Real-time tracking of blue whales using DIFAR sonobuoys

BRIAN S. MILLER

Australian Marine Mammal Centre, Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050 Australia
Brian.Miller@aad.gov.au

ABSTRACT

Passive acoustic tracking of blue whales has been proposed as a key component in a strategy to obtain a circumpolar abundance for Antarctic blue whale as proposed in a project of the IWC Southern Ocean Research Partnership. While a theoretical basis for passive tracking of blue whales has been demonstrated, there are substantial differences between these theoretical scenarios and a fully-operational, dedicated, real-time, tracking program. 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. We present preliminary results from two research voyages in Bass Strait where a fully-operational, dedicated, real-time tracking system was used to locate pygmy blue whales at a distance of more than 60 km. The core element of the acoustic tracking system consisted of DIFAR sonobuoys, VHF radio receivers, and custom analysis software driven round the clock by a team of acousticians. The tracking system operated continuously during the voyages recording nearly 500 hours of audio, while acousticians processed over 7000 blue whale calls all in “real-time”. During the 20 days at sea 32 vocalising blue whales were “targeted” and, of these, 29 yielded visual sightings of one or more blue whales giving a combined success rate greater than 90%. While there are many differences between the Bass Strait and the colder waters around Antarctica, acoustic detection ranges of blue whales in the Southern Ocean far outstrip visual sighting ranges, so real-time acoustic tracking may be able to increase the total number of whale encounters, thus making more efficient use of expensive ship time. The success of the real-time tracking system during these two voyages supports the use of acoustics as a key tool in determining the circumpolar abundance of blue whales in the Southern Ocean.

KEYWORDS: BLUE WHALE, ACOUSTICS, SURVEY – VESSEL, SOUTHERN OCEAN, AUSTRALASIA, VOCALISATION

INTRODUCTION

Background

The Antarctic Blue Whale Project has the primary aim of estimating the circumpolar abundance of Antarctic blue whales (*Balaenoptera musculus intermedia*) in the Southern Ocean. Given the visual sighting survey programme IDCR/SOWER saw so few Antarctic blue whales over the 30 years of its lifespan, it is not likely that repeating this method will yield a quality circumpolar abundance estimate any time soon. Thus, there is a need to develop methods to greatly increase the numbers of encounters relative to a sighting survey design (Kelly et al. 2010). Antarctic blue whales are audible over ranges much larger than they can be seen (Sirović et al. 2007, Samaran et al. 2010, Gavrilov et al. 2011); therefore passive acoustic monitoring and tracking of blue whales has been suggested as a key component of the Southern Ocean Research Partnership (SORP) Antarctic blue whale research programme (Kelly et al. 2010).

Passive acoustic localisation, via arrays of hydrophones, has been used to study marine mammals for over thirty years. Watkins and Schevill first used a hydrophone array to measure the source levels of marine mammal vocalisations in 1972. Despite many advances in this field, passive localisation systems still require specialised hardware, software, and significant technical expertise to be effective. Real-time passive acoustic localisation of various cetacean species has been achieved with stereo hydrophone arrays (eg Leaper et al. 1992), multi-hydrophone towed and drifting arrays, (Hayes et al. 2000, Møhl et al. 2007), widely spaced hydrophones mounted on the ocean floor (Morrissey et al. 2006, Sirović et al. 2007, Samaran et al. 2010), and directional sonobuoys (Greene et al. 2004, McDonald 2004, Wade et al. 2006).

McDonald (2004) points out several advantages of using Directional Frequency Analysis and Recording (DIFAR) sonobuoys for passive acoustic tracking of baleen whales. Such advantages include fewer DIFAR sensors required and potentially higher accuracy than omnidirectional hydrophones. Sonobuoys have an established tradition in whale research and several hundred have been deployed as a part of the IWC-SOWER cruises from 1999-2009, however these sonobuoys were typically used for monitoring rather than real-time tracking of whales.

