Software for real-time localization of baleen whale calls using directional sonobuoys: A case study on Antarctic blue whales

Brian S. Miller,[1] Susannah Calderan,[1] Douglas Gillespie,[2] Graham Weatherup,[3] Russell Leaper,[4] Kym Collins,[1] and Michael C. Double[1]

[1]*Australian Marine Mammal Centre, Australian Antarctic Division, Kingston, Tasmania, Australia*

[2]*Sea Mammal Research Unit, Scottish Oceans Institute, University of St. Andrews, St. Andrews, Scotland*

[3]*St. Andrews Instrumentation, St. Andrews, Scotland*

[4]*School of Biological Sciences, University of Aberdeen, Tillydrone Avenue, Aberdeen, United Kingdom*

brian.miller@aad.gov.au, susa@scoter.org, dg50@st-andrews.ac.uk, gw@sa-instrumentation.com, r.c.leaper@abdn.ac.uk, kymcollins77@gmail.com, Mike.Double@aad.gov.au

Abstract: Directional frequency analysis and recording (DIFAR) sonobuoys can allow real-time acoustic localization of baleen whales for underwater tracking and remote sensing, but limited availability of hardware and software has prevented wider usage. These software limitations were addressed by developing a module in the open-source software PAMGuard. A case study is presented demonstrating that this software provides greater efficiency and accessibility than previous methods for detecting, localizing, and tracking Antarctic blue whales in real time. Additionally, this software can easily be extended to track other low and mid frequency sounds including those from other cetaceans, pinnipeds, icebergs, shipping, and seismic airguns.

[CFM]
Date Received: November 28, 2015 **Date Accepted:** February 18, 2016

1. Background

Directional frequency analysis and recording (DIFAR) sonobuoys have been in use in whale research programs for the past two decades (Blackwell *et al.*, 2012; Blackwell *et al.*, 2013; Gedamke and Robinson, 2010; Greene *et al.*, 2004; Guerra *et al.*, 2011; McDonald and Moore, 2002; McDonald, 2004; McDonald *et al.*, 2001; Miller *et al.*, 2014; Miller *et al.*, 2015; Oleson *et al.*, 2007; Rankin *et al.*, 2005; Rivers, 1997; Širović and Hildebrand, 2011; Swartz *et al.*, 2003; Thode *et al.*, 2000; Wade *et al.*, 2006; Wade *et al.*, 2011). These studies indicate that sonobuoys comprise an efficient means for synoptic-scale acoustic monitoring of baleen whales allowing for coverage of broad pelagic areas in relatively short time periods. Sonobuoy surveys effectively combine the low-frequency performance of fixed acoustic sensors (i.e., high signal-to-noise ratio in the 0–4 kHz band; Mellinger *et al.*, 2007) with the broad spatial and temporal coverage and localization ability of a towed hydrophone array (i.e., covering thousands of kilometers in days or weeks; Van Parijs *et al.*, 2009).

To localize sounds, each DIFAR sonobuoy contains a compass, azimuthal acoustic vector sensor, and an omnidirectional hydrophone. Differences in the phase and amplitude detected among the vector sensors and the hydrophone can be used to estimate the bearing to a sound source with respect to the magnetic compass. The signals from these sensors and hydrophone are typically multiplexed and transmitted to a nearby vessel or aircraft using VHF radio. This radio link reduces low-frequency noise by allowing placement of the sonobuoy far from self-noise sources (i.e., research vessels) and by eliminating low-frequency (i.e., <1 kHz) "flow-noise" prevalent on towed hydrophone arrays.

Bearings from a single DIFAR sonobuoy allow researchers to home in on vocalising animals from tens to hundreds of kilometres away (McDonald, 2004; Miller *et al.*, 2015; Wade *et al.*, 2006), while bearings to the same source received on multiple DIFAR sensors allow accurate triangulation of the source's geographic position (Blackwell *et al.*, 2012; Greene *et al.*, 2004; Miller *et al.*, 2015). Furthermore, the acoustic bearings and calibrated received pressure levels from a single DIFAR sonobuoy facilitate identification of the sound source as well as estimation of the source level (Greene *et al.*, 2004; McDonald *et al.*, 2001; Rankin *et al.*, 2005; Thode *et al.*, 2000).

