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A framework for cetacean density estimation using slow-moving autonomous ocean vehicles

Len Thomas, Danielle Harris

Centre for Research into Ecological and Environmental Modelling, University of St Andrews
The Observatory, Buchanan Gardens, St Andrews Fife, KY16 9LZ, Scotland, UK
phone: (0)1334-461801 fax: (0)1334-461800 email: len.thomas@st-andrews.ac.uk

Holger Klinck

Center for Conservation Bioacoustics, Laboratory of Ornithology, Cornell University

David K. Mellinger

Cooperative Institute for Marine Resources Studies, Oregon State University

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Also in collaboration with: Jay Barlow

NOAA Southwest Fisheries Science Center, 8901 La Jolla Shores Drive, La Jolla CA 92037

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LONG-TERM GOALS

In this project, which started in April 2015, we focused on cetacean density estimation using autonomous underwater vehicles such as ocean gliders and profiling floats. These instruments are of particular interest to the Navy and have the potential to play a key role in future marine mammal monitoring efforts. The major advantage of gliders and other autonomous vehicles over prior methods is their ability to provide both spatial and temporal coverage of an area during a survey.

Our goal was to develop a general framework for estimating cetacean density from data collected by autonomous ocean vehicles. We investigated key aspects of survey design, data collection and data analysis, leveraging already-funded projects that collected data from profiling gliders to form case studies. Data from three different Navy-relevant locations (Gulf of Alaska, Mariana Island Range Complex, Hawaii Range Complex) were utilized. We selected four species for analysis: a baleen whale, two deep diving odontocetes and a delphinid. For each species and site, we initially planned to demonstrate how the general framework could be applied to produce estimates of animal density, or call density if call rates were needed for the method but not available.

One key component of the framework was to estimate the probability of detecting vocalizations on the autonomous vehicles as a function of range. To do this, we utilized the tracking abilities of the hydrophones at the US Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) and the Southern California Offshore Range (SCORE) during additional glider/profiling float deployments, which took place in June 2010 (AUTEC) and Dec 2015 (SCORE). However, relying on the instrumented ranges necessarily restricts the inferences about density that can be made in other locations; therefore, we also undertook an additional experiment in July 2016 to estimate glider detection probability in a non-instrumented area, using an ad-hoc array of non-profiling drifting sensors.

OBJECTIVES

The overall goal was to develop a general framework for estimating cetacean density from data collected by autonomous ocean vehicles such as ocean gliders and floats, taking into account species' acoustic and behavioral differences and environmental variation. We identified five primary objectives, four of which made use of data from previous or planned glider/float deployments; in the fifth we conducted an additional field experiment to estimate the probability of detecting cetacean vocalizations from a glider without the requirement for a dense array of fixed hydrophones.

Our planned objectives were:

1. Evaluate whether ocean glider data can be analyzed in a design-based framework using surveys done as part of an existing project in three areas of naval interest (Gulf of Alaska, Mariana Island Range Complex, Hawaii Range Complex). This objective does not apply to floats as they cannot be steered along designed survey tracks.

2. Quantify ocean glider/float survey effort and evaluate encounter rates of example species at the same three areas of naval interest. The example species aimed to include at least one deep diving odontocete (sperm or beaked whale), one shallow-diving delphinid, and one baleen whale.

3. Develop a methodology for estimating the probability of detecting cetacean vocalizations on ocean gliders/floats using data collected as part of existing projects at AUTECH and SCORE.

4. Estimate population densities, or call densities if average call rates are needed but not available, of example species at the three areas of naval interest using ocean glider data.

5. Develop an experiment that does not rely on a large Navy test range to estimate a species' probability of detection by an ocean glider. Perform a test at or close to SCORE and compare results with detection probability estimates derived using the SCORE array.

APPROACH

This project leveraged the following realized ocean glider deployments:

- a 1-week deployment of two gliders and a profiling float at AUTECH in June 2010.
- a 4-week deployment in the Mariana Island Range Complex (MIRC) in October 2014 using a single glider and in February 2015 using two gliders;
- a 4-week deployment in the Hawaii Range Complex (HRC) in January 2015 using a single glider;
- a 4-week deployment in the Gulf of Alaska (GOA) in July 2015, also using a single glider; and
- a 2-week deployment of one glider and two profiling floats at SCORE in winter 2015.

We also conducted our own dedicated 2-week deployment in July/August 2016, where one glider, one profiling float and an array of non-profiling drifting instruments were deployed in the Catalina Basin (discussed further below).

To achieve the primary objectives, we have evaluated all deployment tracks from the GOA, HRC, and MIRC sites and have run simulations to assess whether ocean glider data are suitable for design-based analyses, i.e., the degree to which the planned track lines were adhered to. Furthermore, an analysis has been conducted to demonstrate the interaction between glider movement and animal movement, and the potential effects of movement on detection probability estimation, which may lead to bias in eventual density estimates.

Cetacean detection records for all sites were produced as part of other projects. Using these results, example species were selected and encounter rates for these species calculated at the GOA, HRC, and MIRC sites. A literature review was conducted to see whether encounter rates of the example species could be compared with encounter rates from previous visual surveys in

these areas. Finally, using the estimated encounter rates, we estimated the required glider survey effort in these naval areas of interest to achieve density estimates with a reasonable level of precision. These estimates will aid the design of future surveys in these areas for continued monitoring. Typically, density estimates with a coefficient of variation of less than 0.2 are desirable (Buckland *et al.*, 2001). Encounter rates for profiling floats were also estimated from the AUTEK, SCORE and Catalina datasets.