The theoretical basis for real-time passive acoustic tracking of blue whales in the southern ocean was demonstrated during 36 hours of real-time tracking that occurred during the 2010 Antarctic Whale Expedition (Gales 2010). However, fog and poor weather upon reaching the acoustically targeted whale precluded visual confirmation that the tracking and targeting was effective. However, the acoustic tracking during this voyage served as a proof of concept and prompted the development of a fully-operational, dedicated, real-time, tracking program to locate blue whales.

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. Each DIFAR sonobuoy contains 3 hydrophones, a magnetic compass, signal processing circuitry, and a VHF radio transmitter. The signal processing circuitry combines the signals from the 3 hydrophones 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 (Maranda 2001). For localisation of targets, magnetic bearings must be corrected for local magnetic declination either using a chart, or by using a measurement to a target at a known location *eg* the research vessel (McDonald 2004).

Sonobuoys send signals via VHF radio a recording chain, which typically consists of a VHF receiver that is connected to a recording device. The recording device, typically some form of analog-to-digital converter and digital storage, is used to save telemetered data, while an acoustician typically monitors the incoming audio data aurally as well as visually via software that displays a visual representation of the audio in real-time. Selected sounds, such as whale vocalisations, can be identified and further analysis can be applied in order to obtain information such as the absolute sound pressure level or the direction of the sound source.

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 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. The distance over which a signal can be received from a sonobuoy depends on the height of the receiving antenna and the sensitivity of the receiver. Prior studies using DIFAR sonobuoys report a typical range of approximately 18 km with an unspecified antenna height (McDonald 2004), and 18.5 m with an antenna height of approximately 26m (Gedamke and Robinson 2010) however neither study reports the sensitivity of the receivers.

Being able to acoustically detect and localise (ie. track) blue whales is the first step in determining whether acoustics can increase the number of encounters with Antarctic blue whales and therefore make more efficient use of the limited Antarctic survey time. In the following sections a real-time whale tracking system based on DIFAR sonobuoys is described, and we present the results of field trials in which the system is used to track pygmy blue whales in real-time. The idea is not to present an ideal tracking system, rather to present a starting point for future research involving real-time tracking of blue whales.

METHODS

Trial Voyages

Visual and acoustic (DIFAR) surveys were conducted in Bass Strait on board the research vessel, MV Eastern Voyager for 10 days in January and for 9 days in March 2012. 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 AN/SSQ DIFAR 53D sonobuoys were deployed throughout the research area. Sonobuoys were initially deployed every four-to-six hours, but upon detection of blue whales they were deployed more frequently in an adaptive fashion as targeting requirements dictated (see discussion section below). Audio from deployed sonobuoys was recorded and monitored in real-time.

Visual Survey Methods

A visual survey team was operating in parallel to the acoustics team throughout daylight hours when sighting conditions were favourable. The visual team maintained a constant lookout to visually detect whales that were not vocalising. Visual observations took place from either the flybridge (approximately 5.7m in height) or the foredeck (approximately 3.5m in height). All sightings, effort and weather were stored using Logger 2000 software (developed by the International Fund for Animal Welfare), which stores data in a Microsoft Access database, and upon sightings of whales, the research vessel proceeded to close on animals to determine species and group composition and behaviour. Upon approaching pygmy blue whales, the visual sightings team attempted to take photographs for identification of individual whale. The visual team maintained a constant lookout to visually detect whales that were not vocalising.

Acoustic Equipment

The recording chain for all sonobuoy deployments through 25 March 2012 included a high gain (3 dB) communications antenna with a peak frequency centred at 161 MHz and masthead amplifier (Minicircuits ZX60-33LN-S+) connected to a passive four way splitter (Minicircuits ZMSC-4-3-BR+). The highest point of the antenna was approximately 14 m above sea level. The antenna, amplifier, and splitter were connected with LMR400 low loss cable, and each output of the four way splitter connected to the DIFAR input of a WiNRaDiO 2902i. On 25 March the masthead amplifier failed and was removed from the recording chain. This failure prompted the use of recently acquired WiNRaDiO G39WSBe sonobuoy receivers. The voltage output of all of the sonobuoy receivers were calibrated as a function of modulation frequency before the voyage, and DIFAR outputs from each of the 2902i and G39WSBe were connected to an instrument input of an analog-to-digital converter. The A/D converter used throughout both voyages was a RME Fireface UFX.

