Application of Density Estimation Methods to Datasets Collected From a Glider

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LONG-TERM GOALS

This project started in August 2013 and has as long-term goal the extension of population density estimation methods based on detections of marine mammal vocalizations to datasets collected by an unmanned moving platform. The moving platform under consideration is an electric underwater glider, which offers the potential of surveying a larger area than a fixed, single sensor while measuring the environmental conditions. The glider also has the potential to surface and transmit data using a satellite modem. Moreover, fitting the glider with two hydrophones, one on each wing can provide bearings to vocalizing animals. Density estimation from glider datasets will be developed from recordings made during sea trials in Italy in June 2014, August 2015, and the sea trial currently taking place in the Gulf of Mexico. The datasets will be analyzed for the presence of specific species that occur in the locations where the acoustic data was recorded. For example, the data recorded off the west coast of Sardinia, Italy, contained echolocation clicks of sperm whales (*Physeter macrocephalus*). This species is also known to occur in the Gulf of Mexico where data is currently being collected.

OBJECTIVES

The objective of this research is to extend existing methods for cetacean population density estimation from fixed passive acoustic recordings to datasets recorded from an underwater glider. The current project will benefit from data collections with combined environmental sampling provided by the glider's Conductivity, Temperature and Depth (CTD) sensor. Because gliders offer low-cost, long-duration, all-weather, remote-area operation, it is our goal to extend its usability to population density estimation surveys offering another tool to aid those involved in marine mammal research, monitoring, and mitigation planners.

APPROACH

Approach to Estimating Population Density from a Glider Dataset
A first generation Slocum (Teledyne-Webb Research) electric glider (Webb *et al*., 2001) owned by Portland State University's Northwest Electromagnetics and Acoustics Research (NEAR) Laboratory was fitted with two High Tech, Inc., hydrophones (model # HTI-92-WB). The hydrophones were mounted one on each wing of the glider spaced 3 feet (ca. 0.9 m) apart, thus giving the possibility of estimating the direction information of the marine mammal/acoustic source. The glider, named *Clyde*, can dive to a maximum depth of 200 meters, driven in a saw-tooth vertical profile by adjusting its buoyancy. The methodology employed in this study to estimate population density of marine mammals is based on the works of Zimmer *et al*. (2008), Marques *et al*. (2009), Küsel *et al*. (2011), Ainslie (2013), and more recently, "Cetacean density estimation from novel acoustic datasets by acoustic propagation modeling" (Küsel *et al.*, *submitted*). In the latter, this study's PIs investigated the effects of call bandwidth, multipath arrivals, and the choice of detection range in the population density estimation. An alternative approach was also suggested to estimate click signal-to-noise ratio (SNR) by calculating ray arrivals, adding noise levels and frequency dependent attenuation, and convolving the result with a click source function. Because such approach considers the entire click bandwidth, the average probability of detection of thousands of click realizations, and hence the density estimate, were shown to match more closely expected probability of detection and density of a synthetic data set.

A revised flowchart with required steps for a single-sensor, cue-counting, density estimation approach, where a cue has been defined as a clicking event (Küsel *et al*., 2011), is shown in Figure 1.

Fitting the glider with two recording sensors, instead of one, provides the opportunity to investigate other density estimation modalities (Thomas and Marques, 2012), such as individual or group counting. In this sense, bearings to received sounds on both hydrophones will be computed in a similar way as has been presented by Lewis *et al*. (2007) using a towed hydrophone array. The analysis of one and two sensors will also provide data with which to compare different density estimation methodologies. The possibility of constructing whale tracks from bearings can provide extra information not only on animal counts, but also on calling intervals. Knowledge of calling intervals can help estimate the cue production rate. In summary, the extra information derived from having two sensors as opposed to a single one will be examined in terms benefits to density estimation studies.