Data collected at AUTEK have been used to develop a method to estimate the probability of detecting vocalizations on an ocean glider/profiling float. For some species, the range hydrophones could be used to localize individuals, effectively setting up detection trials for the ocean glider/profiling float, which could then be modelled using a logistic regression approach (similar to Marques *et al.*, 2009; Kyhn *et al.*, 2012). A simulation approach was also implemented using existing acoustic tag data combined with propagation modelling (extended from Gkikopoulou, 2018, and similar to approaches used in Marques *et al.*, 2009 and Küsel *et al.*, 2011). The original aim was to then apply the resulting detection function (a statistical model describing detection probability of vocalizations as a function of distance from an instrument) generated for the ocean glider to the surveys in the GOA, MIRC, and HRC to estimate call densities. For species for which suitable call rate data were available, animal densities were to be estimated.

We also conducted a field effort (in July/August 2016) that aimed to estimate detectability of cetaceans from a glider without using instrumented Navy range hydrophones. We used an acoustically-equipped glider and profiling float, which the Oregon State University team has developed in collaboration with other institutions, and autonomous non-profiling drifting hydrophones (DASBRs), which have been developed by Jay Barlow's team at NOAA/NMFS Southwest Fisheries Science Center (SWFSC). We co-deployed these sets of instruments in an area south and east of Santa Barbara Island in the Channel Islands archipelago, California. We initially explored using the drifting sensors in the same way as the range hydrophones; to localize vocalizations to then set up trials for the glider/float. However, we also explored an additional method using the Catalina data: in the event that localization and/or the subsequent trial-based method is not successful for a given species, an array of hydrophones can potentially be used in a spatial capture-recapture analysis (SCR, also known as spatially explicit capture-recapture, Borchers, 2012; Borchers *et al.*, 2015). The glider/float can be included as additional sensors to create a combined array, allowing estimation of detection probability for each type of sensor.

Note that support for the SWFSC contribution to the field effort was funded through a separate award (N0001416IP00059).

WORK COMPLETED

The project has achieved many of its original goals. Teamwork was facilitated in several ways: project members met approximately every fortnight via telephone/video conferencing, and most team members were present for part of the 2-week fieldwork period in July/August 2016. In addition, Co-PI Harris was based at both the Cooperative Institute for Marine Resources Studies

(CIMRS) in Newport, Oregon (Jul – Dec 2016) and the Bioacoustics Research Program, Cornell University, Ithaca, New York (Jan 2017 – July 2017), as part of the project management plan. In-person meetings with the majority of the project team present took place in June 2017, March 2018 and June 2018. Finally, part of the project team (Co PIs Harris and Klinck, and S. Fregosi) were able to meet in person during a research visit by Co PI Harris to Cornell University in May 2019.

Track evaluation (Task 1): This task has been completed and a manuscript has been submitted, with results from this task being combined with the finalized results of Task 2 for publication (Harris *et al.*, submitted). The initial results of Task 1 were presented in the FY2016 progress report, with updated results presented in the FY2019 progress report. The updated results (1) considered three simulated scenarios (a uniformly distributed animal population, one with a local density hotspot, and one with a broader density hotspot), (2) increased the number of survey design simulations to 500 iterations and (3) included a realized glider track from MIRC in the simulation, as well as realized tracks from GOA and HRC. Harris *et al.* (submitted) also included simulation results using the planned deployment tracks from the MIRC, GOA and HRC deployments, which could then be compared to the realized deployment tracks.

Quantifying survey effort (Task 2): This task has been completed. Results from the simulation study to demonstrate the interaction between glider movement and animal movement have been included in Harris *et al.* (submitted). These results were updated from the FY19 report by running the simulation for a slower glider speed of 0.25 cm/s. In addition, the project target species were selected in this task as fin whales, two beaked whale species (Blainville's and Cuvier's beaked whales), and Risso's dolphins. The literature review to determine the encounter rates from previous visual surveys in the regions of the MIRC, HRC and GOA deployments was also completed and compared to acoustic encounters in the same regions. The required level of effort to achieve a CV of 0.2 were calculated for each dataset and example results were presented in the FY19 report. Encounter rates for profiling floats were also estimated from the AUTEK, SCORE and Catalina datasets.

Estimating probability of detection (Task 3): This task has been completed. First, a comparison of fin whale detections across the SCORE array and mobile instruments and an investigation into differences in encounter rates on the glider due to flow noise were reported in the FY18 and FY19 annual reports. These results have been combined into a submitted manuscript (Fregosi *et al.*, under review).

Secondly, three methods to estimate detection probability from glider/float data have been demonstrated across the project. Glider and float data from AUTEK were analyzed, which resulted in the estimation of the probability of detecting Blainville's beaked whales on a glider using (1) the trial-based method described above and (2) a simulation-based approach. The simulation approach is an alternative method, which could be used in the event that other methods such as trial-based and SCR cannot be used. These initial glider detection probability results were presented in the FY18 annual report with updated results on the trial-based method being included in this report. Two manuscripts are being prepared for submission (Harris *et al.*, in prep; Gkikopoulou *et al.*, in prep). The multi-instrument deployment at Catalina (Task 5) has provided detections of Cuvier's beaked whales on the glider and profiling float, as well as the

DASBRs. Spatial capture recapture analysis using the glider/profiling float detections as well as those on the DASBRs has been demonstrated with initial results presented in the FY19 annual report and updated results reported here.

