Source levels of Antarctic blue whale calls measured during the 2013 Antarctic blue whale voyage: preliminary results

Brian Miller[1], Russell Leaper[2], Susannah Calderan[1], Kym Collins[1], and Mike Double[1]

7 May 2014

1 Australian Marine Mammal Centre, Australian Antarctic Division. 203 Channel Highway, Kingston, TAS 7050. Australia
2 School of Biological Sciences, University of Aberdeen, Tillydrone Avenue, Aberdeen AB24 2TZ, UK

ABSTRACT

Determination of the distances over which whale calls may be detected depends on a number of factors that can interact in complex ways. The factors that determine these distances are the source level of the call, the propagation loss, and the sensitivity of the detector. The source level of the call is effectively a measure of the intensity of the sound measured at the animal. The propagation loss is attenuation that occurs as the call radiates, refracts and reflects throughout the environment. The sensitivity of the detector is the ability to discriminate the call from noise. Acoustic detection was used to locate blue whales during the 2013 Antarctic Blue Whale Voyage of the SORP. Here we present preliminary estimates of source levels of Antarctic blue whale song and propagation loss measured during this voyage. We also highlight additional data collected that could be used for further measurements of source level and propagation loss. Measurements of source level and propagation loss are not only important to determine the detection range of sonobuoys deployed during voyages, but are also essential if acoustic data are to be used for abundance estimation via distance estimation (eg. point-transects).

Keywords: Blue whale; SORP; passive acoustics;

INTRODUCTION

Background

Passive acoustic monitoring (PAM) has formed an important part of Antarctic blue whale research since at least 1996 (Ljungblad et al. 1998, Rankin et al. 2005). Presently there are two ongoing IWC-SORP research programmes that use PAM to study Antarctic blue whales: the Antarctic Blue Whale Project (Hammond et al. 2013) and the Acoustic Trends Project ("SORP Acoustic Trends Project" 2014).

Under certain circumstances PAM can be used to estimate the density of whales; however this typically requires knowledge of the source level (ie. intensity) of whale vocalisations and/or the distance over which these vocalisations can be detected (Thomas & Marques 2012). Additionally some knowledge of the typical acoustic behaviour of the whales is required (eg. Oleson, Calambokidis, Burgess, et al. 2007, Oleson, Calambokidis, Barlow, et al. 2007). For Antarctic blue whales, knowledge of source levels and detection distance is sparse and contained in a small number of studies (Sirović et al. 2007, Samaran, Guinet, et al. 2010, Samaran, Adam, et al. 2010). Here we supplement these data on source levels and acoustic propagation of Antarctic blue whales calls with a preliminary analysis of the acoustic and visual data collected during the 2013 SORP Antarctic Blue Whale Voyage (ABWV).

Estimation of Source Level and Propagation Loss

The level of an acoustic source (ie. a whale call) can be determined using the sonar equation:

$$RL = SL - PL \tag{1}$$

where SL is the source level, RL is the received level (including in-band noise), and PL is the propagation loss (Urick 1983). Accurate estimates of source level depend upon accurate knowledge of propagation loss, which in turn requires accurate knowledge of the location (in three dimensions) of the source, receiver, and propagation paths. Once the source and receiver locations are known, the propagation loss can be estimated using an acoustic propagation model suited to the particular propagation path(s).

Acoustic propagation in the Southern Ocean

Acoustic propagation in polar regions is different than in mid-latitudes or tropics (Urick 1983). The Southern Ocean has a relatively stable, uniform hydrographic regime, at least at high-latitudes in the open ocean environment where stratification is generally stable and without strong fluctuations. While seasonal noise levels have been measured in the Antarctic and appear to be somewhat predictable (eg. Gedamke et al. 2007), there are still relatively few empirical estimates of acoustic propagation loss available in the scientific literature (Širović et al. 2004, Sirović et al. 2007).

Sirović et al., (2007) estimated propagation loss of blue whale calls in the Antarctic from a whale calling at a shallow depth and hydrophones moored in approximately 3000 m of water. Using a relatively simple model of propagation loss Sirović et al., (2007) found their measurements best fitted a model of the form $PL=10\cdot\log_{10}(r^{1.78})$, where the range, r, was the horizontal distance between the hydrophone and acoustically located whale call. A plausible physical interpretation of this result is that propagation losses from a shallow source to a bottom-mounted receiver followed spherical spreading (ie. an inverse square law: $PL=10\cdot\log_{10}(r^2)$), but with slightly reduced losses possibly due to multipath from the sea-floor and surface.

