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Marine mammal tracks from two-hydrophone acoustic recordings made with a glider

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Abstract. A multinational oceanographic and acoustic sea experiment was carried out in the summer of 2014 off the western coast of the island of Sardinia, Mediterranean Sea. During this experiment, an underwater glider was evaluated as a potential tool for recording marine mammal sounds for population density estimation studies. To this end, an acoustic recording system was also tested, comprising two hydrophones connected to an off-the-shelf voice recorder installed inside the glider. Analysis of the recorded acoustic data by a human analyst indicated the presence of sperm whale (*Physeter macrocephalus*) regular clicks as well as dolphin clicks and whistles. Further analysis of the data consisted in cross-correlating clicks recorded on both data channels for the estimation of the direction (bearing) of clicks, and realization of animal tracks. Insights from this bearing tracking analysis is expected to aid in population density estimation studies by providing further information on animal movement and location.

1 Introduction

Autonomous underwater vehicles (AUVs) such as gliders are being used ever more frequently as a tool in ocean research. A glider moves through the water by controlling its buoyancy to dive and surface, which enables it to glide forward with the use of horizontal mounted wings. Given their mode of operation, gliders provide a platform that is acoustically very quiet. Because of the quiet acoustic characteristics, a growing area of application is passive acoustic monitoring of marine mammals. Increasing amounts of marine mammal recordings are being obtained by fitting gliders with hydrophones (e.g. Klinck et al., 2012; Baumgartner et al., 2013).

Gliders have most often been fitted with a single hydrophone, and recordings from both mysticetes (baleen whales) and odontocetes (toothed whales, dolphins, and porpoises) have been made in this manner. More specifically, beaked whales (Ziphiidae sp.), sperm whales (*Physeter macrocephalus*), and delphinids, which all produce highly broadband high-frequency echolocation clicks, were detected in real time from a glider off Hawai'i in 2009 to study habitats and vocalization behavior (Klinck et al., 2012). In addition, sei whale (*Balaenoptera borealis*) vocalizations were recorded by a glider to study their diel vocalization patterns (Baumgartner and Fratantoni, 2008). The ability of gliders to perform and report real-time detections of four different kinds of baleen whales and their different call types has also been tested successfully by Baumgartner et al. (2013).

The overall objective of this work is to evaluate the use of two hydrophones mounted on an ocean glider for marine mammal population density estimation studies. Some advantages of using a glider for such studies include the acquisition and reporting of real time data, the *in-situ* measurement of sound speed information, which is important for estimating detection distances, and the possibility of estimating animal bearing from data received on multiple hydrophones mounted on the platform. In addition, moving sensors such as gliders have an advantage over fixed sensors since they can be relocated as needed and cover a larger geographic area. The specific objective of this paper is to describe the two-hydrophone bearing tracking methods and results. Insights from this bearing tracking analysis is expected to aid in population density estimation studies (Marques et al., 2013) by providing further information on animal movement and location.

2 Methodology

2.1 Acoustic Recording System

The Northwest Electromagnetic and Acoustics Research Laboratory (NEAR-Lab) at Portland State University (PSU), Portland, OR, owns a first-generation, 200-meter Webb-Teledyne Slocum glider (Webb et al., 2001) named *Clyde*. Clyde was fitted with two High-Tech Inc. hydrophones, model HTI-92-WB (with pre-amplifiers). The hydrophones, each with a sensitivity of -159 dB re 1 $\mu\mathrm{Pa/V}$, were mounted on the wings of the glider at a horizontal separation of approximately 0.9 m.

An inexpensive, off-the-shelf linear pulse code modulation (PCM) recorder manufactured by Tascam (model DR-07 MKII) was adapted to fit inside the glider's science bay as a stand-alone sensor. It was not connected to the glider's computer, and it was independent of glider operations. The recorder was equipped with enough batteries (8 AA alkaline) to record continuously for up to 24 hours (Fig. 1). In its original configuration, the recorder allowed only continuous recording. The maximum recording time was a function not only of power consumption but also of available storage. Data was recorded to a single micro-SD card, for which the maximum capacity could not exceed 32 GB. The acquisition system offered a sampling frequency of 96 kHz at 16-bit resolution, and was capable of recording two channels of data, one from each hydrophone.

Testing of the acoustic recording system and data collection took place during an opportunistic sea-trial.

2.2 Sea Trial

The sea trial REP14-MED (Recognized Environmental Picture 2014 – Mediterranean) took place 6-26 June 2014 in the Sardinian Sea, Western Mediterranean Sea. It's objective was to obtain environment knowledge and uncertainty (geographical, meteorological, oceanographic and acoustic) to support NATO (North Atlantic Treaty Organization) operations. Two vessels participated in the 2014 campaign, the NATO research vessel *Alliance* and the German research vessel *Planet*. During the experiment both physical oceanography and acoustic data were collected, although acoustic experiments were only conducted from the NRV Alliance (Onken et al., 2016).

