Estimating drift of DIFAR sonobuoys when localising blue whales

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ABSTRACT

During a 2013 study of Antarctic blue whales, pairs of directional (DIFAR) sonobuoys were used to obtain 2D locations of vocalising blue whales. Accuracy of this acoustic localisation system was investigated by comparing acoustic localisations to a photogrammetric video track of surfacing locations of a whale. Only the deployment locations of the sonobuoy were known during the voyage, however sufficient data were collected that could potentially enable estimation of the drift of these sonobuoys. We derive a statistical method for estimating drift direction and speed of a drifting sonobuoy with a known deployment location. Maximum likelihood direction and speed of drift of the sonobuoy are obtained from a time series of acoustic bearings to the known position of the research vessel. Acoustic locations to an Antarctic blue whale were then computed under the assumptions 1) that buoys did not drift, and 2) that buoys drifted at a constant speed and direction. Acoustic locations of the whale were then compared against those interpolated from highly accurate photogrammetric video tracks. In the test case presented here, correcting for sonobuoy drift substantially increased the accuracy of estimates of location. Guidelines are proposed to determine when location estimates are likely to be robust to buoy drift.

KEYWORDS: ACOUSTICAL DETECTION, BLUE WHALES, ACOUSTIC SOURCE LOCALISATION, SIGNAL PROCESSING TECHNIQUES FOR ACOUSTIC INVERSE PROBLEMS

INTRODUCTION

Sonobuoys have been a valuable tool for acoustic monitoring of a variety of whale species for decades (Barlow and Taylor, 1998; Laurinolli et al., 2003; Ljungblad et al., 1982; McDonald and Moore, 2002; McDonald et al., 2001; Norris et al., 1999; Richardson and Fraker, 1985; Richardson et al., 1986; Rone et al., 2012). Directional (DIFAR) sonobuoys that give bearings to vocalising whales have proven particularly effective for species that make very low-frequency vocalisations such as blue, fin, and bowhead whales (Gedamke and Robinson, 2010; Greene et al., 2004; McDonald, 2004).

Both Greene et al., (2004) and McDonald, (2004) provide an overview of the operating principles of DIFAR sensors, so we provide only a brief summary of their operation here. A single DIFAR sensor can provide both received acoustic pressure and information about the direction of arrival (ie. bearing) of a sound source. Two-dimensional localisation of a sound source can be achieved with as few as two sonobuoys under favourable source-receiver geometries (Greene et al., 2004; McDonald, 2004). Bearings from DIFAR sonobuoys are referenced to magnetic north, as determined by an onboard fluxgate compass, and the nominal precision of a DIFAR bearing is specified to be within ±10° degrees (Greene et al., 2004; McDonald, 2004). Thus the accuracy and precision of localisation depend on accurate knowledge of the location 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 sensor. Knowledge of the accuracy and precision of the DIFAR bearings are of special interest to those performing real-time localisation (eg. Rone et al., 2012; Wade et al., 2006). Data on the precision of acoustic localisations are also required for estimating source levels (Blackwell et al., 2012; McDonald et al., 2001; Thode et al., 2000).

Greene et al. (2004) describe a method for estimating localisation accuracy using bearings from two or more DIFAR sensors moored to the sea floor at a known location. In their study, the orientation of the sensors was fixed, and the magnetic compass within the DIFAR sensor was not used. Sensor orientation was then calibrated against sounds transmitted from known locations. This process yielded bearing precision of approximately 1° compared to the nominal DIFAR specification of ±10°.

Similarly, McDonald, (2004) investigated the accuracy of bearings from DIFAR sonobuoys by comparing acoustically and GPS-derived bearings to a blue whale. After discarding bearings from “short range calls” McDonald found the standard deviation of bearing angles to be approximately 2°. He suggests that there may be further methods to improve the precision and quantify the accuracy of DIFAR sonobuoys, but reports that such methods were not warranted given the small standard deviation found during his preliminary analysis and the small number of blue whale tracks available for further measurement.

Real-time acoustic localisation using DIFAR sonobuoys has been proposed as an important component of a research collaboration that aims to estimate the abundance of Antarctic blue whales (Peel et al., 2014). While trial voyages have demonstrated acoustic localisation techniques are good enough for visual observers to locate whales (Miller 2012; Double et al 2013), few quantitative measurements of the precision and accuracy of these localisation methods have been reported (Miller et al., 2014a). Such quantitative measurements are not only important for developing more accurate acoustic tracking methods, but also for estimating source characteristics, modelling acoustic propagation, and quantifying the detection range of whale vocalisations.