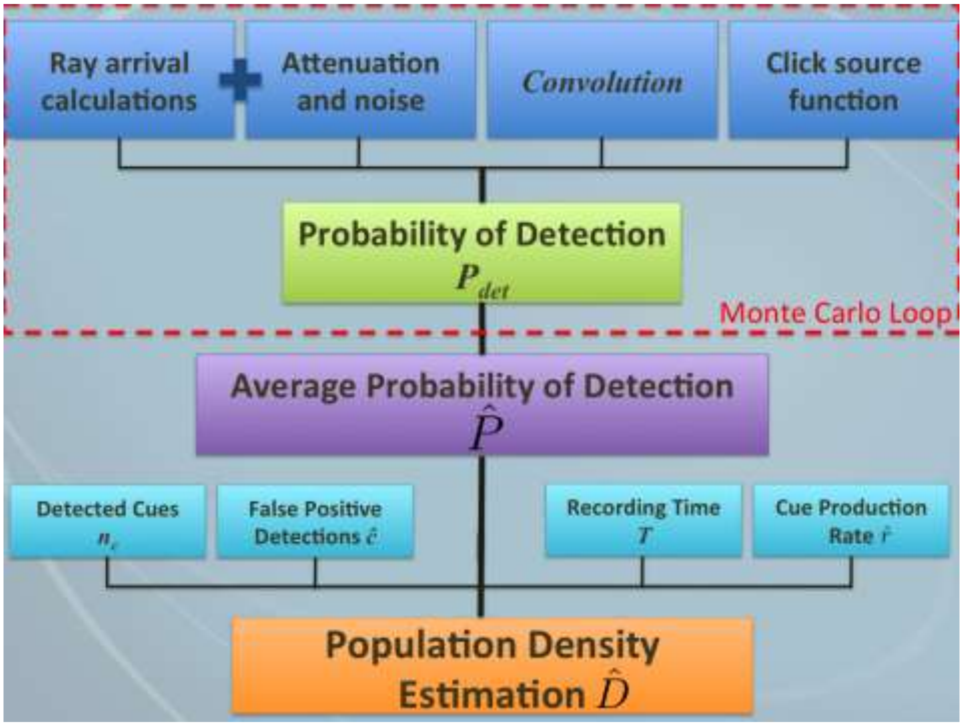


Figure 1. Updated flow chart with the newly suggested steps for estimating population density of a species from single sensor datasets (Küsel et al., submitted).

The choice of target species will be largely dependent on the dataset obtained after a glider mission. Systematic compilation of marine mammal data present in the area, noting the observation time of year, from literature, stock assessments, visual observations, and acoustic sensors can aid in realizing what species will be expected during a given field experiment. The required animal acoustic behavior will come from information available in the literature and from available acoustic tag data sets. From literature information on the target species' diving behaviors when emitting sounds, a 3D random distribution of simulated animals will be created taking into account their orientations with respect to the glider. The probability of detecting a cue as a function of distance from the hydrophone is necessary to estimate a detection function for each call type, or for each species. This can be accomplished by measuring the signal-to-noise ratio (SNR) of detected calls from a subsample of the data set and then estimating the proportion of those within an SNR bin that were detected. We further simulate the SNR of randomly distributed calls along the glider track by calculating ray arrival information, adding ambient noise levels from the data set and frequency-dependent attenuation to it and convolving with a click source function. The SNR of each realization is then computed from spectrograms of each realization, as is done with the data set to build the detection function.

WORK COMPLETED

Acoustic Recording System:
An inexpensive, off-the-shelf linear PCM recorder manufactured by Tascam (model # DR-07 MKII) was adapted to fit inside the glider's science bay. The data acquisition system offers a sample frequency of 96 kHz, and is capable of recording two channels of data at 16-bit resolution.

On its first generation, the acoustic acquisition system was equipped with enough batteries (8 AA alkaline) to record data continuously up to 24 hrs. to a single 32 GB micro-SD card. The system was tested during the REP14-MED cruise described below. One of the drawbacks of this system was the inability to program the recording unit in advance. Slocum gliders should be held under vacuum for at least one day prior to deployment to make sure there are no leakages inside the vessel. With the original design, the Tascam was turned on, placed inside the glider, and vacuum was held for only one hour prior to glider deployment. Therefore, a few improvements were planned after the first test field.