As part of the experiments, 10 gliders were assigned parallel tracks along an east-west direction perpendicular to the west coast of the island of Sardinia. Our glider was assigned the northernmost track, and was deployed at $40°$ 00' N 07° 22' E at

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12:16 CEST (Central European Summer Time) on June 09, 2014 (Fig. 2). It was programmed to dive between 15 and 170 m in the see-saw pattern typical of Slocum gliders at an angle of 26 degrees. It was also initially programmed to surface every 2 hours to send navigation data back to the glider pilots at NATO's Centre for Maritime Research and Experimentation (CMRE). In the absence of strong currents, a correctly ballasted Slocum glider can travel at speeds of approximately 0.25 $\mathrm{m/s}$.

Data recording was initiated about one hour prior to deployment while the glider was still on board the NRV Alliance, and ended when the 32 GB micro-SD card inside the recorder was full, approximately 23 hours later. A total of 15 acoustic files containing 22 hours of 2-channel continuous data were recorded between June 09-10 when the glider was located in deep waters (deeper than 2000 m) off of the west coast of the island of Sardinia.

During a mission far from ship- or land-based radio transponders, gliders communicate at pre-designated surfacing points via Iridium satellite. Communications with Clyde were completely lost around 23:10 CEST on June 10, after acoustic recording had terminated. Its location was re-found only on June 11 around 21:20 CEST via an emergency location beacon in the glider that communicates through a separate (Argos) satellite system. The glider was finally sighted at 17:36 CEST on June 12 at 07° 34' E 40° 03' N and recovered shortly thereafter, at 17:47, by RV *Planet* (Fig. 2). A hardware malfunction caused not only the loss of communications but also the loss of some navigation files and CTD (conductivity, temperature, and depth) information. Fortunately, glider data files were recovered for the period when the acoustic recorder was on.

2.3 Data Processing and Analysis

The acoustic data was saved by the Tascam recorder in waveform audio file format (.WAV). Of the 15 files recorded, 14 had a duration of 1:33:09 hours. The last file had a duration of 1:20:17 hours, at which time storage was full. The glider was deployed 1:43:58 hours after the beginning of recordings, implying that the first file (file 01) contained only recordings made above water. After a glider deployment, a series of test dives are performed to check on the overall functionality and ballasting of the vehicle. Therefore, most of file 02 contained recordings made while the glider either made shallow dives or was at the surface. It also appears from the acoustic data that the glider started its primary mission, navigating to its pre-assigned west-east track perpendicular to the coast of Sardinia, approximately 40 minutes after the actual deployment. The remainder of the data in file 02 did not show any significant marine mammal events. Discounting the first two files, a total of approximately 19.9 hours of data were available for analysis.

Preliminary analysis of the recorded data involved visual inspection of spectrograms by a trained marine bioacoustician for the detection and classification of marine mammal calls. Results presented in this work were derived from file 06. This file was chosen due to the extent of marine mammal activity and also due to the fact that the glider did not surface during its recording, providing roughly 1:30 hours of uninterrupted data. The data were recorded between 19:47 and 21:20 (CEST) on June 09, 2014. Manual inspection of this file identified sperm whale clicks (Fig. 3) as well as clicks and whistles (Figs. 4 and 5) from one or more unknown species of dolphins.

Closer evaluation of data spectrograms and power spectral density plots indicated high energy content at frequencies above 30 kHz (Figs. 4 and 5). This increase in power with frequency was considered an artifact given the well-known relationship between frequency and attenuation in the ocean (Jensen et al., 2011), where high frequencies are highly attenuated. Moreover,

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no known physical phenomena would produce the observed elevated noise levels at high frequencies. Another feature observed in the data set was the presence of high-amplitude, impulse-like spikes, or *glitches*. These features were conspicuously present throughout channel 2, but at lower intensity, and not simultaneously, in channel 1. Even though glitches resembled marine mammal clicks at first glance, whether looking at the time series or spectrograms, closer inspection revealed a characteristic shape and sound suggestive of an electronic artifact produced by the acoustic acquisition system. One example of such feature can be observed in Fig. 5, between 1 and 1.5 s by a strong *click-like* feature, which happens to be concurrent with a *real* click arrival. It was observed in spectrograms that the lower frequency of spikes was 0 kHz, unlike marine mammal clicks.