The instrument inputs of the UFX (analog inputs 9-12) can receive approximately 80 Volts peak-to-peak, and have an adjustable preamplifier with a gain that can be set between 10-65 dB. At 10 dB gain, the full scale input voltage of the UFX is approximately 24.58 V peak-to-peak. At 20 dB gain, the full scale input voltage is approximately 7.70 V peak-to-peak. The digitised signals from the UFX were saved as 16-bit WAV files with 48 kHz sample rate using passive acoustic monitoring software Pamguard. Pamguard also provided for viewing of spectrograms, while RME TotalMix software allowed the incoming audio to be monitored via noise-cancelling headphones.

Acoustic Signal Processing

Sonobuoy Compass Correction

Each sonobuoy required validation that it was functioning reliably and “calibration” of the magnetic compass before it was used for tracking whales. The location of the sonobuoy deployment and the position of the vessel were collected via a GPS receiver, and the deviation of the magnetic compass within the sonobuoy and the local magnetic anomaly were calculated in the following fashion: Audio clips 10 seconds in duration were collected every 30 seconds as the vessel steamed away from the sonobuoy after deployment. Acoustically derived bearings to the research vessel, θ_a, were computed from these audio clips. The “true” bearings between the sonobuoy’s deployment location and the vessel, θ_t were also computed using the GPS onboard the vessel. The correction angle, θ_c, for each 10 second audio clip was computed as

$$\theta_c = \theta_t - \theta_a$$

Typically 15-30 measurements of angle θ_c were made as the vessel moved away from the sonobuoy, and the angular mean, $\bar{\theta}_c$, and standard deviation, σ_c, of these measurements were calculated. The sonobuoy was considered unreliable if σ_c was greater than 10°. For reliable sonobuoys, $\bar{\theta}_c$ was used as a single correction that incorporated both the inherent error in the magnetic compass of the sonobuoy as well as the local magnetic variation.

Processing Whale Calls

Audio clips of blue whale sounds and any vessels in the area were saved separately from the raw audio stream for further processing. This step was facilitated by a custom Pamguard plugin that automatically created a WAV file containing the audio of any user selection made on the Pamguard spectrogram window.

CLASSIFICATION OF WHALE CALLS

Once a clip had been saved, the acoustics operator ran a Matlab script that performed several further steps of processing. First, the operator was shown two spectrograms of the audio clip and prompted to classify the sounds for further analysis. One spectrogram showed the full bandwidth of the omnidirectional sensor (4800Hz sample rate, 2048 sample time slices, 87.5% time overlap between slices), while the other spectrogram showed bandwidth corresponding to that of blue whale vocalisations (250Hz sample rate, 250 sample time slices, 98.4% time overlap between slices). Next, a lookup table of sonobuoy deployments was used to determine from which sonobuoy and receiver the audio clip was generated. Sonobuoy and receiver calibration factors were then applied to the spectrum of the audio clip in order to compute sound pressure levels with respect to 1µPa in 1Hz bins. The audio clip was then normalised so that the value of the largest sample was 1, which Matlab interprets as full scale for a WAV audio file. Normalisation was important for demodulation of the directional information contained in the composite DIFAR signal.

DIFAR SIGNAL DEMULTIPLEX

For each audio clip, DIFAR directional signals were demodulated using a version of Greenridge Science's demodulation software (http://www.greeneridge.com/software.html) that was provided by Mark McDonald (http://www.whaleacoustics.com/toolssoftware.html) running under Matlab version 7.0.2. Demodulation of DIFAR signals was most effective when the signal-to-noise ratio was high and favoured longer 'tonal' signal types as opposed to short broadband clicks. The output of the demodulator was 3 binary files that represent the audio signals from the omnidirectional hydrophone and the two orthogonal directional hydrophones. These audio signals were low-pass filtered and resampled to reduce processor and memory requirements for subsequent signal processing steps. Calls classified as blue whale vocalisatoins were resampled to a sample rate of 250Hz, while all other calls (*eg* audio clips of the research vessel) were resampled at a rate of 4800Hz.

