Accuracy and precision of DIFAR localisation systems: Calibrations and comparative measurements from three SORP voyages

BRIAN S. MILLER[1], JASON GEDAMKE[2], SUSANNAH CALDERAN[1], KYM COLLINS[1], CATRIONA JOHNSON[1], ELANOR MILLER[3], FLORE SAMARAN[4], JOSH SMITH[5], AND MICHAEL C. DOUBLE[1]

1 – Australian Marine Mammal Centre, Australian Antarctic Division. Kingston, Tasmania, Australia Brian.Miller@aad.gov.au

2 – Ocean Acoustics Program, NOAA Fisheries Office of Science & Technology, National Oceanic and Atmospheric Administration. Silver Spring, MD, USA

3 –Otago University Marine Mammal Laboratory, University of Otago – Dunedin, New Zealand

4 – PELAGIS Observatory CNRS-UMS 3462, University of La Rochelle, France

5 –Murdoch University Cetacean Research Unit, Murdoch University, Perth, Australia

ABSTRACT

Passive acoustic localisation of blue whales has been a key component of Antarctic blue whale research, and is likely to become a key tool for future research conducted as a part of the Southern Ocean Research Partnership's Antarctic Blue Whale Project. This document presents methods to measure the accuracy and precision of a sonobuoy-based localisation system. These methods can be used in-situ to 'calibrate' the magnetic compass in each sonobuoy during real-time tracking of whales. Here we compare the accuracy and precision of localisations across several different data sets each collected on different voyages using different instrumentation. This document also includes additional information on the calibrations of the individual components of the sonobuoy localisation systems and provides recommendations regarding future development and deployment of sonobuoy-based localisation systems for passive acoustic localisation of whales.

KEYWORDS: PASSIVE ACOUSTICS; INSTRUMENTATION; SORP;

BACKGROUND

Passive acoustic tracking of blue whales is a key component of the Antarctic Blue Whale Project of the Southern Ocean Research Partnership (Kelly et al. 2010, 2012). Because passive acoustic tracking relies upon the use of complex electronic systems, it is important to understand the capabilities and limitations of the hardware and software that comprise the system in order to understand what constitutes sensible use. Passive acoustic monitoring for baleen whales during IDCR-SOWER and SORP voyages employed DIFAR (directional) sonobuoys (AN/SSQ 53D or 53F) for detection and localisation (Clark & Fowler 2001, Rankin & Barlow 2005, Gales 2010, Miller et al. 2012a, Double et al. 2013). Here we investigate the capabilities and limitations of these passive acoustic monitoring systems with a focus on the accuracy and precision of localisation (ie. bearing measurements).

Each DIFAR sonobuoy contains 3 acoustic sensors, a magnetic compass, signal processing circuitry, and a VHF radio transmitter. Acoustic sensors include an omnidirectional pressure sensor (ie. hydrophone), and two orthogonally oriented particle velocity sensors that are directional, and the data from these sensors and the magnetic compass can be combined to yield the magnetic bearing (ie. localisation) of detected sounds. The signal processing circuitry filters, amplifies, and combines the signals from the acoustic sensors and magnetic compass in a way that facilitates transmission via VHF radio. The magnetic compass in each sonobuoy has a nominal accuracy of ± 10° with respect to magnetic North (Greene et al. 2004). For localisation of sound sources, magnetic bearings must be corrected for magnetic deviation either using a chart, model, or by empirical measurement to a target at a known location (eg. the ship; Greene et al. 2004, McDonald 2004).

Sonobuoys typically send signals via VHF radio to a recording chain (eg. Figure 1), which consists of at least one VHF receiver connected to a computer via an analog-to-digital (A/D) converter. Each VHF receiver receives continuous transmission from a single sonobuoy within the range of VHF reception (approximately 10 nmi). A software program typically records the output from the A/D converter as digital audio files and displays a visual representation of the audio in real-time. Selected sounds can be further analysed by the operator using additional software (eg. McDonald, 2004). To date, analysis from DIFAR sonobuoys has focused on determining absolute sound pressure levels (eg. Miller et al., 2013), and obtaining the angle of arrival of the sound (ie. bearing from the buoy to the animal).

Knowledge of the accuracy and precision of the DIFAR bearings are of special interest to those performing real-time tracking. These quantities depend on accurate knowledge of the position of the sonobuoy, the local magnetic declination, the accuracy and precision of the sonobuoy compass, accurate calibration of the VHF receivers and recording chain, and the ratio of signal to noise present at each hydrophone. Here we describe a simple method to measure these quantities and estimate the accuracy and precision of the localisation system. We then apply these technique to data gathered during the 2010 Antarctic Whale Survey (Gales 2010) and the 2012 Blue whale voyages (Miller et al. 2012b) with a focus on comparing the recording chains and understanding the factors that affect precision and accuracy.