Automated detection of sperm whale regular clicks was performed by running a simple energy sum detector with the aid of the software *Ishmael* (Mellinger, 2001). Sperm whales produce broadband regular clicks, also called usual clicks (Whitehead and Weilgart, 1990), that are highly directional (Møhl et al., 2000), with durations of 100 µs, and with center frequency reported around 13.4 kHz (Møhl et al., 2003). Ishmael produces a detection function which represents the likelihood that a call of interest is present. The detection function has arbitrary amplitude units and a threshold is chosen with respect to its height (Mellinger, 2001). For this data set, a detection threshold of 0.05 was used to detect clicks with energy in the frequency band between 2 and 20 kHz, which is consistent with the frequency band of sperm whale regular clicks (Zimmer et al., 2005). The energy sum detector was applied to channels 1 and 2 separately and detections were saved to corresponding files that logged initial and end times of each detection. Click durations from Ishmael detections ranged from 5 to 16 ms. Channel 1 produced more detections than channel 2 (43762 and 33325, respectively). Even though visual inspection seemed to indicate that glitches occurred more often on channel 2, their frequent presence on channel 1 could be a possible explanation for the larger number of detections. In addition, spectrogram levels were higher on channel 1 than on channel 2. Therefore, some clicks detected on channel 1 probably did not have enough energy to be detected on channel 2. The cause for this difference in energy levels could be due to the acoustic acquisition system.

Due to the noisy character of the data, especially in the low and very high frequencies, a bandpass filter was applied to the time series so that signals of interest could be distinguished. Hence, a fourth-order Butterworth bandpass filter was designed such that it had a flat frequency response between 1.8 and 28 kHz, with frequencies outside this band attenuated up to 185 dB.

Next, in order to estimate the direction from which the clicks came, the time difference of arrival (TDOA) of clicks received in the two channels was estimated. The biased estimate, which normalizes the cross-correlation by the number of samples, was calculated. The correlation lag τ, or time difference of arrival, is given by the maximum absolute peak of the cross-correlation of a time window containing a single detection. Here, each detection from channel 1 centered on a time window of 16 ms (which corresponds to the maximum detection duration given by Ishmael) was cross-correlated with the same time window from channel 2. Such a time window was found sufficient to guarantee that only one click was present in the time series. By assuming a nominal sound speed of 1500 $\mathrm{m/s}$ in the ocean and taking the hydrophone separation of 0.9 m, it was found that the maximum possible TDOA between arrivals of a click on both hydrophones was $T = 0.6$ ms. This value of T was compared to the estimated τ to select sperm whale echolocation clicks received on both channels as well as to eliminate glitches, which were also detected by Ishmael. The sampling frequency with which the data was recorded provided good time resolution ($\Delta t =$ 0.01 ms) at such small time scale.

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The estimated TDOA was then used in the formula below to find the direction of arrival of each detected click, keeping in mind the right-left ambiguity of the estimate. The direction of arrival, or bearing angle (θ) was calculated by

$$\theta = \cos^{-1}\left(\frac{\tau c}{L}\right), \tag{1}$$

where c is the sound speed (1500 $\mathrm{m/s}$) and L is the hydrophone separation distance (0.9 m). Results from the bearing estimation are presented in the next section.

3 Marine Mammal Bearing Tracks

Clicks (sperm whales) present in just over one minute of data from the onset of file 06 were manually annotated and compared to detections made by Ishmael as a qualitative measure of detector performance. The results of this comparison given by bearing angles calculated from both sets of detections are shown in Fig. 6. Manual annotation yielded more clicks than the automatic detector. However, both detection methods seemed to agree very well. It can be suggested from this preliminary result that at least two animals, possibly three, were producing echolocation clicks during the time of recordings.

Bearing angles for all the detections of file 06 that were considered clicks from the cross-correlation analysis are shown in Fig. 7. This corresponds to just over one hour and thirty minutes of data. Sperm whale vocal activity was observed in the beginning of file 06 (Fig. 3), whereas dolphin clicks seemed to be mostly present roughly in the last 20 minutes of data (Figs. 4 and 5). Shorter time segments within this figure are examined in detail to get a better picture of animal movement.

Two shorter segments of estimated bearing angles are shown in Fig. 8. The upper plot shows bearing angles estimated from clicks recorded during the first 8 min from the beginning of file 06. By zooming into this shorter period of data, it is possible to realize two different tracks closely following each other. As always with passive acoustic monitoring, other animals could possibly be present without being detected, either because they were not vocalizing, or because they were further away from the sensors and therefore their clicks fell below the detection threshold.

The second zoomed in plot of Fig. 8 shows 25 min of estimated bearings towards the end of the file, where dolphin clicks were more predominant. It is worth noting that detections were made between 2 and 20 kHz; hence, estimated bearings in this window could correspond to either sperm whales (the target of the click detector) or dolphins, whose clicks had enough energy in the sperm whale frequency band to elicit a detection. At first glance, the results shown in this plot seem to indicate the presence of a few tracks. It is interesting to note, however, that they look almost as mirror images of each other, but with different degrees of offset. It may be possible that these are produced from multipath arrivals. Manually inspecting spectrograms from about 60 to 70 min revealed that most clicks, especially the stronger ones, occurred in pairs, which can indicate multipath. However, without knowing more about the location of the animals it is hard to really assess the true nature of the double clicks.