Estimating densities (Task 4): This task was partially completed during the project. A density estimation framework was determined for each target species and presented in the FY18 annual report. We anticipate being able to estimate animal and call density for three of the original target species: fin whales, Blainville's and Cuvier's beaked whales (due to the detection process for Risso's dolphins proving more time consuming than planned and additional work required on the SCR analysis). Further, due to differences in the acoustic systems used in the HRC, MIRC and GOA deployments compared to the systems used at AUTEK, SCORE and Catalina, it was not appropriate to transfer the detection functions estimated at these latter sites back to the HRC, MIRC and GOA datasets. Therefore, we have worked towards producing call and animal density estimates at AUTEK, SCORE and Catalina, as detailed below.

Field experiment (Task 5): This task has been completed. Details of the analysis of the Catalina DASBR dataset were given in the FY18 annual report. A manuscript detailing three-dimensional tracking of Cuvier's beaked whales from the DABSR array using a Bayesian state-space model has been published (Barlow *et al*, 2018). Further, the DASBR data have been combined with the glider/profiling float data in an SCR analysis to determine detection probability of Cuvier's beaked whales from the different instrument types, as discussed above.

Work under the NOAA Southwest Fishery Science Center portion of this project (Award Number: MIPR #N0001416IP00059) was completed in FY18. However, Co-PI Barlow continued to work with the other project members on analyses and publications throughout the duration of the project.

MAIN RESULTS

Track evaluation (Task 1):

The main conclusion from Task 1 is that, despite deviations from a planned survey track, simulated glider surveys contained low levels of bias when analyzed in a design-based framework (Table 1). Further, most of the predicted bias appears to be due to the initial design of the surveys (Table 2) so, in these cases, deviations from the trackline contribute minimally to the overall predicted bias. Finally, this analysis has demonstrated the utility of DSsim, an R software package (R Core Team, 2018) dedicated to assessing potential bias in distance sampling survey designs through simulations (Buckland *et al.*, 2015).

Table 1. Simulation results (n = 500) using three realized glider tracks (GOA 2015, MIRC 2014 and HRC 2014) and three types of simulated population. Values are mean percentage bias with the standard deviation of the bias given in parentheses. Median bias is also given in square brackets for comparison.

Scenario→ Survey↓	Population 1 (uniform density)	Population 2 (small hotspot)	Population 3 (large hotspot)
GOA	0.53 (14.0) [-1.09]	6.19 (13.9) [4.26]	6.89 (14.2) [7.06]
MIRC 2014	-0.08 (15.4) [-1.26]	-0.07 (14.9) [0.17]	-2.06 (15.9) [-3.48]
HRC	-1.36 (14.2) [-1.73]	2.22 (14.5) [2.35]	-7.22 (14.1) [-8.21]

Table 2. Simulation results (n = 500) using three planned glider tracks (GOA 2015, MIRC 2014 and HRC 2014) and three types of simulated population. Values are mean percentage bias with the standard deviation of the bias given in parentheses. Median bias is also given in square brackets for comparison.

Scenario→ Survey↓	Population 1 (uniform density)	Population 2 (small hotspot)	Population 3 (large hotspot)
GOA	-1.90 (12.5) [0.98]	4.26 (13.2) [5.84]	6.94 (13.2) [6.88]
MIRC 2014	-0.56 (14.9) [-0.50]	0.86 (15.7) [0.44]	-1.43 (14.4) [-0.84]
HRC	-0.92 (14.5) [-1.36]	3.05 (14.6) [2.21]	-6.98 (14.3) [-7.54]

Quantifying survey effort (Task 2):

These results demonstrate that animal movement cannot be ignored when considering slow-moving autonomous vehicles for animal monitoring, and density estimation methods should be selected accordingly (i.e., a cue-counting or snapshot-based approach, as outlined below). The analysis to quantify the potential effects of animal movement in a distance sampling survey using a glider was based on results from Task 5, which estimated Cuvier’s beaked whale swim speeds of 1.2 m/s. Glider speed data from the previous deployments were used in the analysis. Simulation software produced by Glennie *et al.* (2015) was extended to replicate a glider survey and was used to simulate two distance sampling surveys, where detection probability is not certain. The first simulation assumed that each survey transect took 4 hours to complete, covering 3.6 km, and animal movement was ignored. Based on 500 simulations, mean bias was 158.0% (standard deviation: 11.5%). A second simulation was based on a snapshot approach, which should remove bias caused by animal movement. In this case, the simulated glider data were analyzed in 1-minute snapshot time periods, where the glider only moved 15 m. As expected, mean bias was much reduced to -2.7% (s.d. 11.3%).

A comparison of visual surveys in the HRC, GOA and MIRC glider deployment areas with the completed glider surveys demonstrated the potential utility of gliders for density estimation surveys. Results presented in the FY19 annual report demonstrated that visual surveys may have low sightings rates of target species, resulting in density estimates with very high uncertainty i.e., coefficient of variation values greater than 1.0 (e.g., Bradford *et al.*, 2017). In contrast, acoustic encounter rates on gliders can be high. For example, fin whale encounters spanned 53% of the total recording time of the 33-day glider deployment at HRC. Using an adapted expression from Buckland *et al.* (2015), the total amount of monitoring effort required per species was estimated, assuming a density estimate with a target CV of 0.2 was desired.

$$K = \frac{K_0}{n_0} \cdot \frac{b}{\{cv_t(\bar{D})\}^2} \quad (\text{Eqn.1})$$

Where K is the required number of snapshots, K_0 is the number of snapshots from an existing pilot study, n_0 is the number of snapshots with detections from the pilot study, b is a multiplier (recommended to be set to 3 in Buckland *et al.*, 2001) and $cv_t(\bar{D})$ is the target CV of the density estimate.

Despite being subject to various assumptions about the acoustic encounters (detailed in the FY19 annual report), these calculations highlighted that acoustic surveys have the potential to reduce the effort required for density estimation surveys, given they can lead to higher encounter rates compared to visual surveys.

