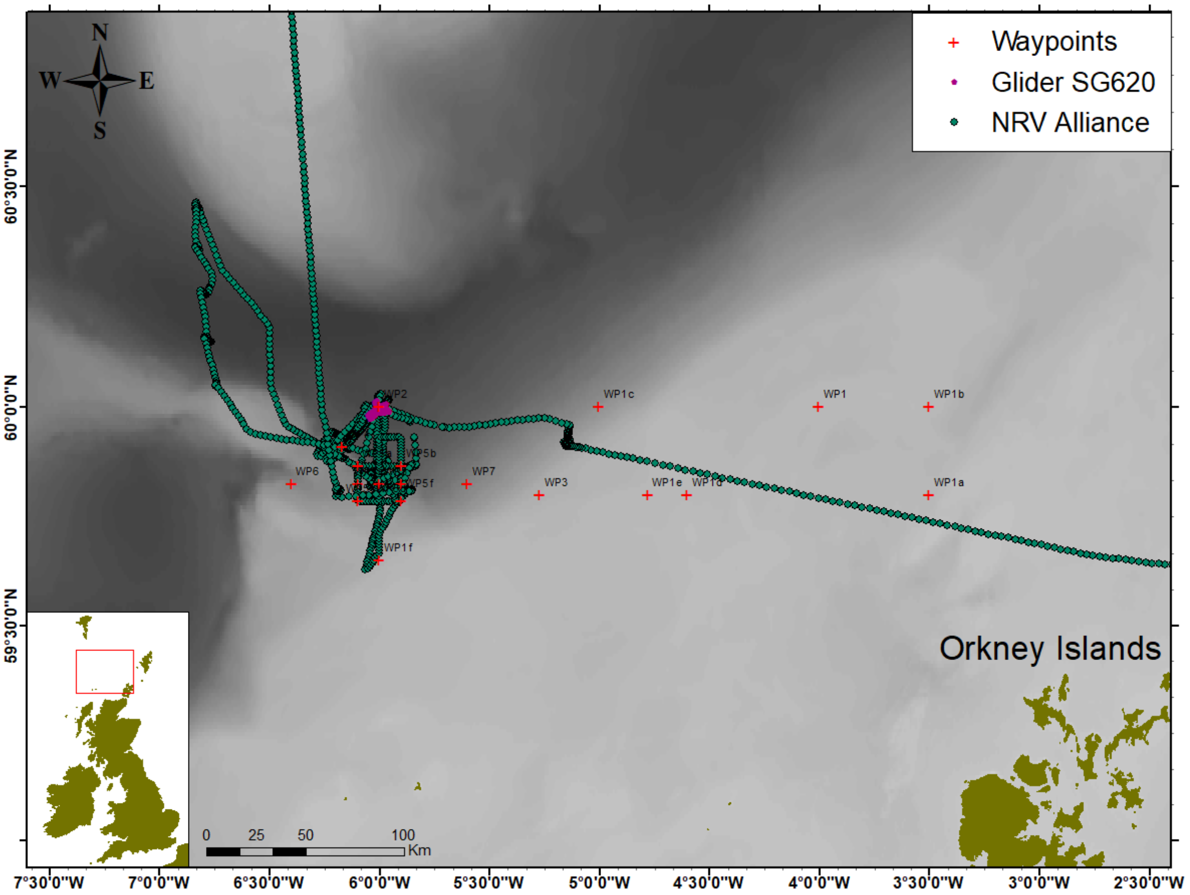

Figure 8: Map of glider Melonhead (sg620) track in relation to Research vessel.

5.2.1 Marine life

Clicks and whistles from cetaceans were detected, from two identified species: Sperm whale (Figure 9) and Long-finned pilot whales (Figure 10). Short and distant events were identified frequently during the first 3 days of the survey. A close encounter with a large pod of long-finned pilot whales was recorded from 02/06/2017 21:00 to 03/06/2017 03:00.

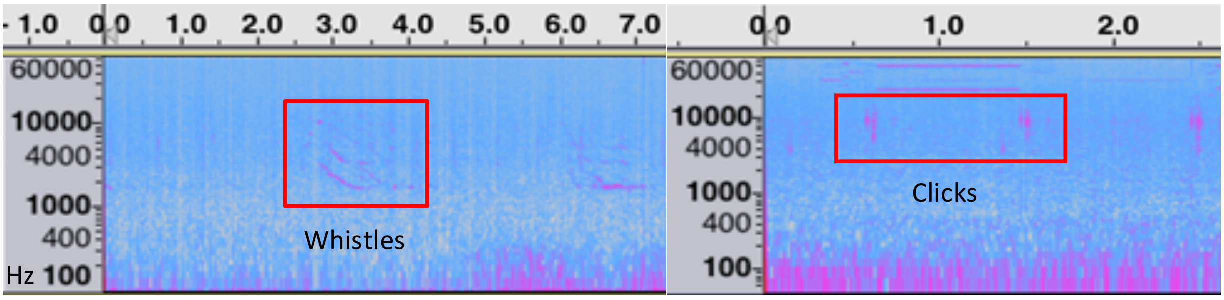

Figure 9: Spectrogram showing sperm whales whistles in the range 3-5 kHz and clicks at 5-10 kHz.

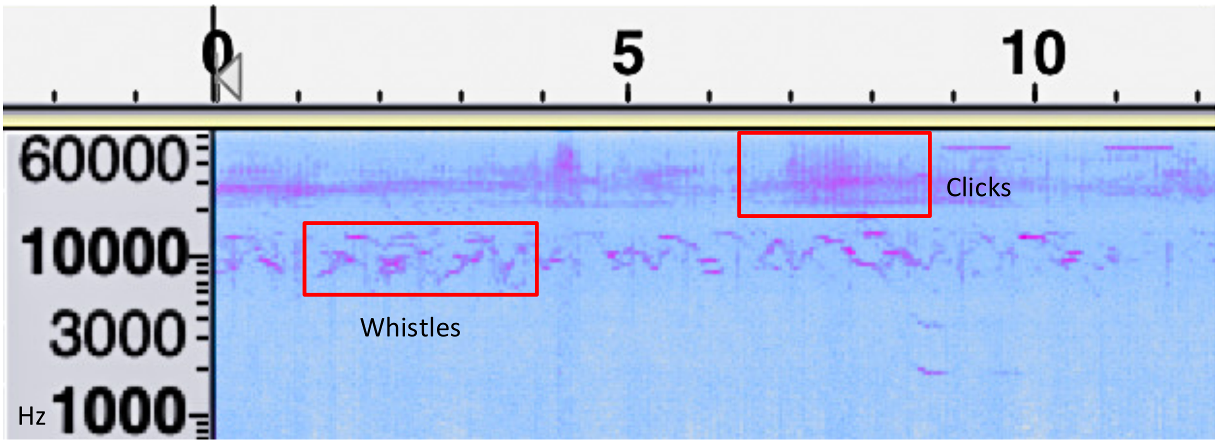

Figure 10: Spectrogram showing long-finned pilot whales with whistles around 10 kHz and clicks centred at 30 kHz.

5.2.2 Anthropogenic signals

Throughout the whole dataset, a distant seismic survey was detected (Figure 11) with a low frequency (0 – 300 Hz) impulse sound at a 10 seconds period. Acoustic signals from nearby ships (e.g. echosounders, imaging sonar and acoustic modems) were also detected, as well as engine noise (Figure 12). Signals from the one of the Vemco V16TP pingers mounted on the Slocum gliders were detected at 69 kHz. Other signals detected were likely to be the Seaglider's altimeter (13 kHz) and Research vessel's echosounder (33 kHz), Figure 12.

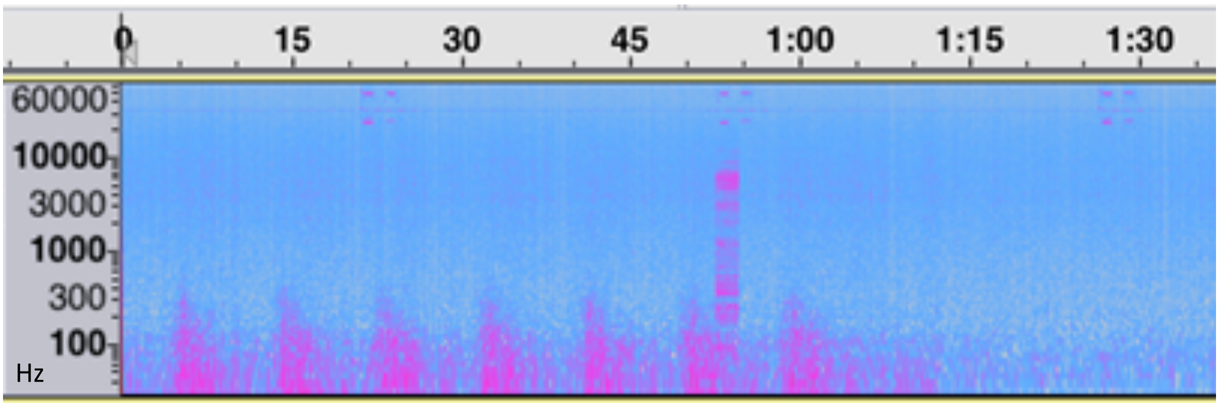

Figure 11: Spectrogram showing seismic survey in the range 0-300 Hz with a 10-second period.