Finally, a polar plot (Fig. 9) was made combining all estimated bearings. This shows the clicks' directions of arrival, including the left-right ambiguity inherent in a two-sensor arrangement.

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4 Discussion and Conclusions

In this work, a glider was fitted with an inexpensive, off-the-shelf acoustic acquisition system. Evaluation of glider operations and of the acoustic system was performed during the REP14-MED sea-trial off the west coast of the island of Sardinia, Mediterranean Sea. About 20 hours of dual-channel continuous acoustic data were recorded in deep water (>1500 m), and contained calls of sperm whales as well as dolphins.

The successful use of a good quality and inexpensive voice recorder connected to a pair of hydrophones led to subsequent improvements to the system. In its original configuration, the Tascam recorder did not allow for the implementation of any recording schedule other than continuous recording, restricting data collection to a maximum of 23 hours. On the other hand, Slocum gliders have the potential to stay deployed for a few weeks at a time. Another drawback of the recording system was an inability to start and stop recording via remote command. Thus nearly two hours of data, almost 10% of total capacity, were recorded while the vehicle was still on board the NRV *Alliance*. An improved second generation was devised after this experiment with added storage capacity and connected to a micro-controller serving as a programmable interface.

The quality of the data was generally acceptable, and even though recordings amounted to less than a day, sperm whales and dolphin calls were identified over several hours in the data set. However, random short-duration glitches of seemingly electronic origin were also present throughout, but not concurrent on, both channels. To identify and potentially fix the source of such glitches, more testing needs to be done with the acoustic acquisition system. Even though some processing needed to be done in order to remove glitches from detections, they did not compromise the usability of the data set. Even though both hydrophones were from the same manufacturer, with the same sensitivity and pre-amps, their outer shells are slightly different. On a more recent experiment one of these hydrophones stopped working completely and it came to our attention that water might have leaked inside the sensor. This could potentially explain the difference in levels observed between the two channels.

Detection of thousands of sperm whale and dolphin clicks in a data segment of approximately 1 hour and 30 minutes was enough to test the usefulness of two hydrophones in the glider. Some advantages of having two sensors mounted on a glider, instead of a single hydrophone, for detecting marine mammal sounds include the potential to estimate animal tracks and inter-call intervals, and the removal of multipath arrivals. In fact, by estimating the angle of arrival of detected clicks, at least a few tracks (animals) could be realized from the data. Such information can be valuable to density estimation methods, either directly for estimating the percentage of time a species produces sound during one day (Marques et al., 2013), or indirectly for giving another measure of how many animals are present in a given location surveyed by the glider. However, studies are still needed to investigate the effects of the movement of the glider on density estimates, especially with respect to data collection at different depths.

More data analysis needs to be done to identify the dolphin species observed in file 06 as well as all the times that sperm whales were present. Longer tracks could potentially be realized by combining results from multiple files and observing the continuation of clicking activity. Furthermore, knowledge of animal behavior such as usual group size can also complement tracking information. Another interesting question that needs to be answered is the resolution of the tracks and how far apart (in degrees) tracks (animals) can be distinguished from one another. Integration of glider navigation data (depth, heading) with acoustic recordings could provide further insights into the location and behavior of the vocalizing animals. Environmental data collected by the conductivity, temperature, and depth sensor of the glider could further provide information for estimating detection ranges of received call.

Finally, a major hardware malfunction was identified in Clyde during the sea-trial. A corrupt piece of hardware affected the glider's navigation and communications. Fortunately, the problem was tracked down with the help of the engineers on board the NRV *Alliance* after Clyde was recovered. A new piece of hardware was subsequently installed and glider operations have resumed normally.

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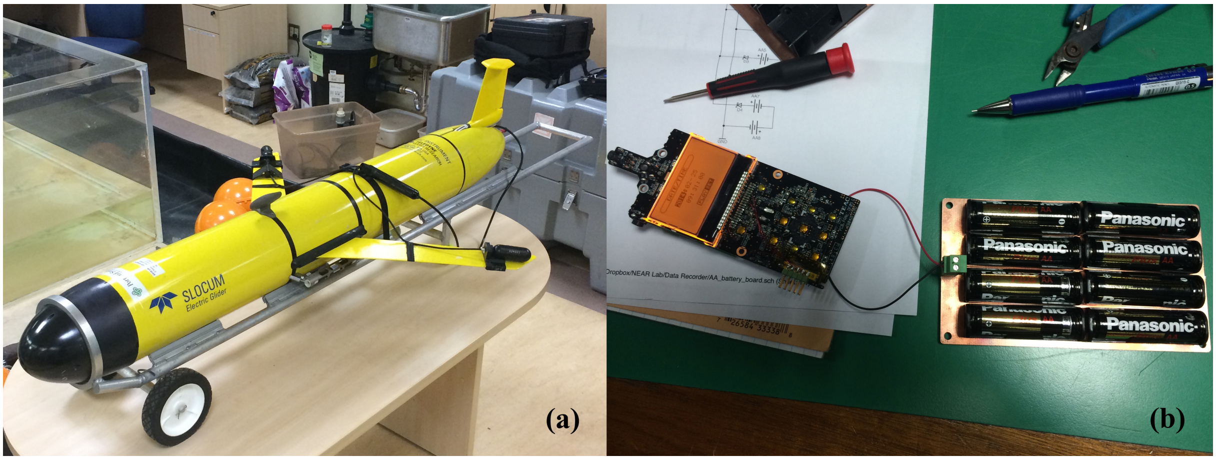