While Sirovic et al. (2007) measured propagation loss in the Antarctic from a shallow source to a deep receiver, it has been suggested that most of the energy from sounds produced from a shallow source are likely to be retained in a surface duct (Urick 1983, Hall 2005). Thus acoustic propagation between a shallow source and shallow receiver (such as a sonobuoy) would be better represented by a different model than that used by Sirovic et al. (2007). A simple model for propagation loss in a surface duct can be written as:

$$PL = \begin{matrix} 10\log_{10} r_0 + 10\log_{10} r \\ 20\log_{10} r \end{matrix} \quad \begin{cases} r > r_0 \\ r \le r_0 \end{cases} \tag{2}$$

In this model the quantity r_0 represents an initial range over which spherical spreading occurs (ie. the height of the surface duct), and the quantity $10\cdot\log_{10}(r)$ represents cylindrical spreading losses at ranges $r>r_0$ (Urick 1983). By substituting equation (2) into equation (1), we obtain a simple equation for propagation loss in the Antarctic surface duct that can be expressed as:

$$SL = RL + 10\log_{10} r_0 + 10\log_{10} r + \epsilon \tag{3}$$

where ϵ represents an error term that encompasses both process and measurement error. The parameter r_0 can be visualized as the height of the surface duct. Here we also assume that noise levels are much less than the received levels, and thus are not included in the model. While spherical and cylindrical propagation losses represent idealized scenarios, these relatively simple equations have straightforward physical interpretations. Thus, many empirical studies of propagation loss use these two scenarios as a baseline for comparisons. Additionally, these simple models of propagation loss are often the most appropriate when the locations of the sound source and/or receivers are not precisely known.

Estimating source and receiver location

Accurate and precise models of acoustic propagation require not only accurate knowledge of the physical environment, but also accurate and precise knowledge of the locations of the sound source and receiver(s) (Urick 1983). In the case of blue whales, source locations are not always known very precisely, but rather estimated from acoustic localisations (Thode et al. 2000, Sirović et al. 2007, Samaran, Guinet, et al. 2010, Gavrilov et al. 2011) or visual location methods (eg. McDonald et al. 2001).

During the 2013 Antarctic Blue Whale Voyage both acoustic and visual (ie. sightings when a whale is at the surface) localisation methods were used to estimate the location of calling whales (Double et al. 2013, Miller et al. 2013). Additionally, during a few encounters whales at the surface could be precisely localised using photogrammetric video tracking (Leaper & Gordon 2001). Here we describe methods to estimate source levels and propagation loss using these highly precise photogrammetric tracks. We then explore the potential to derive estimates of source level and propagation loss using the entire set of acoustic detections and visual sightings.

METHODS

All data were collected during the 2013 Antarctic Blue Whale Voyage and the specific details of data collection can be found in the voyage plan (unpublished) and cruise reports (Double et al. 2013, Miller et al. 2013). We consider only a subset of the acoustic detections during the voyage, specifically those calls comprising Antarctic blue whale song, or 'Z'-calls. More specifically, we only consider the first tonal unit, which has been referred to as Unit A (Miller et al. 2013).

Acoustic data sets

For this study of source level and propagation loss, we divided the data from the voyage into two different sets. The first data set involved a single encounter in which a singing Antarctic blue whale was both precisely located via photogrammetric video tracking and acoustically recorded with two DIFAR (directional) sonobuoys. These data are also presented in Miller, Leaper, et al. (2014) and Miller, Wotherspoon, et al. (2014). This data set represents the most precise data both in terms of whale and receiver locations, and can be thought of as providing a basic test of the validity of the methodology used to estimate source levels. Furthermore, this data set follows relatively straightforward and well-established methods for the estimation of source level from accurate visual sightings (eg. McDonald et al. 2001). We refer to these data as the *Fine-Scale* data set (Figure 1).

