Estimating drift of directional sonobuoys from acoustic bearings

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Abstract: A maximum likelihood method is presented for estimating drift direction and speed of a directional sonobuoy given the deployment location and a time series of acoustic bearings to a sound source at known position. The viability of this method is demonstrated by applying it to two real-world scenarios: (1) during a calibration trial where buoys were independently tracked via satellite, and (2) by applying the technique to sonobuoy recordings of a vocalising Antarctic blue whale that was simultaneously tracked by photogrammetric methods. In both test cases, correcting for sonobuoy drift substantially increased the accuracy of acoustic locations.

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1. Introduction

Sonobuoys have been a valuable tool for acoustic monitoring of a variety of whale species for decades (Laurinolli *et al.*, 2003; Ljungblad *et al.*, 1982; McDonald *et al.*, 2001; McDonald and Moore, 2002; Norris *et al.*, 1999; Richardson *et al.*, 1986; Richardson and Fraker, 1985). Directional frequency analysis and recording (DIFAR) sonobuoys which give bearings to vocalising whales have proven particularly effective for studying species that make very low frequency vocalisations, such as blue, fin, bowhead, and right whales (Gedamke and Robinson, 2010; Greene *et al.*, 2004; McDonald, 2004; Miller *et al.*, 2015; Rone *et al.*, 2012).

Both Greene *et al.* (2004) and McDonald (2004) provide an overview of the operating principles of DIFAR sensors. In brief, a single DIFAR sensor can provide both received acoustic pressure and information about the direction of arrival (i.e., bearing) of a sound. Two-dimensional localization 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 determined by an on-board fluxgate compass, and the nominal precision of a DIFAR bearing is specified to be within $\pm 10^\circ$ (Greene *et al.*, 2004; McDonald, 2004). Thus the accuracy and precision of localization depend on the accuracy and precision of the sonobuoy compass, the local magnetic declination, and knowledge of the location of the sonobuoy. Accurate and precise localizations are especially important when conducting real-time localization to track endangered species whose low numbers make them otherwise difficult to locate (e.g., Peel *et al.*, 2014; Rone *et al.*, 2012; Wade *et al.*, 2006), and also when using acoustic localizations for distance sampling or estimating source levels (Blackwell *et al.*, 2012; Marques *et al.*, 2013; McDonald *et al.*, 2001; Thode *et al.*, 2000).

Greene *et al.* (2004) describe a method for estimating localization 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

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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 acoustically-derived bearings from drifting DIFAR sonobuoys to a blue whale by comparing with locations from a GPS tag. After discarding bearings from "short range calls" McDonald (2004) found the standard deviation of bearing angles to be approximately 2°.

Precise knowledge of the location of drifting sonobuoys is not always available over the whole duration of a recording. Sonobuoys are designed to drift freely with wind and ocean currents, and often only the location of deployment is accurately known. While newer models of sonobuoys have GPS capabilities to transmit their location, to date these have not typically been available in substantial quantities for use by civilian scientists. While sonobuoys deployed in close proximity are designed to have similar drift to each other (i.e., low differential drift rates), this is only relevant if (1) sonobuoys are deployed at the same time and in the same water mass, and (2) the relative, rather than absolute, location of the sound source is sufficient. Neither of these conditions is guaranteed when deploying sonobuoys from scientific vessels for bioacoustics research (e.g., to acoustically localize baleen whales).

However, the location of a drifting sonobuoy may be estimated 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; the noise from another vessel with such locations received through the Automatic Identification System, or it could be vocalisations from a whale with locations determined from visual methods (e.g., measured range and bearing).

Here we develop a maximum likelihood (ML) method for estimating sonobuoy drift. We then test the method by comparing the estimated drift of sonobuoys with that measured from the attached satellite trackers. We then apply the method to a real-world dataset to compare localizations from drifting sonobuoys with photogrammetrically-derived locations of an Antarctic blue whale obtained during a research voyage in 2013.

2. Methods

2.1 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 $\theta_1,\theta_2,\ldots,\theta_n$ to the sound source, and the precision of these measurements is measured to have standard deviation $\sigma = 7°$ (Miller *et al.*, 2014a). The location of the calibration sound source $z = z_0,z_1,\ldots,z_n$ 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 calibration source at time t_k for $k \geq 0$. We then assume the errors in bearing, $\Delta_k = \theta_k - \Theta_k$, are normally distributed with mean zero when wrapped into $[-180°, 180°)$.

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

$$\mathrm{p}(\varphi, \mathrm{r}|\theta_1, \ldots, \theta_n) = \prod_{k=1}^{n} \frac{1}{\sqrt{2\pi}\sigma} e^{-\left({\Delta_k}^2/2\sigma^2\right)}. \quad (1)$$

Estimates of φ and r were then determined by numerically maximizing the likelihood using the function *fminsearch* from MATLAB version 2014a. All spherical geometry calculations (e.g., great circle paths and bearings) were computed using the M_Map software package (Pawlowicz, 2014). To provide a measure of the uncertainty in drift speed and direction, standard errors (SEs) were calculated from the inverse Hessian of the negative log-likelihood at the estimate (Pawitan, 2001).