The second generation of the recording system was part of a senior undergraduate project. The off-the-shelf Tascam recorder was linked to a low power consumption microcontroller so that a recording schedule could be programmed well in advance and the unit placed inside the glider on sleep mode. More data storage was also added to the system, amounting to four 32 GB micro-SD cards. In total the recording capacity of the Tascam increased to 96 hrs. of continuous recording. The improved system was tested during the GLISTEN15 Cruise (described below) and is also currently being used to record data in the Gulf of Mexico.

Data Collection:
REP14-MED Cruise: The sea-trial REP14-MED (Recognized Environmental Picture – Mediterranean) took place 6-26 June 2014 in the Sardinian Sea (Western Mediterranean) and was part of a series of multinational sea experiments dedicated to *Rapid Environmental Assessment*. Several gliders (2 ACSA Sea Explorers, 3 Kongsberg Sea Gliders, and 12 Teledyne-Webb Slocum Gliders) were deployed from the NRV Alliance (NATO-STO Centre for Maritime Research and Experimentation, formerly NATO Undersea Research Centre) and positioned perpendicular to the coast at regular intervals in order to collect oceanographic and/or acoustic data (Fig. 2). Each glider dove along its own transect back and forth from deep to shallow water for approximately 2 weeks, until they were recovered.

The glider *Clyde* was deployed at (40° 00'N, 07° 22'E) on June 9, on deep waters on the northern most transect shown on the right panel of Fig. 2. This opportunistic experiment provided a chance to test the glider's operation at sea as well as the first generation of the off-the-shelf acoustic acquisition system adapted to fit inside the glider. However, communications with *Clyde* were lost about one day after deployment. After almost a day without communications, on June 11 at about 21:20, *Clyde* was located through the *Argos* satellite system. Such satellite tracking system is an emergency feature of Slocum gliders in case communication through *Iridium* fails. However, it only allows for location information of the instrument equipped with its system. It was sighted at 17:36 on June 12 at (40° 03'N, 07° 34'E) and recovered shortly after, at 17:47, by RV *Planet*, which was also participating in the sea trial.

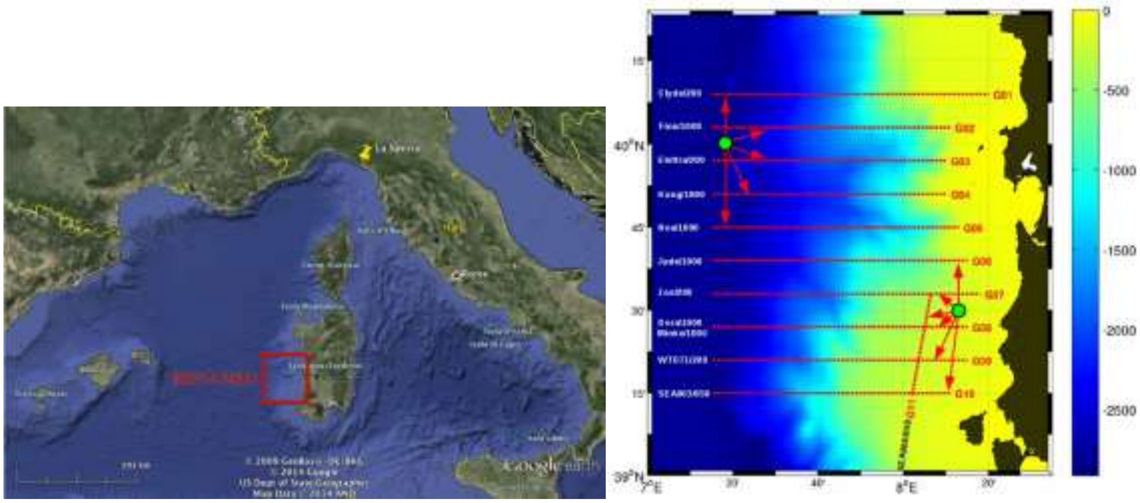


Figure 2. Left: Image showing the area of REP14-MED sea-trial (red box) in the context of the Western Mediterranean Sea and the island of Sardinia, Italy. Source: Google Earth. Right: Tracks of each of the 12 gliders deployed during the experiment. Green dots represent deployment sites. Source: REP14-MED Cruise Report.