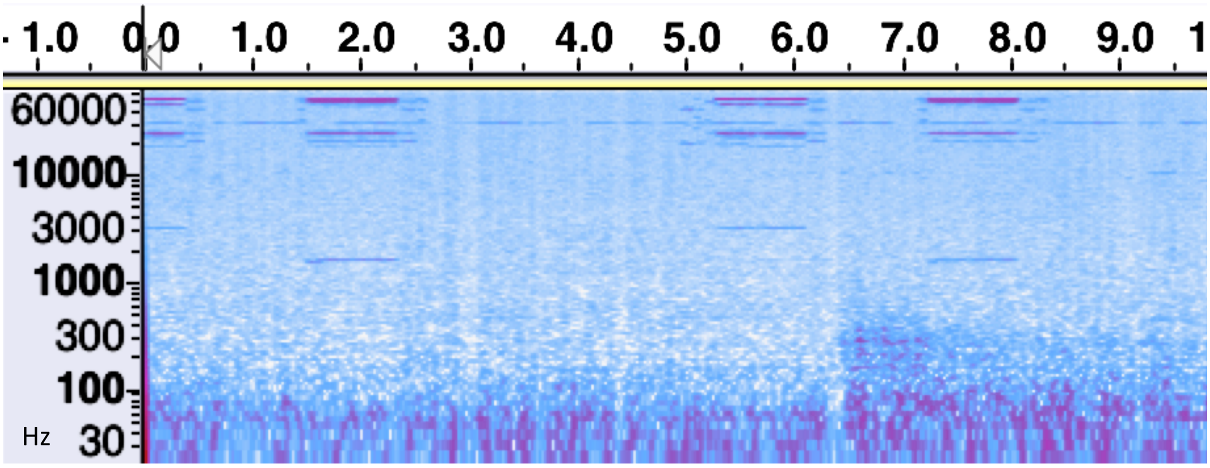

Figure 12: Spectrogram showing glider self-noise, Vemco pinger (69 kHz), Altimeter (13 kHz) and Research vessel sounder (33 kHz).

5.3 Glider BOM (187)

Different mission types were used within the deployment to maximise energy efficiency, maximise passive acoustic data quality and a compromise of these two (Table 3). For the standard mission, the Glider operated within its maximum water depth of 200 m. The altimeter and thruster were switched off for the Drift and Slient yo's missions, to reduce noise interference, and the depth range was limited to prevent the glider hitting the bottom (Doran, 2017). Examples each type of mission are as follows (times are all in UTC):

- 21/05/2017 10:22 to 13:45 – Standard mission with thruster
- 25/05/2017 06:35 to 09:36 – Silent Yos
- 27/05/2017 12:01 to 14:43 – Standard mission with thruster
- 29/05/2017 07:49 to 08:57 – Silent Yos
- 28/05/2017 11:01 to 17:42 – 2 x 3 hour drift missions
- 29/05/2017 10:35 to 15:48 – 1 x 5 hour drift mission

Although the proximity of other gliders in the fleet is included in Table 5, it is not expected that the Jasco acoustic recorder on glider 187 would have detected these gliders. This due to the frequency that the Vemco pingers were transmitting, 69 kHz, at being outside the optimum range of the Jasco transducer, 0-64 kHz. Experiments were conducted using glider 187 and gliders 552 and 553 between waypoints WP1a and WP1b to investigate the differences in acoustic signals on either side of the front. Drift missions were carried out at the thermocline, where internal waves are expected, to measure the effect of vertical displacement on the glider and acoustic detections. The track of Glider 187 is shown in Figure 2.

Table 3: Glider mission types used by Glider 187 during the MASSMO4 deployment (Doran, 2017).

Mission Type	Mission Parameters
Standard Mission	Used for transit between waypoints and had the Glider conducting saw-tooth profiles through the water column with dive and climb angles set to maximise energy efficiency. Thruster usage was optional for these missions.
Drift Mission	Glider programmed to drift at a constant depth for a set period of time, reducing self-noise of the glider during PAM experiments.
Silent Yo's	Glider completed saw-tooth profile with restrictions to internal mechanics and no thruster use. Silent Yo's reduced self-noise, and were used during PAM exercises, particularly those conducted during transit.

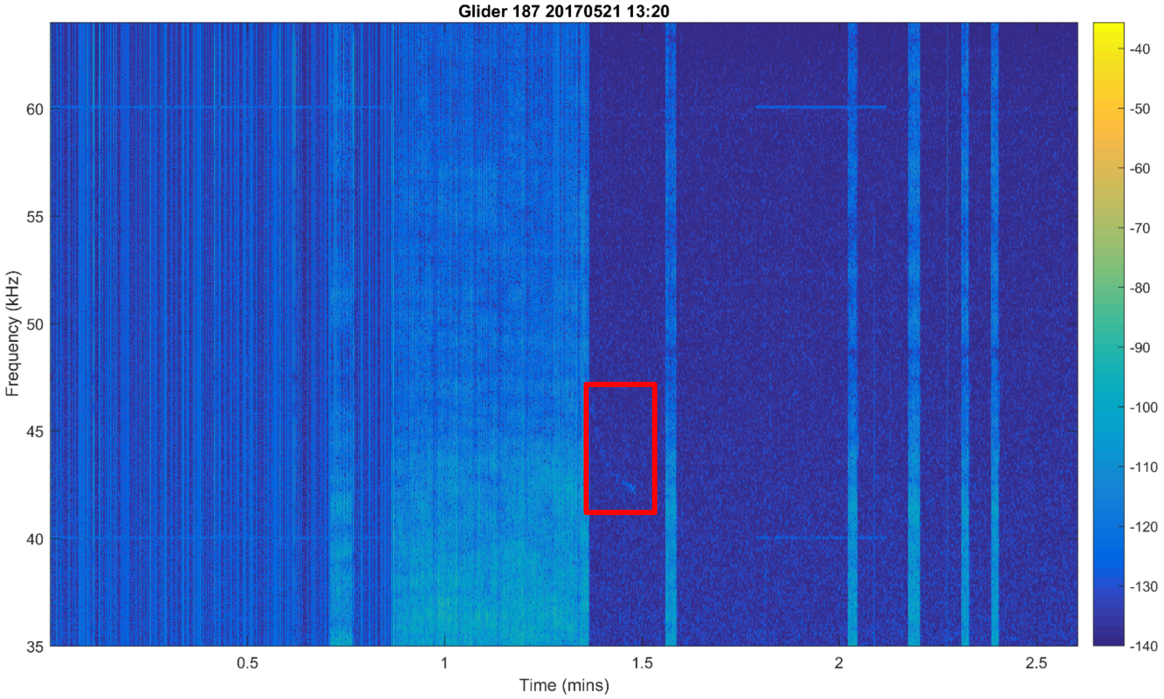

Figure 13: Spectrogram showing glider self-noise during a period of thruster testing. The box highlights a downsweep feature.

An example spectrogram showing data from during a standard mission with thruster use is show in Figure 13. The noise from the thruster covers the whole range of the spectrum, potentially covering any signal of interest. Narrow signals at 40 and 60 kHz can be seen, possibly from echosounders. The spectrogram shown in Figure 13 is the result of an initial look at the data using the Matlab spectrogram function, more sophisticated analysis using software such as PAMGuard would reveal greater detail and more features.

5.4 C-Enduro Thomas

The C-Enduro Unmanned Surface Vehicle (USV), *Thomas*, successfully collected 12-days of continuous underwater sound recordings as it travelled from Orkney, across the shelf waters, to the continental shelf-edge. These acoustic recordings were analysed for marine mammals vocalisations and anthropogenic signals.

5.4.1 Marine life

Sperm whales were detected on 31/05/2017, 02/06/2017 and 03/06/2017, in the area of the continental shelf-edge in water depths of 300-1000 m. The sperm whale vocalisations were echolocation clicks associated with foraging dives. Most detections were of single whales, although two whales were detected during a few 1-min intervals. In comparison with acoustic detections of sperm whales on previous USV surveys, click detections during this survey were of low amplitude and fragmented, rather continuous over several tens of minutes. This may be due to the whales being distant from the C-Enduro.