Unfortunately, precise knowledge of the location of sonobuoys is not always available over the whole duration of a recording. Sonobuoys drift freely with ocean currents, and often only the location of deployment is accurately known. While some models of sonobuoy do have GPS capabilities, these models have not typically been available for use by whale researchers.

However, the location of a drifting sonobuoy may, in theory, be determined from a time series of sounds received from a source with known locations. This source could be the self-noise of the research vessel with locations being determined via a GPS receiver, or it could be vocalisations from a whale with locations determined from visual methods (eg. measured range and bearing). In order to determine direction and speed of drift, acoustic bearings to the known source should ideally cover a wide arc, *ie.* a large range of angles (Nardone and Aidala, 1980).

Here we investigate the accuracy and precision of a DIFAR localisation system comprising two drifting sonobuoys deployed from a research vessel. We combine methods from Greene et al., (2004) and McDonald, (2004), and Miller et al., (2014a) in order to correct for magnetic declination, and we develop a statistical method for estimating sonobuoy drift. We compare the accuracy of DIFAR localisations to photogrammetrically-derived locations of an Antarctic blue whale obtained during a research voyage in 2013.

METHODS

Data collection

Data used in this study were collected from the *FV Amaltal Explorer* during the 2013 Antarctic Blue Whale Voyage of the Southern Ocean Research Partnership (Double et al., 2013). Methods for acoustic monitoring and localisation of Antarctic blue whales followed those of (Miller et al., 2013), including “calibration” of the sonobuoy compass in order to obtain a correction that included the compass deviation and local magnetic anomaly. During approach, whales were recorded with a video-photogrammetric system (described by Leaper and Gordon, 2001) so that the location of surfacing could be determined accurately.

Over the course of the voyage there were 48 incidents where high-quality recordings of Antarctic blue whales were obtained simultaneously on two sonobuoys. However, here we follow the precedent of (McDonald et al., 2001) and restrict our analysis to a single recording session in which we were able to not only obtain high-quality acoustic recordings from two sonobuoys simultaneously, but also photogrammetric video tracks of the vocalising whale. Additionally, during this session, the research vessel passed within audible range of one of the sonobuoys several hours after deployment, thus providing a known sound source for calculation of sonobuoy drift.

Analysis

Estimating sonobuoy drift

We consider the drift direction, ϕ, and speed, r of a sonobuoy, deployed at known location x_0. At times $t_1 ,t_2 ,\ldots,t_n$ the buoy reports bearings $\vartheta_1, \vartheta_2,\ldots \vartheta_n$ to the ship, and the precision of these measurements is known to have standard deviation σ (Miller et al., 2014a). The location of the ship $z_0 = x_0, z_1,\ldots,z_n$ at these times is known precisely.

We assume that the buoy drifts along a great circle at a constant rate r for the duration of its life. Let $x_k = x(x_0,\varphi,r,t_k)$ denote the position of the buoy at time t_k, where x_0 is the deployment position and ϕ is the initial direction of the drift in degrees, and let $\Theta_k = \Theta(x_k ,z_k)$ denote the true bearing from the buoy to the boat at time t_k for $k \geq 0$. Further, we assume that the observed bearings are normally distributed about the expected bearings modulo 360°.

The likelihood, which can then be used to compute the maximum likelihood estimates of ϕ and r, takes the form:

$$\mathrm{p}(\varphi,\mathrm{r} \mid \theta_1,\ldots,\theta_n) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi\sigma}} e^{-\left(\frac{(\theta_k - \Theta_k + 180)^2}{2\sigma^2}\right)} \qquad 1$$

Whale tracks

Locations of the whale obtained from video tracking, w_k, were assumed to correspond to the “true” location of the whale when at the surface due to the high accuracy and precision of photogrammetric video tracking (Leaper and Gordon, 2001). Linear interpolation between successive photogrammetric locations was used to create whale tracks at times $t'_1 ,t'_2 ,\ldots,t'_m$, at which there were acoustic bearings, $\beta_1, \beta_2, \ldots, \beta_m$, from the sonobuoy to the whale. We denote the true acoustic bearings from the sonobuoy to the whale as $B_j = B(x_j, w_j)$.