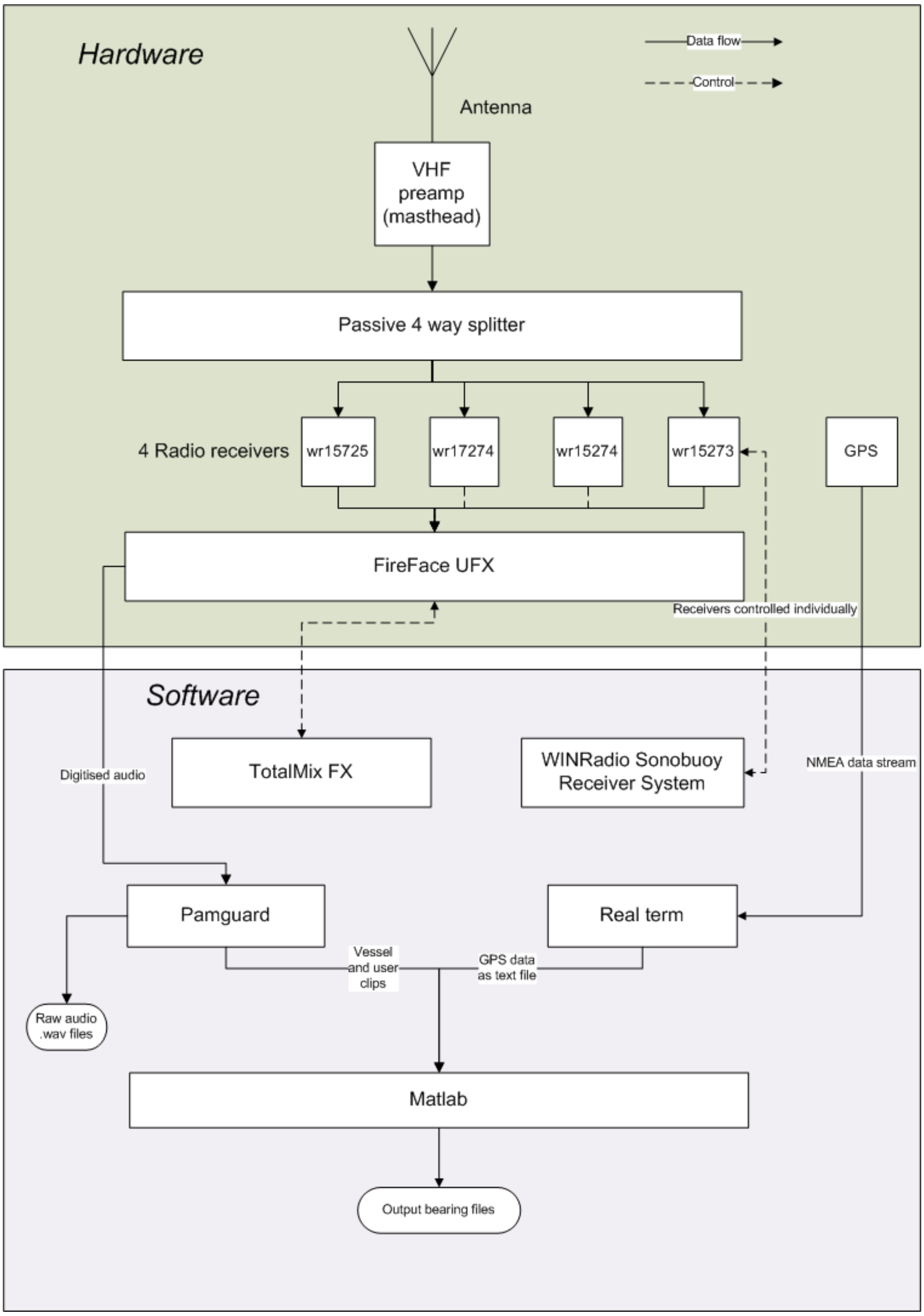

Figure 1 – An example sonobuoy recording and analysis system: data flow and control

During the Antarctic Whale Expedition in 2010 sonobuoys were deployed according to vessel operations. During long transects where the Research Vessel *Tangaroa* was moving consistently (at a typical cruising speed of 10 knots), deployments occurred regularly and without regard to sightings of whales in order to independently acoustically survey for distributions of vocalising whales. When *RV Tangaroa* was in the vicinity of whales, sonobuoys were deployed opportunistically in order to attempt to record sounds from the species known to be in the immediate area (e.g. humpback, minke, fin whales). Here we re-analysed data from 27 of the 111 sonobuoys that were deployed during this voyage (Appendix B) to determine the accuracy and precision of the bearings. This analysis included buoys deployed on 5-6 March, when the research vessel attempted to close on an acoustically detected blue whale(s), as well as buoys deployed in the westernmost portion of the survey track in the vicinity of the magnetic South Pole.

During the 2012 voyages, visual and acoustic (DIFAR) surveys were conducted in Bass Strait on board the vessel, *MV Eastern Voyager* for 10 days in January and for 9 days in March. Surveys were only conducted during suitable weather (ie. Beaufort Sea State less than 6). Typical cruising speed of the research vessel was 7 knots. Throughout both the January and March surveys sonobuoys were typically deployed every four-to-six hours, but upon detection of blue whales they were deployed more frequently. All valid “calibrated” sonobuoys (sensu Miller et al. 2013, Miller, Collins, et al. 2014) on both surveys were used for measurements of accuracy and precision.

Table 1 - Components and technical specifications of three different sonobuoy-based localisation systems used for whale research.

Equipment and Measure	March 2012	January 2012	2010 AWE
Antenna Type	Omnidirectional	Omnidirectional	Omnidirectional
Gain (dB)	3	3	3
Centre freq. (MHz)	161	161	c. 160
Height (m)	14	14	21
Splitter	Minicircuits ZMSC-4-3-BR+	Minicircuits ZMSC-4-3-BR+	Connect N Play 50 Ohm TV Splitter
Insertion loss (dB)	6	6	c. 7
Masthead amplifier	Minicircuits ZX60-33LN-S+/None	Minicircuits ZX60-33LN-S+	ARR GaAsFET
dB Gain @160 MHz	21	21	23.4
VHF Cable	LMR400 - coaxial	LMR400 - coaxial	50 ohm coaxial
VHF Recievers (March)	WiNRaDiO G39WSBe	WiNRaDiO 2902i	ICOM PCR1000
Noise floor* dBm	-120	-120	-108
Analog-to-digital converter	RME Fireface UFX	RME Fireface UFX	NIDAQ 6062E
Pk-pk Range (V)	80	80	10
Sample Rate (kHz)	48	48	48
Gain (dB)	20	10-20	13.98
Bit-Depth (bit)	16	16	12
Additional Signal Processing	None	None	NI SCXI 1305 Filter
Research Vessel	MV Eastern Voyager	MV Eastern Voyager	RV Tangaroa
Length (m)	24	24	70

Accuracy and precision of bearing measurements

To compare the function of each of these three systems, the accuracy and precision was measured in a standardised way. In general, the signal processing methods for analysing data from DIFAR sonobuoys followed those of Miller (2012) and Miller et al. (2013, 2014), including “calibration” of the sonobuoy compass in order to obtain a correction that included the compass deviation and local magnetic anomaly. In fact, the “calibration” process itself includes an inherent assessment of the precision and accuracy of a single sonobuoy.