All acoustic detections of delphinids were also located above the continental shelf-edge, and occurred between the 31/05/2017 and 03/06/2017. The majority of acoustic encounter consisted of both whistles, frequency-modulated tonal calls, and broadband echolocation clicks. Whistles were heard prior to the onset of echolocation, at the beginning of encounters, and after detection of echolocation clicks had ceased. This reflected the greater detection range for delphinid whistles than for click trains. Detections of whistles without click trains probably indicated animals at a greater distance. There was a single, 3-min encounter, which consisted of echolocation clicks only.

Delphinid whistle shape was highly variable, but the same whistle was sometimes repeated several times in succession. Detections may have been any of several dolphin species known to inhabit the region, including Atlantic white-sided dolphin (Lagenorhynchus acutus), short-beaked common dolphin (Delphinus delphis), Risso’s dolphin (Grampus griseus), and common bottlenose dolphin (Tursiops truncatus). However, there was an absence of detections of burst-pulse calls, which would have suggested ‘blackfish’ species, including killer whale (Orcinus orca) and long-finned pilot whale (Globicephala melas). Rates of echolocation click detection were very high at times and click repetition rates regularly exceeded 400 clicks/s. The prolonged periods of intense echolocation detected were a clear indication that the vocalising animals were at close range to the C-Enduro.

There were no acoustic detections of baleen whales, beaked whales, or Narrow Band High Frequency species (including harbour porpoise) during this survey. No marine mammals were detected as the C-Enduro travelled across the shelf waters to the continental shelf-edge.

Table 4: Summary of marine mammal detections. DPM is the number of detection positive 1-min intervals. The total number of recording effort 1-min intervals was 12,256. (Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

Species / Species Group	Vocalisation Type	DPM
Baleen Whale	tonal calls	0
Baleen Whale	click train	0
Sperm Whale	click train	248
Delphinid	tonal calls	203
Delphinid	click train	110
Beaked Whale	click train	0
Narrow Band High Frequency species	click train	0

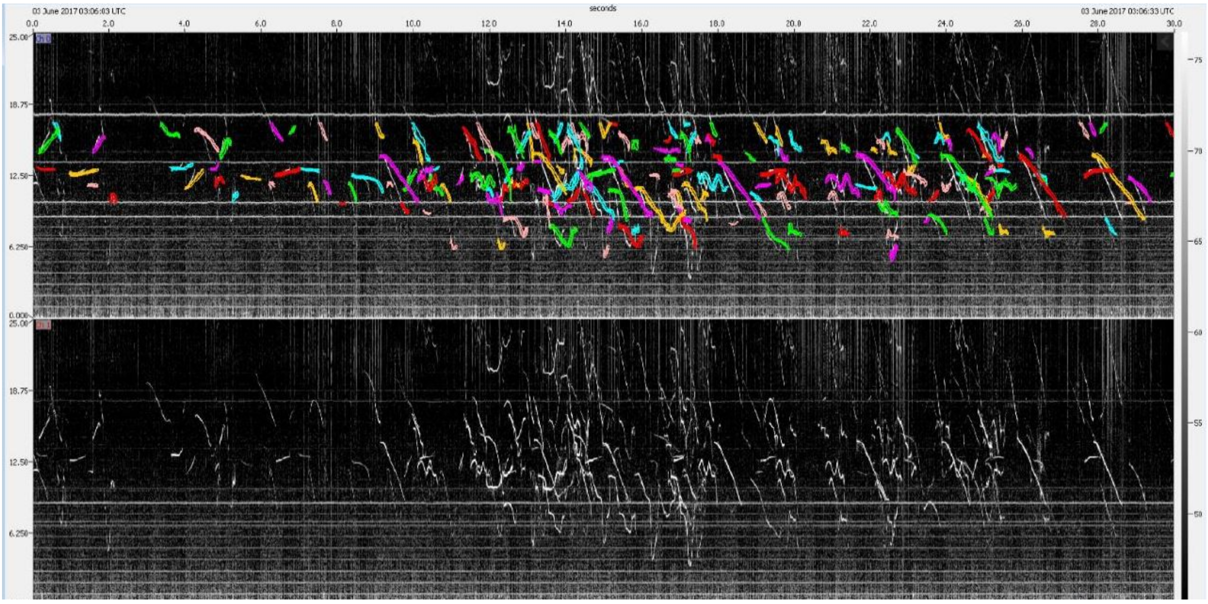

Figure 14: spectrogram from the Pamguard software showing the raw data in the upper and lower panels, with automatic delphinid whistle detections overlaid on the upper panel (0-25 kHz, 30 s period).

5.4.2 Anthropogenic signals

The C-Enduro recorded various observations including boat noise, sonars and mechanical 'squeak'. Unidentified low frequency signals detected could have resulted from airguns, self-noise or possible detonations. Noise from passing vessels was seen in the 0-1 kHz range and sonar pulses at 12 kHz and 66 kHz were recorded. Two resonant transient sounds, detected on the morning of 31/05/2017, resembled single detonations. These observations are listed in See appendix for .

5.5 AutoNaut

Unfortunately, the deployment the AutoNaut USV was cut short due to damage to the vessel's mast. However, the integrated towed hydrophone system functioned well, recording underwater sound continuously. The AutoNaut is quieter than a conventional motor vessel and has a low profile, reducing the possibility of noise masking marine mammal vocalisations in the hydrophone recordings and that animals will modify their behaviour in response to the AutoNaut. The sound recordings were analysed for the period 25/05/2017, 09:45 to 26/05/2017, 06:30

5.5.1 Marine life

There were three harbour porpoise detections were recorded during the 2-day period and one additional detection that was likely to be this species (Figure 15). The definite porpoise detections occurred 15 km west of the Orkney mainland, in a water depth of approximately 60 m (Figure 15), and were recorded within a 1-h period. The likely detection was recorded 15 minutes before recovery of the AutoNaut. The harbour porpoise detections were comprised of trains of narrowband, high frequency echolocation clicks with peak energy at 125-145 kHz.

5.5.2 Anthropogenic signals

A vessel was detected passing the AutoNaut at 25/05/2017, 19:04 UTC, and cavitation noise and a 50 kHz echosounder were recorded when the support boat approached to recover the AutoNaut. High frequency pulses, probably from an acoustic transponder, were detected in three periods from 25/05/2017, 22:38 UTC until 26/05/2017, 01:07 UTC. These sounds were generally detected as regular groups of four pulses, with an interval between pulses of 0.23 s and 11 s between groups, and had an unusual frequency modulated (FM) spectrum. Also detected was a signal at about 100 kHz, which may have been a 'seal-scaring' device.