OBTAINING BEARINGS

Downsampled signals were used to compute the angle of arrival of sound as a function of frequency using Mark McDonald's DivarV10 software (http://www.whaleacoustics.com/toolssoftware.html). This software performs a beamforming analysis using both the directional and omnidirectional signals from the sonobuoy (as opposed to an arctangent bearing estimator that uses only the directional signals). DifarV10 used the "Bartlett" estimator for computing bearings, which is said to be more "robust" but less precise than the minimum variance estimator (Mark McDonald Pers. Comm.). The result is an ambiguity surface showing beamformer power as a function of bearing and frequency as described by McDonald (2004).

The spectrogram and the ambiguity surface were plotted side-by-side with identical frequency scales, and the operator then selected from the ambiguity surface the bearing (to the nearest degree) that most clearly represented the signal of interest. Typically this corresponded to the frequency bin of the sound source that contained the highest signal-to-noise ratio, rather than simply the peak energy. Care was taken by the operator to avoid frequency bins that also contained non-target noise sources as these could potentially bias the bearing towards the noise source and away from the target. Typical noise sources included other vessels, non-target whales, and self/electrical noise that occurred as VHF reception degraded with distance from the sonobuoy.

The operator-selected bearing, frequency and associated sound pressure level and ambiguity surface amplitude at the selected frequency were then recorded in a log file of acoustic detections. Additional metadata including the date and time, sonobuoy deployment number, deployment location, compass correction, VHF receiver, and preamplifier gain was also recorded for each processed bearing. In March, the user selected classification of each sound was also recorded along with each bearing, and groups of bearings were further classified into *acoustic tracks*.

Tracking and Targeting

Bearings to blue whales were plotted on an electronic map using the matlab package m_map to draw local bathymetry, coastlines, and also to ensure that bearings followed great-circle arcs. The most recent bearing was plotted in a different color from older bearings, and older bearings were color coded according to the elapsed time in order to provide a quick visual indication of the time series of detections.

The term *acoustic track* was used to denote any set of bearings that are believed to come from a whale or group of whales in the same location. *Targets* were defined as acoustically tracked whales that were pursued by the research vessel in an attempt to encounter. *Targets* were considered *aborted* when pursuit was abandoned due to inclement weather, gear failure, or encountering other whales. *Targets* were considered *missed* when the whale stopped calling and the visual team failed to sight a whale in the area where the whale was last heard. Targeting was considered *successful* upon visual confirmation of the *target*.

There were differences in acoustic tracking effort and record-keeping between the January and March voyages. In January, three acousticians each took turns on duty following a roster of 4 hours on-duty followed by eight hours off-duty with no overlap between shifts. In March, four acousticians had shifts of the same duration and duty cycle as January, however there was an hour overlap in shifts with both the prior and following acoustician in order to maintain continuity of tracking and targeting efforts. Futhermore in March, a lead-acoustician was on duty for a floating 12 hour shift in order to perform maintenance on the acoustic systems, check data integrity, fill-in during any gaps in the roster, facilitate communications with the visual sightings team and vessel crew, and provide synoptic views of the acoustic situation to the voyage leader. In January there was no systematic record keeping for each new *acoustic track* and *target*, and the acoustician on-duty directed the vessel to a *target* of their choosing in consultation with the voyage leader. In March, a systematic log of all *acoustic tracks* and *targets* was kept and updated at 15 minute intervals. Acousticians on-duty then chose *targets* from these *acoustic tracks* in consultation with the lead-acoustician.