To compare the accuracy and precision of the entire recording chain, we consider all the “calibrated” acoustic bearings obtained by that recording chain. These included all bearings for which we had accurate knowledge (ie. a GPS fix) of the location of the research vessel. “Calibration” data were systematically collected in-situ during the 2012 voyages by seven different acousticians (ie. a single acoustician analysed all of the bearings for a single sonobuoy). In contrast, bearing data from the 2010 voyage were obtained via post-processing of the data by a single acoustician. For all “calibration” bearings, care was taken by the operator to avoid bearings that corresponded to sources of noise other than the research vessel, as these could potentially bias the bearing.

Bearing error and covariates

The error for each bearing was calculated as the difference between the “calibrated” acoustic bearing and the actual position of the ship. Thus the process for computing accuracy was somewhat circular in that bearings used to obtain the “calibration” were also used in the assessment of precision and accuracy. However, a sonobuoy was considered unreliable if the standard deviation of the bearing errors was greater than 10° (that of the DIFAR specification). Unreliable sonobuoys were excluded from further analysis.

A number of covariates was also inspected to investigate potential causes of and correlations with bearing error. Covariates included the distance between the buoy and ship, the duration since deploying the buoy, and the peak power of the beamformed signal (ie. maximum of the DIFARGram/ambiguity surface).

RESULTS

Calibration of the magnetic compass for each sonobuoy yielded accurate and unbiased mean bearings to the research vessel (Table 2). The 95% limits of bearing error were within ±10° for the 2012 surveys and within ±14° for the 2010 survey. Standard deviation of bearing error was 7.4° for the 2010 survey, 9.2 for the 2012 survey in January, and 4.7° for the survey in March 2012. Figure 2 shows the distribution of errors from the three voyages, while Figure 3 shows the error as a function of distance, time, and beamformer power. As expected beamformer power and distance were inversely correlated.

The fundamental frequencies produced by the vessels were variable due to changes in propeller speed and the Doppler effect, but were usually around 1025 Hz for the *Tangaroa* (Figure 4). The fundamental frequency for the *Eastern Voyager* was much more variable, but had a mode around 780 Hz in January and 660 Hz in March. The change between January and March may have been caused by a thorough cleaning of the hull and propeller, or differences in usual steaming speeds. Changes in fundamental frequency did not appear to affect the accuracy or precision of acoustic localisations.

Table 2 - Summary of error distribution for 3 voyages.

Measure	**2010**	**2012 January**	**2012 March**
Number of measured bearings to the vessel	1809	1271	983
95% of bearing error (deg)	[-13, 14]	[-10, 10]	[-9, 10]
67% of bearing error (deg)	[-4, 6]	[-4, 4]	[-4, 3]
Mean error (deg)	0.00	0.02	0.00
Standard deviation of error (deg)	7.4	9.2	4.7

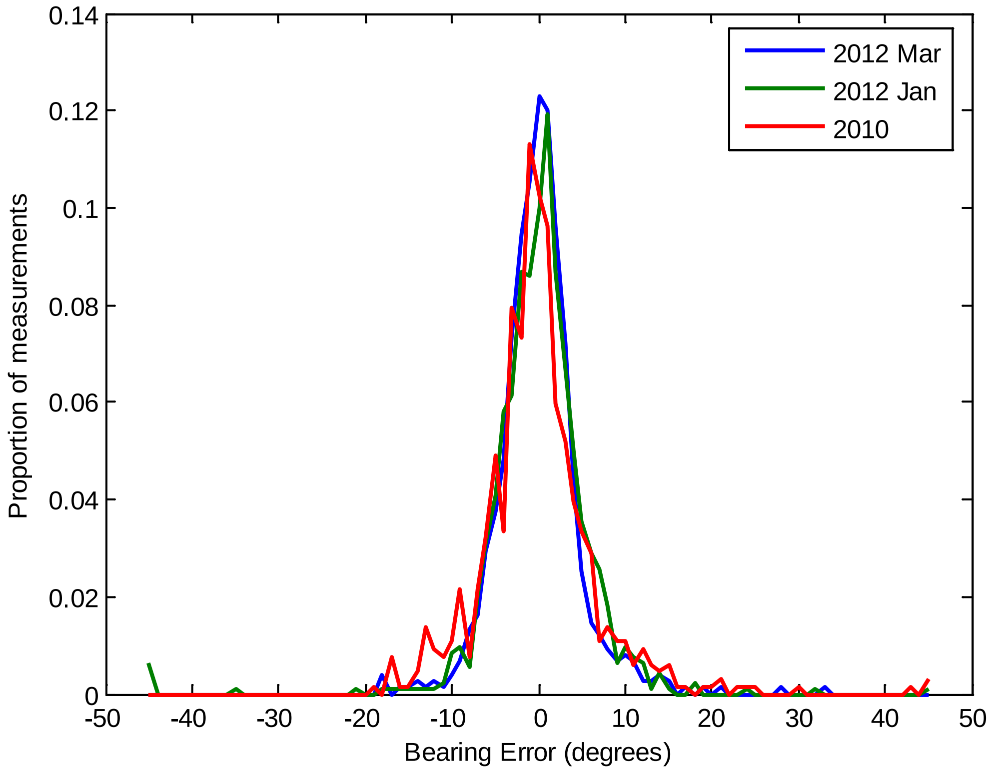

Figure 2 - Distribution of sonobuoy errors for three voyages.