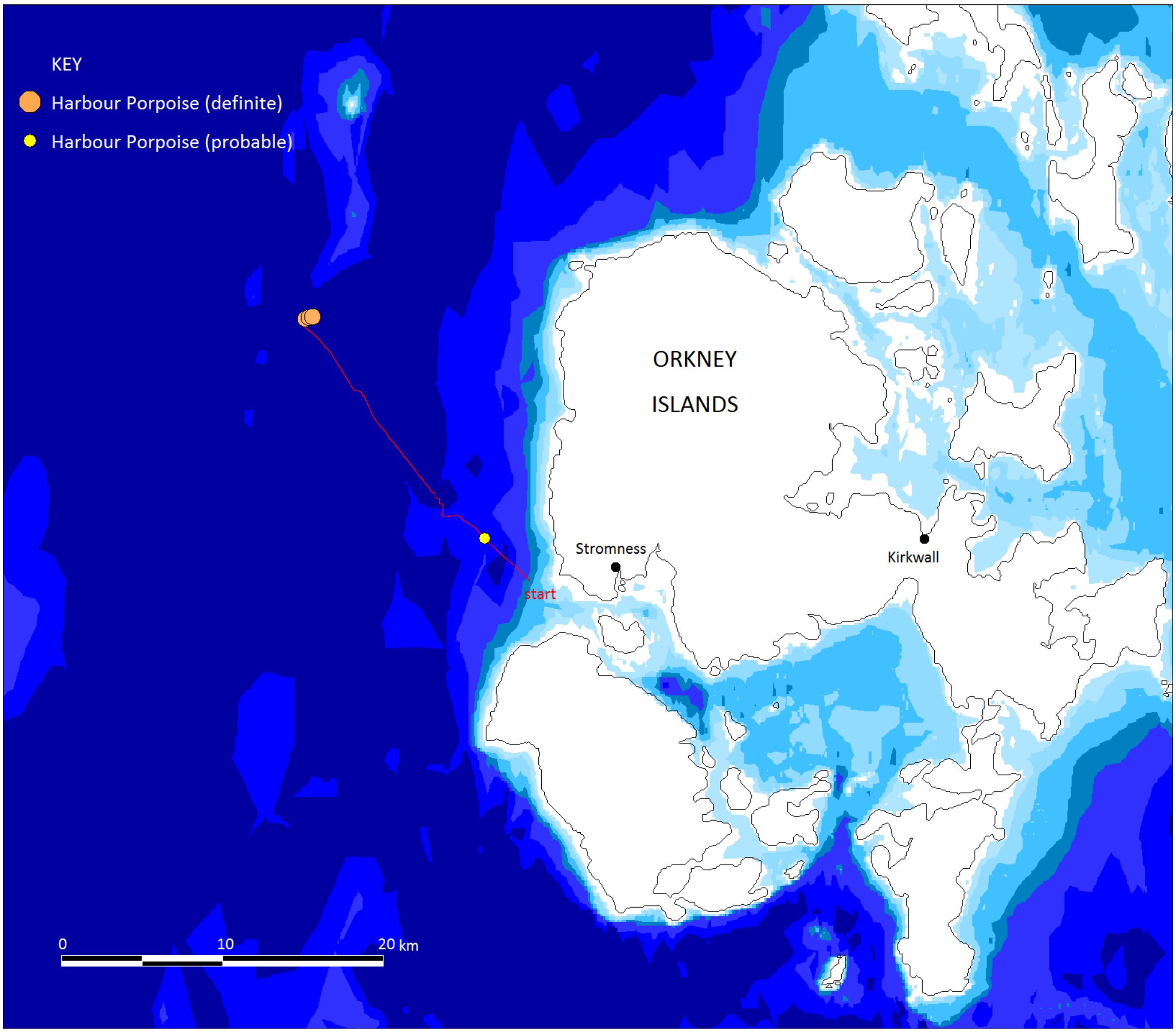

Figure 15: Map of the AutoNaut track and harbour porpoise detections.

5.6 List of observations and potential events for analysis

See appendix for a complete list of observations recorded during the MASSMO4 deployment

6 Quality control

- Thrusters cause well defined periods of noise, which cover other signals, however this can be planned for
- Electrical system noise and cable vibration noise were seen for some MAS, this would be resolved for future deployments

6.1 Gliders

A Hardware malfunction on Melonhead (sg620), from the PAM unit, caused a strong distortion of the recorded signal. Therefore, it was not possible to conduct any background noise analysis. Geophysical sources (e.g. wind, rain) could not be monitored, neither could the impact of a loitering dive on the flow noise. The use of thrusters caused well defined periods of noise, which covered any other possible signals. As switching on and off the thrusters can be controlled, the effects of this noise can be planned for.

6.2 C-Enduro

Significant electrical noise was present throughout the data, over most of the frequency spectrum. The C-Enduro power system was identified as the main source of this interference, with additional noise when the diesel generator was charging the power packs. This system noise raised the background sound level within bands to which the click trigger threshold was linked and this may have resulting in quieter clicks, of lower source level or at greater distance, not being detected. Broadband clicks and tonal vocalisations are clearly visible against the continuous narrow-band noise on the spectrograms, as shown in Figure 17 (Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018).

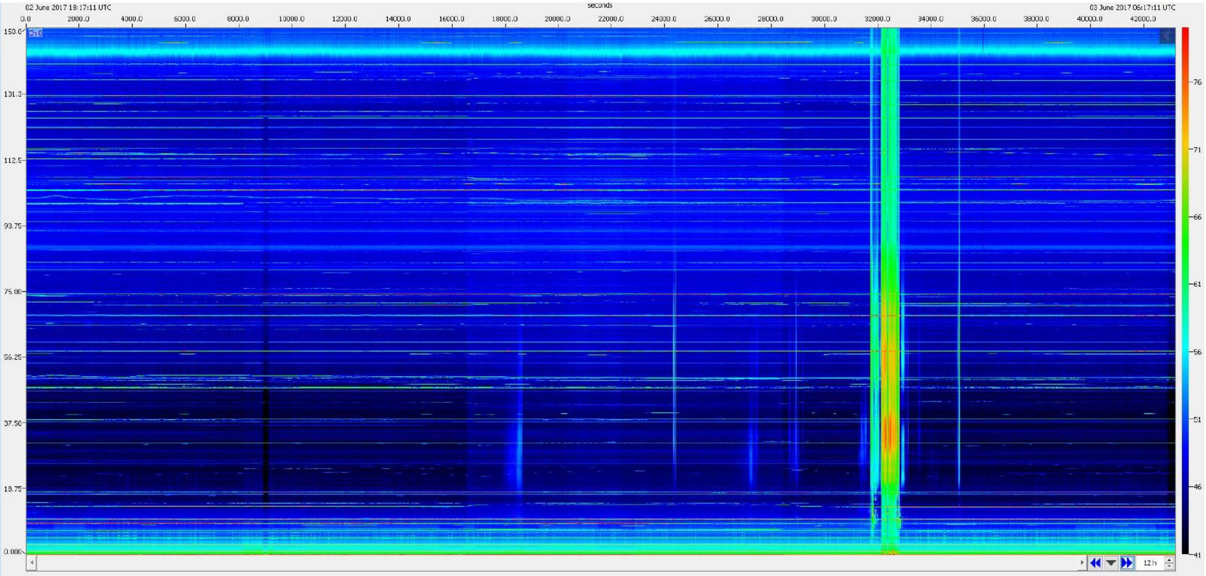

Figure 16: A full bandwidth (0-150 kHz), long-term spectral average (LTSA) display showing a 12-h period spanning 2nd-3rd June 2017. The clusters of broadband acoustic energy resulted from the vocalisations of delphinid cetaceans. Electrical noise occupies much of the frequency spectrum.

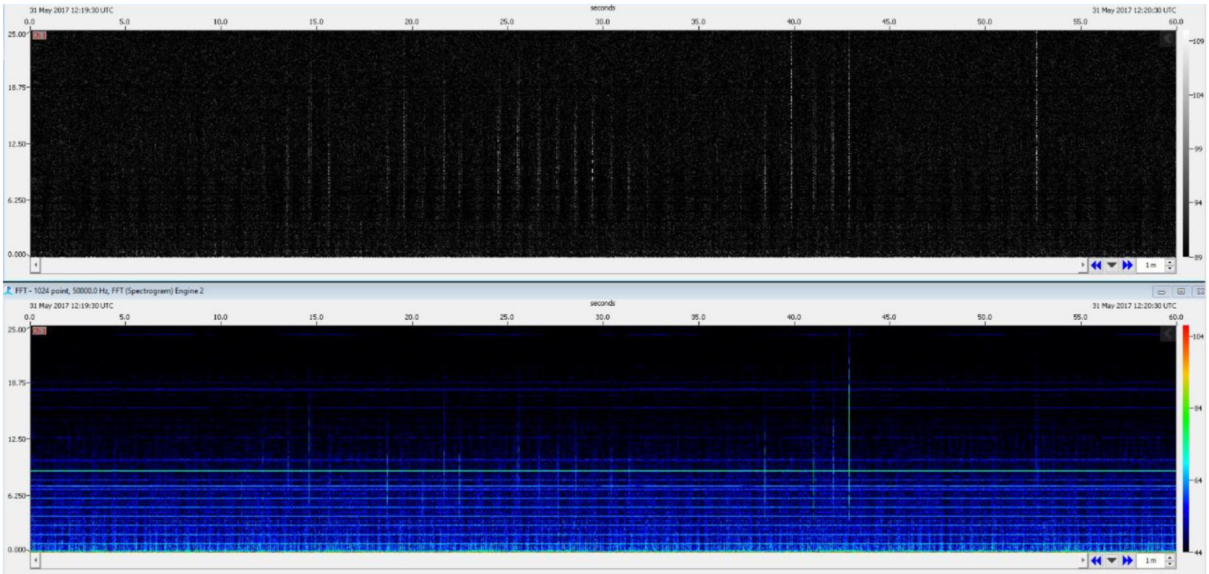

Figure 17: Spectrograms (0-25 kHz, 60-s period) of a sperm whale click train. The lower panel displays the raw audio data; the upper panel shows the same data with noise reduction methods applied. Spectrogram parameters: sampling rate 50 kHz, FFT length 1024 samples, 50% hop, Hann function, 3 dB filter bandwidth 68 Hz, frequency resolution 48.8 Hz, time resolution 20.5 ms.

6.3 AutoNaut

Noise from cable vibration was seen at low frequencies and narrowband system noise present at approximately 6.5 kHz. Resolving these problems and optimising PAM integration on the AutoNaut for marine mammal detection will be the focus of future development.