Figure 1. (a) The PSU glider *Clyde* with hydrophones attached to the tips of its wings. (b) The acoustic recording system (modified Tascam voice recorder) and battery pack.

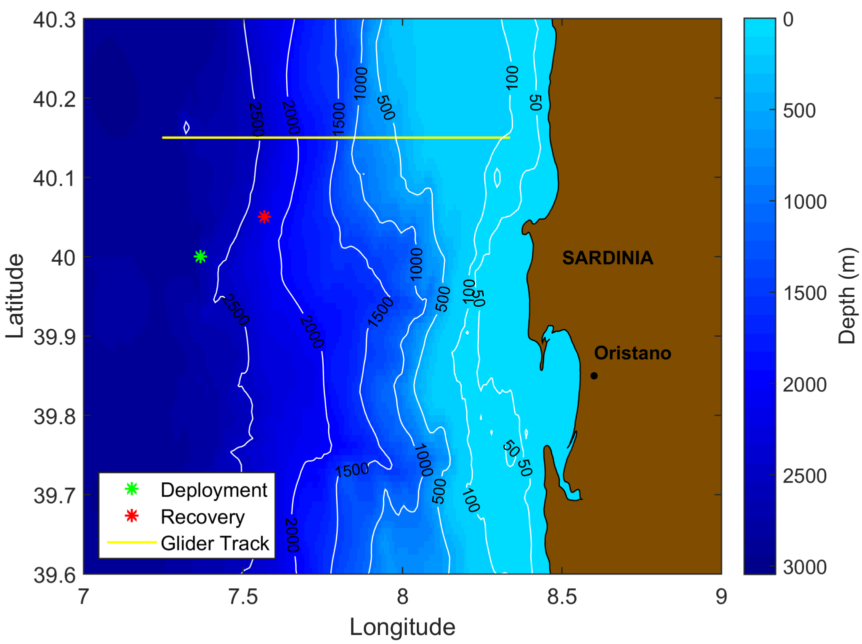

Figure 2. Bathymetry off the west coast of the Island of Sardinia showing the glider's deployment (green star) and recovery (red star) locations, as well as *Clyde's* pre-assigned track.

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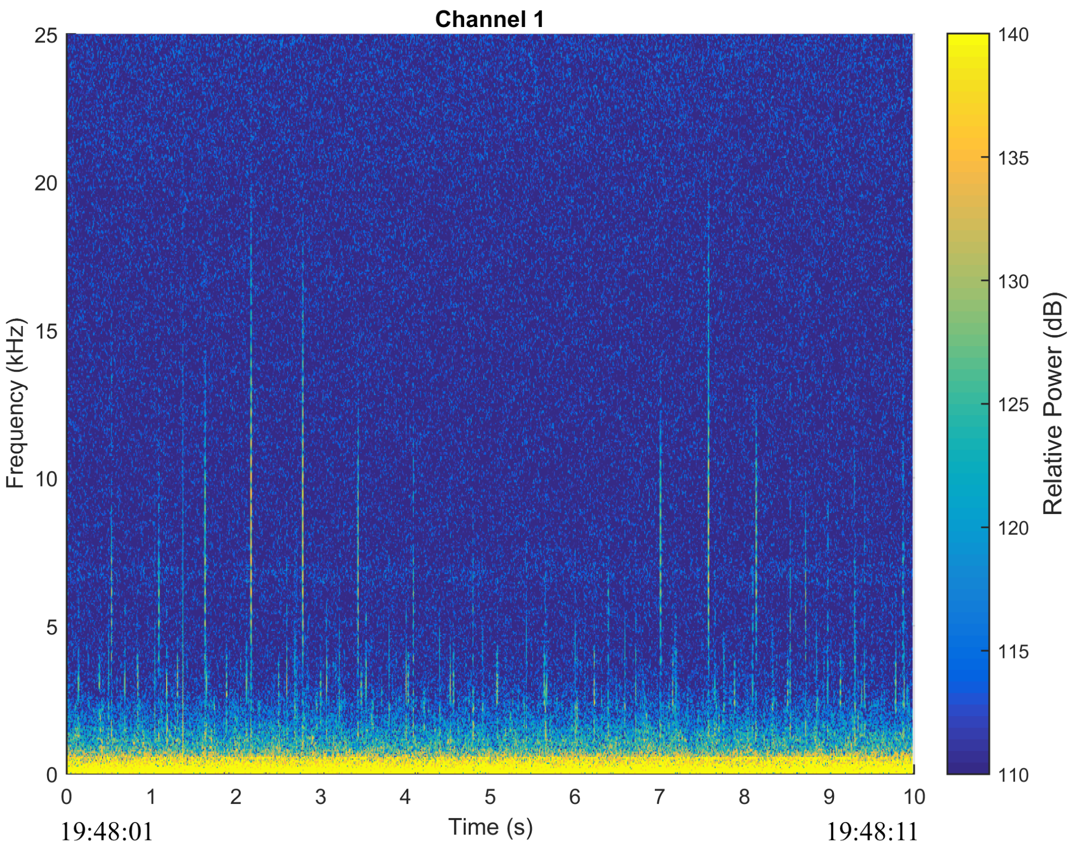