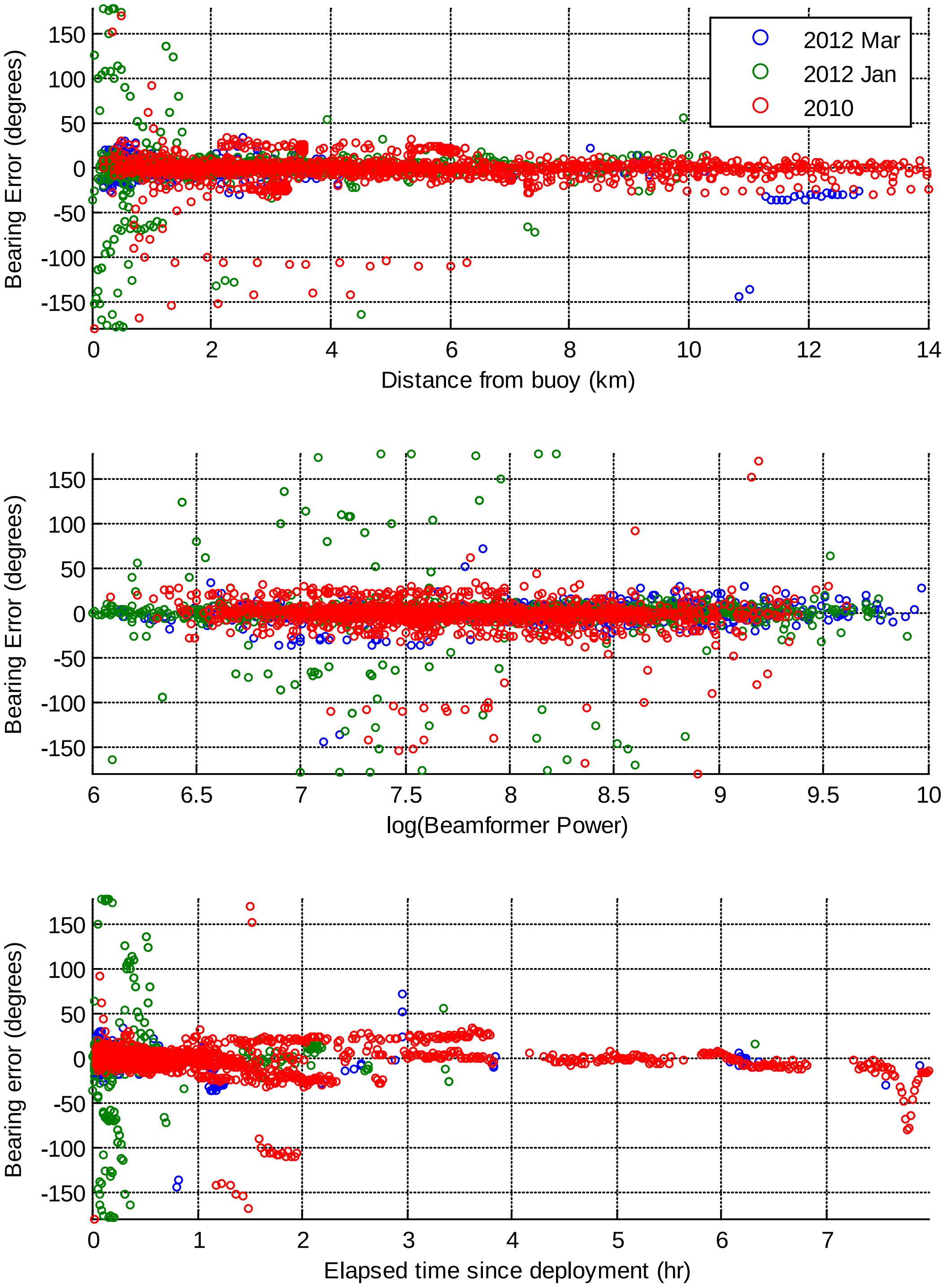

Figure 3 - Scatter plots showing bearing error as a function of distance to the ship, beamformer received power, and time since deployment . Many of these points were excluded from the distributions shown in Figure 2 due to excessive distance, time, or low beamformer power.

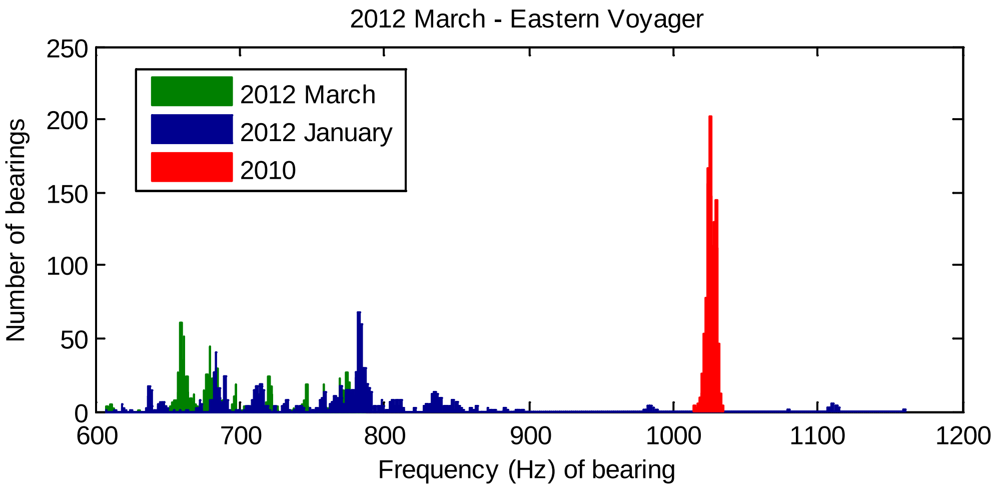

Figure 4 - Histogram of the frequency (Hz) selected for each acoustic bearing to the ship.