7 Conclusion and recommendations

- The MASSMO4 deployment collected a novel set of data, characterising the acoustic environment
- Signals from marine mammals, shipping and seismic surveys were clearly identified
- There is the potential to locate and track signals by processing the data from multiple MAS
- System and thruster management can be planned to improve data quality, when required
- Instrumenting single vehicles with multiple array hydrophones for 3D location of a sound sources.
- Using multiple autonomous vehicles for automatic location, identification and tracking with a view to following targets, such as migrating whales.
- Increased investment into specialist skills to improve the quality of the data recorded and analysis of data.
- Characterisation of the acoustic signature of individual platforms to reduce inherent noise pollution/contamination of monitored signals.
- Calibration of the acoustic-vehicle system to minimise platform effects on its frequency response.

The MASSMO4 deployment collected a novel set of data, characterising the acoustic environment in relation to oceanographic features such as stratified layers, internal waves and fronts. Signals from marine mammals, shipping and seismic surveys were clearly identified in the acoustic data and there is the potential to locate and track such signals by processing the data from the surface and underwater autonomous vehicles.
For the towed hydrophone systems, mounted on the surface vehicles, cable noise and damage were issues. Electronic noise from other systems on board also caused problems. These can be resolved through a re-design of the system. Noise from the propulsion systems could be reduced or certain systems can be shut off when listening for faint signals, e.g. BOM's drift and Silent Yo's missions, to improve data quality.

7.1 Further data analysis and future deployments

Considerable further experimentation is required to assess the role of autonomous vehicles as effective platforms for marine acoustic monitoring for determining environment status. For future experiments, 3D location of a sound source could be determined from a single vehicle with an array of multiple hydrophones. By coordinating with other vehicles, location error could be reduced and this would increase the ability to effectively monitor a larger area. In addition, multiple MAS could be used for automatic location, identification and tracking of a target with a view to following it. This would allow, for instance, migrating whales to be tracked and followed over large distances for long-term predictions of location.

Marine acoustic sensors mounted on autonomous vehicles permit sustained measurements over large areas, supplementing standard platforms and even offering the potential for replacing them for some tasks (e.g. regular transects by ship or fixed moorings). This study demonstrates that collaborative networks of multiple autonomous platforms are able to detect and locate acoustic sources and characterise acoustic signals with higher temporal and spatial resolution than for single platforms in isolation.

Before autonomous platforms, such as ocean gliders, can be considered effective platforms for marine acoustic monitoring however, critical limitations in endurance and geolocation must first be overcome. Increased power capability with new and emerging batteries and increased instrument efficiency will likely improve endurance incrementally. Alternative methods and new sensors may however, need to be developed before autonomous vehicles can be considered capable of replacing current platforms, such as ships and moorings. Geolocation remains a problem due to the inherent difficulty of transmitting data or sound sources over long distances in our oceans. This prevents vehicles identifying their immediate position relative to fixed points, but also restricts transfer of data without surfacing. Despite this, the potential increase in areal coverage and reduction in cost that such autonomous platforms offer, does promote further experimentation and development so that they might contribute to statutory monitoring purposes, such as MSFD reporting, in the future.

7.2 Additional spectrograms (not show in the individual platform reports)

7.2.1 Glider Melonhead (sg620)

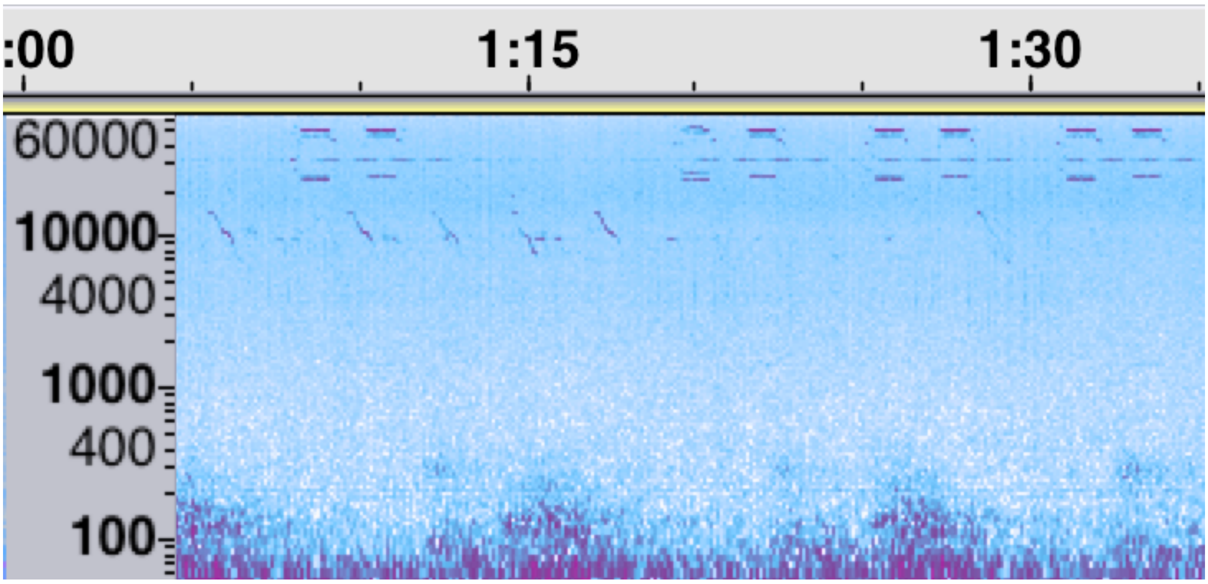

Figure 18: Glilder self noise and other anthropogenic sounds.

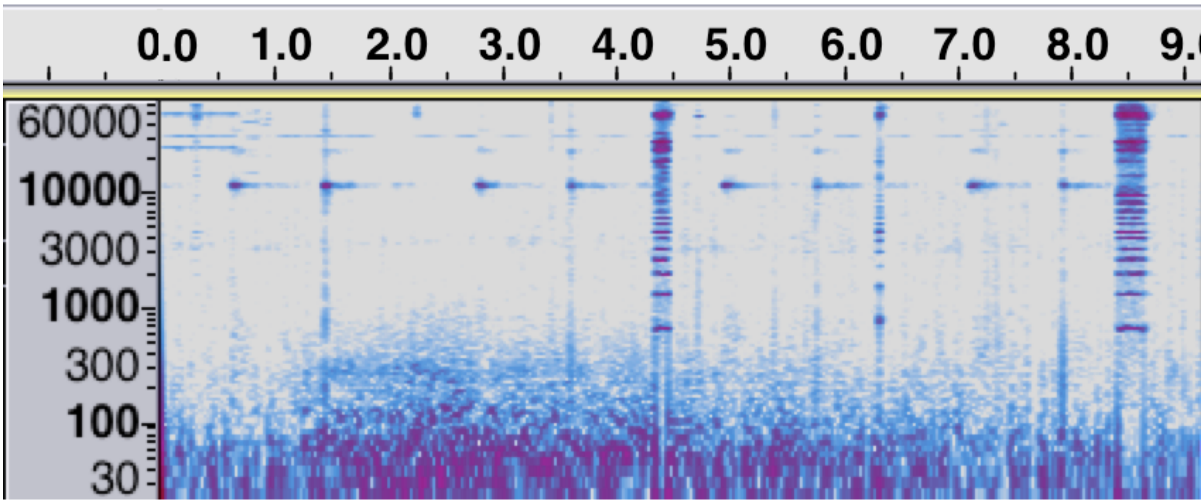

Figure 19: Glider altimeter (13 kHz) and broad band noise events.

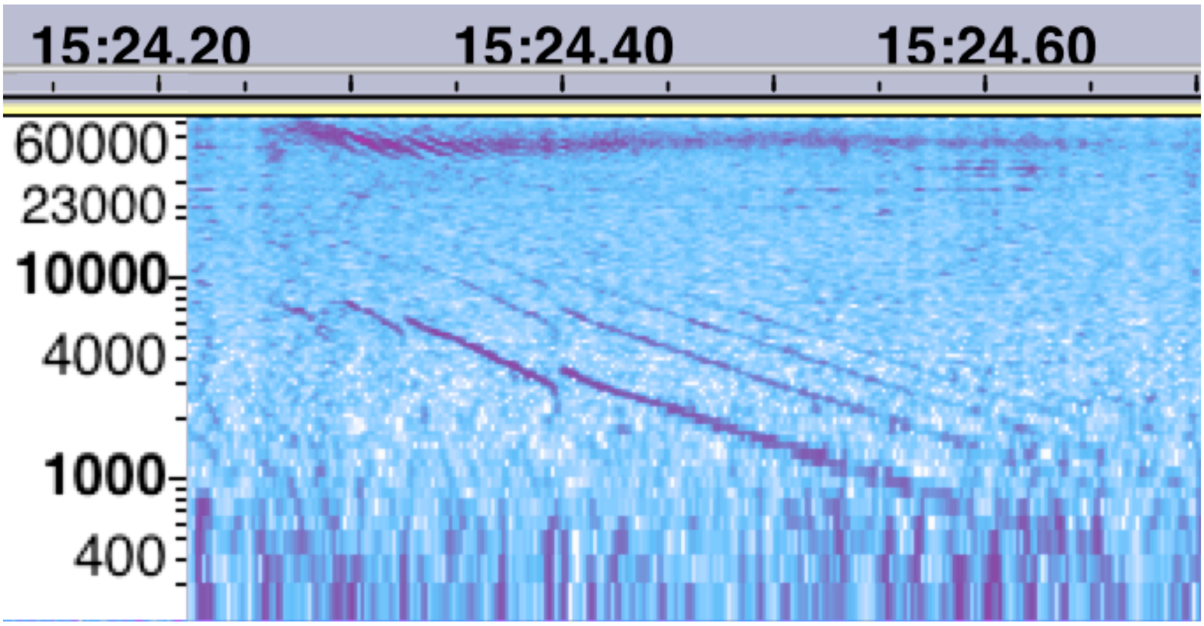

Figure 20: Down-sweep features.

