PASSIVE ACOUSTIC DENSITY ESTIMATION OF BALEEN WHALES:

USING SONOBUOYS TO ESTIMATE WHALE DENSITY

Final Report

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Project Background

Passive acoustic monitoring (PAM) may provide a cost effective means for estimating cetacean density, especially in remote areas or areas with poor weather conditions that make visual-based methods difficult. There are a variety of hardware devices capable of providing PAM for marine mammals, including seafloor mounted hydrophones, drifting buoys, and towed hydrophones. In recent years, sonobuoys have seen increasing use in PAM studies; sonobuoys are expendable drifting low-frequency hydrophones that have integrated directional sensors within the unit. The U.S. Navy has provided a moderate supply of surplus sonobuoys for research purposes, and many of these are supplied to NOAA Fisheries Science Centers for work on marine mammals. This project examines the feasibility of applying PAM for density estimation to sonobuoy data. Many of the lessons learned and software applications developed apply towards any study of baleen whales using sonobuoys.

The initial proposal for this study examined a novel approach to density estimation of baleen whales in Navy areas of concern; this approach would apply data collected from sonobuoy studies during NMFS surveys to novel sonobuoy surveys conducted by the Navy in regions of concern. The basic premise is that sonobuoys could be deployed at evening stations during NMFS line-transect shipboard cetacean surveys to estimate call density for specific baleen whale calls. A robust estimate of whale density is estimated during these same surveys using visual line-transect survey methods. As whale density for these surveys is known (estimated with a narrow confidence interval), a multiplier can be estimated that translates the estimated call density to the estimated whale density for this region. This multiplier could, in theory, be applied towards novel sonobuoy data (collected on the same call types in the same region and time of day, year) to estimate the whale density in that area. In theory, this approach would allow the Navy to estimate whale density in an area of concern in a timely manner.

In order to estimate call density from sonobuoys, we must:

- Identify appropriate data collection methods
- Identify appropriate acoustic analysis methods
- Identify and test an appropriate statistical approach for estimating call density

The originally intended study, where a multiplier to translate call density to whale density is developed during one set of surveys and applied to another novel survey, fundamentally requires that the data is collected in a standardized manner. Any differences between the methods between the two surveys would necessarily affect the multiplier, increasing the error. Therefore, a specific deployment protocol was identified for deployment, calibration, and station recording.

Acoustic analysis of sonobuoy data includes detection and classification of calls attributed to baleen whales, as well as bearing angle estimation using the DIFAR processing. There were a large number of problems identified at each stage of acoustic analysis during this project. Problems were addressed where possible, and suggested future research and software modifications have been identified for problems could not be addressed within the scope of this project.

The survey design included paired sonobuoy stations, where sonobuoys included vector sensors providing estimated bearing angles to sound sources. The initial intention was to apply point transect survey methods to this data; however, it became clear that this statistical method was not appropriate for the data because it assumes sound source locations are known without error (a fundamental assumption in point transect survey methods). A search for a more appropriate statistical approach to density estimation that does not rely on range estimation resulted in consideration of a relatively new approach: Acoustic Spatial Capture Recapture (ASCR or Acoustic SCR). Preliminary examination of this statistical approach will be presented here.

This final report will provide a brief summary of results, focusing on the final phase of this project. Detailed results will be provided in the Sonobuoy Data Collection Protocol (NOAA Technical Memorandum) and in peer-reviewed journal publications. This report will identify the potential uses as well as concerns, limitations, and suggestions for future use of these methods. The methods developed, and lessons learned, in this project could apply not only to the originally intended study, but to independent studies of call density estimation using sonobuoys or to studies using sonobuoys to localize marine mammal calls.

Data Collection Methods

National Marine Fisheries Service is the largest user of sonobuoys provided by the Navy (Anu Kumar, pers. comm.), where sonobuoys are used to study baleen whales during large shipboard cetacean surveys. Sonobuoy data used for this study were collected during two large-scale NMFS shipboard cetacean surveys (CalCurCEAS 2014 and HICEAS 2017) and during several single-day playback sea trials. Data collected during these NMFS cetacean surveys typically fall into one of three categories: (1) opportunistic buoys (in the presence of sighted cetaceans), (2) sonobuoy stations (for larger scale assessment), or for (3) real-time tracking (to detect, track, and approach target species for focused studies). In addition to sonobuoy data collected during large NMFS surveys, we conducted several playback experiments with sonobuoys to address specific concerns related to calibration and bearing angle estimation. We used these combined opportunities to identify a suggested protocol for data collection using sonobuoys (see Appendix A for Sonobuoy Station Protocol and Appendix B for Opportunistic Sonobuoy

Protocol). Detailed protocol for data collection, including suggested recording hardware, are provided in a NOAA Technical Memorandum (Rankin et al., in preparation).

Preparation and Deployment of Sonobuoys

Sonobuoys are engineered for deployment from airplanes or vessels as intact units; recent sonobuoys supplied to NMFS consist primarily of AN/SSQ 53-F. Users have the option to adjust the radio frequency channel, depth of hydrophone deployment, time until scuttle (hours), sensor preference (Omni-directional or DIFAR sensor), and automatic gain control. Full explanation and setting suggestions are provided in the protocol (Rankin et al., in prep.).

In an effort to minimize ocean pollution, research scientists have frequently modified sonobuoys by removing sonobuoy components that are not critical to their use, such as the upper plastic cap, parachute, and the outer metal container. Modification of these components can have unintended consequences and lead to unsuccessful deployment or changes to the selected preferences. For reasons that are detailed in the protocol, we highly recommend that sonobuoys be deployed in their original state without modification.

Ideally, sonobuoys will provide a low- noise recording of sounds of interest; however, vessel noise also provides a means of calibrating the sonobuoys to improve the DIFAR bearing angle estimation. Ideally, once sonobuoys are deployed, the vessel will follow a specific pattern of vessel movement to allow for individual sonobuoy calibration and drift calibration. Once these noise samples have been obtained, the vessel would ideally move to a location close enough to each buoy to allow for strong reception of sonobuoy signals, but far enough that it contributes minimal noise to the recordings. Calibration methods include individual sonobuoy calibration and an estimate of sonobuoy drift; combined, these calibrations will improve the accuracy of the estimated bearing angles and localizations. Our protocol outlines specific suggestions regarding vessel movement for sonobuoy stations and for opportunistic sonobuoy deployments.

Sonobuoy Calibration

DIFAR sonobuoys contain an omnidirectional sensor (hydrophone) as well as two directional particle velocity sensors (orthogonal North-South and East-West sensors) that work in conjunction with the internal magnetic compass to provide an estimated bearing angle to sounds (McDonald 2004). Production Sonobuoy Specifications requires the estimated bearing angles to be accurate to within ± 10°; however, the accuracy and precision is further affected by local magnetic deviation and individual sonobuoy variation. A means of calibrating each sonobuoy based on DIFAR localization to a sound source with known location (research vessel) has been implemented in Pamguard DIFAR module (Miller et al. 2014). Subsequent bearing angle estimates are modified by a single calibration value that incorporates the local magnetic deviation of the compass as well as individual buoy variation.