During both voyages effort was made to conduct *acoustic tracking* and *targeting* under a wide variety of sighting and acoustic conditions in order to populate the sample space in order to determine which factors most affected the success of *acoustic targeting*. When possible, two sonobuoys were deployed simultaneously in order to obtain crossbearings to calling whales. Upon computing a crossbearing, the acousticians then steered the vessel to the estimated location of the whale. When *targeting* with only a single sonobuoy, the acousticians typically followed the bearing lines from the sonobuoy to the *target whale*.

RESULTS

The voyages focussed on the area bounded by 141.0-143.0ºE and 38.0-39.5ºS (Figure 1c). Of the six weeks allocated across both surveys, weather allowed for a total of 20 survey days (10.5 days in January and 9.5 days in March). A total of 131 sonobuoys were deployed (Figure 1a) with nearly 90% of these valid and reliable. More than 500 hours of audio was monitored in real-time yielding nearly 7000 bearings to blue whales in total. VHF reception range for sonobuoys ranged between 10-18 km, and was inversely correlated with the swell height. Sixty *acoustic tracks* were obtained and 39 whales were *targeted* in total. Seven *targets* were aborted due to bad weather and were excluded from further analysis. Three *targets* were *missed* and 29 *targets* were found, yielding a total targeting success rate of 91%. The mean distance travelled per successful *target* was 12.7km, however both voyages successfully *targeted* a whale over more than 60km (Figure 1d). The metrics of acoustic effort and data were comparable between January and March with similar numbers of sonobuoys, hours of recording, whale calls processed, and number of *targets* (Table 1).

Sighting effort covered 1508nmi over 242 hours. There were 70 alleged blue whales sighted in January and 37 sightings in March (Figure 1b). Identification photographs of 24 different individuals were obtained in both January and March with only one resighting between the two voyages yielding a total of 47 individual whales identified across both voyages.