A total of 15 acoustic files corresponding to approximately 23 hrs. of continuous data, were recorded. Note that at least a few hours of recordings were made while the glider was still above the water, prior to deployment. However, the deployment occurred in deep waters (deeper than 1500 m), which are good environments for marine mammals such as sperm whales and beaked whales. Files containing dive and CTD information from *Clyde* were lost since they were renamed with erroneous time stamps due to a malfunction of one piece of its hardware. The loss of communication was also diagnosed to the malfunction of the same hardware piece, namely the persistor.

After the experiment in Italy and in order to prepare the glider for future deployments, it was sent back to the manufacturer for proper diagnosis, fixing and calibration of its systems. Both persistor and flash memory card were replaced.

GLISTEN15 Cruise: The GLISTEN15 (Glider sensors and payloads for tactical characterization of the environment 2015) sea trial was carried out from August 26th to September 9th, 2015, in the Capraia Basin, Tyrrhenian Sea, Italy (Fig. 3). The acoustical trial was carried out with the aid of the NRV Alliance (NATO-STO Centre for Maritime Research and Experimentation, formerly NATO Undersea Research Centre), and had as objective to develop remote sensing capabilities using underwater gliders as the main platform.

During this second opportunistic experiment, which the PI's were invited to participate, *Clyde* flying operations could be tested once again after having undergone major repairs. The second generation of the acoustic acquisition system was also tested during this experiment. The experimental area covered shallow waters of less than 200 m. Furthermore, an active sound source was played during most of the experiment. Therefore, marine mammal activity was not expected during the experiment.

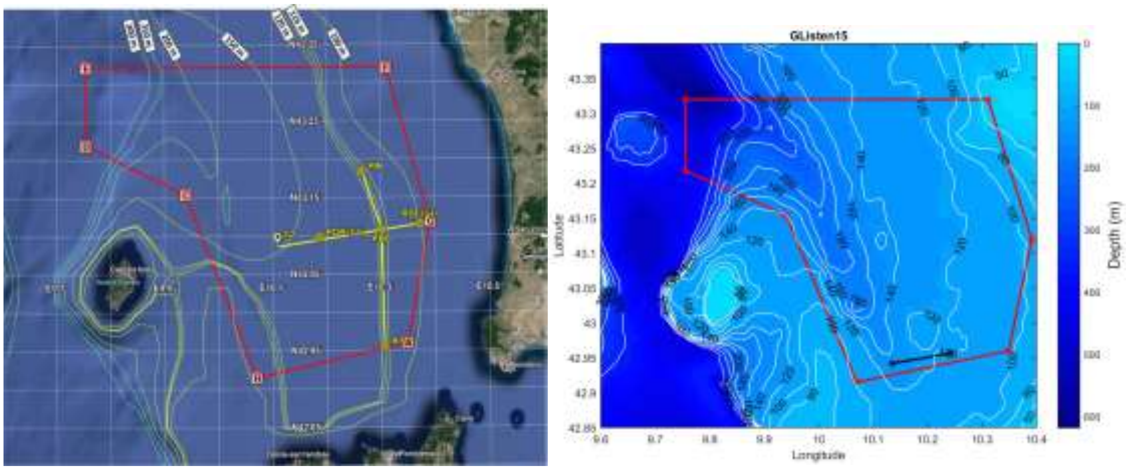


Figure 3. Left: Capraia basin with experimental area delimited by the red polygon. Yellow tracks correspond to ship track, with deployment points for moored instruments. Source: GLISTEN15 Cruise Report. Right: Planned track (black line on bottom of red polygon) for glider Clyde in the experimental area.