Calibration can also provide a means for identifying the precision of the bearing angle estimates provided by a sonobuoy. Some sonobuoys do not provide stable bearing angle estimates; the variability in the calibration values may be used as indicators of unreliable buoys.

For individual sonobuoy calibration to be successful, it is imperative there be sufficient vessel noise to obtain a series of quality DIFAR bearing estimates of the sound. A full description of suggested protocol for obtaining calibration estimates is provided in the protocol (Rankin et al., in prep.).

Drift Calibration

Sonobuoys, by nature, drift from their initial deployment location. This drift will vary based on the wind and currents at both the surface and depth. While the drift can be estimated in a similar manner to the individual sonobuoy calibration (using the vessel noise), the requirements for vessel movement are very different. The intention of estimating sonobuoy drift is to improve the estimate of the location of the sonobuoy, so that estimated bearing angles are not assumed to be from the original deployment location.

While buoy calibration should be completed during straight line transit during a short window after buoy deployment; drift calibration should be conducted as a time series of noise samples separated by both time and compass bearing to the buoy location (Miller et al. 2018). Ideally, after completion of any recording, the vessel would conduct a final transit by the sonobuoy to provide additional noise samples for calibration. A full description of suggested protocol for obtaining drift calibration estimates is provided in the protocol (Rankin et al., in prep.).

Pamguard Acoustic Analysis

Pamguard's DIFAR module is the first user-friendly open source software designed for DIFAR bearing angle estimation; development of this software will allow for increased use of DIFAR sonobuoys for studying marine mammals. Throughout this project we have worked closely with the developers to address bugs and identify improvements. Some of these improvements have been incorporated into software updates; additional suggested improvements are identified in Appendix C. Some of these improvements are minor, and others are significant enough to require dedicated funding to accomplish. There are numerous scripts (in Matlab and R) that function using the current version of the DIFAR module, and changes to the DIFAR module will require subsequent changes to these scripts. Therefore, we strongly encourage that the suggested changes to Pamguard be completed as one large modification rather than a series of incremental changes that each require modification of the associated Matlab/R script.

Detection and Classification of Calls

At the time of analysis, there was no method for applying DIFAR estimation to auto-detected calls; therefore, manual detection and matching of calls across channels was made by a trained acoustician. While this may be sufficient for specific studies, we found it to be extremely problematic for this large-scale study. We have identified a list of suggested improvements to the Pamguard DIFAR module that will help alleviate these problems.

Call density studies require detection of specific calls; similar calls that may have different call rates must be estimated differently. For example, fin whales show stereotyped variability in their 20 Hz call structure that suggests there are several types of 20 Hz pulses, each produced with different call rates. Differentiation of these pulse variants was found to be difficult for a trained human observer (Rankin et al. 2016), but can be accurately classified by a computer (E. Archer, unpublished data). Likewise, some similar calls may be produced by different species (e.g., 40 Hz downsweeps produced by fin and sei whales, Rankin et al. 2007) and studies have suggested that they can be classified using high resolution measurement of their call structure (Ou et al. 2015). Automated detection and classification by Pamguard and/or externally scripted code is suggested to address the problems with human identification and classification.

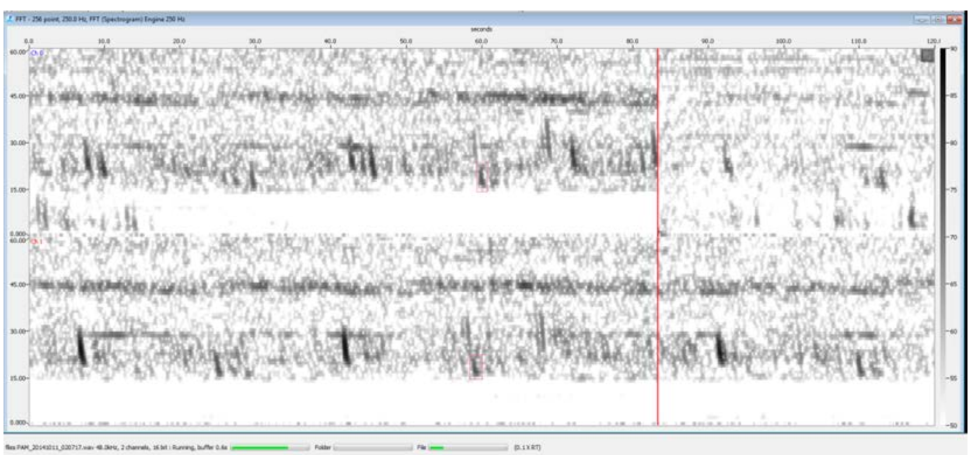

Figure 1. Spectrogram of fin whale pulses with variable signal-noise-ratios as viewed in DIFAR module of Pamguard.

Likewise, we found that matching of calls across channels was problematic, especially when calls occur in high density. For example, fin whales can produce short 20 Hz pulses in long, stereotyped series (song); detection of multiple singing whales at the receivers can make manual matching of individual calls across hydrophones an impossible task (Fig. 1). As the distance between the hydrophones increases, the time delay of arrival for a sound increases, making it increasingly difficult to determine which calls were the same. Pamguard currently contains several options for automated detection and localizing; however, most of these methods rely on small hydrophone separations. Dedicated examination of options for large aperture localization of low frequency sounds should be tested to determine viability; these approaches could then be integrated into the Pamguard DIFAR module to allow for automated matching across multiple channels. Currently, the user must decide to examine channels separately (and then match specific calls across channels later), or examine channels jointly (in which case the calls must have significant overlap in the time domain). Alternative approaches should be considered and tested.

Many of the components necessary to improve the detection, classification, and matching of calls across channels already exists within the Pamguard framework. While there are numerous changes necessary to make these pieces coordinate with the DIFAR module, modifications will primarily consist of bringing these pieces together in a seamless manner.

DIFAR Estimation

The Pamguard DIFAR module provides a user-friendly and very capable platform for DIFAR bearing angle estimation. We found the platform itself to be excellent, but the methods to estimate bearing angles are prone to errors associated with signal to noise ratio and the selection box size relative to the signal (swept signals necessitate larger ratios of background noise to box the signal). For signals less than 10 dB above ambient noise, the estimated bearing angle is increasingly influenced by the background noise (Fig. 2). This is a fundamental problem related to these methods for DIFAR.

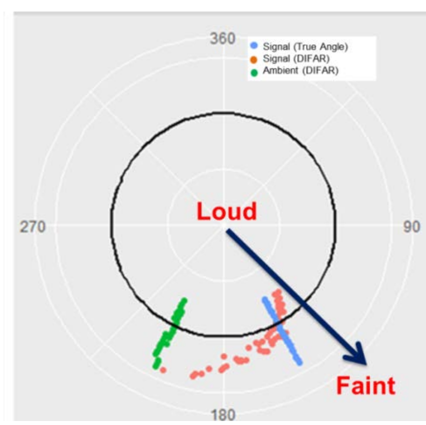

Figure 2. Polar plot showing the known bearing angles for playback signals according to their signal to noise ratio (SNR); SNR decreases with increasing distance from the center of the plot. Bearing angles to ambient noise are shown as green dots, and the true (known) bearing angle for playback sounds are shown as blue dots. The estimated bearing angles (red dots) approximate the true bearing angles for sounds greater than 10 dB above ambient (inside the solid black circle); these estimates are increasingly influenced by the bearing angle of the ambient noise with decreasing SNR.