Estimating probability of detection (Task 3):

The noise analysis using the SCORE glider data showed that, in general, glider vertical speed had a positive relationship with spectrum levels below 40 Hz. However, the relationship of glider speed and flow noise was complicated, with multiple interactions with dive state and pitch, with a stronger relationship at 12 Hz. At 3 kHz, no relationship with vertical speed was observed. Results are presented in full in Fregosi *et al.*, (under review).

In the AUTECH Blainville’s beaked whale analysis, depth was retained as a significant covariate in the detection function model estimated using the trial-based method. Similar to the initial results presented in the FY18 annual report, both the click- and snapshot-based analyses suggest that detection probability at zero horizontal distance from the glider is not certain (Fig 1) and detection probability increased with glider depth. As expected, the probability of detecting beaked whales in a 1-min snapshot was generally higher than the detection probability of a single click at the same ranges. We note, however, that there is an initial increase in detection probability as a function of range in the snapshot data, which could be due to two reasons. First, this could be an artefact of a reduced sample size of observations at smaller distances; the rug plots in Fig. 1 show that there was a reduction of trials at distances less than 1000 m. Secondly, it is feasible that a foraging group of beaked whales in a 1-min snapshot period may be more detectable at larger ranges than expected due to their orientation and click beam pattern (e.g., see Hildebrand *et al.*, 2015, for a similar discussion). These results correspond to the acoustic behaviour and foraging ecology of Blainville’s beaked whales (e.g., Tyack *et al.*, 2006).

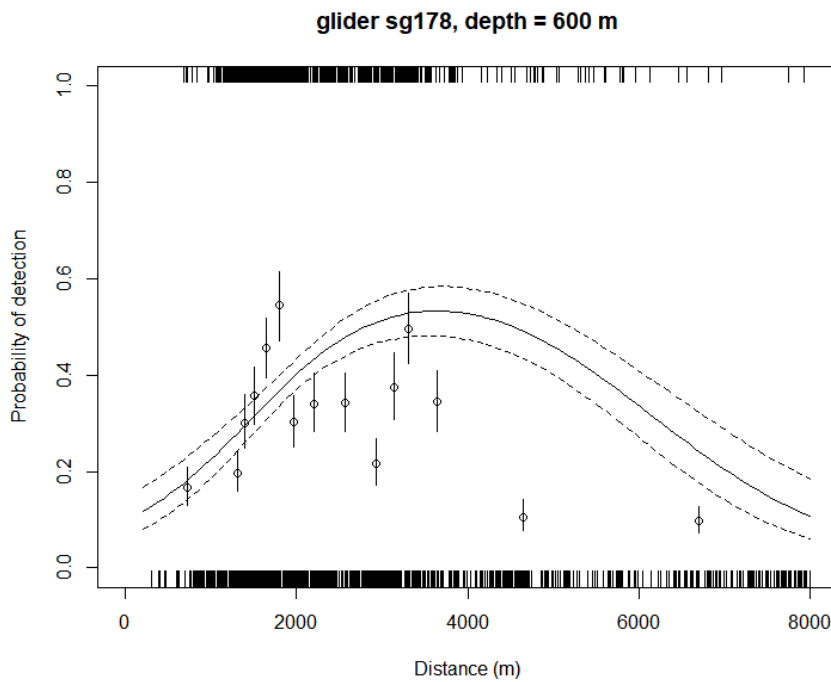
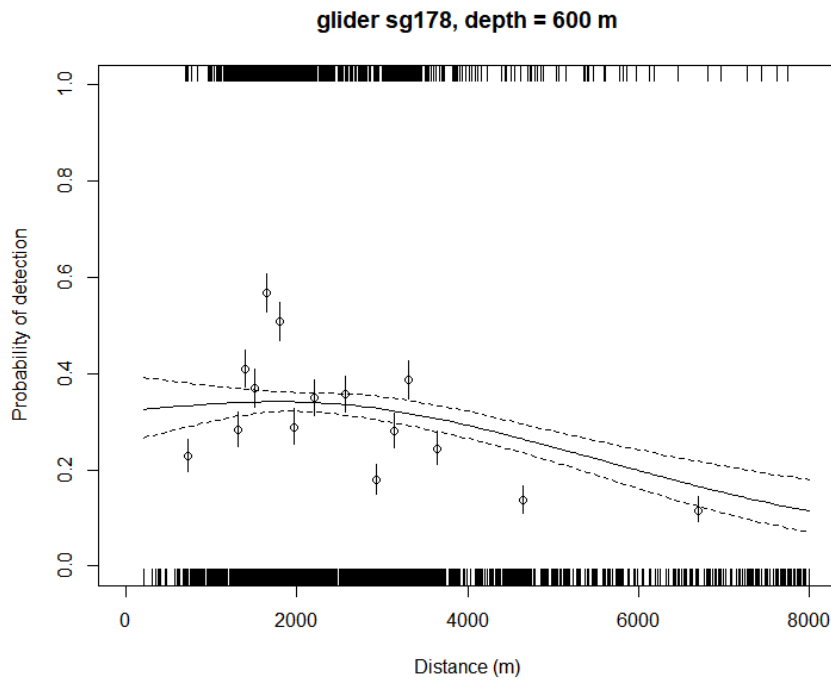


Figure 1. Detection probability as a function of range for (top) individual Blainville’s beaked whale clicks and (bottom) Blainville’s beaked whale clicks occurring in a 1-minute snapshot at 600 m depth. Generalized Additive Models were fit using logistic regression. Model standard errors are displayed (dotted lines). The 0-1 data used to fit the models are displayed as (a) proportions of detected clicks/snapshots (open circles) with 95% confidence intervals (vertical lines) in 15 distance bins with a similar number of trials and (b) rug plots (vertical black lines at the top and bottom of each plot).