2.2 Sonobuoy calibration trial

We applied the methods above to maximize the negative log-likelihood of Eq. (1) using data collected during a sonobuoy calibration trial conducted off San Diego, CA. The calibration trials were designed to test the effect of the detection angle on the precision and accuracy of the bearing angles (for single sonobuoys) and on the precision and accuracy of triangulations (for pairs of sonobuoys). However, here we restrict our analysis solely to the estimation of drift.

Four 53 F DIFAR sonobuoys were deployed in a square, with approximately 1 nmi (2 km) between each sonobuoy. Sonobuoy stations were labeled according to their approximate orientations (NW = northwest, NE = northeast, SW = southwest, and SE = southeast). Initial plans for the calibration trials were for the research vessel to drive a circle around the group of four sonobuoys, stopping at regular angular intervals to playback underwater sound. However, in the event, playback locations did not fully encircle all sonobuoys (Fig. 1).

SPOT Trace GPS tracking devices (SPOT LLC, Covington, LA) were placed in waterproof containers and attached to floats connected to the sonobuoys to independently measure the actual position of drifting sonobuoys during the trial at approximately 5 min time intervals. Acoustic bearings, θ, were measured for each playback, and the GPS position of the ship was used as the location of the calibration source, z. SPOT tracks, assuming constant direction and rate of drift between satellite updates, were then compared with those estimated from the results of Eq. (1).

2.3 Antarctic blue whale acoustic localization

We also tested our drift estimation method with a real-world bioacoustics dataset containing data recorded on a DIFAR sonobuoy during an Antarctic whale research voyage in 2013. Detailed data collection methods for the voyage, including a description of the hardware, deployment protocols, and "calibration" of the sonobuoy compass, are described in detail in Miller *et al.* (2014b, 2015, 2016). This dataset was chosen because the research vessel passed within audible range of one of the sonobuoys several hours after deployment. Additionally, the ship was conducting a focal-follow of an Antarctic blue whale with a modern digital version of the video-photogrammetric system described by Leaper and Gordon (2001). Focal follows and video-photogrammetic methods provided updates on whale location that could be used to assess improvements in acoustic localization when using Eq. (1).

Sonobuoy drift was estimated using acoustic bearings to the engine and propeller noise from the ship in the 300–400 Hz band, and locations of the ship were recorded from the ships GPS receiver every second. In contrast with the calibration trial, no independent measures of sonobuoy drift were available during the Antarctic blue whale voyage, so instead we conducted a performance assessment to investigate whether accounting for sonobuoy drift would reduce the error in acoustic bearings to the focal whale. Specifically, we measured the residual error between the acoustically and photogrammetrically derived bearings assuming (1) no drift and (2) drift estimated from our ML method.

Locations of the whale obtained from photogrammetry were assumed to correspond to the true location of the whale when at the surface due to the high accuracy and precision of photogrammetric tracking (Leaper and Gordon, 2001). Acoustic bearings to the whale were obtained only when the whale was underwater and vocalizing, so linear interpolation between successive photogrammetric locations was used to

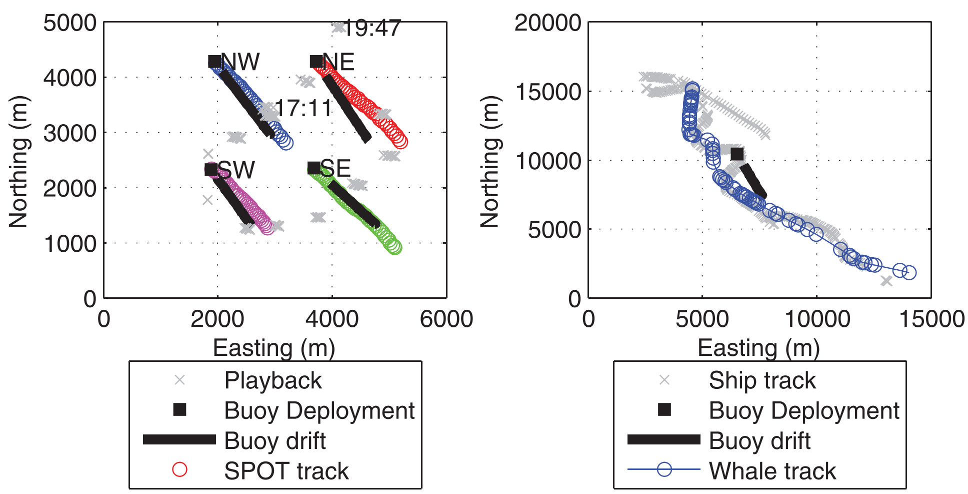

Fig. 1. (Color online) Map of the calibration trial during sound playback experiments (left) and blue whale acoustic localization (right). Open circles show measured GPS locations from SPOT Trackers (left) and vocalisations along whale video tracks (right). Filled squares show the deployment locations of each sonobuoy. Thick lines show the drift of sonobuoys based on parameters estimated using Eq. (1). Gray crosses show the location of sound playbacks (left) and the track of the research vessel (right). Sound playbacks started at 17:11 UTC and continue counter-clockwise until 19:47 UTC.

estimate whale locations at the times when acoustic bearings from the sonobuoy to the whale were available (Fig. 1).