DISCUSSION

Magnetic declination and system performance

The methods described above yielded an accurate, apparently unbiased, and reasonably precise estimate of sonobuoy compass correction as well as a quantitative measure of sonobuoy performance.

Sources of error

There are several sources of error in the passive localisation system. As per the manufacturer's specifications, DIFAR sonobuoys have a specified accuracy of ±10 degrees. Our results were largely in accord with these specifications. However, the specification appears to require various unstated assumptions regarding the levels of self-noise present in other parts of the recording chain (essentially the absence of all other error sources). Further errors in bearing may arise from acoustic and electrical noise present at the hydrophones and in the VHF transmitter and receiver. Such noise sources likely represent a significant source of error on top of that specified by sonobuoy manufacturers. For example, the slightly wider 95% thresholds that occurred in the recording chain used in 2010 may have been due to the relatively low 12-bit dynamic range of the NIDAQ recorder and its relatively coarse, fixed options for selecting an appropriate gain.

Another potential source of error for the 2010 voyage is that the audio frequency response of the ICOM radio is not flat (Appendix A). The VHF receiver was modified to boost low-frequency signals (0-200 Hz) and attenuates signals over 4 kHz with levels at 15 kHz down 6 dB. This low frequency boost and high frequency attenuation could potentially introduce a source of error in bearing calculation since the beamformer makes use of signals from the omnidirectional hydrophone in conjunction with the directional hydrophones. This error would likely create a flattened ambiguity surface (ie. smaller vertical distances between power peaks and troughs). Furthermore, there is also phase distortion that results from the audio filters in the ICOM receivers. Because the attenuation and distortion spans the 12-18 kHz frequency band, which contains signals from the directional hydrophones, such distortion may contribute to "gain imbalance" (Greene et al. 2004). The WiNRaDiO receivers, in comparison to the ICOM receivers, have a relatively flat frequency response throughout the audio bandwidth, and thus they may not require any additional measures to correct for "gain imbalance."

Yet another potential source of error may come from the movement of sonobuoys as they drift away from their deployment locations over time. Several deployments longer than 1 hour in duration (Figure 3) do suggest that sonobuoy drift may be an important source of error as the bearings show increased error with increasing duration of deployment.

Additional sources of error could arise from compass 'drift' near the south magnetic pole. The spatial variation in magnetic declination and the magnitude of the magnetic dip in the Southern Ocean are much greater than at lower latitudes and increase as a function of proximity to the South magnetic pole. The acoustic methods proposed here require the magnetic compass to obtain directions to the whales. At some point near the magnetic pole the horizontal component of the magnetic field will be smaller than can be measured by the magnetic compass in the sonobuoys. Data from the 2010 Voyage indicate that DIFAR sonobuoys are still functional with a horizontal component of the magnetic field as small as 4200nT. The region outside the circle on Figure 5 denotes the area where DIFAR sonobuoys are expected to provide accurate bearings to whales.

While it is presently unclear whether DIFAR sonobuoys will provide reliable bearings near the South Pole (i.e. 64°S, 137°E at the time of writing), it is expected that clarity on the issue will be resolved shortly (e.g. the minimum magnetic field required for DIFAR compass can be measured in a laboratory setting or at the very least specified by the manufacturer). Near the South Pole, bearings to whales could potentially be obtained using the time of arrival differences among multiple sonobuoys. However, this technique requires deploying more sonobuoys in logistically more complex patterns to achieve the same results as DIFAR sonobuoys. While such techniques are not ideal, the lack of reliance on directional sensors and a magnetic compass could also help to mitigate any disruptions to the supply of affordable DIFAR sonobuoys for whale research. In the interim, a conservative approach would be to assume that passive acoustic tracking would have reduced performance around the South Pole.

In order to reduce the magnitude of bearing errors, audio clips should be excluded from analysis when the source is very near to the sonobuoy (ie. within 500 m). The peak power of the ambiguity surface showed little relationship with bearing error, and thus appears to provide little indication of whether a sonobuoy is functioning correctly. A better measure of the correct function of the sonobuoy appears to be the standard deviation of bearings computed during the “calibration” process. Thus, simply applying the “calibration” procedures in-situ should reveal the precision and accuracy for each sonobuoy. By assessing these “calibrations” in aggregate we have revealed information on the performance of the entire recording chain.