The results of the simulation also showed depth dependent detectability of Blainville’s beaked whale calls, and a greater detection probability for snapshots than clicks (Fig 2). However, the simulated detection functions differed from the trial-based detection functions, with the trial-based probabilities being larger at the same ranges. Possible reasons for these differences are that the trial-based method may have contained incorrect matches between the localizations and detections on the glider, and that the simulation may have simplified the detection and classification algorithm used on the glider recordings.

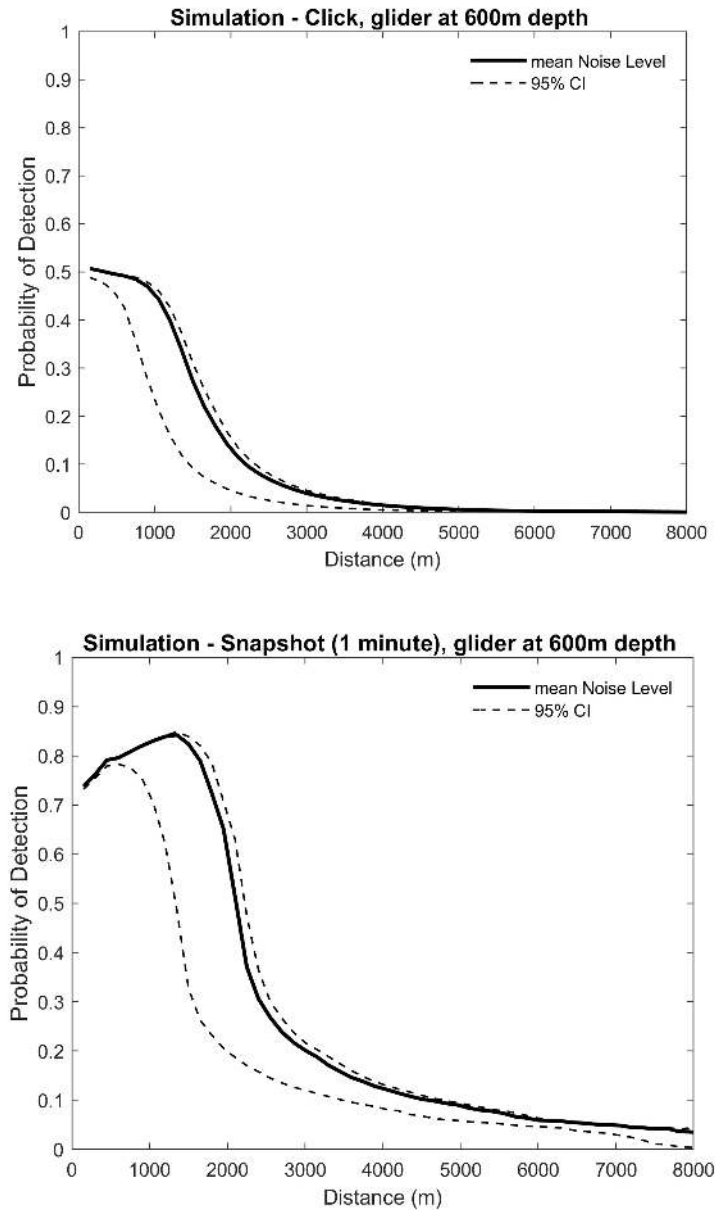


Figure 2. Detection probability as a function of range for (top) individual Blainville’s beaked whale clicks and (bottom) Blainville’s beaked whale clicks occurring in a 1-minute snapshot as estimated from a simulation approach.

In the Catalina analysis focusing on Cuvier’s beaked whales, detections were encountered on all instruments, though there were a limited number of minutes where Cuvier’s beaked whales were detected simultaneously on multiple types of instrument (detailed in the FY19 annual report). This meant that trial-based detection probability estimation could not be implemented here. However, these data were analyzed using SCR in the ‘secr’ R package. We have demonstrated that it is possible to implement an SCR analysis using the combined instrument data, though more work is required to adequately reflect the movement of the instrument array in the analysis software (our latest results presented below use average locations of the array assumed to be fixed in space and time). Further, instrument type has been successfully included as a covariate in the detection function model, allowing instrument-specific detection functions to be estimated (Fig. 3, Table 3). The width of the instrument-specific detection functions is controlled by σ (the scale parameter) and our results show that all instrument-specific σ values were reasonable, including the estimated confidence intervals (Table 3). The estimation of detection probability at zero horizontal distance from all instruments was estimated to be certain, which is in contrast to the AUTECH results discussed above for a glider and a similar species. However, the confidence intervals around the parameter estimates for both the glider and profiling float are currently extremely large, and so these results can only be compared with the AUTECH results once the movement of the array is included in the SCR analysis (to be continued as part of S. Fregosi’s PhD thesis work).