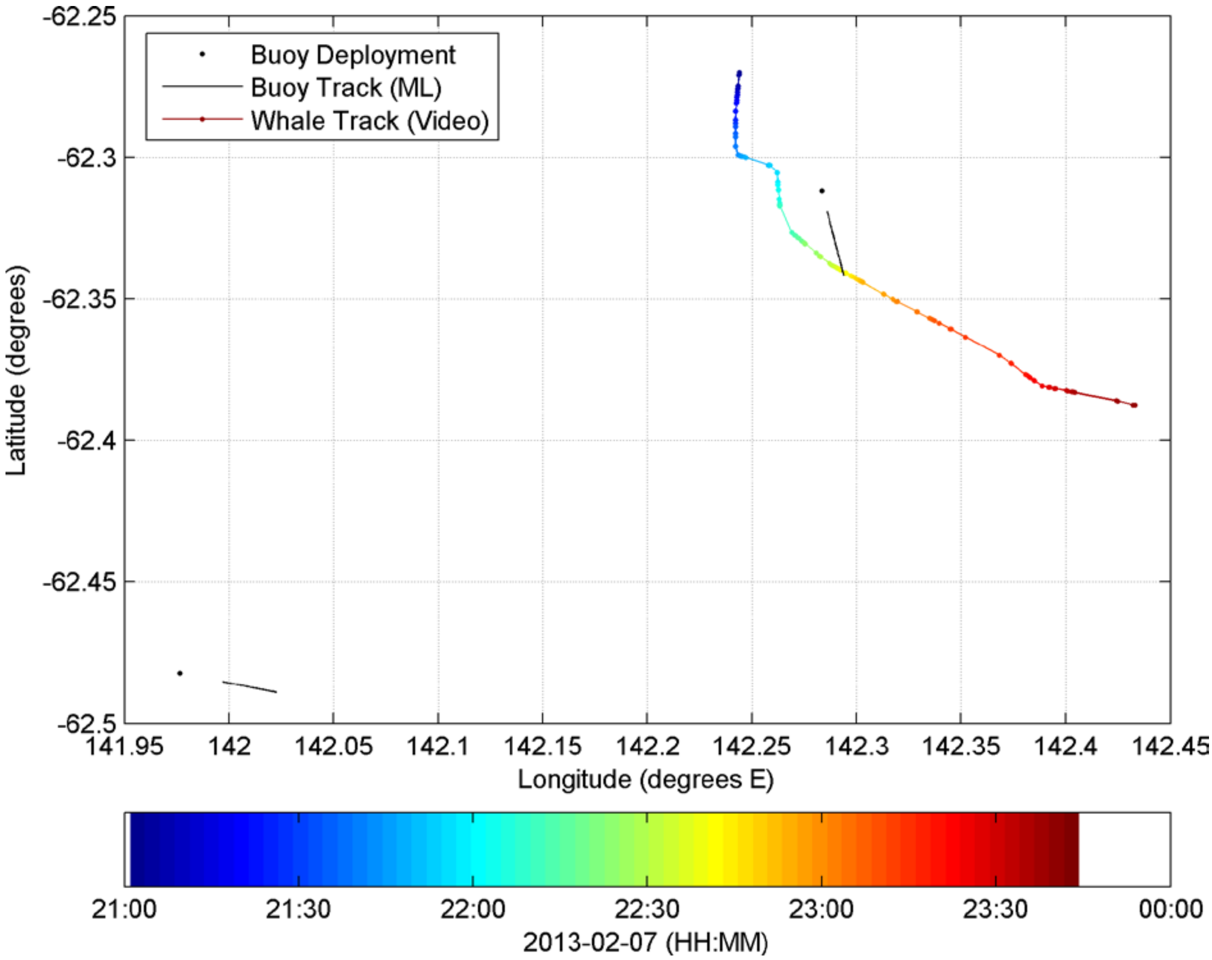

Figure 1 - Photogrammetric video track and acoustic detections comprising the *Fine-Scale* data set. Coloured symbols correspond to the source location of acoustic detections interpolated from the photogrammetric track. Black dots indicate the deployment location of sonobuoys, and black lines indicate the track of the sonobuoys throughout the duration of the video track.

The second data set consisted of all of the acoustic detections that occurred on sonobuoys that were further than 30 km from a visual sighting. We refer to these data as the *Broad-Scale* data set (Figure 2). The *Broad-Scale* data set was similar to that presented in (Miller et al. 2013), but without acoustic detections that occurred during close-range targeting and monitoring. No attempt was made to estimate sonobuoy drift, nor was there an attempt to estimate movement of visually sighted whales. Thus, the precision of source and receiver locations as well as the synchronicity between visual sightings and acoustic detections was potentially lower for the *Broad-Scale* data set than for the *Fine-Scale* data set in absolute terms (Miller et al. 2013). However, it was more likely that the relative precision of source and receiver locations (ie. as a proportion of the total distance between the two), of acoustic detections that were more than 30 km from a sighting would not be substantially different (Miller, Wotherspoon, et al. 2014). Additionally, the use of a large number of acoustic detections and visual sightings provided a large number of independent acoustic calls from a larger number of whales.