While DIFAR sonobuoys have seen limited use in whale research over the past two decades, greater adoption has primarily been limited by two factors:

availability of military (i.e., export-controlled) DIFAR sonobuoys and availability of integrated end-user software to process and analyse data collected from sonobuoys in real time. Here we address the latter of these limitations.

To date researchers have used disparate bespoke tools for working with DIFAR data including the DIFAR Demultiplexer by Greeneridge Sciences Inc. (Greeneridge Sciences Inc., 2016), beamforming software from WhaleAcoustics (WhaleAcoustics, 2011) as well as acquisition and display software such as PAMGuard (PAMGuard, 2016), ISHMAEL (ISHMAEL, 2016), and MATLAB scripts (Mathworks Inc., Natick, MA). Additional custom software and extensive modification of these tools has often been a requirement in order to accommodate different survey designs and/or localize different species or call types on subsequent voyages; thus narrowing the focus and reducing the accessibility of these systems. Furthermore, the *ad hoc* nature of these modifications can lead to a range of problems including inefficient workflow unsuitable for real-time operation, cumbersome (and potentially error-prone) management of data, and software instability that may ultimately result in unexpected downtime and/or data loss.

2. PAMGuard DIFAR module

In response to these limitations, DIFAR localization software was developed by the Australian Marine Mammal Centre and the University of St. Andrews within the open-source framework of PAMGuard (Gillespie *et al.*, 2008; PAMGuard, 2016). PAMGuard is industry standard software for cetacean passive acoustic monitoring, and its flexible and modular architecture allows it to be used not only in industry for monitoring during offshore development but also by scientists conducting marine acoustic studies (e.g., Gillespie *et al.*, 2013; Miller *et al.*, 2013). The PAMGuard DIFAR Localization module has been built to work in conjunction with existing modules of PAMGuard that provide for the acquisition, filtration, resampling, and display of acoustic data; the acquisition and mapping of positional/spatial data, management of hydrophone deployment metadata, automated detection of vocalizations, measurement of signals and noise, and data storage. The new DIFAR localization module provides for the classification, localization, and tracking of acoustic signals from DIFAR sonobuoys. A typical DIFAR processing chain within PAMGuard, including the new DIFAR localization modules, is shown in Fig. 1.

PAMGuard's core modules are used to acquire DIFAR signals from an analog-to-digital converter connected to a sonobuoy radio receiver. Core modules are also used to display a spectrogram of the multiplexed DIFAR data for quality control purposes and to display a spectrogram of the signal from the omnidirectional hydrophone on which the operator can manually mark sounds of interest or can apply automatic detectors. Multiplexed data from manually marked sounds and automated detections are then placed in the DIFAR localization queue for further analysis. While waiting in the queue, the spectrogram of audio from the omnidirectional hydrophone is displayed with metadata to provide the operator with a visual overview of the workflow. The operator can then assign a user-defined classification to queued sounds at which point the data will be sent from the queue for further DIFAR processing. This involves demultiplexing the data from the three sensors and computation of the DIFAR ambiguity surface using algorithms ported from previous MATLAB software (Greene *et al.*, 2004; McDonald, 2004).

To provide full functionality within the freely distributable open-source version of PAMGuard, the DIFAR module includes an open-source frequency-domain demultiplexer for the extraction of signals from the directional sensors. However, the PAMGuard DIFAR module can also integrate with the widely used, well tested, and faster performing time-domain demultiplexer sold by Greeneridge Science (Greeneridge Science Inc., 2016).

After demultiplexing, beamforming algorithms are used to obtain an estimate of the signal power as a function of tonal frequency and magnetic bearing (D'Spain, 1994; McDonald, 2004). For a given detection, the bearing and frequency with the highest power will usually represent the direction of the vocalisation, and the DIFAR module can automatically suggest this as the default estimate of bearing. There is also the option to allow the user to select a different bearing and frequency from that which has been automatically suggested. While the automatically generated bearings are almost invariably the ones chosen, a, side-by-side display of the spectrogram and bearing-frequency ambiguity surface enables the operator to quickly judge whether a bearing is likely to be unreliable due to noise (Fig. 2).