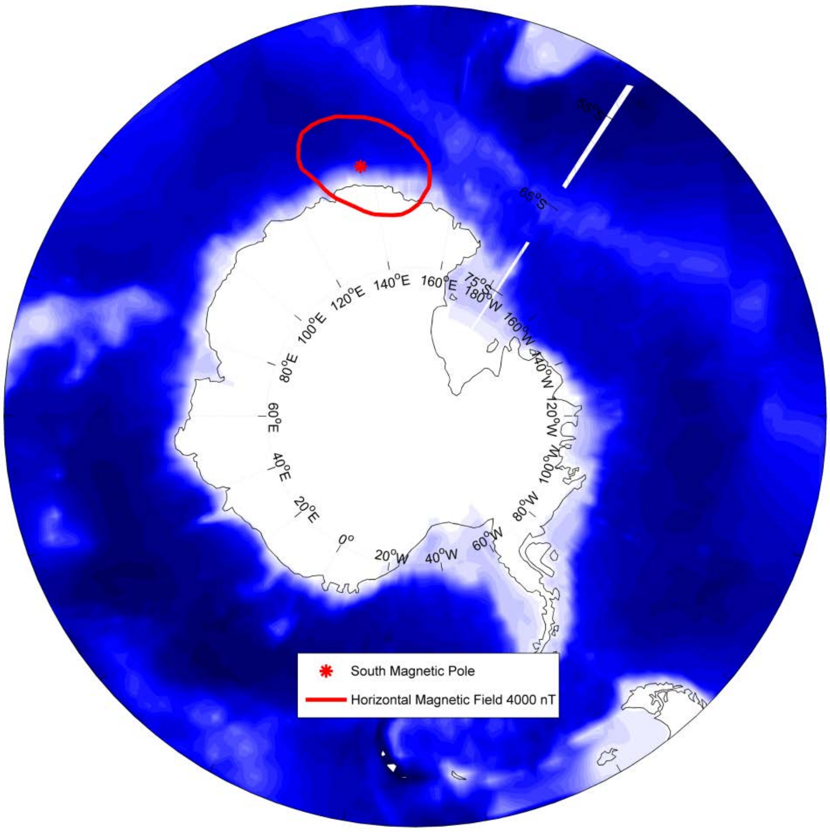

Figure 5 - The region outside the red circle denotes the area where DIFAR sonobuoys are expected to provide accurate bearings to whales. DIFAR sonobuoys deployed nearer to the magnetic pole may not provide accurate bearings due to weak horizontal component of the magnetic field which may cause the compass drift.

Sonobuoy failure

The methods used to determine accuracy and precision also provide useful metrics for assessing whether or not the sonobuoy and recording chain are working correctly. Typically sonobuoy failure becomes obvious in the first few minutes after deployment because the sonobuoy fails to transmit or the received signal contains obvious distortion. In these cases another sonobuoy can quickly be deployed. Occasionally, sonobuoys will appear to transmit normally but yield inaccurate bearings. This type of failure may have occurred in some sonobuoys in all of these surveys. Typically, the spectrum of the DIFAR signal should indicate when such a failure has occurred. Failed buoys may be missing carrier tones at 7.5 or 15 kHz, or the sidelobes of the 15 kHz carrier tone may be absent, excessively large, or noisy in some other way.

Furthermore, according to Mark McDonald, who wrote the core of the analysis software, there may be a potential problem with usage in some oceangographic settings whereby bearing errors of 180 degrees occur. The problem typically occurs in deep water lacking a strong thermocline and may be related to seafloor reflections of the signal (M. McDonald, *pers comm*) However, such errors should create a bimodal distribution with peaks 180 degrees from each other, which was not observed here. Tracking of the ship normally is helpful in correcting magnetic deviation errors and may help with 180 degree errors, however sometimes the 180 degree error occurs with the whale call but not the ship (M. McDonald *pers comm*). Experienced operators and use of multiple buoys seems to be the best guide to figuring out when such errors are occurring.

Next steps

Now that the accuracy and precision of the existing and past tracking systems has been characterised, the next steps involve adding redundancy to the passive acoustic tracking system and streamlining the real-time operations. Redundancy is most easily achieved by creating multiple independent sets of instrumentation that can be swapped should any component fail. Streamlining of real-time operations may include improvements to Matlab software, but may also focus on incorporating DIFAR signal-processing into freely available passive acoustic software such as PAMGuard (Miller, Gillespie, et al. 2014). The characterisation of the DIFAR tracking systems, as per this document, may be useful for planning or when conducting simulations of whale tracking (Peel et al. 2014) to assess sonobuoy deployment strategies.

Efforts should be made to address errors in localisation arising from buoys drifting away from the location of deployment. Under some circumstances the new location of sonobuoys can be obtained either through re-sighting the buoy or from acoustic bearings to the ship (Miller, Wotherspoon, et al. 2014). In such circumstances the ship must be moving much faster than the sonobuoy, and it must have sufficient change in position in order to provide a range of reciprocal bearings that allow triangulation of the buoys new position. Such methods become very valuable for localisation accuracy during long deployments, strong currents, or some combination of the two.

ACKNOWLEDGEMENTS

Special thanks to all of the excellent and dedicated staff whose tireless work made the 2010 and 2012 voyages possible. Thanks to the excellent crew and scientists aboard the *RV Tangaroa* and *MV Eastern Voyager.* Thanks to Chris Donald for supplying the DIFAR sonobuoys used in this research. Thanks to Mark McDonald for the DIFAR analysis software and his advice throughout these studies. Thanks to Sarah Laverick, and Simon Childerhouse for their involvement in organising the 2012 voyages. Special thanks to voyage leader Natalie Kelly and to Rob Slade for encouragement and support during the respective March and January voyages in 2012.

REFERENCES

Clark CW, Fowler M (2001) Status of archival and analysis effort of acoustic recordings during SOWER and IWC cruises 1996-2000. Rep Submitt to Sci Comm Int Whal Comm SC/53/IA28 [Paper available from Off J Cetacean Res Manag

Double MC, Barlow J, Miller BS, Olson P, Andrews-Goff V, Leaper R, Ensor P, Kelly N, Wadley V, Lindsay M, Peel D, Calderan S, Collins K, Davidson M, Deacon C, Donnelly D, Olavarria C, Owen K, Rekdahl M, Schmitt N, Gales N (2013) Cruise report of the 2013 Antarctic blue whale voyage of the Southern Ocean Research Partnership. Report SC65a/SH/21 submitted to the Scientific Committee of the International Whaling Commission. Jeju Island, Republic of Korea

Gales N (2010) Antarctic Whale Expedition: Preliminary science field report and summary. R.V. Tangaroa Feb/Mar 2010.

Greene CRJ, McLennan MW, Norman RG, McDonald TL, Jakubczak RS, Richardson WJ (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

Kelly N, Double MC, Peel D, Bravington M V., Gales N (2010) Strategies to obtain a new abundance estimate for Antarctic blue whales : a feasibility study. Rep Submitt to Sci Comm Int Whal Comm SC-63-SH3:1–15

Kelly N, Miller BS, Peel D, Double MC, Mare WD La, Gales N (2012) Strategies to obtain a new circumpolar abundance estimate for Antarctic blue whales: survey design and sampling protocols. Rep Submitt to Sci Comm Int Whal Comm 64/SH10:34

Maranda BH (2001) Calibration Factors for DIFAR Processing.