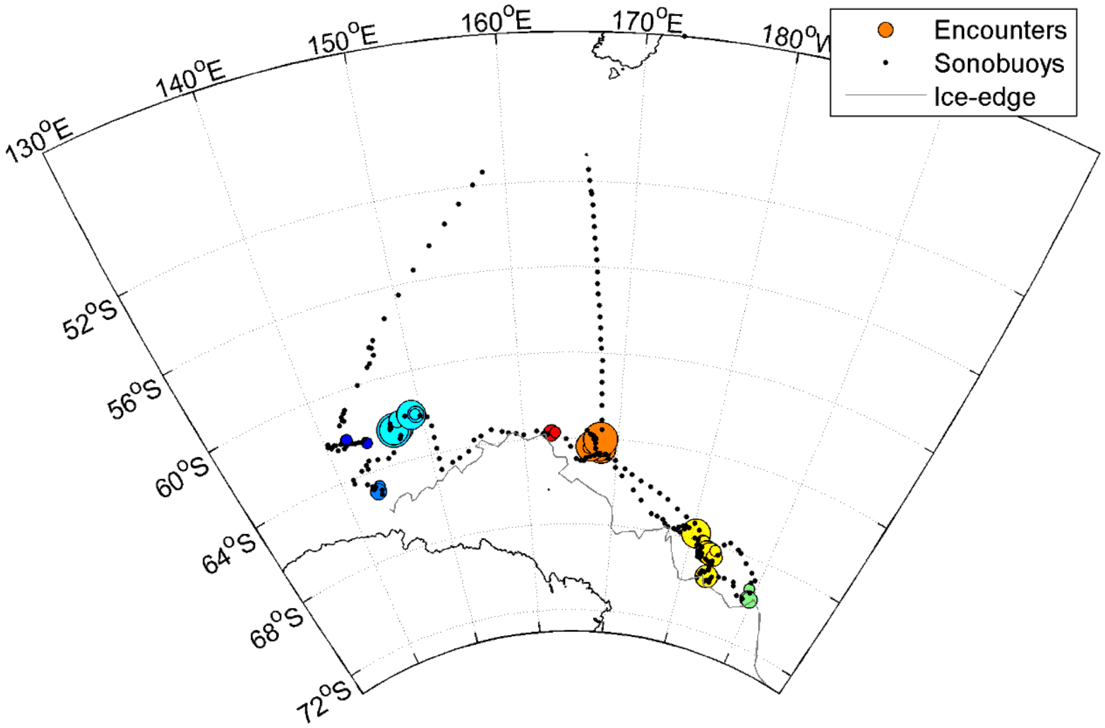

Figure 2 – Map of the *Broad-Scale* data set. Coloured circles correspond to the visual sightings (ie. source locations) with the size of the symbol proportional to the number of whales in the encounter. Black dots indicate the deployment location of sonobuoys (ie. receiver locations). Only sonobuoys with acoustic detections of Antarctic blue whale song are shown.

Acoustic analysis

Estimation of source levels and acoustic propagation was conducted similarly for both data sets. The "true" locations of (groups of) whales were taken from the visual/photogrammetric observations that were made during the 2013 ABWV. Acoustic detections of song unit A were assigned to one of these (groups of) whales if the acoustically derived bearings passed within a predefined tolerance of the location of these visual observations. The received level of each acoustic detection was measured and the distance between the receiver and the visual sighting was calculated. These received levels and distances were then fitted to a model of acoustic propagation in a surface duct (equation 3) with the source-level, SL, and surface duct height, r_0, as free parameters. The free parameters were fit to the data by minimising the error term, ϵ, in equation 3 (ie. minimising the difference between the modelled and measured received levels).

For the *Fine-Scale* data set, detections of individual calls were assigned to a photogrammetric track for measurement of received levels and distances. To account for the precision of acoustic bearings from DIFAR sonobuoys, only acoustic detections with bearings within 10 degrees of the photogrammetric video track at the time of detection were assigned to that sighting (Miller, Gedamke, et al. 2014). When determining the distance between receiver and source, sonobuoy drift was taken into account using the methods described in (Miller, Wotherspoon, et al. 2014) to provide a more accurate estimate of the location of the receiver.

For the *Broad-Scale* data set we first estimated the *best-bearings* for each sonobuoy (ie. modal-peak of the circular distribution of all bearings from each sonobuoy). The calculation of best-bearings is described in (Miller et al. 2013, Miller, Collins, et al. 2014), though in those publications they were referred to as the "peaks of the bearing-density function". Using a large number of detections from "calibrated" sonobuoys to determine each *best-bearing* ensured that they were representative of the true location of the sound source (Miller, Gedamke, et al. 2014). The *best-bearings* from each sonobuoy were then used to assign a group of detections to a group of visually sighted whales (Figure 2). The received level was measured for each individual detection within a *best-bearing* and the mean received level of these detections was used in the acoustic propagation model. Mean sound pressure levels were computed in the linear units rather than dB. Acoustic bearings that were within 30 degrees of a visual sighting were assigned to that sighting. The higher tolerance of 30 degrees was used in order to accommodate movement of whales that might occur due to the potentially long timespan that could arise between acoustic detections and initial visual sighting of a group of whales (Miller et al. 2013).

Alternate acoustic propagation models

In addition to using a model of propagation loss in a surface duct (equation 3), we also considered two slightly more complex models for propagation loss of the *Fine-Scale* data set. For both of these models we computed the propagation loss using the ray-tracing program Bellhop (Porter 2011). The only difference between these two models was the sound-speed profile. The first model used a sound speed profile derived entirely from the World Ocean Atlas (Antonov et al. 2010, Locarnini et al. 2010) near the location of the *Fine-Scale* data set, while the second model used a sound-speed profile derived from a CTD cast during the 2013 ABWV near the location of the *Fine-Scale* data set (Figure 3). During the voyage CTD casts were conducted to a depth of 750 m, thus the remainder of the second sound speed profile was derived from the World Ocean Atlas. These alternative models of propagation loss were qualitatively compared to the simple model of a surface duct by plotting the propagation loss as a function of distance.