3. Results

3.1 Sonobuoy calibration trial

For the calibration trial, the ML estimated movement of sonobuoys was similar to that measured by the SPOT GPS trackers (Fig. 1). Differences in drift direction and speed were small ranging from 0.3°–8.4° and 0.02–0.14 km/h (Table 1). ML estimates of drift captured the general south-eastern trajectories of all four sonobuoys.

3.2 Antarctic blue whale localization

The sonobuoy in the Antarctic dataset was estimated to drift along a course of 160.3° at a speed of 1.01 km/h from our ML-estimation method (Fig. 1). Residual bearing errors to whale locations were calculated via linear interpolation between photogrammetric locations assuming ML drift and no drift. Residuals were generally much lower in the model that corrected for sonobuoy drift (mean −4.5° standard deviation = 13.7°) than in the model that did not (mean 10.7° standard deviation 26.3°) (Fig. 2). Like the sonobuoy, the focal whale (and following ship) also moved in a south-eastern direction, passing close to the sonobuoy around 22:15 UTC. Residual errors of acoustic bearings to the whale reach a maximum this time in both models, as do sound pressure levels of whale vocalizations and ship noise (not shown).

4. Discussion

When using drifting DIFAR sonobuoys without integrated GPS or other methods of locating buoys post-deployment, one can measure bearings to a known source throughout the duration of each recording in order to estimate sonobuoy drift. We were able to use our method to estimate drift direction and speed of a DIFAR sonobuoy with reasonable fidelity using data from our calibration trial despite the fact that drift estimation was not the intended purpose of the trial. In our second scenario, we successfully applied the technique to estimate the drift of a sonobuoy during a recording of an Antarctic blue whale, again without any intent or field protocols to estimate drift at the time the data were collected.

The track of the known source (e.g., playback or ship) is likely to be an important factor when using our method to estimate drift. Nardone and Aidala (1980) formally describe ship manoeuvres required to measure a target's position and motion via bearing-only target motion analysis (TMA). Those manoeuvres and mathematics are likely relevant here too, since our application has several aspects in common with TMA. Our datasets contained a wide range of angles and distances to the playback source, and these were spread out relatively uniformly in time. Thus, we unknowingly executed a suitable manoeuvre during both of our examples. However, too narrow a range of bearings to the known sound source would likely render the drift motion unobservable, similar to attempting to triangulate with close to co-linear bearings.

Improved knowledge of the position of a sonobuoy consequently improved the accuracy and precision of acoustic localizations of the focal whale. A benefit of this improvement was the ability to unequivocally determine which vocalisations in the recording were from the target whale and which were from other animals in the area. Improved localization arising from improved knowledge of the sonobuoy location is especially important at close ranges where small errors in position yield large changes in bearing. When localising blue whales off California, McDonald *et al.* (2001) discarded calls at close range. However, by estimating sonobuoy drift we were able to reduce errors and potentially allow the inclusion of close-range calls for tracking whales. Improved close-range tracking is especially relevant when using acoustic

Table 1. Drift speed (km/h) and direction (degrees relative to true North) of sonobuoys measured by SPOT trackers and estimated by the ML method during the calibration trial. SEs are included in parentheses following ML estimates.

Sonobuoy	Number of playbacks	ML speed (SE)	SPOT speed	ML direction (SE)	SPOT direction
NE	311	0.652 (0.012)	0.634	139.4 (0.70)	134.5
NW	324	0.545 (0.003)	0.635	141.6 (0.45)	139.3
SE	276	0.435 (0.003)	0.570	134.5 (0.88)	134.8
SW	338	0.438 (0.011)	0.511	145.7 (0.67)	137.3

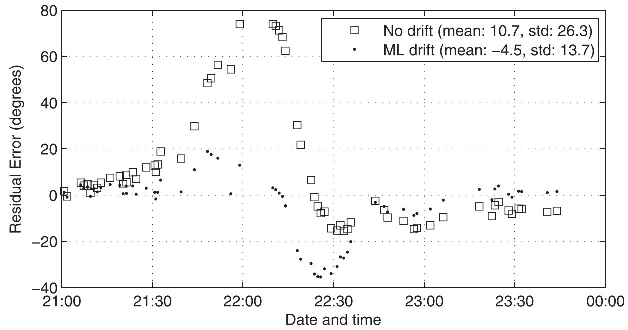

Fig. 2. Residual error in bearings from the sonobuoy to the focal whale assuming (1) no drift (squares) and (2) ML drift estimated using Eq. (1) (dots).

localizations for distance sampling, estimating source levels, or investigating sound propagation.

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