An alternative approach to DIFAR bearing angle estimation was recently developed by Aaron Thode at Scripps Institution of Oceanography that may alleviate many of the problems associated with the current method of DIFAR bearing angle estimation. Preliminary analysis suggests that this alternative method will allow for simple examination of the background noise, improved detection and improved bearing angle estimation down to 0 dB above ambient (Fig. 3). We will be contributing data towards a peer-reviewed publication of these methods in the near future. Because these methods show such great promise, we highly recommend that they be incorporated into a future modification of the Pamguard DIFAR module (see Appendix C).

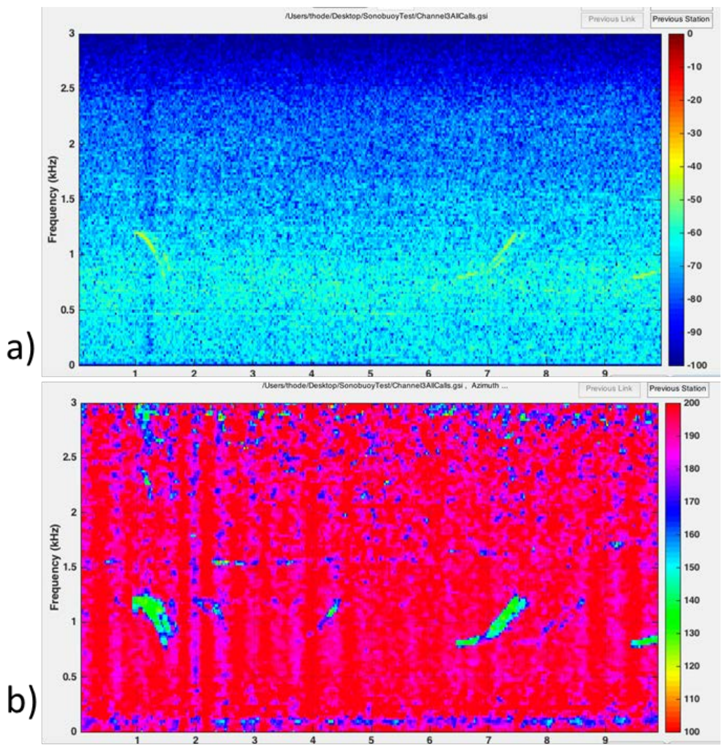

Figure 3. Plot of a) spectrogram and b) azigram for the same recording segment. Frequency (y-axis) and time (x-axis) are the same for both graphs; however, the color represents signal intensity for the spectrogram (a) and color represents azimuth, or bearing angle for the azigram (b).

Limitations and Suggested Improvements to Pamguard DIFAR Module

The Pamguard DIFAR module, initially developed for long-range detection and tracking of blue whales in the Antarctic, is by far the most user-friendly approach available. We worked closely with the developers, Brian Miller and Doug Gillespie, throughout this project. Both have been very receptive of our suggested modifications, many of which have already been integrated into recent Pamguard updates. The open-source platform and willingness of the developers to consider improvements leaves little concern regarding future improvements.

We have developed a list of suggested improvements that we will provide to the developers (Appendix C). Some of these require significant time and will require additional funding to allow for proper implementation. There are numerous custom scripts (in R and Matlab language) that have been developed to work with Pamguard output (both database and Binary files). Any modifications to Pamguard data output will require concomitant modifications to these custom scripts. Therefore, we highly recommend that these modifications be considered in one large version update, rather than a series of incremental modifications.

PAMsbuoy Acoustic Analysis

Pamguard provides an excellent platform for acoustic analysis; however, additional processing and analysis of data output is necessary for producing final results. Typically researchers develop their own custom script to work with data, and often these scripts are written in Matlab. In an effort to simplify post-processing and facilitate advanced analyses, we have developed custom script designed to work directly with Pamguard output for the DIFAR module. This script is written in the R programming language, which is open-source and freely accessible. This script accesses all data within Pamguard (from the database and binary files), calculates an improved sonobuoy calibration as well as a drift estimation, provides a series of summaries and visualizations for reports and publications, and provides a formatted output for use with other advanced analytical software. While the software is currently under development, it is available via GitHub repository, and when it has been thoroughly tested, we will publish it on the CRAN R Repository.

Sonobuoy Calibration

Calibration of the sonobuoy is critical for both improving bearing angle accuracy, and understanding the precision of bearing angles estimated for a particular sonobuoy in a particular environment. Pamguard DIFAR provides a means for calibrating the buoys and applies the mode of this calibration to all following bearing angles. PAMsbuoy will allow the user to examine the distribution of the calibration samples to estimate both the precision and accuracy of the bearing angles (Fig. 4a), and decide (1) if the sonobuoy is good enough to be used (Fig. 4b), and (2) what measure of calibration you would choose to apply to your bearing angles. If the bearing angles for a buoy are shown to either have extremely poor accuracy or precision, the user can then decide to eliminate these buoys from further analysis or re-examine these samples to determine if re-sampling might improve the calibration. Calibration values will be applied towards bearing angle estimates in all further analyses within PAMsbuoy.

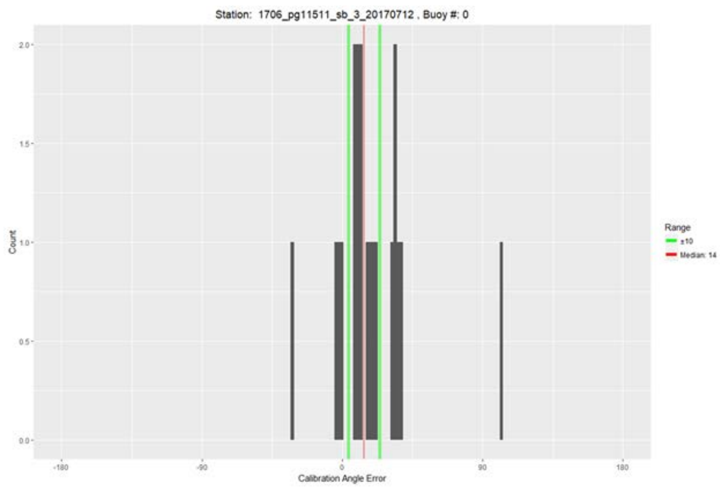

Figure 4a. Sonobuoy calibration error distribution plot provided by PAMsbuoy. Plot provides distribution of calibration angles with the mean angle error (red vertical line) and ±10° error bars around the mean (green vertical lines).