Models created in Bellhop showed strong dependence on the depth of the sound source. We used a depth of 30 m for the sound source. However, this depth was based on the measurements of the calling depth of blue whales made in the eastern Pacific Ocean (Oleson, Calambokidis, Burgess, et al. 2007), and may not be representative of actual calling depths of Antarctic blue whales.

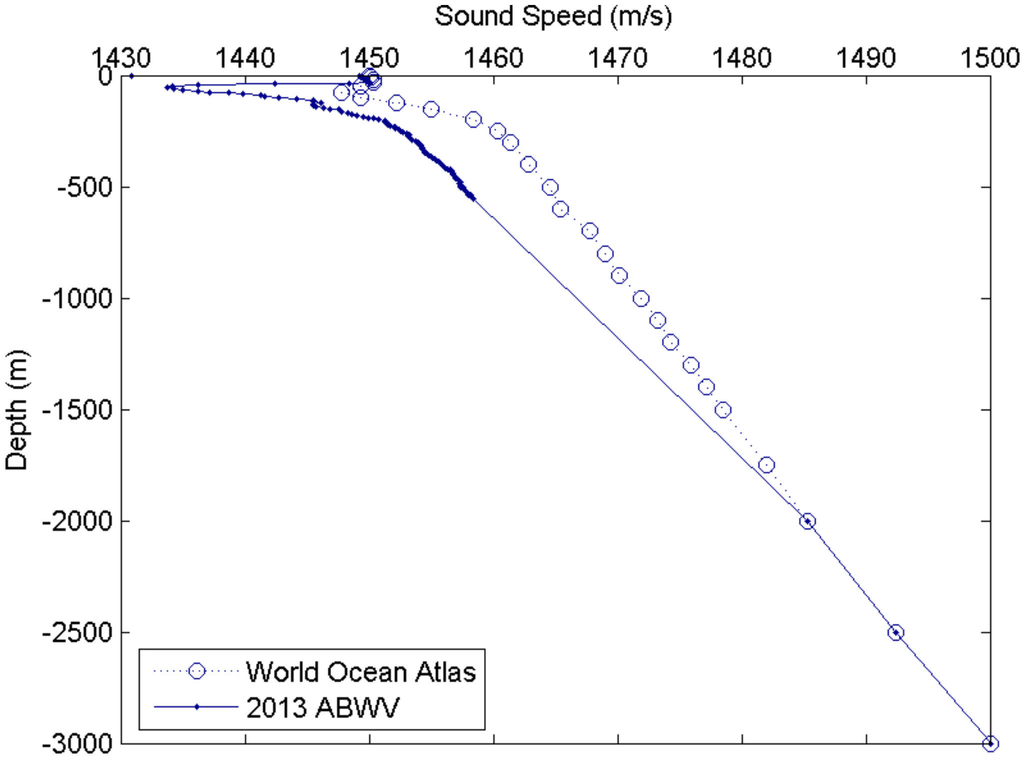

Figure 3 - Sound speed profiles used for alternative models of propagation loss. These sound speed profiles were derived from locations near that of the *Fine-Scale* data set (described in the text).

RESULTS

Fine-Scale

The *Fine-Scale* data set contained 116 acoustic detections of unit A from 58 calls (ie. the same call was measured on two sonobuoys). A source level of 182 dB re 1 µPa rms and a duct height of 1146 m gave the best fit to the measured received levels and distances (Figure 4). Applying the best fit model to the distances and received levels from these 116 detections yielded a standard deviation of source level of 1.9 dB (calculated in the logarithmic, rather than linear domain).