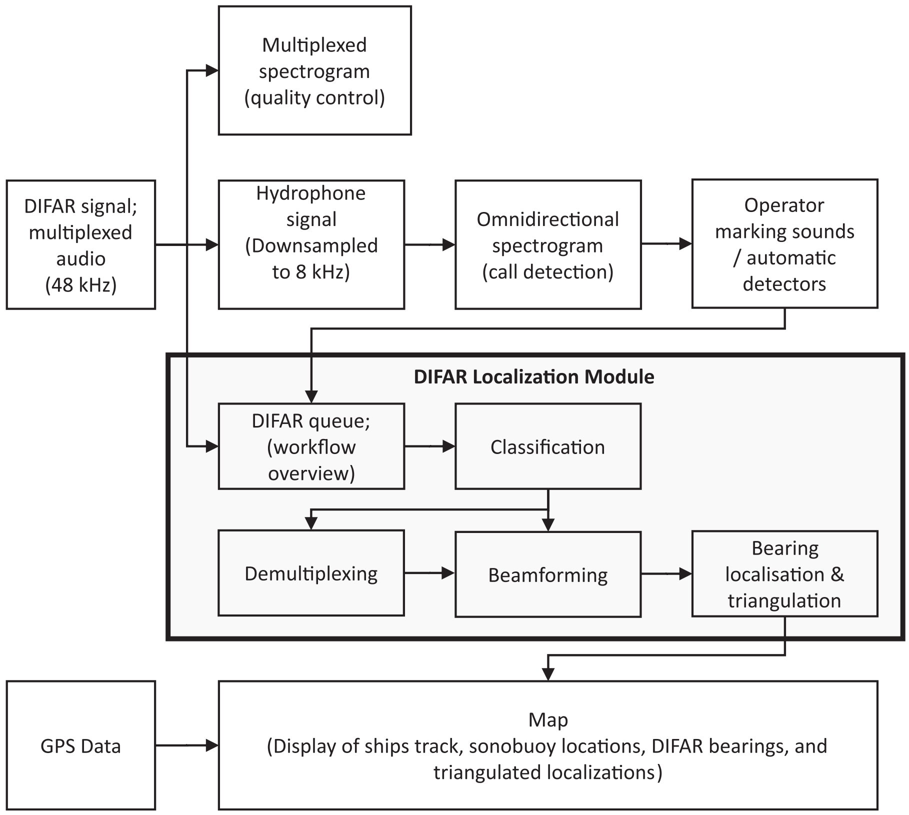

Fig. 1. A typical workflow showing core modules and their relationship to the DIFAR localization module within the PAMGuard software.

2.1 Calibration

Calibrating the magnetic compass in DIFAR sonobuoys is essential for obtaining reliable localizations, and this process typically involves measuring several magnetic bearings to sound sources at known locations (Greene *et al.*, 2004; McDonald, 2004; Miller *et al.*, 2015). The PAMGuard DIFAR localization software provides options for largely automating this calibration process. The module also allows easy creation and modification of sound classifications, each with user-definable durations/bandwidths. These classifications allow the signal processing to be optimised with respect to the sound source (e.g., the noise from the survey vessel, an upswept tone played through an underwater loudspeaker, shots from seismic airguns, a whale at a known location, etc.).

DIFAR sonobuoys potentially allow for calibrated measurements of received sound pressure levels. However, DIFAR hydrophones have a shaped frequency