Figure 3. Spectrogram of 10 s of data from channel 1 of file 06 showing sperm whale regular clicks (narrow vertical bars). Time stamps are local time (CEST) on 09 June 2014. The relative power corresponds to the power in dB minus the hydrophone sensitivity of -159 dB re 1 μPa/V.

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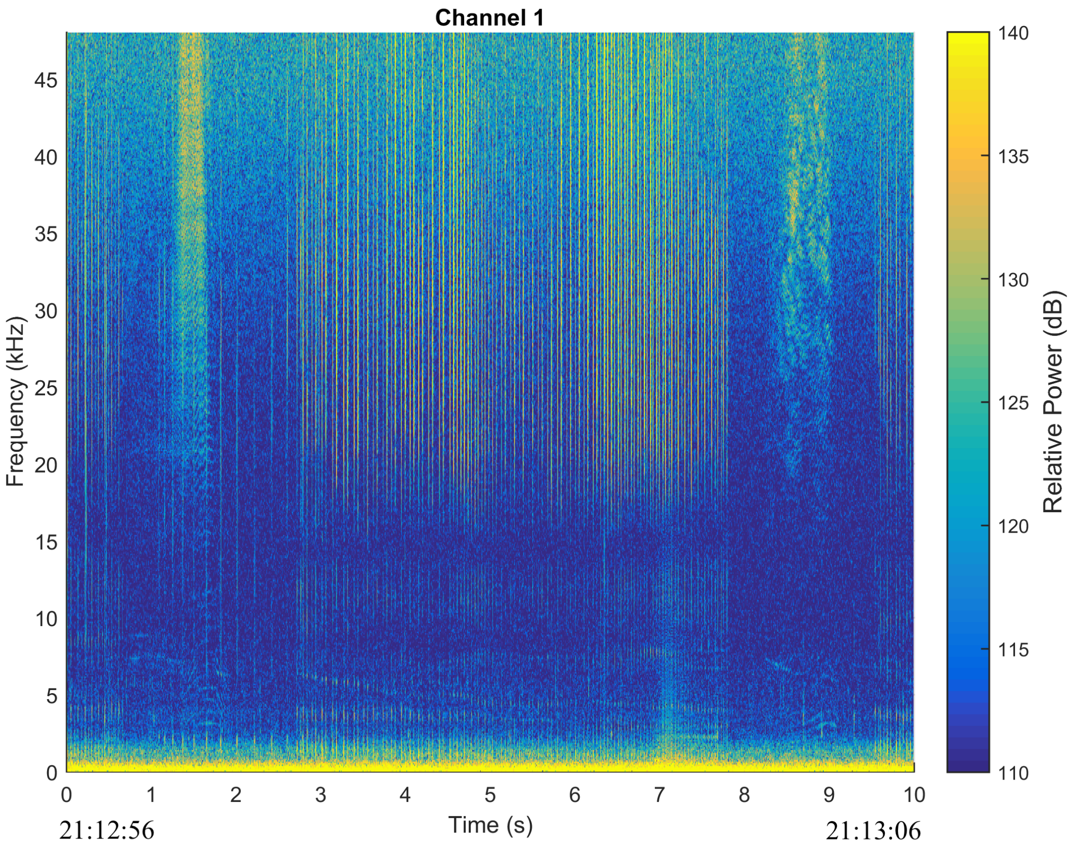

Figure 4. Spectrogram of 10 s of data from channel 1 of file 06 showing dolphin clicks (vertical bars mostly above 15 kHz between 2.8 and 8 s), burst pulses (mostly above 15 kHz between 1-2 s and 8.4-9 s), and whistles (roughly horizontal features between 1-10 kHz). Note that the frequency range is different from the previous plot. Time stamps are local time (CEST) on 09 June 2014. The relative power corresponds to the power in dB minus the hydrophone sensitivity of -159 dB re 1 $\mu\mathrm{Pa/V}$.