7.2.2 Glider Pancake (404)

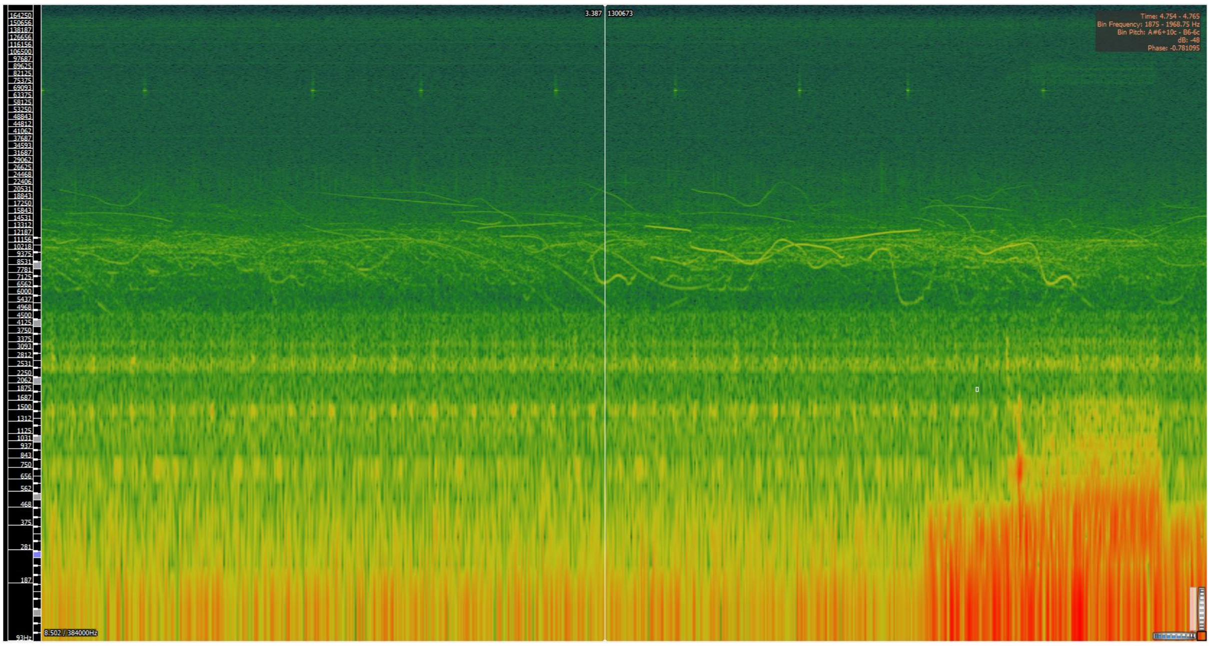

Figure 21: Dolphins/pilot whales and the Vemco pinger

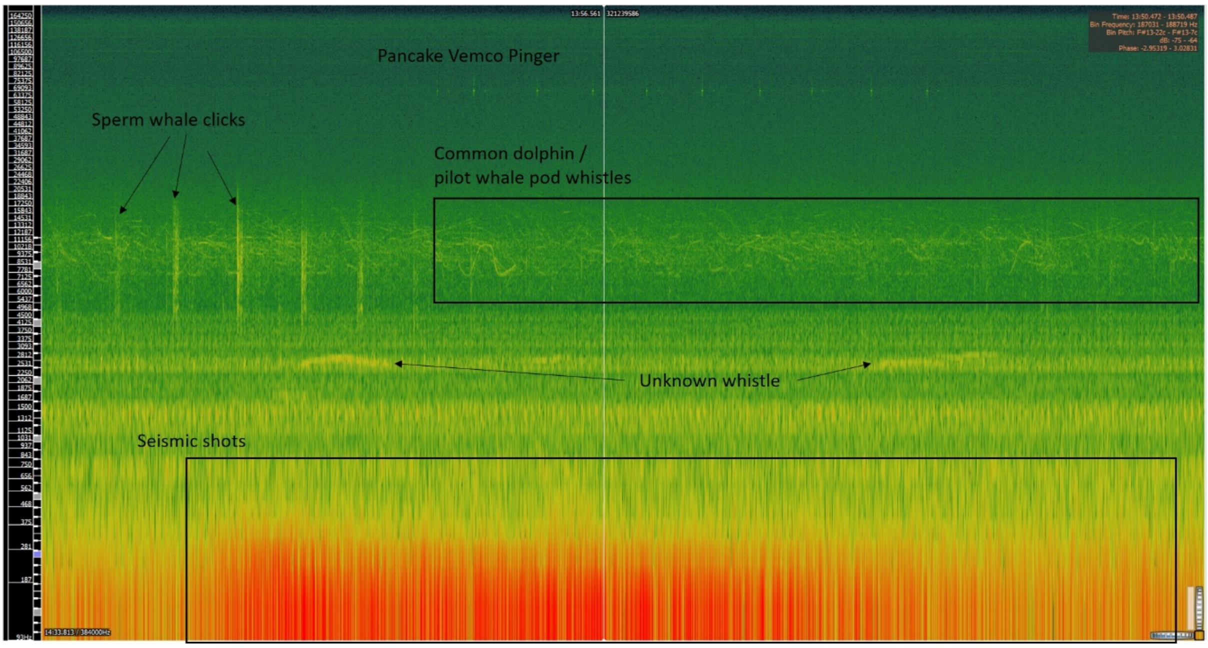

Figure 22: Marine mammal vocalisations, seismic survey shots and the Vemco pinger

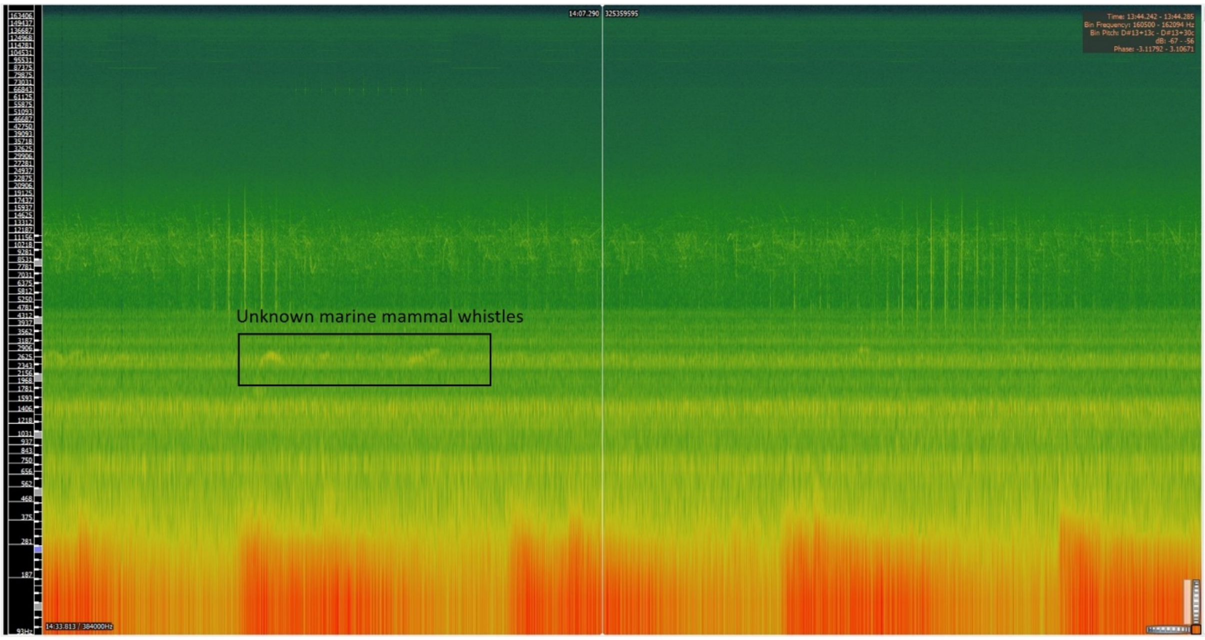

Figure 23: Marine mammal vocalisations, seismic survey shots and the Vemco pinger

8 Bibliography

Arnold, R. T., Bass, H. E., & Atchley, A. A. (1984). Underwater sound from lightning strikes to water in the Gulf of Mexico. *Journal of the Acoustical Society of America, 76*(1), 320-322.