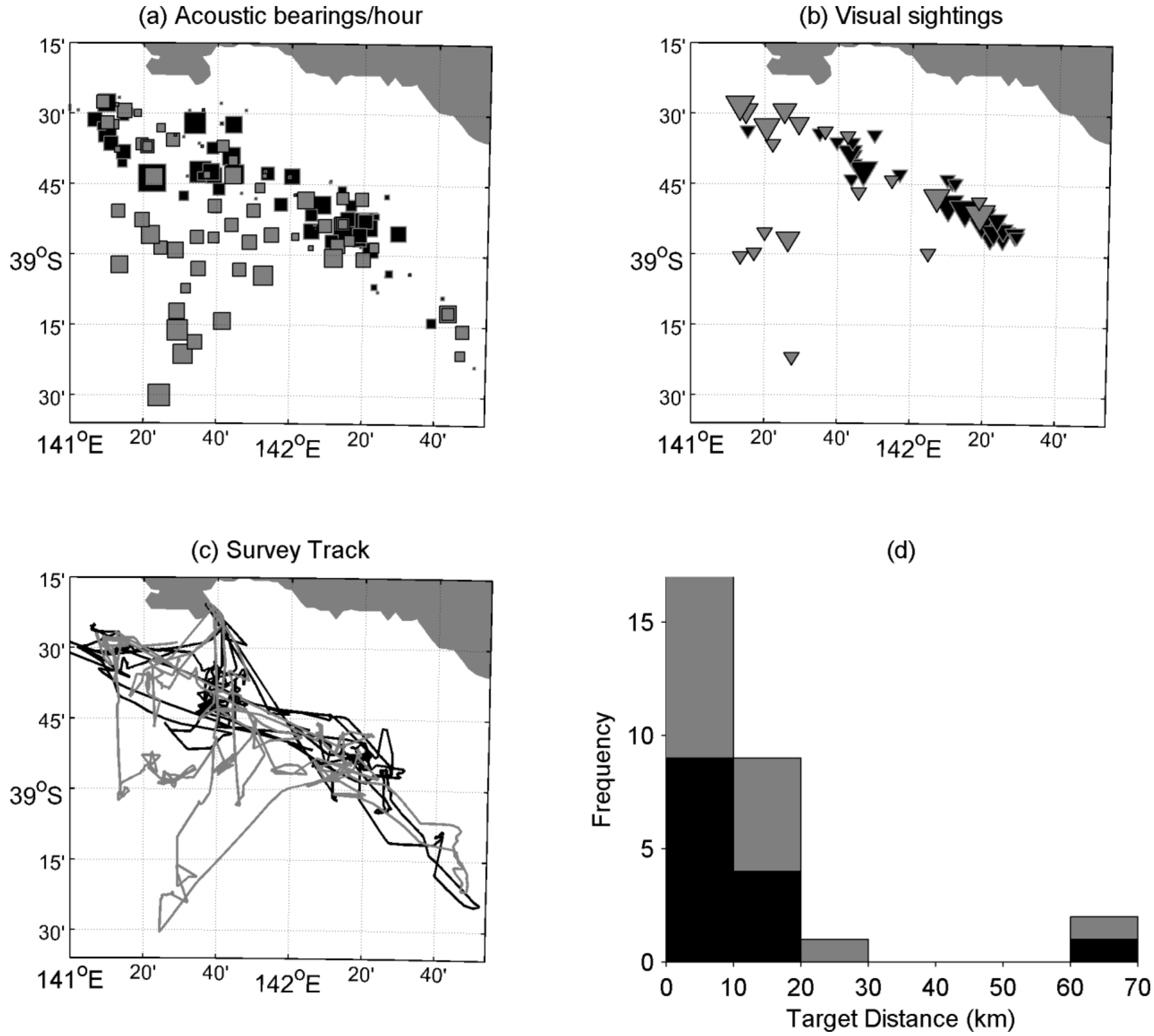

Figure 1 –Sonobuoy locations (a), visual sightings (b) of blue whales, Size of square is proportional to the number of bearings to whales per hour. Size of the triangles is proportional to the group size for each sighting. Survey track (c), and distance travelled from start of targeting to target whale location (d). Data from January are shown in black while data from March is in gray.

Table 1 - Acoustic tracking and targeting metrics

	January	March	Total
Number of active sonobuoys	68	63	131
Number of invalid buoys	8	7	15
Hours of audio monitored	234.7	268.8	503.5
Whale calls processed	3667	3331	6998
Acoustic tracks	31	29	60
Crossed bearings	*	490	>490
Targets chased	19	20	39
Targets aborted	3	4	7
Targets missed	2	1	3
Targets successful	14	15	29
Distance surveyed (nmi)	784.5	723.5	1508.0
Visual survey hours	127.0	115.7	242.7
Photographic Identifications	24	24	47

* Calculation and logging of cross bearings was not performed.

DISCUSSION

The real-time passive acoustic tracking and targeting system was shown to be highly effective at locating blue whales. The acoustic tracking system operated continuously around the clock throughout both voyages, and was generally able to guide the research vessel to blue whales over a range of distances exceeding 60km.

While the metrics were similar between January and March, the structure of the surveys and the nature of the *acoustic tracking* were very different between the two surveys as evidenced by the survey tracks in Figure 1. The January voyage was developmental in nature as much of the equipment was being used for the first time. The month in between the two surveys was used to refine the methods, protocols, and software developed during the January voyage, and as a result acoustic tracking and targeting during the March voyage was much improved. The higher number of successful *targets* despite a shorter amount of time on the water is evidence of this improvement.

While January was successful, the success was somewhat dependent on opportunities for the acousticians to rest during bad weather, and it was fortunate that the survey was split into manageable chunks of time. The level of effort and fatigue of the acoustics team in January was unlikely to be sustainable 24 hours a day for the duration of an Antarctic voyage. Having two additional acousticians onboard in March yielded an acoustics roster that appeared to be sustainable for the entire voyage despite initial sea-sickness at the start of the voyage, a bout of influenza in the middle of the voyage, and a final uninterrupted week of acoustic tracking 24 hours/day. Other benefits of the larger acoustics team were the ability to record additional information and better continuity of *tracking* and *targeting*. These advantages provided voyage leaders with a synoptic view of the situation which proved highly useful for decision making and could help to prevent resampling of the same individuals. While both the January and March voyages were successful, feedback from acousticians at the end of the March voyage indicated that including an additional 'floating' lead-acoustician on the opposite 12 hour shift would be ideal. This would bring the total size of the acoustics team to six.