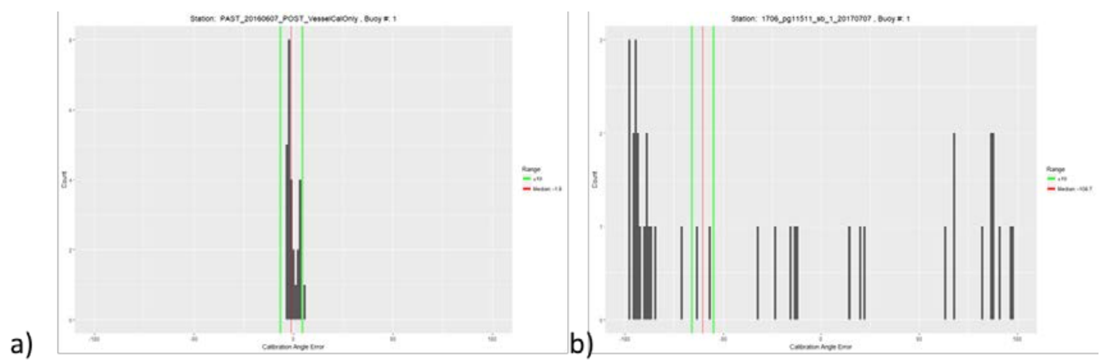

Figure 4b. Sonobuoy calibration error distribution plots for a) a 'good' sonobuoy (high precision) and b) a 'bad' sonobuoy (low accuracy and precision).

Drift Calibration

Estimation of sonobuoy drift may serve to greatly improve localization and tracking of sound sources, especially with increased time from deployment. This feature is not yet available within Pamguard's DIFAR module. We have worked with Brian Miller to aid in publication of these methods (Miller et al. 2018), and we implemented their approach into PAMsbuoy. Consideration of drift estimation requires thoughtful collection of additional calibration samples well after the buoy has been deployed—consideration of poor calibration samples may lead to an inaccurate drift estimate. We have developed visualizations to allow the user to estimate the validity of the drift estimation (Fig. 4); however, the user will need to determine if the estimated drift calibration is good enough to be applied to bearing angles for further analysis. For example, while drift can be estimated using a single additional calibration point (at some time after the initial deployment), the accuracy of this drift estimation will be inferior to a series of drift calibration points collected at different compass bearings and/or over different sampling times.

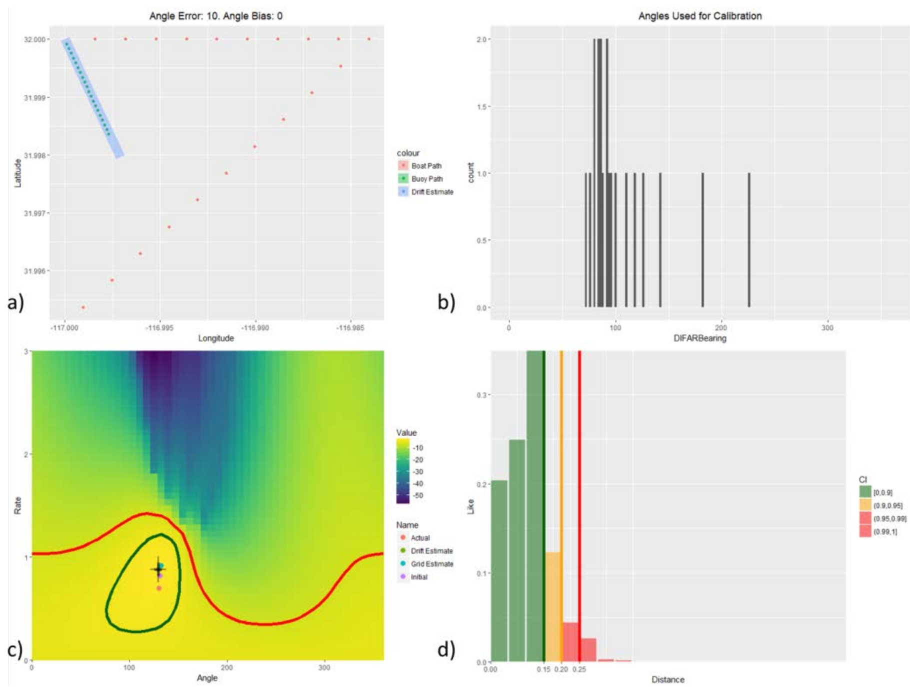

Figure 5. PAMsbuoy visualizations for drift estimation function: a) true drift (green dots) and estimated drift (blue bar) with ship locations used for drift calibration estimations (red dots), b) bearing angles used for drift estimation (bearing angles between green and red dots), c) likelihood surface for the maximum likelihood model used to estimate the drift (each spot on the grid is the calculated likelihood for that rate/bearing angle combination), and d) rough estimation of drift estimate confidence. The estimate of confidence (d) provides an estimate of the distance error (km) at 1 hour after buoy deployment, with 90% (green), 95% (yellow) and 99% (red) estimated error distribution.

Summaries, Output, and Visualizations

PAMsbuoy will provide a few default summary tables and visualizations (e.g. maps and summary tables, Fig. 6, Table 1) for cruise reports and publications. We will also provide a generic report (using RMarkdown) that will provide standard text and results that can be incorporated into cruise reports, etc. We will be open to considering additional summary/visualization functions that we feel will have utility for other users (pending time/resources).

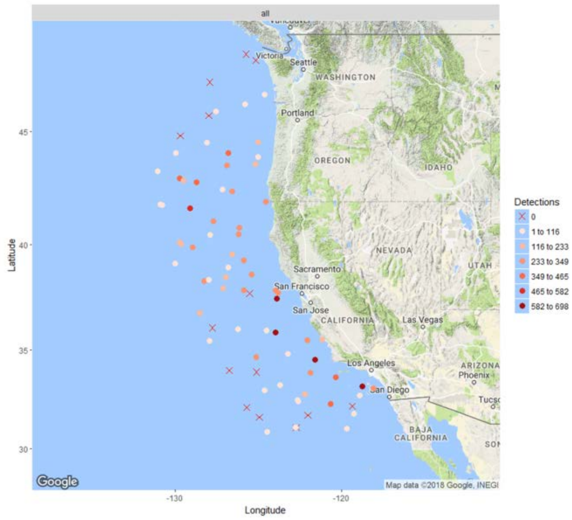

Figure 6. PAMsbuoy map showing sonobuoy locations and number of detections.

Table 1. Example table from a sonobuoy station consisting of two sonobuoys (Channel 0, 1), in which three call types were examined (bma, bmb, bp).

Station	Species [Unique Detections]	Buoy [Detections]	Latitude	Longitude	UTC
1647_SB_S102S103s	bma **[0]**	0 **[0]**	41.81	-130.78	2014-10-01 02:56:06
		1 **[0]**	41.80	-130.76	2014-10-01 02:56:03
	bmb **[3]**	0 **[2]**	41.81	-130.78	2014-10-01 02:56:06
		1 **[2]**	41.80	-130.76	2014-10-01 02:56:03
	bp **[0]**	0 **[0]**	41.81	-130.78	2014-10-01 02:56:06
		1 **[0]**	41.80	-130.76	2014-10-01 02:56:03
1647_SB_S105S106s	bma **[0]**	0 **[0]**	41.82	-130.89	2014-10-02 02:40:19
		1 **[0]**	41.83	-130.86	2014-10-02 02:40:16
	bmb **[0]**	0 **[0]**	41.82	-130.89	2014-10-02 02:40:19
		1 **[0]**	41.83	-130.86	2014-10-02 02:40:16
	bp **[5]**	0 **[5]**	41.82	-130.89	2014-10-02 02:40:19
		1 **[0]**	41.83	-130.86	2014-10-02 02:40:16

Limitations and Suggested Improvements to PAMsbuoy R package

PAMsbuoy is a freely available, open-source R package available on Github (https://github.com/EricArcher/PAMsbuoy).