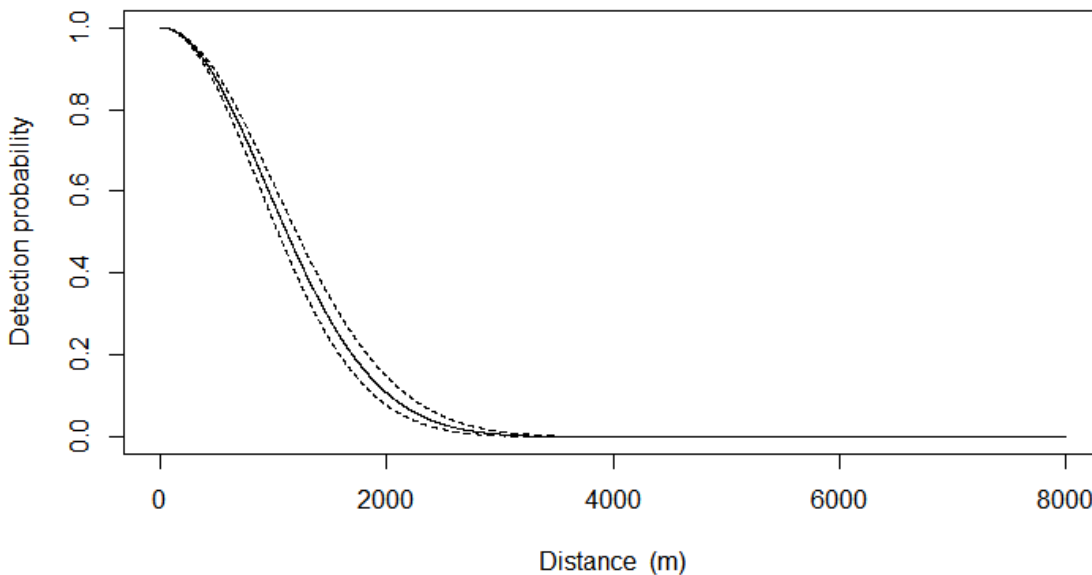


Figure 3. Detection probability as a function of range for Cuvier’s beaked whale clicks occurring in a 1-minute snapshot detected on DASBR instruments as well as a glider and profiling float, estimated using spatial capture-recapture methods.

Table 3. SCR analysis results using multi-instrument data from the Catalina field effort (using a simplified array configuration). Instrument-specific parameter estimates (σ) are given for instrument-specific half normal detection functions with 95% confidence intervals given in parentheses. An estimate of detection probability at zero horizontal distance from the instrument is also estimated ($g(0)$) for each instrument

Instrument→ Parameter↓	DASBR	Glider	Profiling float
σ	946.4 (880.6 – 1017.2)	689.7 (613.7 – 775.2)	890.5 (810.0 – 979.0)
$g(0)$	1.0 (0.99 – 1.00)	1.0 (9.2e-85 – 1.00)	1.0 (1.3e-85 – 1.00)

Estimating densities (Task 4):

There are two general estimators that are suitable for all analyses in this study, one based on cue-counting and one based on snapshots. These estimators both avoid biases caused by animal movement. A density estimation strategy has been decided for each target species (Table 4) and work is ongoing to produce density estimates at a selection of the deployment sites (AUTECH, SCORE and Catalina). The aim is to include the AUTECH density estimate in Harris *et al.*, (in prep) and the Catalina and SCORE density analyses will be conducted as part of S. Fregosi’s ongoing PhD thesis work. We note that due to the differences in target species in the Catalina and SCORE datasets, it will not be possible to compare the detection function results, which was outlined as an original goal.

A density estimator for a cue-based analysis is:

$$\hat{D} = \frac{n_c(1 - \hat{c}_c)}{a\hat{P}_cT\hat{r}}$$

where

- n_c , number of cues
- c_c , false positive proportion of cues
- a , survey area
- P_c , detection probability of cue
- T , total survey effort specified as time
- r , cue production rate
- and D , c_c , P_c , r are all parameters to be estimated

A density estimator for a snapshot-based analysis is:

$$\hat{D} = \frac{n_s(1 - \hat{c}_s)\hat{s}}{a\hat{P}_s k \hat{g}}$$

where

- n_s , number of positive snapshots i.e., snapshots containing detections
- c_s , false positive proportion of snapshots
- s , mean group size
- a , survey area
- P_s , detection probability of a positive snapshot
- k , total survey effort defined as total number of snapshots
- g , probability that a group is vocal in the snapshot period
- and D , c_s , P_s , s , g are all parameters to be estimated

Table 4: summary of detection probability and density analyses for all datasets

Species	Blainville's beaked whales	Blainville's beaked whales	Cuvier's beaked whales	Cuvier's beaked whales	Fin whales
Dataset	AUTEC	AUTEC	Catalina	Catalina	SCORE
What is the unit of detection (n)	(a) cues (click) (b) 1-min snapshot	(a) cues (click) (b) 1-min snapshot	1-min snapshot	1-min snapshot	Cues or snapshot
How to estimate detection probability	Trial using AUTEC locations	Simulation	SCR using DASBR array	Trial using DASBR array	Trial using SCORE tracks

Field experiment (Task 5): The main results presented in Barlow *et al.* (2018) showed that beaked whales produced echolocation clicks and were presumed to be foraging at a mean depth of 950 m, approximately 300 m above the bottom in the basin (Fig 4). Average swim speed was 1.2 m s⁻¹, but swim direction varied during a dive. The average net swim speed was 0.5 m s⁻¹. Results are similar to those obtained from previous tagging studies of this species.