Acoustic analysis was restricted to the duration of the video track. Vocalisations believed to originate from the tracked whale were identified and used for further analysis, while vocalisations believed to be from other whales were discarded. Several criteria, including the type of call, temporal pattern of calling, and received level, were used in addition to the bearing of the vocalisation, to determine whether or not it should be included for further analysis.

We then compared bearings calculated assuming no drift with those calculated assuming sonobuoys drift at constant speed and direction (as per Eq. 1). Additionally we compared crossed-bearings calculated assuming no drift with those calculated assuming constant speed and direction (as per Eq. 1). Crossed-bearings were calculated as the intersection of two great circle paths as described by (http://www.movable-type.co.uk/scripts/latlong.html).

To estimate the accuracy and precision of acoustic crossbearings, the RMS error was computed between each acoustic location and associated photogrammetric location as:

$$E_{rms} = \frac{\sqrt{\hat{d}^2 - d^2}}{d} \qquad 2$$

Where $\hat{d}$ is the distance between the acoustic crossbearing and the sonobuoy, and d is the distance between the photogrammetric (ie. actual) location of the whale and the sonobuoy. Each acoustic location yielded two measurements of RMS error, one for each sonobuoy. RMS errors were then grouped by photogrammetric distance into logarithmically spaced bins, and all of the measurements in each bin were averaged (Figure 3).