There is great flexibility in future PAMsbuoy development and we expect periodic improvements to be made for the next year, at a minimum. The greatest limitation will be modifying PAMsbuoy to work with future versions of Pamguard. Ideally future Pamguard improvements will be conducted in a manner that minimizes reconfiguration of PAMsbuoy (e.g., infrequent larger modifications as opposed to incremental modifications). Updating PAMsbuoy for future Pamguard versions will be completed as resources allow. There is significant room for improvement in PAMsbuoy, including addition of functions for localization and tracking. We hope to work with colleagues in the future to identify needs and, if necessary, funding for the addition of a suite of features to improve standardization and allow for efficient analyses.

In addition, we have decided that restructuring the R package using the S4 object system will improve its effectiveness when used by many users of variable experience (see pages 111-116 of Wickham, 2014). This will be a time-consuming process that will be addressed in the upcoming months as time permits. We strongly feel that this will improve the stability of the software for other users and will ultimately be worth the time commitment required to enable it.

Call Density Estimation

Acoustic Spatial Capture Recapture (ASCR) methods estimate call density from detections of animal vocalizations across an array of detectors (Dawson and Efford 2009, Stevenson et al. 2015). This approach does not assume that we know the location of the sound source. Instead, the models treat the locations as latent variables, which are integrated over in the computation of the likelihood for models fitted by maximum likelihood, or sampled over within an MCMC algorithm for models fitted in a Bayesian framework. Nevertheless, the data must hold some information about these locations, and the more informative the data are about the locations, the more precise the density estimate will be. One particular advantage of ASCR is that additional information is often collected that is informative about the locations; in the case of sonobuoys, we can also consider estimated bearing angles and signal strengths as variables (Stevenson et al. 2015). An example of how ASCR might be applied to detection of a sound on an array of four sonobuoys is shown in Figure 7. In this case, the call was detected on three of the four sonobuoys, with bearing angles providing additional information that allows for the relatively precise estimation of the location of the sound source.

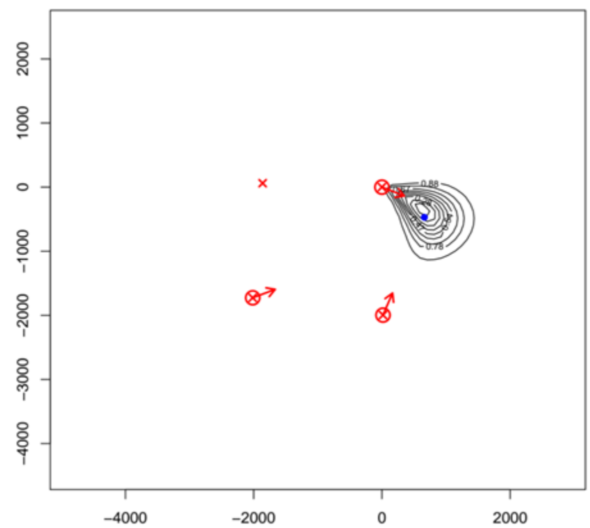

Figure 7. Plot showing this likelihood across space for one particular cue's source location. Red crosses are the buoy locations; circled red cross indicate that cue was detected on this buoy, with bearing angle shown as red arrow. Contours can be considered an estimated probability density function (PDF) for where this particular cue source was located. The blue dot is the true location of the boat for this playback.

A test of simulated data provided an estimate of the expected error for calls for different call densities and hydrophone spacings (Fig. 8). RMSE is a measure of estimator performance (the smaller the better); for ecological studies an RMSE less than 20% is usually considered reasonable. The basic results from the simulations suggested that these methods might be reasonably applied towards a study consisting of paired sonobuoys if: 1) the bearing angles were accurate, and 2) the call densities were sufficiently high. Higher call densities provided call density estimates with acceptable levels of error (~ 20%); appropriate sonobuoy spacing was also less critical for higher call densities (Fig. 8). The results of the simulation suggested that ASCR could be an appropriate analytical approach to estimating call density for paired sonobuoys; an array of more than two sonobuoys would yield improved results.

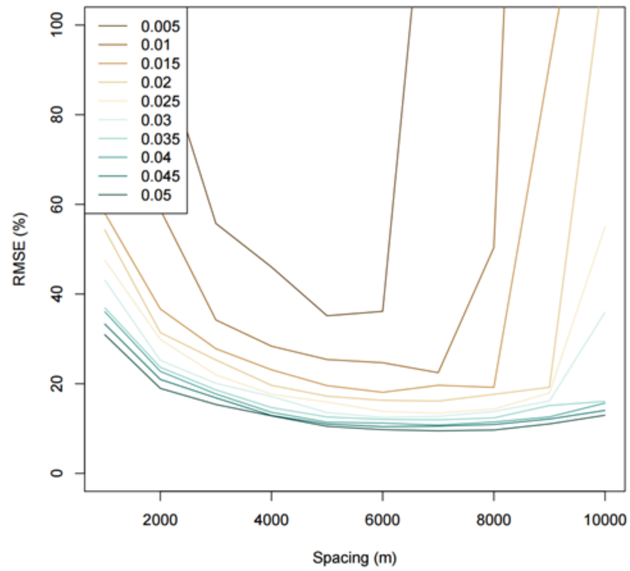

Figure 8. Plot of root mean square error (RMSE) based on spacing between the hydrophones for various call densities. Simulation considered a halfnormal detection function with a sigma set to 3000 m (based on initial detection function of blue whale calls from this study).

Application of these methods to real data collected during the CalCurCEAS survey data found additional problems with the data that precluded call density estimation. Specifically, we identified two scenarios that suggested errors in bearing angle estimation: 1) detections from both buoys with conflicting bearing angles, and 2) detection on one buoy with angle pointing towards the buoy with no detections (Fig. 9). We identified two likely reasons for these errors.

The first concern identified potential inaccurate matching of calls across hydrophones, which in this study was performed by a manual analyst. There appear to be numerous times where the analyst incorrectly paired the calls across hydrophones. While there are methods to minimize this error, they were not available during the initial analysis of this data. We have identified a list of suggested software modifications, many of them related to improve detection and matching across hydrophones. Consideration of these methods should allow for more consistent and accurate pairing across hydrophones and minimization of this type of error.

Second, as noted previously, bearing angle estimation is poor for faint calls. Our results from the playback studies suggest that bearing angle estimates for faint calls (<10 dB above ambient, Fig. 1) may reflect the bearing angle to the prevalent ambient noise, which in this case is likely noise from the research vessel. In fact, during this survey the ship would frequently transit between the paired buoys during recordings; ambient noise would provide an angle that was between the two buoys. To mediate this problem for the future, we modified the data collection protocol to explicitly state where the vessel should be (and not be) during data collection. Consideration of alternative approaches to DIFAR estimation, such as those identified by Aaron Thode (Fig. 3), will further improve the bearing angle estimation for low SNR calls.