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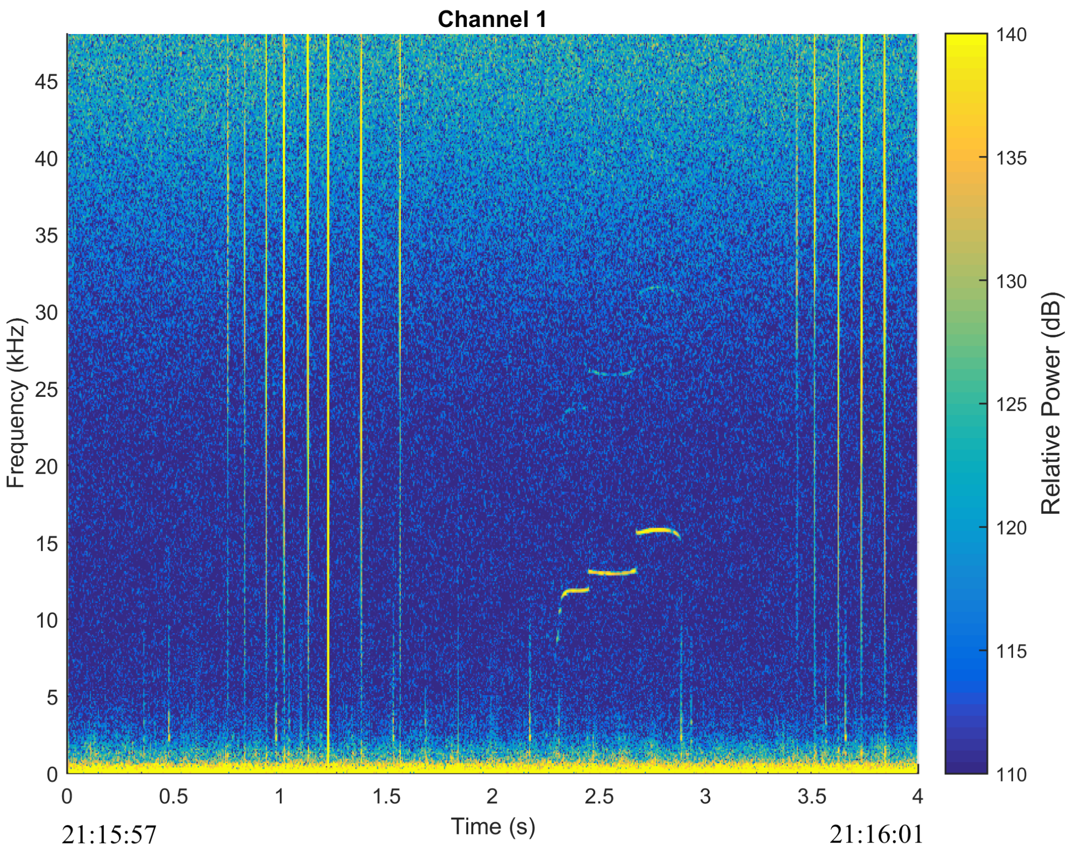

Figure 5. Spectrogram of 4 s of data from channel 1 of file 06 showing sperm whale clicks and dolphin whistles (horizontal features between 2.3-3 s), as well as electrical system noise (glitch - strong vertical bar between 1.0-1.5). Time stamps are local time (CEST) on 09 June 2014. The relative power corresponds to the power in dB minus the hydrophone sensitivity of -159 dB re 1 µPa/V.

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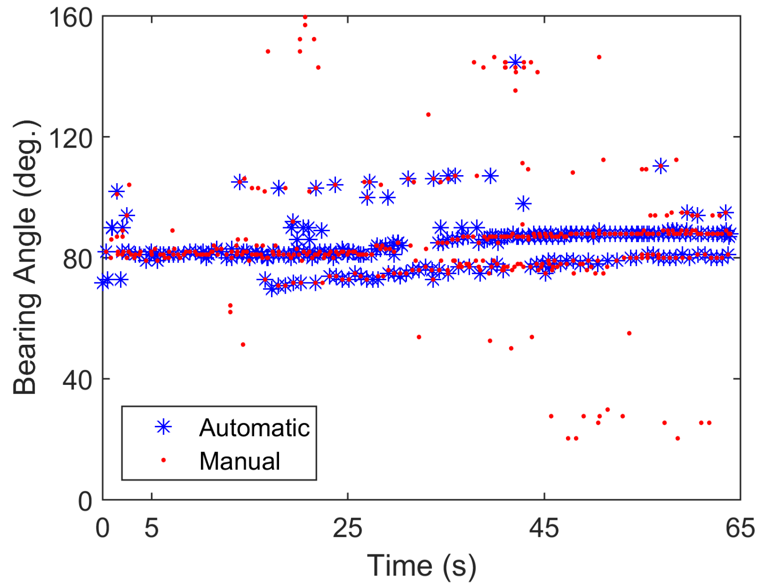

Figure 6. Estimated bearing angles from automatic (blue stars) and manual (red dots) detections made just over 1 minute from the beginning of file 06.