Unfortunately, *Clyde* never made it to the planned track (Fig. 3). Two days after being deployed it started aborting its mission because of failure in the *Argos* satellite communication system. It was then promptly recovered and a water leak was detected inside the vehicle coming through the digifin, which caused the *Argos* failure. Once more, the glider was sent straight back to the manufacturer to fix the leaking digifin.

The new acoustic recording system also showed a strange behavior. It had been programmed to record data for 4 hours during the morning and 4 hours during the early evening on a schedule of 30 minutes on, 15 minutes off. However, recording stopped after two days, the first one being still inside the ship due to a delay in its deployment. Recorded acoustic data is still being processed.

Gulf of Mexico Experiment, September/October 2015: As soon as the leak problem was fixed, *Clyde* was shipped straight to Slidell, LA, for a 2-week mission in the Gulf of Mexico (Fig. 4). The Glider was deployed close to the north point of the experimental area (Fig. 4). Data will be analyzed for the presence of marine mammals, specially sperm whales, and a comparison will be made with recordings on the fixed moorings.

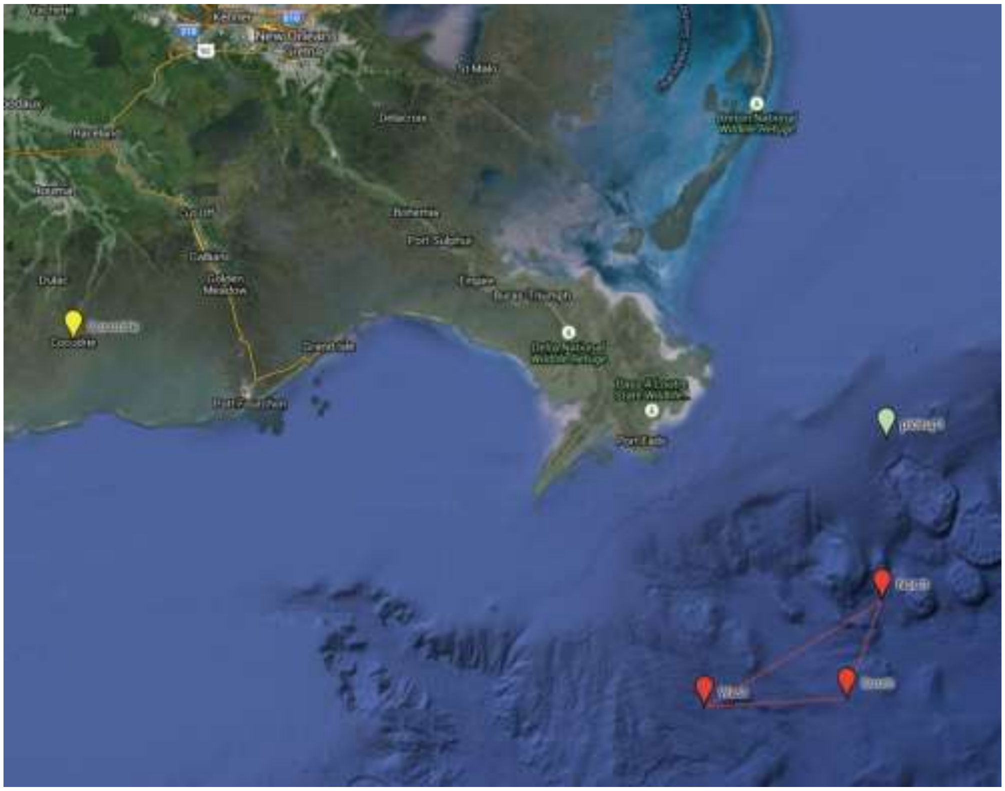


Figure 4. Experimental area in the Gulf of Mexico off of Louisiana. The red pins correspond to the locations of fixed moorings with acoustic recorders. Glider tracks are then the paths connecting the moorings.

RESULTS

The experiment off the west coast of the island of Sardinia in June 2014 was very useful to identify the glider's main operational issue and to evaluate the acoustic recording system for the quality of the data and ease of operation.