RESULTS

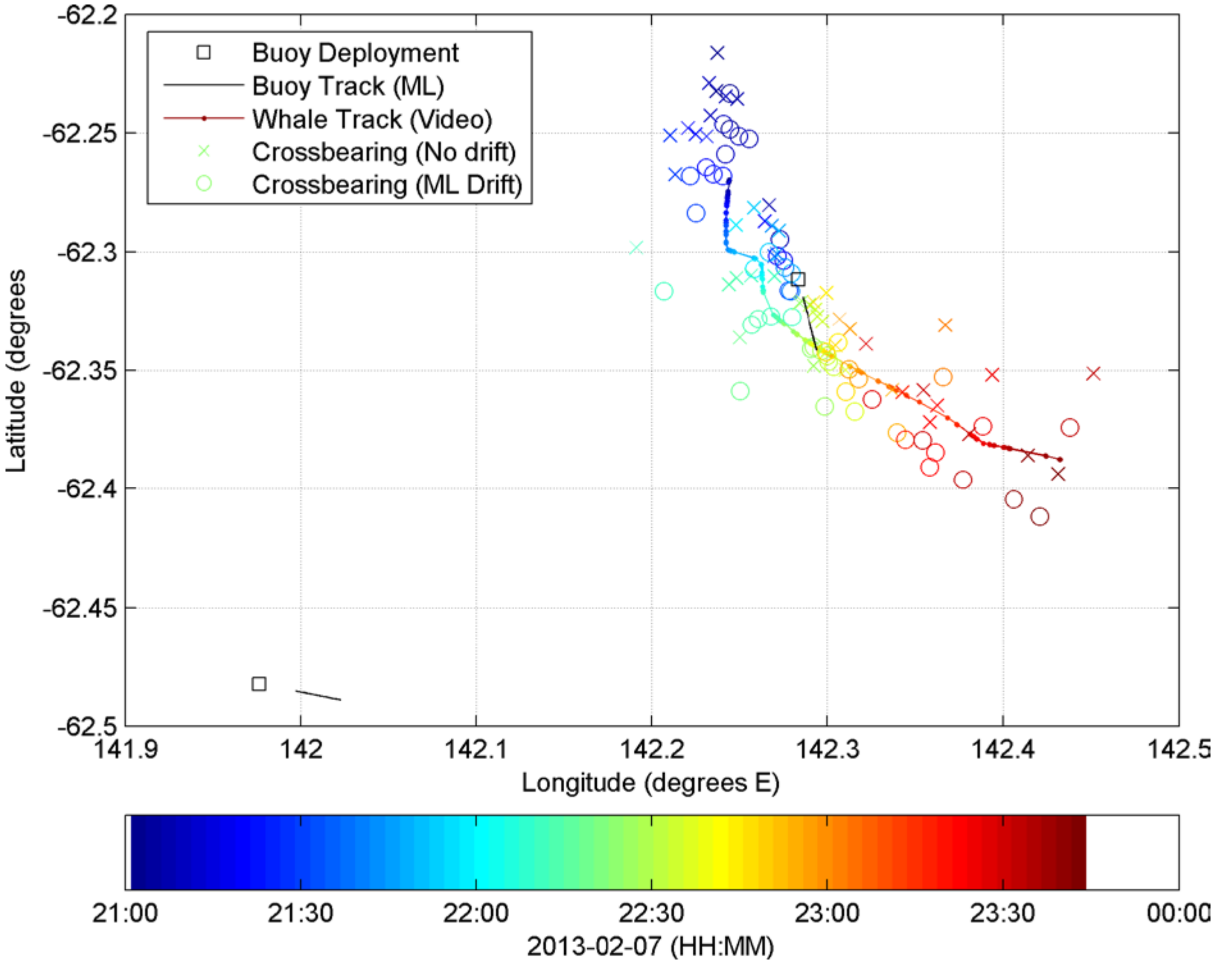

Figure 1 – Schematic showing: video track of Antarctic blue whale movements (coloured dotted line); buoy deployment locations (black squares); maximum likelihood drift of buoys (black line); DIFAR crossbearing locations without accounting for buoy drift (x); and DIFAR crossbearing locations using maximum likelihood drift speed and direction (o). The colour of each marker corresponds to the time of the measurement. Coloured dots along the video track occur at the same time as crossed-bearings and serve as “ground truth” locations.