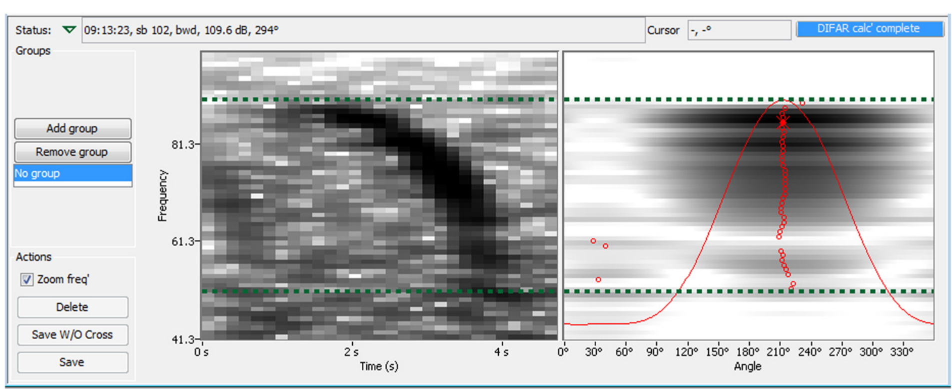

Fig. 2. (Color online) Screenshot of PAMGuard DIFAR module showing the spectrogram of a blue whale FM call (left) and the DIFARGram [i.e., bearing-frequency ambiguity surface *sensu* (McDonald, 2004); right]. The green dashed lines indicate the frequencies relevant for this classification. The red-line on the DIFARGram indicates the normalized sum of energy over the relevant frequencies. Red circles indicate the bearing of highest energy for each frequency bin. The frequency and bearing of overall maximum energy is indicated with a red cross.

response (Greene *et al.*, 2004), which must be corrected along with any shaped frequency response of the receiving hardware when making measurements of received level (Merchant *et al.*, 2015). Earlier versions of PAMGuard included a single parameter for the sensitivity of each hydrophone (i.e., dB V/μPa) and could therefore only compute received levels for hydrophones that had a flat frequency response. The DIFAR module allows for the correction of a shaped frequency response in the recording chain so that calibrated received levels may be calculated (i.e., received levels reported in dB re 1 μPa), and used for modelling acoustic propagation.

2.2 Localization

Bearings to the sound source that have been accepted by the operator are displayed on the PAMGuard map. The opacity of each bearing line is used to indicate how recently it was plotted with older bearings becoming more transparent with time. Bearing lines are color-coded according to their user-defined classification, and the length of each bearing line can be adjusted based on received level to give an approximate indication of the distance to the source. To do this, two simple models of acoustic propagation loss are included in the DIFAR module to determine the length of plotted bearings: geometric inverse spreading, and a surface duct (Urick, 1983).

The module allows for simultaneous recording from multiple buoys as well as triangulation of multiple bearings to calculate a two-dimensional georeferenced location. The DIFAR module automatically determines whether bearings from multiple buoys could have originated from the same source based on time of arrival and type of classification, and if so the intersection point of these bearings is automatically calculated and displayed. A maximum likelihood approach is used to determine the intersection point and estimate the error bounds of the triangulated position. Triangulated positions and error bars are displayed in the PAMGuard map module and use identical color-coding and opacity to the bearings.

2.3 Automation

Throughout the process, from sounds being marked to being classified and then plotted as bearings, the operator can choose to allow PAMGuard to perform the action automatically or to carry it out manually. PAMGuard's whistle and moan detector (Gillespie *et al.*, 2013) and other automated detectors can be used as input in addition to or instead of manual event selection; the system can be set to automatically move selected sounds from the queue to the processing module and to automatically select and/or plot the strongest bearing. While automation can increase the total number of sounds localized, in some situations, the enhanced confidence from manual validation of each step may be preferable, especially when making decisions based upon real-time acoustic data.

3. Case study: acoustic tracking of antarctic blue whales

Recently, the Antarctic Blue Whale Project (ABWP) of the International Whaling Commission's Southern Ocean Research Partnership (IWC-SORP) has developed new research protocols that combine visual sightings and passive acoustic techniques to facilitate the study of Antarctic blue whales (Peel *et al.*, 2014). These new protocols rely upon using DIFAR sonobuoys to detect and home-in on vocalisations from groups of blue whales and to track and locate individuals for the purposes of photo-identification, biopsy sampling, observation of fine scale movements, and investigation of predator-prey relationships (Cox *et al.*, 2015; Miller *et al.*, 2015; O'Driscoll and Double, 2015; Peel *et al.*, 2015). An IWC-SORP voyage in 2013 demonstrated the viability and efficiency of these techniques and their suitability for increasing encounter rates of these rare, sparsely-distributed whales (Miller *et al.*, 2015).