During the 2014 sea trial the glider presented hardware malfunction after its first day in the water performing the mission and therefore had to be brought back on board. Some acoustic data were recorded but was limited to a few hours rather than a full day of recording. Following the seat trial, major system repairs were carried out. A new persistor and flash card were installed and operations were reverted back to normal, including running bench simulations. However, during the sea trial in August/September 2015 another issue arose with the glider and it had to be recovered early and less acoustic data was recorded than originally planned. The glider had to be sent back to the manufacturer for fixing a water leakage issue. Currently, it is flying in the Gulf of Mexico without any issues and collecting acoustic data in deep waters.

Even though *Clyde* only recorded acoustic data for less than a day during the first sea trial in Italy, it was able to record Sperm whale echolocation clicks (Figs. 5 and 6) while diving in waters deeper than 1500 m. Such deep waters are known to be good habitats for species such as Sperm and Beaked whales. Unfortunately, files containing dive and CTD information were lost, and/or have been renamed with erroneous time stamps due to the hardware malfunction.

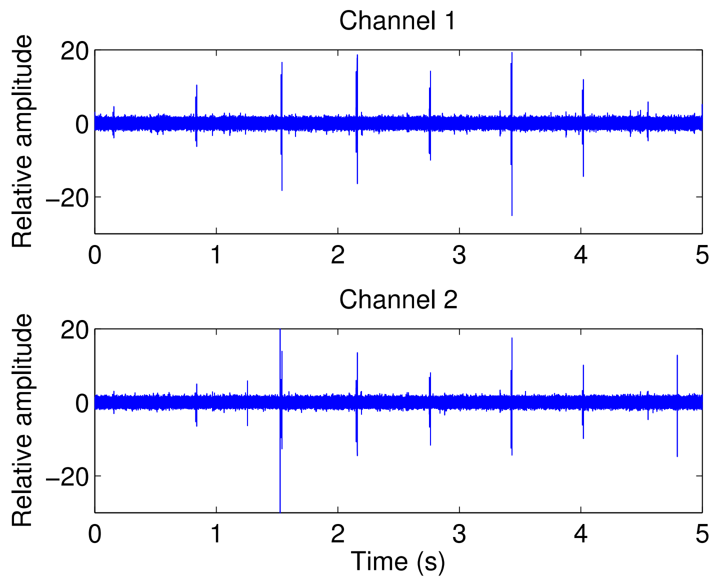
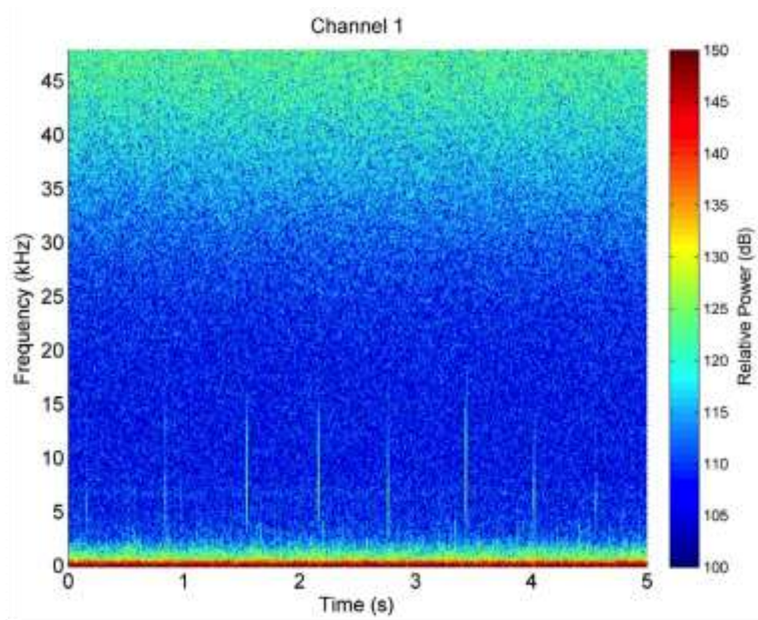


Figure 5. Waveform from both channels recorded of the west coast of Sardinia, Italy, corresponding to 5 seconds of data and showing Sperm whale echolocation clicks.