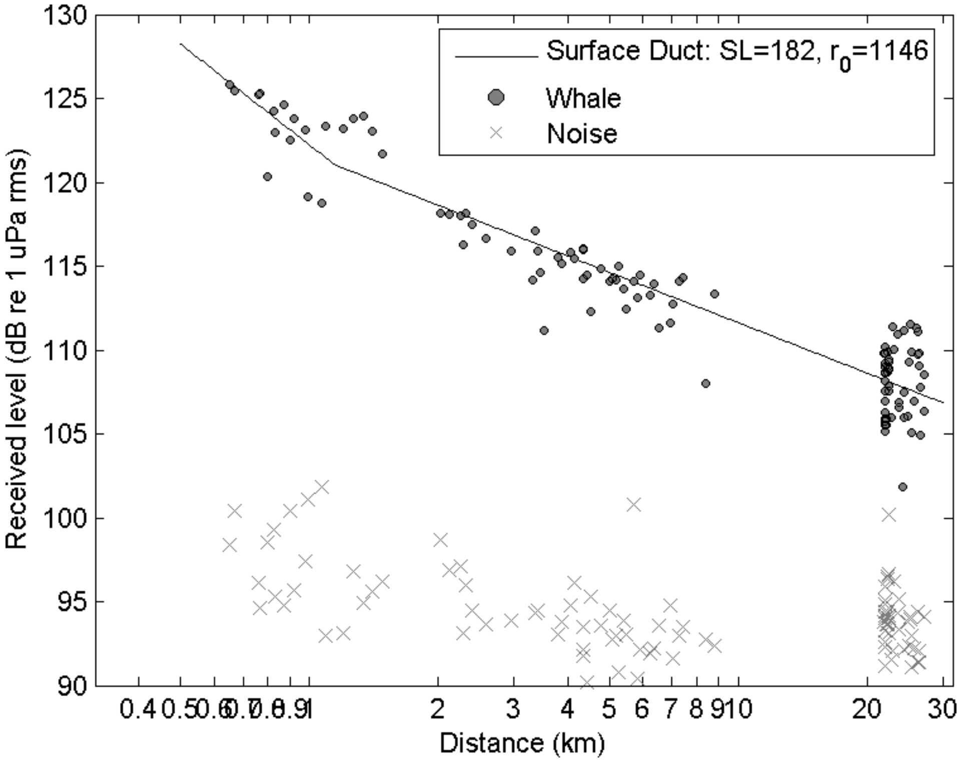

Figure 4 - Received levels and distances measured from the *Fine-Scale* data set. Circles show the received levels of whale calls in the 25-29 Hz band (ie. unit A of Antarctic blue whale song), while crosses show the noise measured in the 25-29 Hz band just prior to the whale call at the same distance. The black line shows the best fit model of a surface duct, which in this case corresponds to a source level of 182 dB re 1 µPa rms and a duct height of 1146 m.

Broad-Scale

The *Broad-Scale* data set contained 6,738 calls, however these calls were grouped together into 340 *best-bearings* that could be assigned to a visual sighting. A source level of 185 dB re 1 µPa rms and a duct height of 774 m gave the best fit to the measured received levels and distances (Figure 5). Applying the best-fit Broad-Scale model to these 340 mean-received levels and distances yielded a standard deviation of the source level of 2.4 dB (calculated in logarithmic rather than linear units).

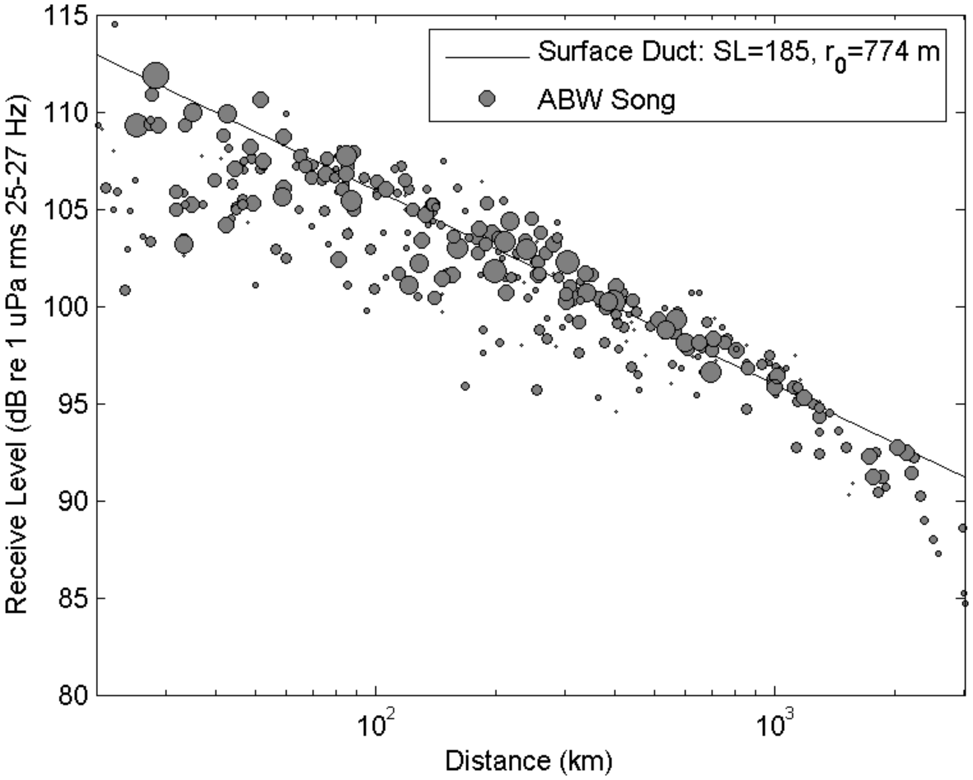

Figure 5 - Received levels and distances measured from the *Broad-Scale* data set. Circles show the received levels of whale calls in the 25-29 Hz band (ie. the first tonal unit of the Z-call). The size of the symbol corresponds to the number of bearings comprising the *best-bearing*. The black line shows the best fit model of a surface duct, which in this case corresponds to a source level of 185 dB re 1 µPa rms and a duct height of 774 m. Distances are in kilometers (ie. 10^3 means 1000 km).