Baumgartner, M. F., & Fratantoni, D. M. (2008). Diel periodicity in both sei whale vocalization rates and the vertical migration of their copepod prey observed from ocean gliders. *Limnology and Oceanography, 53*(5 pt.2), 2197-2209.

Bingham, B., Kraus, N., Howe, B., Freitag, L., Ball, K., Koski, P., & E., G. (2012). Passive and Active Acoustics Using an Autonomous Wave Glider. *Journal of Field Robotics, 29*(6), 911-923.

Blue, J. E., & Gerstein, E. R. (2005). The acoustical causes of collisions between marine mammals and vessels. In H. Medwin (Ed.), *Sounds in the Sea: From Ocean Acoustics to Acoustical Oceanography* (p. 643). Cambridge: Cambridge University Press.

Casaretto, L., Picciulin, M., & Hawkins, A. D. (2016). Differences between male, female and juvenile haddock (Melanogrammus aeglefinus L.) sounds. *Bioacoustics*, 1-15. doi:10.1080/09524622.2015.1130647

Chadwick Jr., W. W., Cashman, K. V., Embley, R. W., Matsumoto, H., & Dziak, R. P. (2008). Direct video and hydrophone observations of submarine explosive eruptions at NW Rota-1 volcano, Mariana arc. *Journal of Geophysical Research, 113*(B08S10), 1-23. doi:10.1029/2007JB005215

Coates, R. F. (1990). *Underwater Acoustic Systems.* London: Macmillan.

Cornell Lab of Ornithology. (2018). *Raven: Interactive Sound Analysis Software*. Retrieved 02 12, 2018, from http://www.birds.cornell.edu/brp/raven/RavenOverview.html

Crone, T. J., Wilcock, W. S., Barclay, A. H., & Parsons, J. D. (2006). The Sound Generated by Mid-Ocean Ridge Black Smoker Hydrothermal Vents. *PLoS ONE, 1*(1), 1-8. doi:10.1371/journal.pone.0000133

de Soto, A. N., & Kight, C. (2016). In M. Solan, & N. M. Whiteley (Eds.), *Stressors in the Marine Environment: Physiological and ecological responses; societal implications* (p. 384). Oxford: Oxford University Press.

Doran, J. (2017). *Blue Ocean Monitoring MASSMO4 Project Report (Project Number: P17012,), initial draft.* Southampton: Blue Ocean Monitoring Ltd.

Dushaw, B. D., Worcester, P. F., Munk, W. H., Spindel, R. C., & Mercer, J. A. (2009). A decade of acoustic thermometry in the North Pacific Ocean. *Journal of Geophysical Research, 114*(C07021), 1-24. doi:10.1029/2008JC005124

Francois, R. E., & Garrison, G. R. (1982a). Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions. *Journal of the Acousitcal Society of America, 72*(3), 896-907.

Francois, R. E., & Garrison, G. R. (1982b). Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption. *Journal of the Acoustical Society of America, 72*(6), 1879-1890.

Gallego, A., O'Hara Murray, R., Berx, B., Turrell, W. R., Beegle-Krause, C. J., Inall, M., . . . Mulanaphy, N. (2018). Current status of deepwater oil spill modelling in the Faroe-Shetland Channel, Northeast Atlantic, and future challenges. *Marine Pollution Bulletin, 127*, 484-504.

Garrett, J. K., Blondel, P., Godley, B. J., K., P. S., Witt, M. J., & Johanning, L. (2016). Long-term underwater sound measurements in the shipping noise indicator bands 63 Hz and 125 Hz from the port of Falmouth Bay, UK. *Marine Pollution Bulletin, 110*, 438-448.

Gervaise, C., Vallez, S., Ioana, C., Stephan, Y., & Simard, Y. (2007). Passive acoustic tomography: new concepts and applications using marine mammals. *Journal of the Marine Biological Association of the United Kingdom, 87*(1), 5-10. doi:10.1017/S0025315407054872

Greene, C. H., Meyer-Gutbrod, E. L., McGarry, L. P., Hufnagle Jr., L. C., Chu, D., McClatchie, S., . . . Pelkie, C. (2014). A wave glider approach to fisheries acoustics: Transforming how we monitor the nation's commercial fisheries in the 21st century. *Oceanography, 27*(4), 168-174. doi:http://dx.doi.org/10.5670/oceanog.2014.82

Hall, R. A., Huthnance, J. M., & Williams, R. G. (2011). Internal tides, nonlinear internal wave trains, and mixing in the Faroe-Shetland Channel. *Journal of Geophysical Research, 116*(C03008), 1-15. doi:10.1029/2010JC006213

Hastie, G. D., Swift, R. J., Gordon, J. C., Slesser, G., & Turrell, W. R. (2003). Sperm whale distribution and seasonal density in the Faroe Shetland Channel. *Journal of Cetacean Research and Managment, 5*(3), 247-252.

Hosegood, P., J., B., & van Haren, H. (2004). Solibore-induced sediment resuspension in the Faeroe-Shetland Channel. *GEOPHYSICAL RESEARCH LETTERS, 31*(L09301), 1-4. doi:10.1029/2004GL019544

Koski, W. R., Abgrall, P., & Yazvenko, S. B. (2011). An inventory and evaluation of unmanned aerial systems for offshore surveys of marine mammals. *Journal of Cetacean Research and Management, 11*(3), 239-247.

Ma, B. B., Nystuen, J. A., & Lien, R.-C. (2005). Prediction of underwater sound levels from rain and wind. *Journal of the Acoustical Society of America, 117*(6), 3555–3565.

MacAyeal, D. R., Okal, E. A., Aster, R. C., & Bassis, J. N. (2008). Seismic and hydroacoustic tremor generated by colliding icebergs. *Journal of Geophysical Research, 113*(F03011), 1-10. doi:10.1029/2008JF001005

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Ward, J. A., Moretti, D. J., . . . Tyack, P. L. (2013). Estimating animal population density using passive acoustics. *Biological Reviews, 88*, 287-309. doi:10.1111/brv.12001

Mellinger, D. K., Stafford, K. M., Moore, S. E., Dziak, R. P., & Matsumoto, H. (2007). Fixed Passive Acoustic Observation Methods. *Oceanography, 20*(4), 36-45.

Merchant, N. D., Faulkner, R. C., & Martinez, R. (2017). Marine Noise Budgets in Practice. *Conservation Letters*, 1-8. doi:10.1111/conl.12420

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., & Parks, S. E. (2015). Measuring acoustic habitats. *Methods in Ecology and Evolution, 6*, 257–265. doi:10.1111/2041-210X.12330

Munk, W., & Wunsch, C. (1979). Ocean acoustic tomography: a scheme for large scale monitoring. *Deep-Sea Research, 26*(A), 123-161.

Oliver, M. J., Breece, M. W., Haulsee, D. E., Cimino, M. A., Kohut, J., Aragon, D., & Fox, D. A. (2017). Factors affecting detection efficiency of mobile telemetry Slocum gliders. *Animal Biotelemetry*, 5-14. doi:DOI 10.1186/s40317-017-0129-8

Pierpoint, C. (2017). *MASSMO4 AutoNaut USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From The Orkney Islands, In May 2017, revison 1.0.* Holsworthy: Seiche Ltd.

Pierpoint, C. (2018). *MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3.* Holsworthy: Seiche Ltd.

Radford, C. A., Stanley, J. A., Tindle, C. T., Montgomery, J. C., & Jeffs, A. G. (2010). Localised coastal habitats have distinct underwater sound signatures. *MARINE ECOLOGY PROGRESS SERIES, 401*, 21–29. doi:10.3354/meps08451

Rudnick, D. L., Davis, R. E., Eriksen, C. C., Fratantoni, D. M., & Perry, M. J. (2004). Underwater gliders for ocean research. *Marine Technology Society Journal, 38*, 73–84.