3.1 Methods

There have been two recent research voyages that have acoustically tracked Antarctic blue whales using DIFAR sonobuoys: the 2013 Antarctic Blue Whale Voyage and the 2015 New Zealand-Australia Antarctic Ecosystem Voyage. Methods and results from acoustic tracking during the 2013 voyage are described in detail in Miller *et al.* (2015), and almost-identical methods and hardware configuration were employed during the 2015 voyage. The main differences in 2015 were the software used and the acoustic monitoring effort. The 2015 voyage was slightly shorter in duration—42 vs 48 days—and not all of those days were available for whale research; additionally the acoustics team comprised only four of the five acousticians from the 2013 voyage. Table 1 shows a summary of the acoustic effort and results of the 2015 voyage in comparison with those from 2013. In relation to data processing, the main difference between the two voyages was the software used.

The software used during the 2013 Antarctic Blue Whale Voyage comprised an assemblage of bespoke and general purpose tools for data acquisition, detection, and localization (Miller *et al.*, 2015). While this system worked, it was fragile, slow, and difficult to use with the operator having to switch between different programs: MATLAB, PAMGuard and EXCEL. Furthermore, the software could not easily be extended, modified, or repaired *in situ* by end-users, thus requiring the presence of a software developer on the voyage to address any unforeseen issues. On the 2015 voyage, the PAMGuard DIFAR localization module was the sole software used for data acquisition, detection, localization and tracking of whales and other sound sources.

On both voyages, during periods with few detections, all calls from Antarctic blue whales were localized. However, for a large proportion of both voyages, Antarctic blue whale calls were so numerous that only a subset of the detections could be localized in real time. This was due in part to the speed of the software workflow and in part to the need for the acoustician to interpret the results, maintain awareness of several vocalising groups, and coordinate actions based on the acoustic data.

3.2 Results

From over 580 h of whale recordings made during the 2015 voyage, 49 167 Antarctic blue whale calls were manually selected with their bearings plotted and displayed on the map. A large proportion of this monitoring time occurred when only one sonobuoy was deployed, yet there was often a need to compare a set of bearings from different buoys received several hours apart to estimate the direction and proximity to vocal aggregations of whales. The mapping facilities and offline viewing capabilities within PAMGuard were important for allowing such comparisons [Fig. 3(a)].

During the voyage, geometric spreading was used to scale bearing lines in temperate waters, while the surface duct model was used in Antarctic waters. Parameters for each model were adjusted *in situ* so that the endpoints of bearing lines broadly agreed with visual sightings of blue whales. As in 2013 (Miller *et al.*, 2015), both tonal and FM calls of Antarctic blue whales (Rankin *et al.*, 2005) were detected within and around vocal aggregations. Tones (26 Hz) could be heard at great distances from the vocal aggregations, while FM and Z calls were only detected much closer to vocal aggregations. Of the 49 167 bearings to calls from Antarctic blue whales, 14 726 could be paired as the same call received simultaneously on two sonobuoys. These were used to obtain 7363 triangulated positions of calling whales [Fig. 3(b)]. Despite having fewer acousticians, deploying fewer sonobuoys, and recording less total audio in 2015, the DIFAR localization module facilitated the acquisition of nearly twice as many bearings and more than double the number of triangulations compared to 2013 (Table 1).

Qualitatively PAMGuard's DIFAR module was more accessible, easier to use, and more stable than software that was used in 2013. Because much of the functionality in the DIFAR localization module was automated, it allowed more time for planning subsequent deployments and tracking strategy. This was an important benefit during real-time tracking as it facilitated close approaches to whales for biopsy, photo-identification, and prey surveys. It also allowed for detailed real-time localization of whales during periods of poor viewing conditions. PAMGuard was the sole software program used to acquire, process, and analyse the acoustic data during the 2015

Table 1. Comparison of acoustic effort and results during the 2013 Antarctic Blue Whale Voyage and the 2015 New Zealand Australia Antarctic Ecosystems Voyage. The DIFAR localization module was used exclusively in 2015 and enabled more efficient processing of calls, resulting in more localizations in 2015 despite a slight reduction in acoustic effort compared to 2013. Only calls, triangulations, encounters, sightings, and identifications of Antarctic blue whales are reported here.