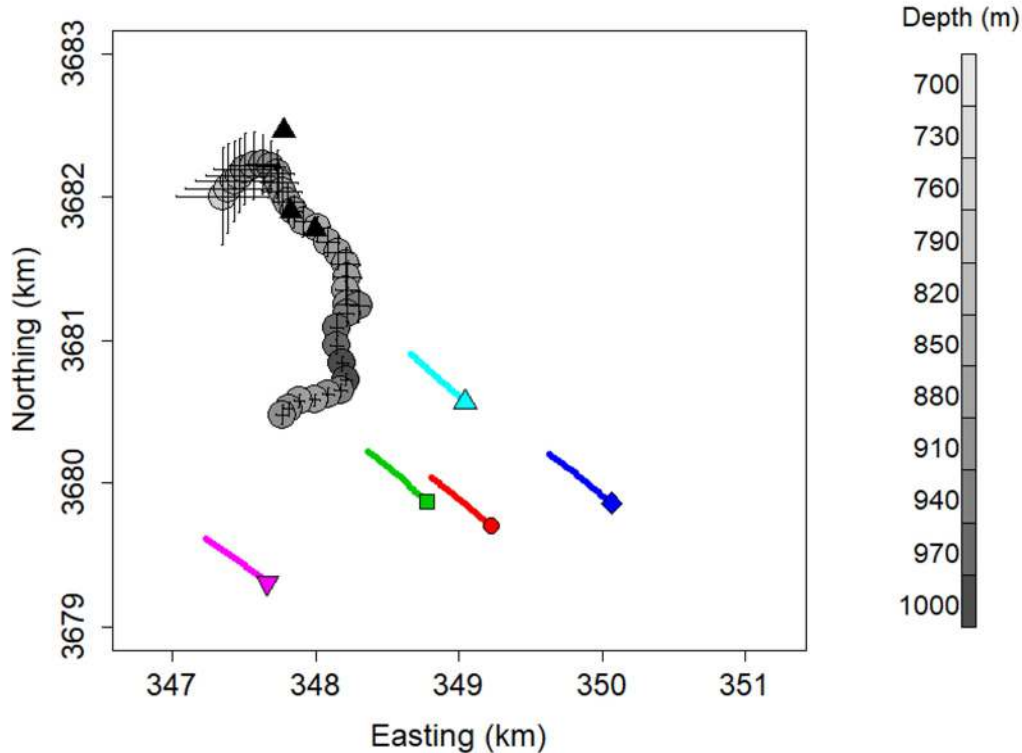


Figure 4. Estimated 3-D tracks of a 35-min dive of a Cuvier's beaked whale (gray circles) detected on five drifting recorders (colored lines indicate buoy drifts over this time period). Grayscale indicates estimated depth of the track. Localizations based on surface reflections are illustrated as black triangles. Location error bars indicate two standard deviations from the Bayesian posterior distributions. Coordinates are for Zone 11 of the Universal Transverse Mercator system.

IMPACT/APPLICATIONS

The Navy has shown increasing interest in using autonomous mobile platforms such as ocean gliders and floats for marine mammal monitoring. By developing methods for density estimation using these platforms, we will enhance the Navy's ability to predict when its operations may come into conflict with marine mammals, particularly acoustically sensitive, prominent/charismatic, or threatened/endangered species. This will enable the Navy to prevent and mitigate harm to those species, better comply with the law, and reduce negative public perception of Navy impacts on these species.

RELATED PROJECTS

Demonstration of a commercially available high-performance PAM glider and profiler float. Funded by the US Navy's Living Marine Resources Program. PI: Haru Matsumoto, Oregon State University.

Autonomous passive acoustic monitoring of marine mammals in the Hawaii Range Complex (HRC), the Gulf of Alaska (GoA), and the Mariana Island Range Complex (MIRC). Funded by U.S. Pacific Fleet/NAVFAC Pacific through HDR, Inc.

PhD research by Selene Fregosi, a graduate student at OSU, funded by a National Defense Science and Engineering Graduate (NDSEG) Fellowship.

Acoustically-equipped Ocean Gliders for Environmental and Oceanographic Research (ONR award N00014-13-1-0682). This award purchased the glider used during the July-Aug. 2016 fieldwork on this project.

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Barlow, J., Griffiths, E. T., Klinck, H. & Harris, D. V. (2018). Diving behavior of Cuvier's beaked whales inferred from three-dimensional acoustic localization and tracking using a nested array of drifting hydrophone recorders. *Journal of the Acoustical Society of America* **144**(4), 2030-2041. <https://doi.org/10.1121/1.5055216>

Fregosi, S., Harris, D. V., Matsumoto, H., Mellinger, D. K., Negretti, C., Moretti, D. J., Martin, S. W., Matsuyama, B., Dugan, P. & Klinck, H. (under review at *Journal of the Acoustical Society of America*). Comparable detections of fin whale 20 Hz calls by mobile and stationary autonomous recorders.

Harris, D. V., Fregosi, S., Klinck, H., Mellinger, D. K. & Thomas L. (submitted to *Journal of Remote Sensing*) Assessing the effect of ocean glider movement on distance sampling assumptions.

PUBLICATIONS IN PREPARATION

Barlow, J., L. Thomas, D. Harris, & E. T. Griffiths. Acoustic detection range and population density of Cuvier's beaked whales estimated from near-surface hydrophones. Target: TBD.

Fregosi, S., Harris, D. V., Matsumoto, H., Mellinger, D. K., Barlow, J, Baumann-Pickering, S., & Klinck, H. (in prep). Comparison of beaked whale detections on simultaneously deployed bottom-moored and autonomous mobile instruments. Target: *Frontiers in Marine Science*

Gkikopoulou K. C., Aguilar de Soto, A., Johnson, M., Tyack, P., Harris D., & Gillespie D. (in prep) Depth dependent detectability of Blainville's beaked whales – implications for density estimation methods from underwater autonomous vehicles. Target: TBD.

Harris, D. V., Fregosi, S., Klinck, H., Mellinger, D. K. & Thomas L. (in prep) Estimating the detection probability of an ocean glider using trials with a fixed hydrophone array. Target: *Journal of the Acoustical Society of America*.