Sea Mammal Research Unit, University of St Andrews. (2018). *PAMGuard*. Retrieved 02 12, 2018, from https://www.pamguard.org/

Sherwin, T. J., Turrell, W. R., & Dye, S. (1999). Eddies and a mesoscale deflection of the slope current in the Faroe-Shetland Channel. *Deep-Sea Research Part 1, 46*, 415-438.

Stanley, J. A., & Jeffs, A. G. (2016). Ecological impacts of anthropogenic underwater noise. In M. Solan, & N. M. Whiteley (Eds.), *Stressors in the Marine Environment: Physiological and ecological responses; societal implications* (p. 384). Oxford: Oxford University Press.

Stommel, H. (1989). The Slocum mission. *Oceanography, 2*, 22-25.

Urick, R. J. (1975). *Principles of Underwater Sound* (2nd ed.). New York: McGraw-Hill.

Vemco. (2018). *Vemco 69 kHz Sea Water Range Calculator*. Retrieved January 31, 2018, from https://vemco.com/range-calculator/

Wenz, G. M. (1962). Acoustic Ambient Noise in the Ocean: Spectra and Sources. *The Journal of the Acoustical Society of America, 34*(12), 1936-1956.

Williams, R., Wright, A., Ashe, E., Blight, L., Bruintjes, R., Canessa, R., . . . Wale, M. A. (2015). Impacts of anthropogenic noise on marine life: Publication patterns, new discoveries, and future directions in research and management. *Ocean & Coastal Management, 115*, 17-24.

Wynn, R., Hall, R., Inall, M., Jones, S., P., M., & B., L. (2017). *Marine Autonomous Systems in Support of Marine Observations (MASSMO): Initial report on the MASSMO4 mission (19 May to 06 June 2017).* Southampton: National Oceanography Centre.

Zimmer, W. M. (2011). *Passive acoustic monitoring of cetaceans.* Cambridge: Cambridge University Press.

9. Appendix

Time (start)	Observation	Platform	System	Ref/source
25/05/2017 12:25	Probably harbour porpoise clicks	AutoNaut	Seiche	(Pierpoint, MASSMO4 AutoNaut USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From The Orkney Islands, In May 2017, revison 1.0, 2017)
25/05/2017 18:48	Boat (possibly support boat)	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

26/05/2017 00:34	Unknown transients, possible distant airguns, but irregular so possible self-noise	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
26/05/2017 05:40	Harbour porpoise click trains (no. of clicks = 99)	AutoNaut	Seiche	(Pierpoint, MASSMO4 AutoNaut USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From The Orkney Islands, In May 2017, revison 1.0, 2017)
26/05/2017 05:57	Harbour porpoise click trains (no. of clicks = 17)	AutoNaut	Seiche	(Pierpoint, MASSMO4 AutoNaut USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From The Orkney Islands, In May 2017, revison 1.0, 2017)

26/05/2017 12:25	Harbour porpoise click trains (no. of clicks = 28)	AutoNaut	Seiche	(Pierpoint, MASSMO4 AutoNaut USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From The Orkney Islands, In May 2017, revison 1.0, 2017)
26/05/2017 10:22	Boat passing (to 10:34)	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
26/05/2017 13:15	Boat passing (to 14:56, peak 13:44 to 13:56)	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

26/05/2017 21:45	Boat passing (to 22:20); regular mechanical 'squeak' at 945 Hz, interval = 0.8 s	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
27/05/2017 05:10	Boat passing (to 06:38)	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

29/05/2017 03:32	Sonar 66 kHz, interval 0.4 s	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
29/05/2017 05:09	Sonar 66 kHz, interval 0.4 s	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

30/05/2017 00:23	Boat passing (to 02:11, peak 00:34-01:17)	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
30/05/2017 11:11	Boat passing (to 12:07)	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

31/05/2017 03:44	Resonant impact / possible detonation	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
31/05/2017 03:52	Resonant impact / possible detonation	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

31/05/2017 21:45	Unknown, possible self-noise 128 kHz, interval = 1.3 s	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
31/05/2017 23:44	Unknown, possible self-noise 128 kHz, interval = 1.3 s	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)

01/06/2017 23:37	Unknown, sporadic transients, 14-24 kHz (also at 23:44 and 23:52)	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
02/06/2017 11:00	Dolphins, Pilot Whales and a Vemco pinger	Glider 404	RS ORCA	R. Mowat
02/06/2017 18:13	Sonar 12 kHz, interval 2.2 s	C-Enduro	Seiche	(Pierpoint, MASSMO4 C-Enduro USV Deployment: Analysis Of PAM Data Recorded During A USV Deployment From TheOrkney Islands, In May-June 2017, revison 1.3, 2018)
03/06/2017 09:26	Low frequency clicks at 10 kHz, 3kHz whistles and 12kHz sonar, over a 14-minute period.	Glider 404	RS ORCA	R. Mowat
05/06/2017 08:19	Seismic shots, glider self-noise, Vemco Pinger and unknown high frequency pings.	Glider 404	RS ORCA	R. Mowat

Table 5: List of events for future data analysis

Time stamp (start)	Time stamp (end)	Platform/s	Event	Expected sound
19/05/2017 10:28	21/05/2017 16:54	187, 552 & 553	Thruster testing on transit to WP1 and tidal front experiment	Thrusters and pingers
21/05/2017 16:54	22/05/2017 12:29	187	tidal front experiment	Pingers
22/05/2017 12:29	23/05/2017 07:40	187, 552 & 553	Gliders in transit to WP1a together	Pingers
23/05/2017 07:40	23/05/2017 22:31	187, 552 & 553	Acoustic detection in shallow tidally mixed waters. Gliders in close proximity, ~ 200 m.	Pingers
23/05/2017 22:31	24/05/2017 08:02	187, 552 & 553	Gliders in transit to WP1b together	Pingers
24/05/2017 08:02	25/05/2017 16:42	187, 552 & 553	Acoustic detection in weakly stratified deep waters. Gliders in close proximity, ~400 m	Pingers
25/05/2017 16:42	26/05/2017 11:50	187, 552 & 553	Gliders in transit to WP1c together, across at tidal front?	Pingers
28/05/2017 11:50	28/05/2017 17:54	187, 552, 553 & C-Enduro	MRV Scotia converged with the Gliders at WP1d and drift dives were conducted	Ship noise and sounders from MRV Scotia, pingers
28/05/2017 17:54	29/05/2017 05:51	187, 552, 553 & C-Enduro	Gliders in transit to WP1e together, with C-Enduro	Pingers & C-Enduro engine noise
29/05/2017 05:51	29/05/2017 16:11	187, 552, 553 & C-Enduro	Internal wave experiment. 187 undertook silent yo's over 30 m, followed by 5.5-hour drift at the thermocline	Pingers & C-Enduro engine noise
29/05/2017 16:11	29/05/2017 17:44	187, 552, 553 & C-Enduro	Gliders on transit towards WP1f.	Pingers
29/05/2017 17:44	31/05/2017 12:14	187	Thruster testing on transit towards WP1f. 187 turned on its thruster at 17:44 and left 552 & 553 behind.	Pingers & thruster noise decreasing with distance
01/06/2017 17:34		404	Research vessel 1 km from 404	Ship noise and sounders
02/06/2017 03:15		187, 552, 553 & C-Enduro	Gliders, C-Enduro & Research vessel converge at WP5 for BCP experiment	Ship noise, sounders and pingers
02/06/2017 09:29		SG620	Research vessel 2 km from SG620	Ship noise and sounders
02/06/2017 20:11	03/06/2017 23:11	187 & 404	Wave glider station, 187 and 404 near(<0.5 km)	ADCP and 187s pinger
02/06/2017 20:30		404	About this time 187 is about 5.3 km from 404	Pinger
02/06/2017 23:30		404	Near WP5, < 1 km from Research vessel	Ship noise and sounders
03/06/2017 02:00		404 & 553	About this time 404 and 553 are about <0.5 km apart	Pinger

03/06/2017 09:15		187 & 404	About this time 187 is about 1.3 km from 404	Pinger
03/06/2017 09:24	05/06/2017 07:41	187 & 552	BCP transect from WP5 to WP1f, then back to WP5	Pinger
05/06/2017 08:19		404 & 553	404 & 553 are < 1 km apart (between WP5 and WP5f), Research vessel is about 5 km away.	Unknown HF sounder/pinger at 167 kHz
05/06/2017 17:00		SG620	Research vessel ~1 km from SG620	Ship noise and sounders
05/06/2017 19:15	06/06/2017 08:00	187	Transit to WP5e, then on to WP5 for recovery by Research vessel	Ship noise and sounders
06/06/2017 10:12		552	Research vessel ~1 km from 552	Ship noise and sounders
06/06/2017 13:03		404	Research vessel ~1 km from 404	Ship noise and sounders