Measure	2013	2015
Sonobuoys deployed	361	320
Failed buoys	43	29
Audio recorded (hours)	733	583
Audio from 2 simultaneous buoys (%)	52	40
Full time acousticians	5	4
Tonal calls analysed in real time	19 395	28 941
FM calls analysed in real time	7639	20 226
Triangulated locations	3146	7363
Visual survey hours	410	435
Visual encounters	33	40
Whales sighted	84	95
Photographic identifications	50	46

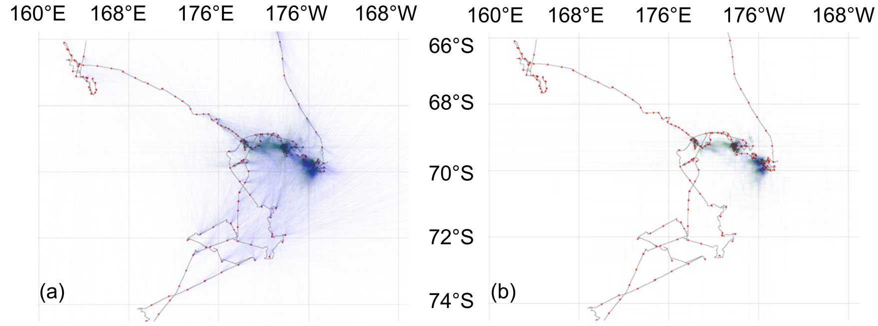

Fig. 3. (Color online) PAMGuard Map in Viewer (Offline) Mode showing 49 167 DIFAR bearings (a) and 7363 triangulated positions (b) from the 2015 voyage. The black line shows the ship's track (GPS). Red dots show the deployment location of sonobuoys. Blue and green lines show acoustic bearings to locations of Antarctic blue whale tonal and FM calls, respectively. Each bearing and triangulation is 98% transparent, i.e., opacity is indicative of the call density. The length of bearings are scaled based on measured received levels, a source level of 182 dB re 1 μPa, and propagation loss in an Antarctic surface duct with a transition range of 2 km: $PL = 10 \log_{10}(r) - 10 \log_{10}(2000)$. Plotting all localizations reveals a vocalizing aggregation of Antarctic blue whales between 69–70°S and 178°E–175°W.

voyage, and the DIFAR localization module enabled a substantially more efficient workflow for real-time localization of Antarctic blue whales.

4. Conclusion

Integrating these DIFAR localization methods into PAMGuard's established framework should increase the uptake of these methods and ultimately add another tool to complement the growing toolbox of real-time marine mammal monitoring platforms such as visual observations, towed hydrophone arrays, cabled acoustic observatories, and autonomous underwater vehicles. PAMGuard is already widely used for monitoring for marine mammals during marine mammal surveys, research voyages, and coastal and offshore developments, and the PAMGuard DIFAR localization module described here integrates elegantly with existing PAMGuard modules and provides a stable, accessible framework with a simple workflow. Furthermore, the DIFAR module's ability to make calibrated intensity measurements and locate low-frequency tonal sounds in real time may also facilitate *in situ* validation of models of anthropogenic noises such as sonar, pile-driving, seismic airguns, and shipping that are increasingly used in management of marine developments. The continued development of this user-friendly software may decrease the need for large teams of specialist acousticians to conduct real-time passive acoustic monitoring via DIFAR sonobuoys, and it is hoped that this software will facilitate standardised protocols for real-time acoustic localization of low-frequency tonal calls of baleen whales. The DIFAR module is available in the current and future PAMGuard releases, and an example configuration file is available via the PAMGuard website (PAMGuard, 2016).

Acknowledgments

Funding for development of the PAMGuard DIFAR module was provided by the Australian Marine Mammal Centre through the Antarctic Blue Whale Project of the Southern Ocean Research Partnership. We thank Greeneridge Sciences Inc. for their donation of a license to use their De-multiplexing software for the development of the PAMGuard DIFAR module. We thank Mark McDonald from WhaleAcoustics for providing his DIFAR (Beamforming) software, which served as the basis and inspiration for the PAMGuard DIFAR module. We thank Shannon Rankin, Jennifer Keating, Melissa Soldevilla, Mariana Melcón, and Fannie Shabangu for patiently testing and providing feedback on early versions of the PAMGuard DIFAR module. We thank the scientists and crew aboard the FV Amaltal Explorer and the RV Tangaroa for their enormous contribution to the success of the 2013 and 2015 research voyages.