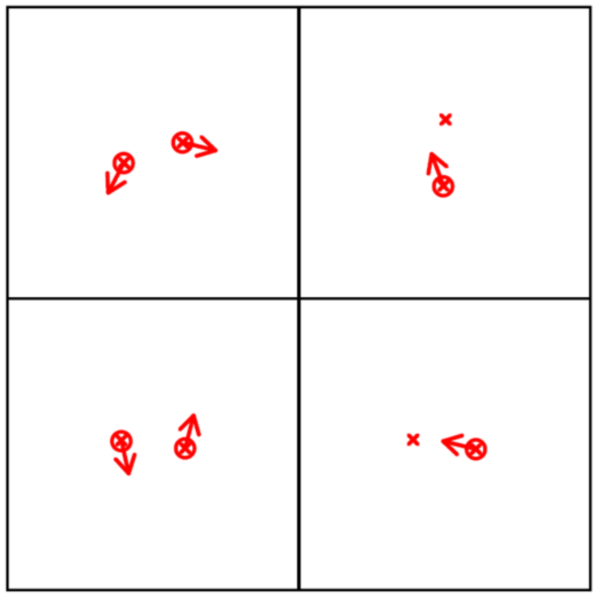

Figure 9. Four examples of problematic bearing angles estimated during the CalCurCEAS survey. The examples on the left identify detections with conflicting bearing angle estimates (angles pointing in the opposite directions) and the examples on the right show estimates that are unlikely to be plausible (detected on only one buoy, but angle pointing in the direction of the buoy that did not detect the call).

Limitations and Suggested Improvements to Acoustic SCR for Sonobuoys

The 'ascr' program is a freely available, open-source R package available on Github (https://github.com/b-steve/ascr).

Simulations suggest that ASCR is an appropriate method for estimating call density from arrays of two or more sonobuoys. Application of these methods will require that data are collected according to the protocol identified (see Appendix A), bearing angles are accurate for all calls (including low SNR calls), and that calls are appropriately matched across detectors. In turn, these will require improved software methods for DIFAR bearing angle estimation and automated matching of calls across detectors. These necessary modifications are outlined in the Suggested Pamguard Modifications (Appendix C).

If time allows, we have identified a subset of test data that we hope to analyze using Aaron Thode's DIFAR estimation method and apply towards Ben Stevenson's ASCR method. This would allow us to further test both analytical methods and identify any additional concerns.

Discussion

Sonobuoys have long served as a tool for detecting and tracking marine mammal calls; this study initially intended to extend their use to estimation of call density and potentially animal density. Due to the large number of unexpected problems encountered, this project has instead served as a 'proof of concept'. We have identified potential solutions to these problems, including suggested changes to data collection, acoustic software modification, and identified analytical approaches appropriate for working with arrays of sonobuoys. Most importantly, we intend to publish these results and encourage appropriate use of sonobuoys in the future.

Specifically, we will publish:

- **Protocol for Sonobuoy Data Collection on NMFS Survey** (*NOAA Technical Memorandum*). This report will outline suggested protocol for deploying sonobuoys and obtaining high quality data for analysis. This format allows for presentation of results in extreme detail in such a way that will be useful for sonobuoy users but would be excessive for journal publication. Expected publication date by April 2018.
- **PAMsbuoy** (*R package*). This software package, currently available on GitHub, will provide improved bearing angle estimation for data output from Pamguard DIFAR module. This will also provide a means of identifying the accuracy and precision of bearing angles estimated from sonobuoys, an estimate of sonobuoy drift, and summary tables/graphics for reports and publications. This platform is flexible and additional functions can be added as desired. This platform is open source, and once it has been tested by colleagues we intend to publish it on the R repository (CRAN). Please email to request access to the GitHub repository during testing the phase. Expected publication date August 2018 (delayed due to S4 conversion).
- **Methods to improve the accuracy and precision of bearing angle estimates to cetacean vocalizations using DIFAR sonobuoys** (*peer-reviewed publication*). Publication intended to serve as a summary of best practices for application of sonobuoy data for marine mammal studies. Will include collaborative work with Brian Miller and Aaron Thode. Expected submission date May 2018)

- **Acoustic Spatial Capture Recapture Density Estimation using Sonobuoys** (*Peer-reviewed publication*). Publication will minimally include results from simulations and examination of playback data. Will include real data if we are able to apply alternative DIFAR estimation method (A. Thode) to a subset of data. Completion dependent on resources and extent of analysis.
- **Ancillary Publications.** We are collaborating with Brian Miller (Australian Antarctic Division) and Aaron Thode (Scripps Institution of Oceanography) to facilitate publication of their methods. Our playback experiment provides a high quality dataset for testing of new algorithms, and we have provided this data towards testing and publication of new methods. Aaron Thode is currently developing his methods and associated manuscript; Brian Miller's work has been published in J. Acoustical Society of America, Express Letters (Miller et al. 2018).

While this project was unable to fully develop and test a method for density estimation using sonobuoys, we have developed a strong approach that will improve the quality and efficiency of marine mammal sonobuoy research going forward. We are working closely with our colleagues (Doug Gillespie, Brian Miller, Ben Stevenson, NMFS Science Centers) to improve data collection and analysis. We intend to publish and share these results and work with colleagues and to add additional functions to our PAMsbuoy software to improve efficiency, consistency, and quality in sonobuoy research going forward.

Acknowledgements

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Appendix A- Sonobuoy Station Protocol

Sonobuoy stations will be conducted during evening CTD operations; data will be used for call density estimation. It is imperative that the protocol is strictly applied. Sonobuoy deployment and calibration will begin when the visual survey team goes off effort at the end of the day, will continue while the towed array is being retrieved, and be completed prior to stopping for the evening CTD station. Successful implementation will require an initial meeting with all acousticians and any officers/crew that may participate in sonobuoy stations. The movements of the ship are important as the ship is acting as a sound source to calibrate the bearing angles derived from the sonobuoy sensors.

REQUIREMENTS

There are insufficient sonobuoys to conduct stations *every* night; station dates will be pre-selected (to avoid sampling bias). Sonobuoy station protocol will be followed for each evening in which the sonobuoy station is assigned unless cancelled by Cruise Leader or OOD.

To reduce radio interference, all shipboard communications should use handheld radios during all sonobuoy recordings.

METHODS

1. **Schedule:** Confirm that it is a Sonobuoy Station Positive date (see schedule, at end).
2. **Preparation:** Prepare 3 sonobuoys set to the channels shown in Table 1 (only two will be used, the third is a prepared backup). Confirm that there are no other sources of interference. Acoustician will open and prepare Pamguard software according to channel designation shown in Table 1 and following detailed instructions.

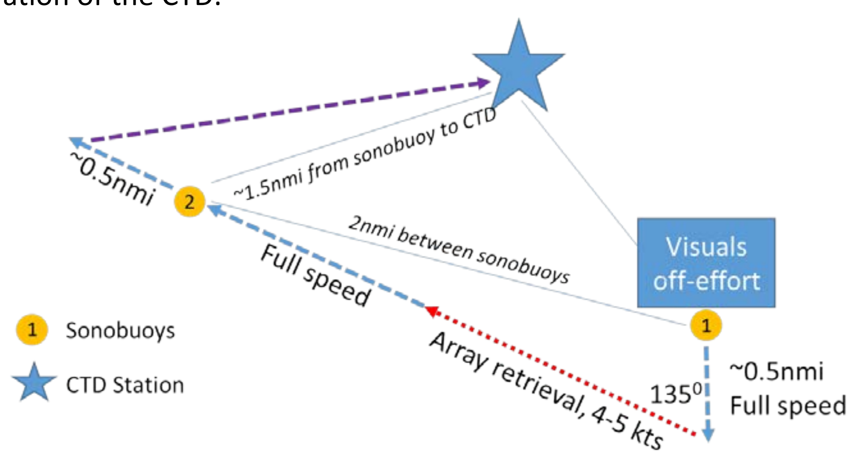
Table 1. Channel configuration for sonobuoy stations.