McDonald MA (2004) DIFAR hydrophone usage in whale research. Can Acoust 32:155–160

Miller BS (2012) Real-time tracking of blue whales using DIFAR sonobuoys. In: Proceedings of Acoustics 2012. Australian Acoustical Society, Fremantle, p 7

Miller BS, Barlow J, Calderan S, Collins K, Leaper R, Kelly N, Olson P, Ensor P, Double MC (2013) Long-range acoustic tracking of Antarctic blue whales. Rep Submitt to Sci Comm Int Whal Comm SC/65a/SH1:1–17

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

Miller BS, Gillespie D, Weatherup G, Calderan S, Double MC (2014) Software for the localisation of baleen whale calls using DIFAR sonobuoys: PAMGuard DIFAR. Submitt to Sci Comm 65b Int Whal Comm Bled, Slov SC/65b/SH:7

Miller BS, Kelly N, Double MC, Childerhouse SJ, Laverick S, Gales N (2012a) Cruise report on SORP 2012 blue whale voyages: Development of acoustic methods. Rep Submitt to Sci Comm Int Whal Comm 64/SH11:16

Miller BS, Kelly N, Double MC, Childerhouse SJ, Laverick S, Gales N (2012b) Cruise report on SORP 2012 blue whale voyages: Development of acoustic methods. Rep Submitt to Sci Comm Int Whal Comm SC/64/SH11:16

Miller BS, Wotherspoon S, Calderan S, Leaper R, Collins K, Double MC (2014) Estimating drift of DIFAR sonobuoys when localizing blue whales. Submitt to Sci Comm 65b Int Whal Comm Bled, Slov SC/65b/SH:8

Peel D, Miller BS, Kelly N, Dawson SM, Slooten E, Double MC (2014) A simulation study of acoustic-assisted tracking of whales for mark-recapture surveys. PLoS One in press

Rankin S, Barlow J (2005) Source of the North Pacific “boing” sound attributed to minke whales. J Acoust Soc Am 118:3346–51

APPENDIX A – RECEIVER AND SONOBUOY CALIBRATIONS

While raw source levels were not computed in this study on bearing accuracy, the fact that DIFAR sonobuoys all have a known sensitivity within 3 dB means that it is possible to obtain relatively accurate estimates of the received level of sounds provided that the recording chain is also calibrated (Maranda 2001). For reference, we include the relevant part of the DIFAR specification, which defines the acoustic sensitivity of a 53B/D/F sonobuoy hydrophones:

- A carrier frequency deviation of ± 25 kHz peak shall result when the omni-directional acoustic receiver is placed in a sound field at 100 Hz having an RMS sound pressure level of 122 ± 3 dB re 1 µPa.
- A carrier frequency deviation of ± 40 kHz peak shall result when the directional acoustic receiver system is placed in a sound field at 100 Hz having an RMS sound pressure level of 122 ± 3 dB re 1 µPa arriving along the maximum response axis of either the sine or cosine channels.

Since the sensitivity of the sonobuoys is specified in terms of frequency deviation (ie. in terms of the VHF signal), the calibration of the radio receivers is an important part of retrieving absolute sound pressure levels from a sonobuoy. The receiver calibration involves measuring the voltage output of the receiver per frequency deviation in Hz. Full calibration requires measuring this quantity as a function of modulation frequency for all modulation frequencies of interest. As an example, we show the frequency response of the VHF receivers used during the 2010, 2012, and 2013 SORP voyages (Figure 6).