It is often stated that acoustic surveys offer a potentially increased detection range over purely visual surveys. During these voyages, the distance travelled to reach most *acoustic targets* was typically under 10km, however 12 targets further than 10km support the assertion that acoustic surveys may offer increased effective range over purely visual surveys of blue whales. The two *target* distances of over 60km hint at the potential of acoustic tracking over longer spatial scales as would be expected to occur when *targeting* Antarctic blue whales in the Southern Ocean.

Distance travelled for each *target* is very likely related to the range of acoustic detection, which in turn depends on the source level of the whale calls, noise-level at the receiver, and attenuation from the physical environment. Being able to model the acoustic detection range *in-situ* would provide a valuable tool, especially in the Southern ocean where detection ranges of blue whales have been reported up to 200km (Sirović et al. 2007). Such models are an obvious next-step for in this research and should be investigated.

The distance over which the VHF signal was received from the sonobuoys was an important part of the tracking system. Having a longer VHF reception range provides the ability to monitor each sonobuoy for a longer duration, which helps mitigate a tradeoff between spatial and temporal monitoring. Placing the antenna as high as possible as well as making effective use of a masthead amplifier provided major improvements to the VHF radio reception. Furthermore, the newer WiNRADiO software defined radio receivers had superior sensitivity and allowed usable operation at moderate ranges without the inclusion of a masthead amplifier.

While the methods and protocols here generated a very high level of success, there is still room for improvement. The only failures to find *targeted* whales occurred when whales stopped vocalising during *targeting*, which was an infrequent occurrence in Bass Strait. Because there were only three failures, it is difficult to determine the reasons for failure, however one thing that the failures had in common was that in no crossbearing localisations were obtained. The ability to obtain crossbearings depended on the survey track, distance to the target whale, and the VHF reception range, so these factors become natural candidates for further study.

Additional improvements might include further automation and integration of various aspects of the acoustic tracking and targeting software. Automated detectors could be used to detect whale calls, while classification and tracking algorithms could be used to assign bearings to particular groups of whales. There is also strong potential for further integration between acoustic targeting software, visual sightings software, and photographic identification efforts. The result of such integration would likely yield very powerful tools for voyage management such as near real-time visualisations of incoming data streams.

This research was made possible due to the provision of expired DIFAR sonobuoys from the Australian Defence Forces, however there is presently no alternative localisation system in place should the supply of expired DIFAR sonobuoys dry up. Furthermore, sonobuoys may only be available to government researchers, researchers in a few select countries, and may be subject to additional export restrictions. As such, an investigation of alternative means of real-time acoustic tracking of blue whales may be prudent in order to lower the barrier of entry for blue whale research worldwide.

CONCLUSIONS

Two research voyages have demonstrated the viability of real-time acoustic tracking of blue whales. A team of at least five trained acousticians is recommended in order to maintain a high level of success while maintain operations 24 hours/day. These voyages demonstrate a tool that can be used to target blue whales in real-time over distances greater than 60km with a success rate in excess of 90%. This real-time tracking system is likely to become a key tool in determining the circumpolar abundance of blue whales in the Southern Ocean.