Sonobuoy #	Sonobuoy Channel	WinRadio Channel	FireFace Channel	Pamguard Channel
1	56	1	1	0
2	60	2	2	1
3	54	TBD	TBD	TBD

** TBD = To Be Determined; backup sonobuoy will use the WinRadio/ FireFace/Pamguard channel of the buoy it is replacing.*

*Ability to replace a failed sonobuoy will depend on the anticipated transit distance for that night. Inquire with the Cruise Leader before beginning the protocol. If there is insufficient time to replace a failed sonobuoy, the data from any working sonobuoys may be recorded, but should be adequately documented. If there is time to replace a failed sonobuoy, then sonobuoy #3 will be deployed as close to the location of the failed sonobuoy as possible. The vessel will then need to repeat the Straight Line Calibration before moving onto the next step.

3. **Deployment:** To ensure that calibration is completed before the CTD station, it is imperative that the sonobuoy protocol begin as soon as possible after cessation of daytime effort. All sonobuoys should be deployed at the same location on the vessel. When the Visual Team ends effort, the Acoustics Team should be prepared to deploy the first sonobuoy. Deployment of sonobuoys will proceed as follows:
    a. **Visual Team Off-Effort for the day**- Acoustic Team deploy sonobuoy #1. Acoustician in lab will immediately hit the 'DEPLOY' button in the DIFAR interface in Pamguard. OOD on watch will mark the position on the navigation screen.
    b. **Straight Line Calibration #1**: Continue in a straight line at full speed (blue line). Acousticians will conduct straight-line calibration in PAMGUARD. When complete (after ~0.5 mi) radio to the Bridge to turn 135^{o} (OOD can choose direction based on prevailing conditions, hazards, etc.) and slow to 4-5 kts.
    c. **Angular Calibration #1 & Array Recovery:** Once steadied up on new course and slowed to appropriate speed, begin recovering towed hydrophone array (red line). OOD determine location of sonobuoy #2 along this track to position sonobuoy #2 2 nmi from sonobuoy #1.
    d. **Ensure 2 nmi distance between sonobuoys:** Once array recovery is complete return to full speed (blue line). OOD will provide a 2 minute warning to Acoustics Team of upcoming sonobuoy station, and then a countdown to the deployment location. Acoustics Team deploy sonobuoy #2 at location indicated by OOD.
    e. **Straight Line Calibration #2**: Continue in a straight line at full speed (blue line). Acousticians will conduct straight-line calibration in PAMGUARD. OOD will determine location of upcoming CTD to ensure it is equidistant to the two deployed sonobuoys at a distance of approximately 1.5 mi to each.
    f. **Angular Calibration #2 & positioning for CTD:** When straight-line calibration complete (after ~0.5 mi) radio to the Bridge to turn toward the CTD station (purple line). Continue to CTD station at full speed. Acoustician should ensure they have adequate sonobuoy radio signal and maintain recordings for the duration of the CTD.



Appendix B- Opportunistic Sonobuoy Protocol

Opportunistic sonobuoys will be deployed on all baleen whale sightings for which we spend > 15 minutes in the area. Successful implementation will require an initial meeting with all acousticians and any officers/crew that may participate in sonobuoy stations.

REQUIREMENTS

Opportunistic sonobuoys will be deployed on baleen whale sightings where photo and/or biopsy attempts are made (or, where the vessel spends > 15 minutes in the area). To reduce radio interference, all shipboard communications should use handheld radios during all sonobuoy recordings.

METHODS

1. **Preparation:** There should always be 3 sonobuoys (minimum) prepared for opportunistic deployment according to the channels shown in Table 1 (only two will be used, the third is a prepared backup). Note that these channels are different than the channels for sonobuoy stations, so that if there is an overlap in time/space, the station can be conducted in systematic fashion without radio interference. Confirm that there are no other sources of interference. Acoustician will open and prepare Pamguard software according to channel designation shown in Table 1 and following detailed instructions.

   Table 1. Channel configuration for opportunistic sonobuoy deployments.

Sonobuoy #	Sonobuoy Channel	WinRadio Channel	FireFace Channel	Pamguard Channel
1	62	1	1	0
2	64	2	2	1
3	54	TBD	TBD	TBD

   ** TBD = To Be Determined; backup sonobuoy will use the WinRadio/ FireFace/Pamguard channel of the buoy it is replacing.*

2. **Deployment:** Deployment of the first buoy will occur in transit to the sighting (so there is ample time to calibrate before reaching the immediate area). The second sonobuoy will (ideally) be deployed in closer proximity to the detection, but such that there is **NOT** a straight line between the two buoys and the sighting, as this complicates localization (Fig. 1a). Ideally the second sonobuoy would be deployed at a small distance to the

sighting, but not between the first sonobuoy and the second sonobuoy; an example of an ideal deployment configuration is shown in Fig. 1b. Every effort should be made to provide some straight-line transit away from the second sonobuoy to allow for calibration.

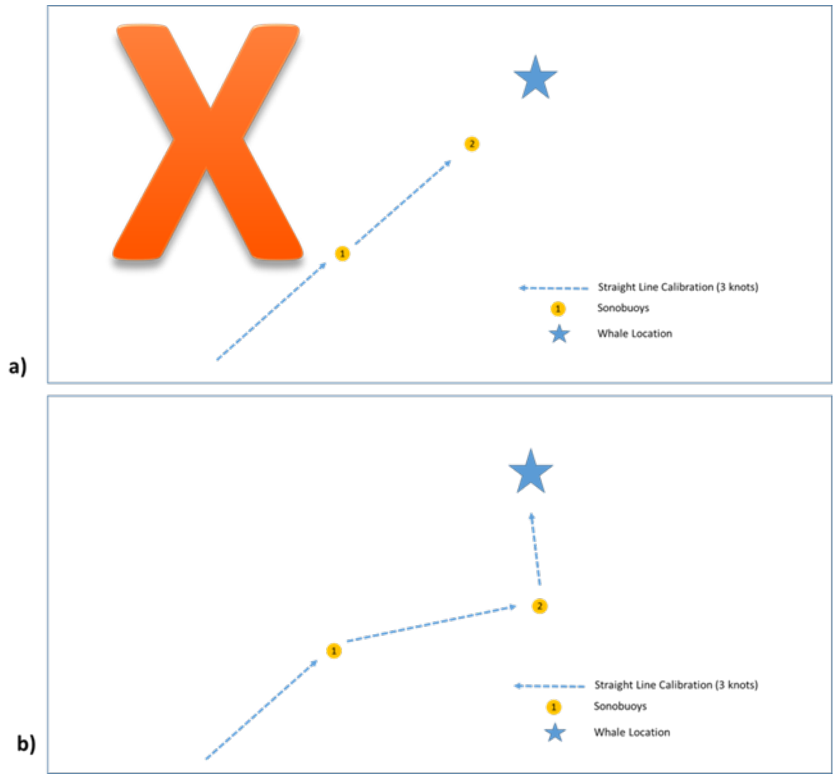


Figure 1. Sonobuoy deployment configuration options for opportunistic sonobuoys. A sub-optimal configuration (1a) where the buoys, vessel, and whale are in a line limits localization options. A preferred configuration will provide significantly different DIFAR bearing angles from each buoy to the whale (1b).