References and links

Blackwell, S. B., McDonald, T. L., Kim, K. H., Aerts, L. A. M., Richardson, W. J., Greene, C. R. J., and Streever, B. (**2012**). "Directionality of bowhead whale calls measured with multiple sensors," Mar. Mamm. Sci. **28**, 200–212.

Blackwell, S. B., Nations, C. S., McDonald, T. L., Greene, C. R. J., Thode, A. M., Guerra, M., and Macrander, A. M. (**2013**). "Effects of airgun sounds on bowhead whale calling rates in the Alaskan Beaufort Sea," Mar. Mamm. Sci. **29**, E342–E365.

Cox, M. J., Miller, B. S., Miller, E., and Double, M. C. (**2015**). "A preliminary investigation of the distribution of krill in the vicinity of Antarctic blue whales," Unpublished paper submitted to the *Scientific Committee of the International Whaling Commission, SC66A*, San Diego, CA.

D'Spain, G. (**1994**). "Relationship of underwater acoustic intensity measurements to beamforming," Can. Acoust. **2**, 157–158.

Gedamke, J., and Robinson, S. M. (**2010**). "Acoustic survey for marine mammal occurrence and distribution off East Antarctica (30-80°E) in January-February 2006," Deep Sea Res. II Top. Stud. Oceanogr. **57**, 968–981.

Gillespie, D., Caillat, M., Gordon, J. C., and White, P. (**2013**). "Automatic detection and classification of odontocete whistles," J. Acoust. Soc. Am. **134**, 2427–2437.

Gillespie, D., Gordon, J., Mchugh, R., Mclaren, D., Mellinger, D., Redmond, P., Thode, A., Trinder, P., and Deng, X. Y. (**2008**). "PAMGuard: Semiautomated, open source software for real-time acoustic detection and localisation of cetaceans," Proc. Inst. Acoust. **30**, 54–62.

Greene, C. R. J., McLennan, M. W., Norman, R. G., McDonald, T. L., Jakubczak, R. S., and Richardson, W. J. (**2004**). "Directional frequency and recording (DIFAR) sensors in seafloor recorders to locate calling bowhead whales during their fall migration," J. Acoust. Soc. Am. **116**, 799–813.

Greeneridge Sciences Inc. (**2016**). http://www.greeneridge.com/software.html (Last viewed 3/11/2016).

Guerra, M., Thode, A. M., Blackwell, S. B., and Macrander, M. A. (**2011**). "Quantifying seismic survey reverberation off the Alaskan North Slope," J. Acoust. Soc. Am. **130**, 3046–3058.

ISHMAEL (**2016**). http://www.bioacoustics.us/ishmael.html (Last viewed 3/11/2016).

McDonald, M. A. (**2004**). "DIFAR hydrophone usage in whale research," Can. Acoust. **32**, 155–160.

McDonald, M. A., Calambokidis, J., Teranishi, A. M., and Hildebrand, J. A. (**2001**). "The acoustic calls of blue whales off California with gender data," J. Acoust. Soc. Am. **109**, 1728–1735.

McDonald, M. A., and Moore, S. (**2002**). "Calls recorded from North Pacific right whales (*Eubalaena japonica*) in the eastern Bering Sea," J. Cetacean Res. Manage. **4**, 261–266.

Mellinger, D. K., Stafford, K. M., Moore, S. E., Dziak, R. P., and Matsumoto, H. (**2007**). "An overview of fixed passive acoustic observation methods for cetaceans," Oceanography **20**, 36–45.

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., and Parks, S. E. (**2015**). "Measuring acoustic habitats," Methods Ecol. Evol. **6**, 257–265.

Miller, B. S., Barlow, J., Calderan, S., Collins, K., Leaper, R., Olson, P., Ensor, P., Peel, D., Donnelly, D., Andrews-Goff, V., Olavarria, C., Owen, K., Rekdahl, M., Schmitt, N., Wadley, V., Gedmake, J., Gales, N., and Double, M. C. (**2015**). "Validating the reliability of passive acoustic localisation: A novel method for encountering rare and remote Antarctic blue whales," Endangered Species Res. **26**, 257–269.