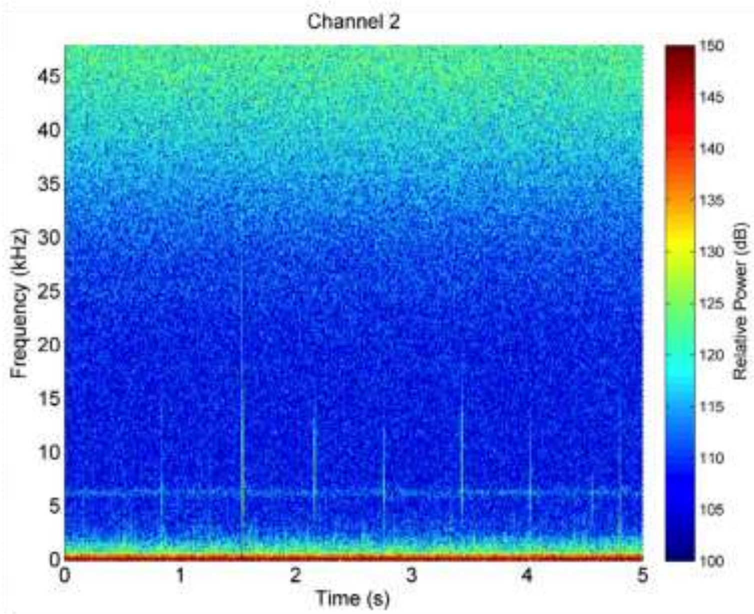


Figure 6. Spectrogram of channel 1 (top) and channel 2 (bottom) corresponding to the 5 seconds of data presented in Fig. 5. Sperm whale clicks are evident between about 3 to 15 kHz as thin vertical lines.

Further analysis of the 2014 data consisted in cross-correlating clicks recorded on both data channels for the estimation of the direction of clicks. By estimating the cross power spectrum, or cross-correlation, between both channels the time lag of a click received at both hydrophones can be realized. By assuming a nominal sound speed of 1500 m/s in the ocean and taking the hydrophone separation at 0.9 m, it is found that the highest expected time lag between arrivals of a click on both hydrophones is equivalent to 0.6 ms. The high sampling frequency with which the data was recorded provides good time resolution ($\Delta t = 1$ ms) at such small time scale. Therefore, in order to estimate the cross-correlation, a time window of 0.02 s (or 20 ms) in duration is chosen. Such short time window guarantees that individual clicks are sampled. The time difference of arrival, or correlation lag (τ), was then used on the formula below to find the direction the click came from, keeping in mind the right-left ambiguity of the estimate. The direction angle (θ) was calculated by:

$$\cos\theta = \frac{\tau c}{L}$$

where, c is the sound speed in the ocean (1500 m/s), and L is the hydrophone separation distance (0.9 m).

In order to have ground truth detections to compare against automatic detections, human analysts manually annotated clicks amounting to over 5 minutes of data from different segments. For each click detected/annotated a bearing angle was calculated. Figure 7 shows bearing angle calculations for two segments from the same data file, the first at the beginning (top plot) and the other at more than one hour into the recording (bottom plot). In one-minute worth of estimates, the presence of “tracks” seems clear. Red stars on the bottom plot correspond to clicks with higher frequency content. They could mean that animals were closer to the recording sensor.

Continuing analysis is making use of automatic detectors in order to construct bearing versus time plots of longer segments of the data. Insights from this spectral analysis are expected to aid in population density estimation studies by providing further information on animal movement and location.