Acoustic propagation models

Qualitative comparisons among the acoustic propagation models revealed broad similarities. The surface-duct that was fit to the *Broad-Scale* data set matched most closely with that of the Bellhop model that used the sound-speed profile from the World Ocean Atlas. The Bellhop model that used a sound-speed profile derived from voyage CTD casts was more similar to the Fine-Scale surface duct.

DISCUSSION

Our results are very similar to previous estimates of the source level of Antarctic blue whales (Table 1). Results from both our data sets appear to be more precise than either of the prior estimates of source level, however we would like to stress the fact that our results are preliminary and must be subject to further more rigorous scrutiny. For the *Fine-scale* data, the additional precision of the source levels is likely due toour method of localisation being potentially more precise than the acoustic methods used during the prior two studies. However, it is somewhat surprising that the precision of the *Broad-scale* data is also very high, given all the potential sources of error in that data set.

Table 1 - Comparison of measurements of the source level of Antarctic blue whale calls.

Study	SL (mean) dB re 1 µPa rms	SL (Std. Dev)	Band (Hz)	n (whales)	n (calls)
Fine-Scale	182	2	25-29	1	60
Broad-Scale	185	2	25-29	>7*	6,738**
Sirović et al. (2007)	189	3	25-29	5	84
Samaran et al. (2010)	179	5	17-30	1	28

* A precise estimate of the total number of individual callers during the voyage was not possible.
** 6,738 calls were averaged to yield 340 *best-bearings*, distances, and received levels.

Potential sources of error in the *Broad-scale* data set include: errors in distance estimation due to whale movement, model mismatch, and/or natural variability in source levels both within and among individual whales. While the long time-spans between many acoustic detections and associated whale sightings (Miller et al. 2013) could potentially result in very large errors in distance due to movement of whales (Olson et al. 2013), it appears that at these long detection distances actual movements of the whales are not enough to generate large changes in received levels. This is likely due to the logarithmic relationship between the two quantities (equation 3). Additionally, the consistency and precision of the broad-scale results suggest that propagation losses in the Antarctic can be estimated using a simple model of a surface duct when propagation occurs between a shallow source and shallow receiver both in deep water (eg. blue whales and sonobuoys during SORP or SOWER voyages).

Given the consistency of our results both internally and with that of prior studies, we conclude that Antarctic blue whales appear to produce song unit A at a relatively consistent source level, regardless of individual, location, or year. This result suggests that there is some natural limit to the maximum source level produced by Antarctic blue whales, and that most whale calls approach this limit. We cannot yet be certain whether this limit is imposed by physical constraints of the vocal anatomy in conjunction with selection pressure to be long, low, loud, and loquacious (Adam et al. 2013), or if it results from the requirement to maintain contact with a constant number of conspecifics (McDonald et al. 2009). However, application of the methods described in this manuscript to the data collected during the IDCR-SOWER surveys may provide a test of the latter hypothesis.

While we have only considered acoustic detections of Antarctic blue whale Z-calls (Rankin et al. 2005, Miller et al. 2013), we would expect that the following methods should also be generally applicable to other calls such as ‘D’ calls. However evidence suggests that ‘D’ calls may not have source levels that are as consistent as those of song calls (Thode et al. 2000, Gavrilov et al. 2011).

CONCLUSIONS

We have greatly increased the number of measurements of the source level of the song of Antarctic blue whales. We have provided strong evidence that call unit A is produced at relatively constant source levels of 180-187 dB re 1 µPa rms in the 25-29 Hz band. We have demonstrated that acoustic propagation from a shallow source to a shallow receiver can be modelled as a simple surface duct with reasonable accuracy. At these levels, and under these propagation conditions, Z-calls of Antarctic blue whales can be detected from thousands of kilometres away.

ACKNOWLEDGEMENTS

Thanks to all the scientists and logistics staff at the Australian Antarctic Division and Australian Marine Mammal Centre for their hard work and support of the 2013 Antarctic Blue Whale Voyage. Thanks to the excellent and professional crew of the *FV Amaltal Explorer*. Thanks to Christopher Donald from Australian Defence for provision of the expired 53D sonobuoys used in this research. Particular thanks are due to Paul Ensor and Jay Barlow for their encouragement, keen visual observations, and excellent guidance of the ship during close approach and video tracking.

REFERENCES

Adam O, Cazau D, Gandilhon N, Fabre B, Laitman JT, Reidenberg JS (2013) New acoustic model for humpback whale sound production. Appl Acoust 74:1182–1190

Antonov JI, Seidov D, Boyer TP, Locarnini RA, Mishonov A V., Garcia HE, Baranova OK, Zweng MM, Johnson DR (2010)World Ocean Atlas 2009, Volume 2: Salinity (S Levitus, Ed.), NOAA Atlas. U.S. Government Printing Office, Washington, D.C.