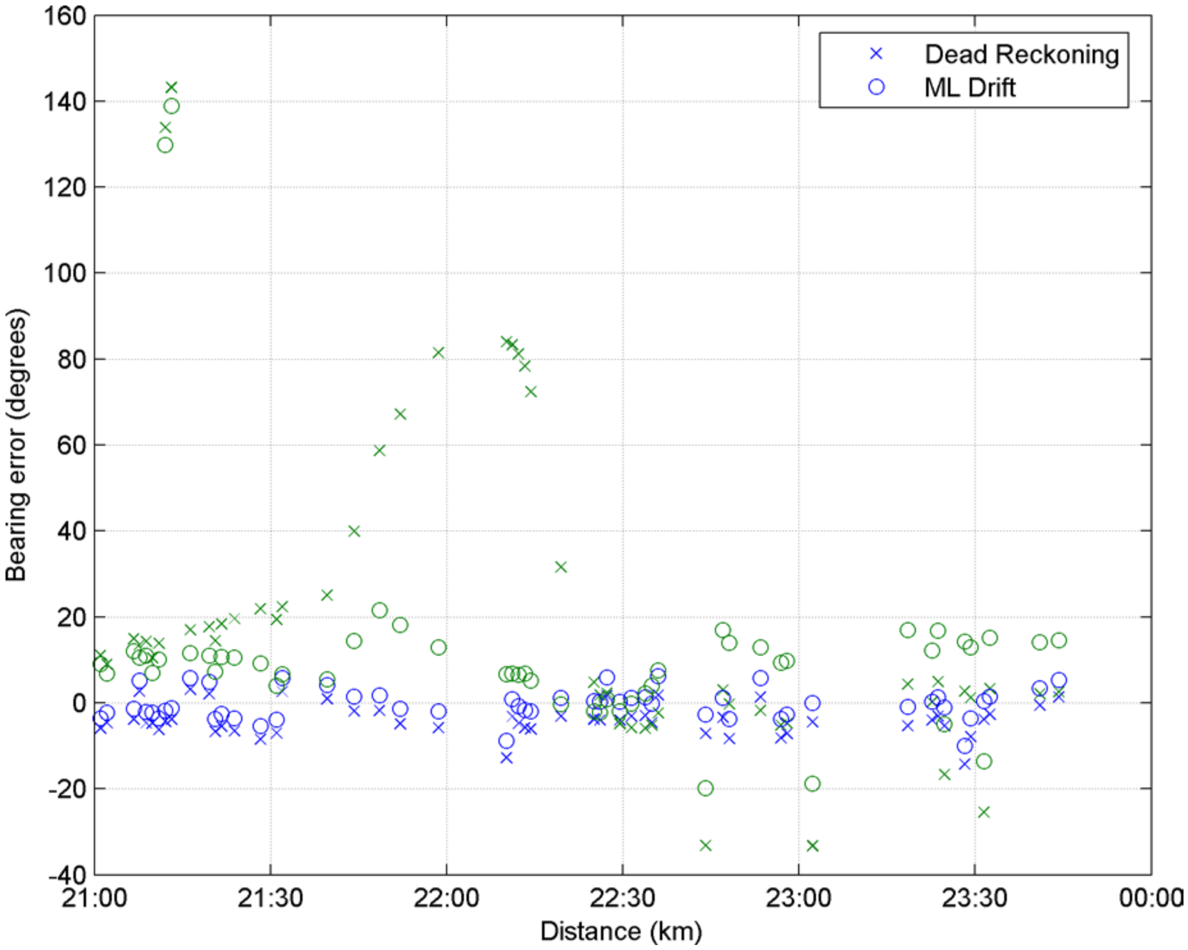

Figure 2 – Bearing error calculated assuming buoys do not drift (x), and assuming constant drift direction and speed according to Eq. 1 (o). Sonobuoy 55 was near the whale (green symbols), while sonobuoy 54 was far away from the whale (blue symbols).

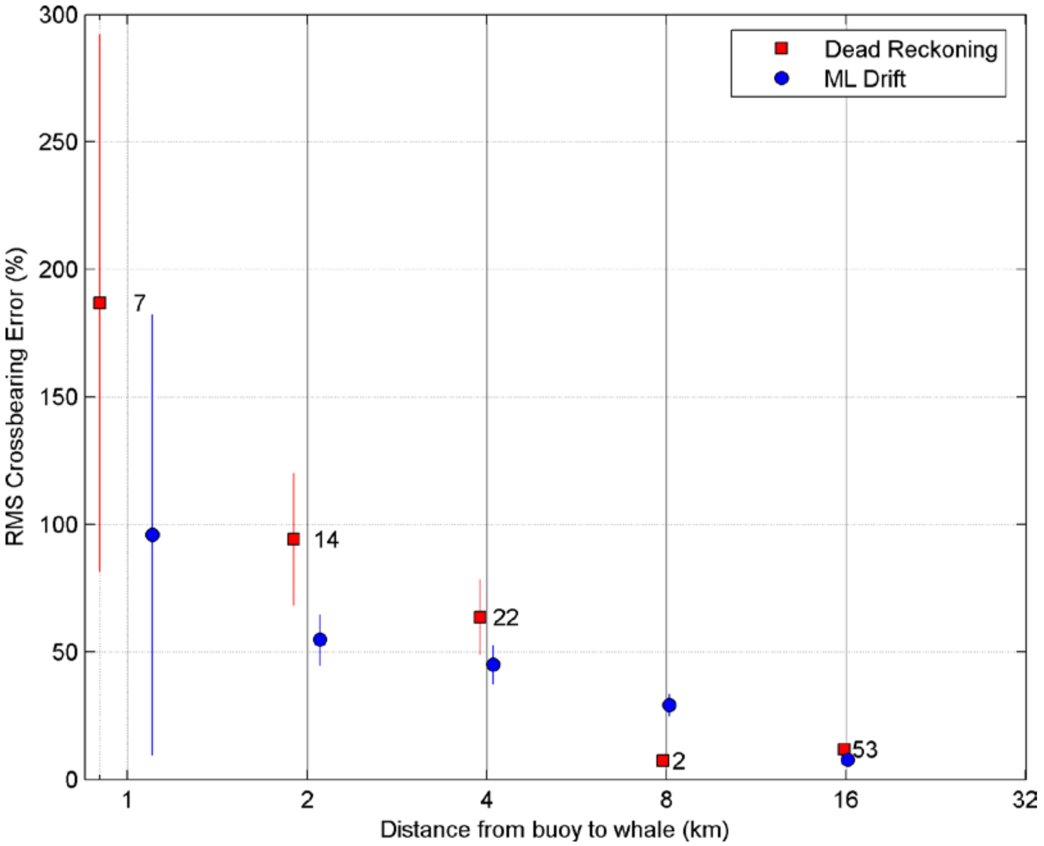

Figure 3 – RMS error in distances between each acoustic and photogrammetric location computed as per Equation 2 in the text. RMS errors are plotted as a function of photogrammetric distances and have been grouped into logarithmically spaced bins. Each acoustic location yielded an RMS error for each sonobuoy. Symbols show the mean and standard deviation for each bin. Blue circles show the errors assuming that sonobuoys drifted at a constant speed and direction as per Equation 1. Red squares show RMS errors assuming that that sonobuoys did not drift from their deployment location. Assuming a constant drift speed and direction yielded higher accuracy and precision than assuming no drift. Increased accuracy and precision was particularly noticeable at short to moderate distances (ie. between 1 and 4 km).