Miller, B. S., Collins, K., Barlow, J., Calderan, S., Leaper, R., McDonald, M., Ensor, P., Olson, P. A., Olavarria, C., and Double, M. C. (**2014**). "Blue whale vocalizations recorded around New Zealand: 1964-2013," J. Acoust. Soc. Am. **135**, 1616–1623.

Miller, B. S., Growcott, A., Slooten, E., and Dawson, S. M. (**2013**). "Acoustically derived growth rates of sperm whales (*Physeter macrocephalus*) in Kaikoura, New Zealand," J. Acoust. Soc. Am. **134**, 2438–2445.

O'Driscoll, R., and Double, M. (**2015**). *Voyage Report TAN1502 New Zealand-Australia Antarctic Ecosystems Voyage* (Wellington, New Zealand).

Oleson, E. M., Calambokidis, J., Barlow, J., and Hildebrand, J. A. (**2007**). "Blue whale visual and acoustic encounter rates in the southern California bight," Marine Mamm. Sci. **23**, 574–597.

PAMGuard (**2016**). www.pamguard.org (Last viewed 3/11/2016).

Peel, D., Bravington, M., Kelly, N., and Double, M. C. (**2015**). "Designing an effective mark–recapture study of Antarctic blue whales," Ecol. Appl. **25**, 1003–1015.

Peel, D., Miller, B. S., Kelly, N., Dawson, S., Slooten, E., and Double, M. C. (**2014**). "A simulation study of acoustic-assisted tracking of whales for mark-recapture surveys," PloS One **9**, e95602.

Rankin, S., Ljungblad, D. K., Clark, C. W., and Kato, H. (**2005**). "Vocalisations of Antarctic blue whales, *Balaenoptera musculus* intermedia, recorded during the 2001/2002 and 2002/2003 IWC/SOWER circumpolar cruises, Area V, Antarctica," J. Cetacean Res. Manage. **7**, 13–20.

Rivers, J. (**1997**). "Blue whale, *Balaenoptera musculus*, vocalizations from the waters off central California," Mar. Mamm. Sci. **13**, 186–195.

Širović, A., and Hildebrand, J. A. (**2011**). "Using passive acoustics to model blue whale habitat off the Western Antarctic Peninsula," Deep Sea Res. II: Top. Stud. Oceanogr. **58**, 1719–1728.

Swartz, S., Cole, T., McDonald, M. A., Hildebrand, J. A., Oleson, E. M., Martinez, A., Clapham, P. J., Barlow, J., and Jones, M. L. (**2003**). "Acoustic and visual survey of humpback whale (*Megaptera novaeangliae*) distribution in the eastern and southeastern Caribbean Sea," Carib. J. Sci. **39**, 195–208.

Thode, A. M., D'Spain, G. L., and Kuperman, W. A. (**2000**). "Matched-field processing, geoacoustic inversion, and source signature recovery of blue whale vocalizations," J. Acoust. Soc. Am. **107**, 1286–1300.

Urick, R. J. (**1983**). *Principles of Underwater Sound*, 3rd ed. (McGraw-Hill, New York).

Van Parijs, S. M., Clark, C. W., Sousa-Lima, R. S., Parks, S. E., Rankin, S., Risch, D., and Van Opzeeland, I. C. (**2009**). "Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales," Mar. Ecol. Prog. Ser. **395**, 21–36.

Wade, P., De Robertis, A., Hough, K., Booth, R., Kennedy, A., LeDuc, R. G., Munger, L., Napp, J., Shelden, K. E. W., Rankin, S., Vasquez, O., and Wilson, C. (**2011**). "Rare detections of North Pacific right whales in the Gulf of Alaska, with observations of their potential prey," Endang. Spec. Res. **13**, 99–109.

Wade, P., Heide-Jørgensen, M. P., Shelden, K., Barlow, J., Carretta, J., Durban, J., Leduc, R., Munger, L., Rankin, S., Sauter, A., and Stinchcomb, C. (**2006**). "Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales Acoustic detection and satellite-tracking leads to discovery of rare concentration of endangered North Pacific right whales," Biol. Lett. **2**, 417–419.

WhaleAcoustics (**2011**). http://www.whaleacoustics.com/ (Last viewed December 2011).