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

Fristrup KM, Thomas RE, Tyack P (2002) Linking the sounds of dolphins to their locations and behavior using video and multichannel acoustic recordings. J Acoust Soc Am 112:1692–1701

Gavrilov AN, Mccauley RD, Salgado-kent C, Tripovich J, Burton CLK (2011) Vocal characteristics of pygmy blue whales and their change over time. J Acoust Soc Am 130:3651–3660

Gedamke J, Gales N, Hildebrand JA, Wiggins S (2007) Seasonal occurrence of low frequency whale vocalisations across eastern Antarctic and southern Australian waters, February 2004 to February 2007. Report SC/59/SH5 submitted to the Scientific Committee of the International Whaling Commission. Anchorage, Alaska

Hall M (2005) Sound propagation through the Antarctic Convergence Zone and comments on three major experiments. In: Proceedings of Acoustics 2005. Busselton, Western Australia, p 475–479

Hammond P, Barlow J, Charassin J-B, Double M, Iniguez M, Walløe L (2013) Antarctic Blue Whale Project Project Overview.

Leaper R, Gordon JC (2001) Application of photogrammetric methods for locating and tracking cetacean movements at sea. J Cetacean Res Manag 3:131–141

Ljungblad DK, Clark CW, Shimada H (1998) A comparison of sounds attributed to pygmy blue whales (Balaenoptera musculus brevicauda) recorded south of the Madagascar Plateau and those attributed to “true” blue whales (Balaenoptera musculus) recorded of Antarctica. Rep Int Whal Comm 48:439–442

Locarnini RA, Mishonov A V., Antonov JI, Boyer TP, Garcia HE, Baranova OK, Zweng MM, D. R. Johnson (2010)World Ocean Atlas 2009 Volume 1: Temperature (S Levitus, Ed.), NOAA Atlas. U.S. Government Printing Office, Washington, D.C.

McDonald MA, Calambokidis J, Teranishi AM, Hildebrand JA (2001) The acoustic calls of blue whales off California with gender data. J Acoust Soc Am 109:1728

McDonald MA, Hildebrand JA, Mesnick S (2009) Worldwide decline in tonal frequencies of blue whale songs. Endanger Species Res 9:13–21

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, Gedamke J, Calderan S, Collins K, Johnson C, Miller E, Samaran F, Smith J, Double MC (2014) Accuracy and precision of DIFAR localisation systems: Calibrations and comparative measurements from three SORP voyages. Submitt to Sci Comm 65b Int Whal Comm Bled, Slov SC/65b/SH:14

Miller BS, Leaper R, Calderan S, Gedamke J (2014) Red shift blue shift: Doppler shifts and seasonal variation in the tonality of Antarctic blue whale song. Submitt to Sci Comm 65b Int Whal Comm Bled, Slov SC/65b/For: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

Oleson EM, Calambokidis J, Barlow J, Hildebrand JA (2007) Blue Whale Visual and Acoustic Encounter Rates in the Southern California Bight. Mar Mammal Sci 23:574–597

Oleson EM, Calambokidis J, Burgess WC, McDonald MA, LeDuc CA, Hildebrand JA (2007) Behavioral context of call production by eastern North Pacific blue whales. Mar Ecol Prog Ser 330:269–284

Olson PA, Ensor P, Schmitt N, Olavarria C, Double MC (2013) Photo-identification of Antarctic blue whales during the SORP Antarctic Blue Whale Voyage 2013. Rep Submitt to Sci Comm Int Whal Comm 65a/SH11:1–6

Porter MB (2011) The BELLHOP Manual and User’s Guide: PRELIMINARY DRAFT. La Jolla, CA, USA

Rankin S, Ljungblad DK, Clark CW, 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 Manag 7:13–20

Samaran F, Adam O, Guinet C (2010) Detection range modeling of blue whale calls in Southwestern Indian Ocean. Appl Acoust 71:1099–1106

Samaran F, Guinet C, Adam O, Motsch J-F, Cansi Y (2010) Source level estimation of two blue whale subspecies in southwestern Indian Ocean. J Acoust Soc Am 127:3800–8

Sirović A, Hildebrand JA, Wiggins SM (2007) Blue and fin whale call source levels and propagation range in the Southern Ocean. J Acoust Soc Am 122:1208–15

Širović A, Hildebrand JA, Wiggins SM, McDonald MA, Moore SE, Thiele D (2004) Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. Deep Sea Res Part II Top Stud Oceanogr 51:2327–2344

SORP Acoustic Trends Project (2014)

Thode AM, D’Spain GL, Kuperman WA (2000) Matched-field processing, geoacoustic inversion, and source signature recovery of blue whale vocalizations. J Acoust Soc Am 107:1286–1300

Thomas L, Marques T (2012) Passive Acoustic Monitoring for Estimating Animal Density. Acoust Today 8:35–44

Urick RJ (1983)Principles of underwater sound, 3rd edn. McGraw-Hill, New York