PRESENTATIONS

Barlow, J., Griffiths, E., Klinck, H. & Harris, D. (2018) 3D acoustic dive tracking of Cuvier's beaked whales using a nested array of drifting hydrophone recorders. Presentation given at The 8th International Workshop on Detection, Classification, Localization, and Density Estimation of marine mammals using passive acoustics, Paris, France, 4-8 June 2018.

Fregosi, S., Klinck, H., Matsumoto, H., Turpin, A., & Mellinger, D. K. (2016). Field comparison of mobile autonomous recorders on a U.S. Navy range. 20th Annual Meeting of the Northwest Student Chapter of the Society for Marine Mammalogy, Seattle, WA, USA, 21 May 2016. (Oral presentation)

Fregosi, S., Klinck, H., Matsumoto, H., Turpin, A., Martin, S. W., Matsuyama, B. M., Helble, T. A., Henderson, E. E., Moretti, D. J., Morrissey, R. P., & Mellinger, D. K. (2016). Simultaneous recordings of marine mammal calls by a glider, float, and cabled hydrophone array. 172nd meeting of the Acoustical Society of America, Honolulu, HI, USA 28 Nov – 3 Dec 2016. (Oral presentation)

Fregosi, S. (2017). Underwater gliders and floats as passive acoustic survey tools. 23rd Annual Markham Marine Science Research Symposium, Hatfield Marine Science Center, Newport, OR, USA 22 June 2017. (Poster presentation)

Fregosi, S. (2018). The How and Why of Using Underwater Gliders to Listen for Whales, Oregon Chapter of the American Cetacean Society, Newport Public Library, Newport, OR, USA 10 February 2018.

Fregosi, S., Harris, D., Mellinger D. K., Barlow, J., Thomas, L. & Klinck, H. (2018). Detection probability of Cuvier's beaked whale clicks from a glider and a deep-water float. 174th Meeting of the Acoustical Society of America, Victoria, BC, Canada, 4-10 Nov 2018. (Oral presentation)

Gkikopoulou, K., Aguilar de Soto, N., Gillespie, D., Johnson, M., Smout, S. & Tyack, P. (2018) Go deep to get high – depth dependent detectability of Blainville's beaked whales and the use of underwater autonomous vehicles as an acoustic platform for density estimation – a simulation approach. Presentation given at The 8th International Workshop on Detection, Classification, Localization, and Density Estimation of marine mammals using passive acoustics, Paris, France, 4-8 June 2018.

Harris, D. (2016) Eavesdropping on the ocean: using passive acoustic monitoring technologies to estimate marine mammal population sizes. Seminar given at Oregon State University, Washington State University and University of Washington, Dec 2016.

Harris, D. & Thomas, L. (2017) A framework for cetacean density estimation using slow-moving autonomous ocean vehicles. Presentation given at the ONR Marine Mammal & Biology Program Review, Arlington, VA, USA, 20-23 March 2017.

Harris, D., Fregosi, S., Klinck, H., Mellinger, D. K., Barlow, J. & Thomas, L. (2017) Evaluating autonomous underwater vehicles as platforms for animal population density estimation. Presentation given at 3rd Joint Meeting: Acoustical Society of America and European Acoustics Association, Boston, USA, 25-29 June 2017.

Harris, D., Fregosi, S., Klinck, H., Mellinger, D. K., Moretti, D. & Thomas, L. (2018) Evaluating cetacean densities using slow-moving autonomous ocean vehicles. Presentation given at 6th Biennial International Statistical Ecology Conference, St Andrews, UK, 2-6 July 2018.

Harris, D., Fregosi, S., Klinck, H., Mellinger, D. K., Moretti, D. & Thomas, L. (2018) Estimating cetacean detection probabilities using slow-moving autonomous ocean vehicles: an example with Blainville's beaked whales. Presentation given at The 8th International Workshop on Detection, Classification, Localization, and Density Estimation of marine mammals using passive acoustics, Paris, France, 4-8 June 2018.

Harris, D. & Thomas, L. (2019) A framework for cetacean density estimation using slow-moving autonomous ocean vehicles. Presentation given at the ONR Marine Mammal & Biology Program Review, Alexandria, VA, USA, 23-26 April 2019.

OTHER RESULTS DISSEMINATION

Press release:

Acoustical Society of America (ASA). "Bioacousticians test passive acoustic monitoring to capture sounds of marine life." ScienceDaily. ScienceDaily, 1 December 2016. www.sciencedaily.com/releases/2016/12/161201094452.htm

Blog: <http://blogs.oregonstate.edu/bioacoustics/?tag=affogato>

SUPPORTED STUDENTS/POST-DOCTORAL ASSISTANTS

The project provided training for Selene Fregosi, who is conducting PhD research at OSU using data from the project and is funded by a National Defense Science and Engineering Graduate (NDSEG) Fellowship.

The project has also provided data for undergraduate research volunteers at OSU: Ciera Edison, Department of Fisheries and Wildlife, Christopher Lundeborg, Department of Biology, Laura McCourt, Department of Biology, Christina Negretti, Department of Animal and Rangeland Sciences.

The project also supported K. Gkikopoulou in a post-doctoral research assistant role for 4 months to implement the simulation-based detection probability estimation method.

HONORS/AWARDS/PRIZES

Scholarships (S. Fregosi): Oregon Lottery Graduate Scholarship (\$2000); Robert Anthony Graduate Scholarship in Population Ecology (\$2000)

Prizes (S. Fregosi): Best poster prize for Fregosi, S. (2017). Underwater gliders and floats as passive acoustic survey tools. 23rd Annual Markham Marine Science Research Symposium, Hatfield Marine Science Center, Newport, OR, USA 22 June 2017.