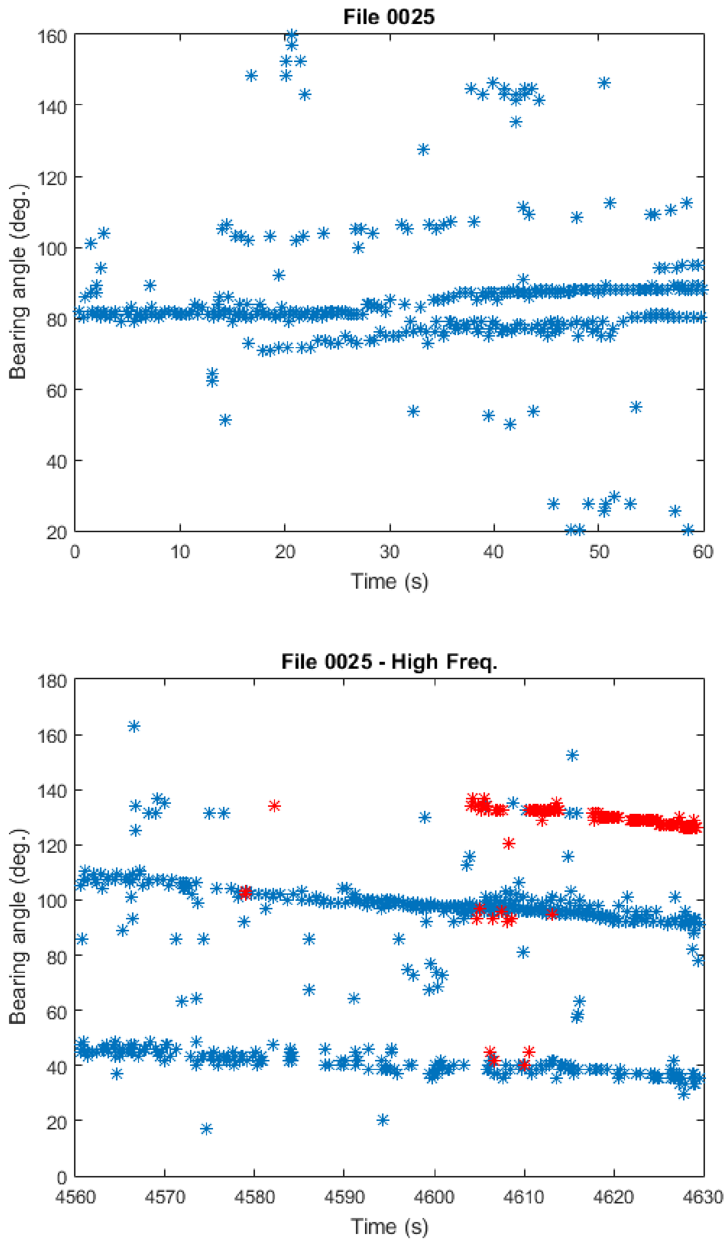


Figure 7. Estimated direction angles from Sperm whale clicks taken from two different segments of data recorded off the West coast of Sardinia, Italy, in June 2014. Top plot corresponds to 1 min of data in the beginning of the file. Bottom plot corresponds to 1:10 minutes of data at a later time in the same file. Possible whale tracks seem evident from these plots. Click detections were performed manually in these examples.

Overall, the operation of the off-the-shelf acquisition system during the first sea trial prompted the development of the second-generation system with more sophisticated electronics. The second generation acoustic recorder, also based on the Tascam recorder, now uses a microcontroller to offer the possibility of being turned on well in advance of a mission and scheduled to start recording at a future date when in the water. It also offers more storage capacity, four times the initial one. This new system was tested in shallow waters of the Tyrrhenian sea, Italy, and is currently recording data in the deep waters of the Gulf of Mexico.

IMPACT/APPLICATIONS

We expect to develop a density estimation method that can be applied to acoustically-equipped ocean gliders, making data from such gliders applicable for a wider range of applications – before-during-after exposure studies, seasonal distribution measurement, population estimates, etc. The application of recently developed density estimation methods to different data sets and marine mammal species also provides opportunities to improve the methodology and make it more general. By improving our capabilities for monitoring marine mammals we hope to contribute to minimizing and mitigating the impacts of man-made activities on these marine organisms.

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PUBLICATIONS

Küsel, E.T., Siderius, M., and Mellinger, D.K., "Single-sensor, cue-counting population density estimation: Average probability of detection of broadband clicks," manuscript submitted for publication to the *J. Acoust. Soc. Am.*