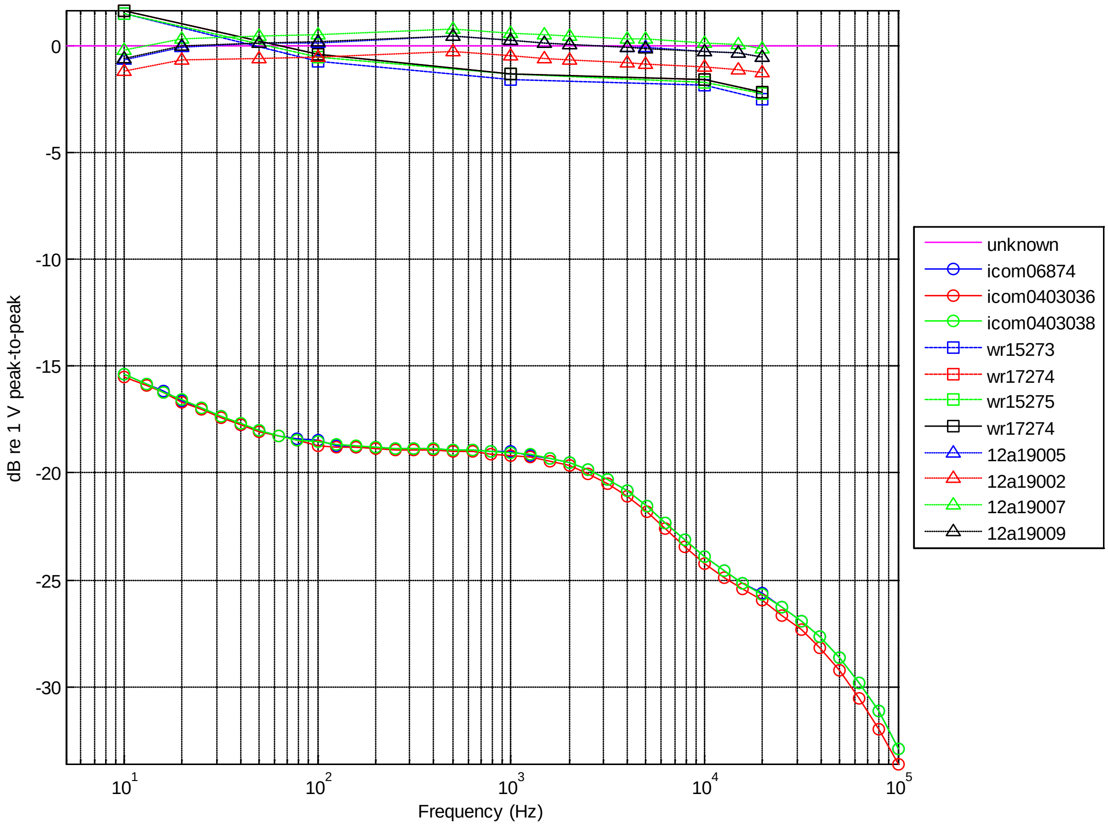

Figure 6 – Receiver calibrations for 11 receivers using 25 kHz frequency deviation. ICOM receivers were calibrated in 2009 and used during the Antarctic Whale Expedition. WinRadio 2909i receivers (WR1XXXX) were used in January and the first half of March 2012. The WinRadio G39e receivers (12a19XXX) were used in the second half of March 2012.

In addition to measuring the frequency response of the VHF receiver, it is worth noting that AN/SSQ 53 sonobuoys do not have a flat frequency response. Instead, the sonobuoys are 'pre-whitened', with strong attenuation below 100 Hz, and a linearly increasing frequency response from 100 to 800 Hz. The frequency response is flat from 800 to 2400 Hz, and begins rolling off steeply above 2400 Hz (Table 3).

Table 3 – Acoustic response (unmodulated) of the sensors in a AN/SSQ 53 sonobuoy as a function of frequency.

Frequency (Hz)	5	10	100	800	2400	9000
Level above/below Ref. Pressure of 122 dB	-30	-20	0	15	15	-20

APPENDIX B – LIST OF SONOBUOY DEPLOYMENTS USED FOR ANALYSIS

2010 *Tangaroa* Voyage

#	startDate	startTime	stopDate	stopTime	lat	long	alt	Ch	Mag. Decl.	Receiver
1	2010-03-05	08:18:10	2010-03-05	09:51:30	-67.7726	165.3005	-120	1	87.0	icom06874
2	2010-03-05	10:12:20	2010-03-05	11:40:00	-68.0420	165.6340	-120	1	89.0	icom06874
3	2010-03-05	12:41:20	2010-03-05	14:03:01	-68.3803	165.8789	-120	1	91.0	icom06874
4	2010-03-05	14:25:50	2010-03-05	15:50:30	-68.6502	165.6999	-120	1	94.0	icom06874
5	2010-03-05	16:29:45	2010-03-05	17:46:10	-68.9957	165.9069	-120	1	96.0	icom06874
6	2010-03-05	19:41:50	2010-03-06	03:45:00	-69.2973	166.2637	-120	1	97.0	icom06874
7	2010-03-06	06:26:00	2010-03-06	09:29:00	-69.2787	166.3364	-120	1	97.0	icom06874
8	2010-03-06	10:05:50	2010-03-06	15:44:15	-69.6198	166.5176	-120	1	85.5	icom06874
9	2010-03-06	11:03:10	2010-03-06	14:40:00	-69.7412	166.4662	-120	2	91.4	icom0403036
10	2010-03-06	13:35:00	2010-03-06	14:40:00	-69.6554	166.7610	-120	3	94.3	icom0403038
12	2010-03-06	16:43:20	2010-03-06	20:36:00	-69.2613	166.2073	-120	1	-88.3	icom06874
13	2010-03-07	06:30:15	2010-03-07	08:46:00	-69.1408	166.5120	-120	1	-104.7	icom06874
14	2010-03-07	09:44:35	2010-03-07	12:35:00	-69.0803	166.5931	-120	1	-100.6	icom06874
16	2010-03-07	19:04:10	2010-03-07	20:24:30	-68.7178	166.8840	-120	1	-95.0	icom06874
80	2010-02-22	15:47:30	2010-02-22	19:14:00	-66.6214	162.9600	-120	1	78.0	icom06874
81	2010-02-23	00:39:45	2010-02-23	01:47:00	-66.0972	162.3684	-120	1	75.0	icom06874
82	2010-02-23	06:54:00	2010-02-23	07:39:00	-65.4358	160.9097	-30	1	70.0	icom06874
83	2010-02-23	11:24:40	2010-02-23	12:40:00	-65.0006	159.9912	-120	1	69.0	icom06874
84	2010-02-23	17:07:50	2010-02-23	18:37:00	-64.9978	158.0593	-300	1	68.0	icom06874
85	2010-02-23	23:26:00	2010-02-24	01:27:00	-65.2275	156.3117	-300	1	71.0	icom06874
86	2010-02-24	06:54:00	2010-02-24	08:48:00	-65.2366	154.4430	-120	1	72.0	icom06874
87	2010-02-24	12:30:40	2010-02-24	14:19:30	-65.3238	152.7595	-120	1	76.0	icom06874
88	2010-02-24	14:51:10	2010-02-24	17:11:00	-65.5926	152.9041	-120	1	78.0	icom06874
89	2010-02-24	23:51:30	2010-02-25	02:52:00	-65.6233	154.2872	-120	1	77.0	icom06874
90	2010-02-25	08:57:41	2010-02-25	10:23:00	-65.7191	155.8908	-120	1	78.0	icom06874
91	2010-02-25	12:57:20	2010-02-25	13:45:20	-65.3511	156.8847	-120	1	-70.5	icom06874
92	2010-02-25	20:23:55	2010-02-25	21:41:15	-65.9214	158.9960	-120	1	-68.8	icom06874

2012 January Bass Strait Voyage – all valid sonobuoys

2012 March Bass Strait Voyage – all valid sonobuoys