DISCUSSION

Error and drift

Bearing error was reduced by taking into account sonobuoy drift (Figure 2). Reduction in error appeared most significant when the whale was very close to the sonobuoy (ie. sonobuoy 55 @22:00). Improvement was less noticeable at long range (ie. sonobuoy 54). The most likely explanation of these observations is that small errors in position yield large changes in bearing at close range. However, it must be noted that bearings to the ship could only be obtained over a very narrow range of angles, so drift for sonobuoy 54 could not be computed from these measurements. Instead, drift of sonobuoy 54 was estimated using bearings to the whale, rather than the ship. This could represent an additional source of error.

The mean bearing error for sonobuoy 55 was not 0, indicating some sort of bias in bearings. The assumption of constant speed and direction of buoy drift is unlikely to hold over long time periods, and this could potentially explain this bias. Additional factors that could contribute to this bias include incorrect ‘calibration’ of the sonobuoy compass, a “gain imbalance” as described by Greene et al., (2004), or changing magnetic anomaly due to proximity to the magnetic south pole. Further analytical efforts are required to account for this bias.

Unsurprisingly, the reduction in bearing error also yielded a reduction in crossbearing error (Figure 3). However the reduction in error occurred only for sonobuoy #55, which was between 1 and 10 km from the whale. Sonobuoy #54, which was 20-30 km from the whale showed no improvement in crossbearing error.

Improvement in the precision of crossed-bearings due to buoy drift will depend not only on the speed and direction of drift relative to the whale, but also on the geometry (in particular distance) of the source and receivers.

McDonald et al., (2001) discarded calls at “close range,” and our results support this as a reasonable approach. However from our dataset we are able to quantify “close range” as less than 4 km. By considering sonobuoy drift when computing cross-bearings we were able to reduce the error in both bearing and crossbearing, especially at “close range.”

Future work

During the 2013 Antarctic Blue Whale Voyage there were 48 instances where pairs of DIFAR sonobuoys were used to obtain series of crossed-bearings to individual whales. Future work on this data set could apply the above methods both to determine sonobuoy drift, and to assess the accuracy of crossed-bearings for these 48 scenarios. A similar analysis could also potentially be conducted on data from sonobuoys that were deployed during the SOWER surveys.

For future data collection, an additional use of these methods would be to determine the ‘optimal’ distances to deploy a sonobuoy both from the whale and from other buoys in order to ensure robust estimates of location and thus source levels. Such knowledge would be useful for determining whether or not to deploy an additional sonobuoy, especially when the availability of sonobuoys is limited.

Finally, it is worth mentioning that the methods listed here are by no means optimal. Improvements to these methods include combining maximum likelihood location of crossed-bearings with maximum likelihood estimates of time of arrival differences (TOAD) for even better precision (Nosal and Frazer, 2007). Furthermore these combined crossbearing, TOAD estimates could further be combined with information on surfacing locations from video tracks or visual sightings. Ultimately, all of these data could also be incorporated into a dynamic model of whale movement such as a kalman or particle filter. Such a filter would not only yield highly accurate locations of the whale, but also improved estimates of the location of drifted buoys, which would in-turn yield improved estimates of acoustic propagation and source-levels.

In addition, for any study using DIFAR sonobuoys it is worth trying to maximise opportunities to measure bearings to a known source such as the research vessel in order to estimate sonobuoy drift. Robust estimates of drift are more likely to be generated when the acoustic bearings to the vessel span a wide range of angles (Nardone and Aidala, 1980). Determination of an appropriate course could be greatly facilitated by in-situ measurement of acoustic bearings to the research vessel in real-time (Miller et al., 2014b).

In addition to acoustic bearings, radio direction finders (White and Garrott, 1990) could also be used in place of acoustic bearings for the measurement of θ in Equation 1. Using the radio signal from the sonobuoy rather than the acoustic signal from the vessel potentially provides a number of advantages such as use of the ships gyro-compass, rather than the magnetic compass of the sonobuoy. Additionally, radio direction finding does not require the acoustic noise from the ship which in addition to lower ambient noise and improved detection ability, also allows for the estimation of sonobuoy drift from acoustically quieted ships, sailing boats, and aircraft.

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