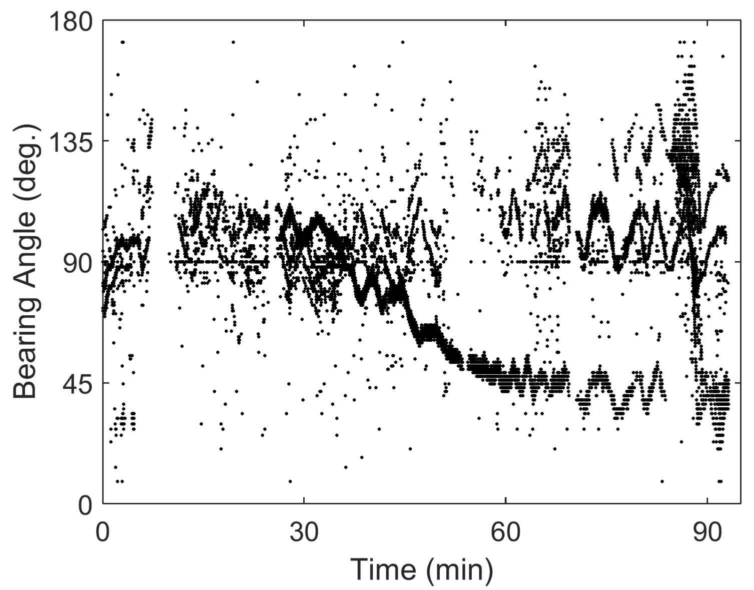

Figure 7. Estimated bearing angles from all clicks detected in file 06.

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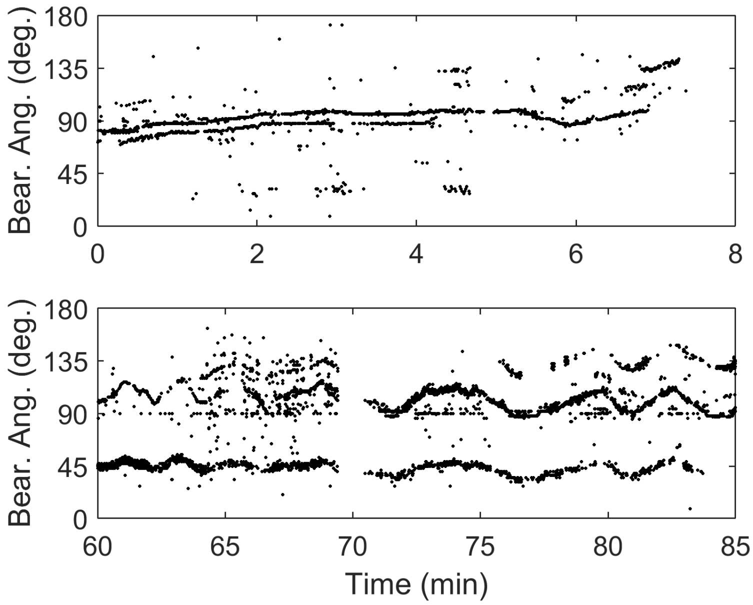

Figure 8. Estimated bearing angles from automatic detections of file 06, for two smaller time windows.

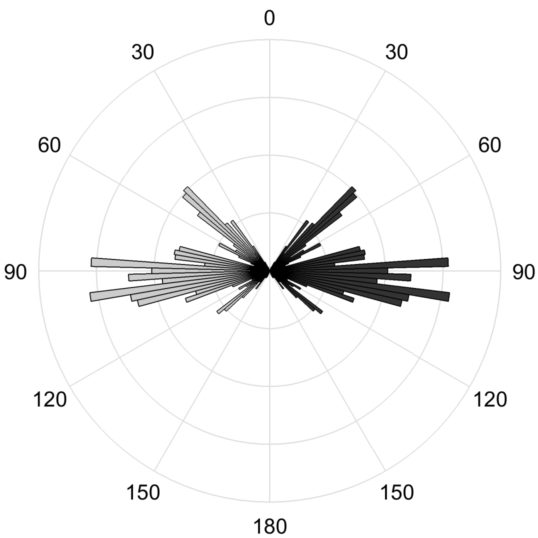

Figure 9. Estimated bearing angles from automatic detections of file 06 plotted in polar form. Angles are relative to the axis of the glider, but glider heading is not accounted for.