ACKNOWLEDGEMENTS

This work would not have been possible without the hard work and dedication of the acousticians: Susannah Calderan, Kym Collins, Catriona Johnson, Elanor Miller, Flore Samaran, Josh Smith; the visual observers: Virginia Andrews-Goff, Dave Donnelly, Paul Ensor, Paula Olson, Natalie Schmitt, Rob Slade; and the voyage leaders Natalie Kelly and Mike Double. Special thanks to Simon Childerhouse and Sarah Laverick for taking care of the voyage planning and pre-voyage management. Chris Donald at DMO graciously loaned us the sonobuoy receivers and supplied the sonobuoys used for this research. Thanks to David Peel for help analysing the data. Thanks to Mark Milnes for help with VHF receivers and understanding DIFAR demodulation. Thanks to Jason Gedamke for discussions about DIFAR tracking of blue whales. Thanks to Simon Wotherspoon for many conversations about tracking and localisation methods. Thanks to Charles Greene, Mark McDonald, and Jessica Crance for help with DIFAR demodulation and tracking software. Thanks to the crew of the Eastern Voyager and the staff from Blue Planet Marine for two excellent voyages. These voyages were supported by the Australian Antarctic Division.

REFERENCES

Gales, N. 2010. Antarctic Whale Expedition: Preliminary science field report and summary. R.V. Tangaroa Feb/Mar 2010. Pages 1-21.

Gavrilov, A. N., R. D. Mccauley, C. Salgado-kent, J. Tripovich, and C. Burton. 2011. Vocal characteristics of pygmy blue whales and their change over time. Source 130:3651-3660.

Gedamke, J., and S. M. Robinson. 2010. Acoustic survey for marine mammal occurrence and distribution off East Antarctica (30-80°E) in January-February 2006. Deep Sea Research Part II: Topical Studies in Oceanography 57:968-981.

Greene, C. R. J., M. W. McLennan, R. G. Norman, T. L. Mcdonald, R. S. Jakubczak, and W. J. Richardson. 2004. Directional frequency and recording (DIFAR) sensors in seafloor recorders to locate calling bowhead whales during their fall migration. Journal of the Acoustical Society of America 116:799-813.

Hayes, S. A., D. K. Mellinger, D. A. Croll, D. P. Costa, and J. F. Borsani. 2000. An inexpensive passive acoustic system for recording and localizing wild animal sounds. Journal of the Acoustical Society of America 107:3552-3555.

Kelly, N., M. C. Double, D. Peel, M. Bravington, and N. Gales. 2010. Strategies to obtain a new abundance estimate for Antarctic blue whales : a feasibility study. IWC SC-63-SH3:1-15.

Leaper, R., O. Chappell, and J. Gordon. 1992. The development of practical techniques for surveying sperm whale populations acoustically. Report of the International Whaling Commission 42:549-560.

Maranda, B. H. 2001. Calibration Factors for DIFAR Processing. Pages 1-28.

McDonald, M. 2004. DIFAR hydrophone usage in whale research. Canadian Acoustics 32:155-160.

Morrissey, R. P., J. Ward, N. DiMarzio, S. Jarvis, and D. J. Moretti. 2006. Passive acoustic detection and localization of sperm whales (Physeter macrocephalus) in the tongue of the ocean. Applied Acoustics 67:1091-1105.

Møhl, B., A. Heerfordt, and M. Wahlberg. 2007. A wideband connection to sperm whales: A fiber-optic, deep-sea hydrophone array. Deep-Sea Research Part I 54:428-436.

Samaran, F., O. Adam, and C. Guinet. 2010. Detection range modeling of blue whale calls in Southwestern Indian Ocean. Applied Acoustics 71:1099-1106.

Sirović, A., J. a Hildebrand, and S. M. Wiggins. 2007. Blue and fin whale call source levels and propagation range in the Southern Ocean. The Journal of the Acoustical Society of America 122:1208-15.

Wade, P., M. P. Heide-jørgensen, K. Shelden, J. Barlow, J. Carretta, J. Durban, R. Leduc, L. Munger, S. Rankin, A. Sauter, and C. Stinchcomb. 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. Biology letters 2:417-419.

Watkins, W. A., and W. E. Schevill. 1972. Sound source location by arrival-times on a non-rigid three-dimensional hydrophone array. Deep-Sea Research 19:691-706.