3. **Straight Line Calibration:** Real-time calibration will begin shortly after deployment for each sonobuoy (see detailed instructions). If variation in bearing angles varies by > 20 degrees while the vessel is traveling on a straight course, then the buoy will be considered to be poor quality. If time/opportunity allows, the third (backup) sonobuoy will be deployed in the location of the poor quality buoy. In this case, the straight line calibration must be completed in full.

4. **Recording:** Continue recording until sonobuoy reception is lost on both sonobuoys.

Appendix C- List of Suggested Pamguard Modifications

While we highly encourage the following modifications to Pamguard, we respectfully request that changes made to data structure (database/binaries) be implemented at one time rather than incrementally. We have developed software that will work with the current database/binary output (Pamguard 2.00.12), and this software will require modification after changes have been made to Pamguard. We prefer to make these changes once rather than incrementally. Also, we are making this list of suggested modifications available to the Pamguard developers; however, we currently do not have funds nor have we identified potential funds. We would be happy to provide a letter of need or any other information (including collaboration) to aid in obtaining funds for these modifications.

Incorporate AziGram (A. Thode) into Pamguard Processing Options. Aaron Thode has developed a unique method to processing DIFAR sonobuoys. Preliminary consideration of these methods has shown they are valuable for improved assessment of ambient/background noise, improved DIFAR bearing angle estimation for low SNR signals (down to 0 dB), and improved detection of low SNR signals (down to 0 dB). These methods are currently in development, and a publication of the methods is planned for 2018. We strongly encourage Aaron Thode to work with Pamguard developers to identify an approach and funding opportunities to implement this modification.

Allow independent modification across channels (in time domain) for call selection box. Currently, the user can box/link all calls, **but the box will be the same size/location on each channel**. This is problematic when there is a time delay in detection of calls, or when there is noise on one or more channels that requires a different box to be drawn. It is particularly bad for short calls (say 1 sec calls which may have little/no overlap). **Ideally, the user will select a box and it will be drawn and linked on all channels (as it currently does), but we would like an option to select and move the box for each channel independently (or delete if the call is not present).**

Note from B. Miller: It is possible to delete clips from the DIFAR queue if there is no call/noise. Modifying the location of a box already in the queue will require added functionality to the ClipGenerator (of which DifarClips) are a subset.

Alternative approaches to DIFAR Angle output. Currently, users are provided with one DIFAR angle per call. We would like to explore ways to improve upon this model. For example, we may make a box, then automatically a sub-box containing 90% of energy is then selected, DIFAR is then taken for slices w/in that box, and then we can either use (1) the distribution of these values or (2) the mean/median (or some other option). This information could be added to the binaries, where it could be exported and integrate into our R package.

Note from B. Miller: Implementation of this feature could be considered following a more detailed explanation regarding the intended gains—does the end result address a deficiency with the existing options and is it useful to all users of the DIFAR module?

Pause Button during analysis. It would be helpful to stop a session and re-start analysis at a later time/date. A pause analysis button with an option to close/save and then open/restart analysis at that point would be helpful.

Access to data stored in Binaries. Not sure what data is stored in the binaries (or could be stored in the binaries), but as we are writing R script to do all this other stuff—it might be a good opportunity to write the script to dive into the binaries and extract any/all relevant information. We are also keen on working with distributions of data rather than a single estimate, when appropriate.

Note from S. Rankin- This was translated to R (by T. Sakai) based on Matlab code created by Pamguard software developers; this has been integrated into the PAMsbuoy R package.

Identify Bad Buoys: wide variability in Calibration values. Some buoys do not provide stable bearing angles, and it would be good to possibly identify this in real time. We suggest an optional threshold setting within the DIFAR Settings dialogue that allows the user to select a threshold of acceptable variation in bearing angle error during calibration. When the variation of the angle errors for the calibration samples surpasses the selected threshold, then a warning is issued at the user interface. The user is then alerted to the fact that this buoy may have excessive variability in the bearing angles. The user can then decide if they should deploy another sonobuoy to 'replace' this one. It would be good if the warning stated the variation in the angles (so the user would know if it was close to the threshold or utter garbage). The PAMsbuoy package includes visualizations and a method for identifying the quality of calibration angles from a buoy. After a period of testing to identify strengths and limitations, it would be beneficial to add similar methods into real-time DIFAR in Pamguard.

Dummy-Proof Calibration Selections. Calibrations are less accurate when we are very close, or when the vessel is turning. In our post-processing, we may consider entire distribution of the calibration data. We would like to identify and eliminate calibrations that may be prone to excessive error for these 'known' reasons. We can do this in post-processing, but it may be beneficial to have an internal real-time process that identifies potential problems. For example, prior to accepting a calibration, there may be a warning that the vessel is w/in XX km of the buoy or that the vessel appears to be turning excessively. The user could then decide to eliminate that calibration and obtain additional ones.

Sonobuoy Deployment Notification. We would like to find a robust approach to identifying the exact time a sonobuoy is deployed. If we are correct, the data is first front-loaded, and then later it is deployed via the DIFAR module interface. This creates several lines in the database, and currently we are using the last of the lines (for each channel) to identify the deployment location. We are concerned this may lead to errors. Would it be possible to 'tag' an entry when it is created from this DIFAR module DEPLOY selection? For example, it would put a "D" in a new column to identify that entry as a deployment.

Note from B. Miller: This has now been implemented in version 2.00.11!

Link autodetectors in Pamguard- Implementation and testing of autodetectors to DIFAR module with consideration of manual over-ride to ensure appropriate boxing of calls across channels (for example, moving the boxes to improve bearing angles, see suggestion#2).

Note from B. Miller: Autodetectors can already be linked to the DIFAR module. There are already a few options for manual oversight: Automated detections can be automatically assigned a pre-determined DIFAR classification via the DIFAR Settings menu. If automated detections aren't automatically assigned a classification (i.e. classification is Default), then they will remain in the queue until the operator manually assigns a classification or deletes them. Instead of resizing the clips/boxes, the process would involve deleting a clip from the queue/DIFARGram and redrawing the box on the spectrogram. See my response to suggestion #1 about resizing.

Note from S. Rankin: This approach will likely lead to problems related to consistency across users and user error. A more robust approach should be considered.

Species Name in Lookup Table. It may be helpful to provide species names in the lookup table. The code (used w/in DIFAR), when linked to the lookup table, may provide additional information regarding the full name of the 'species'. This may include vessel noise for calibration (vessel name) and complete common & scientific names for species (and additional information for call type). This information could then be used in the PAMsbuoy package to allow for more complete development of tables, graphics, and reporting.