LOCALIZING BOWHEAD WHALES IN THE CHUKCHI SEA USING ASYNCHRONOUS HYDROPHONES

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1 Introduction

Marine mammal localization is required for assessing behavioural effects from underwater anthropogenic noise. Passive acoustic monitoring using widely-distributed autonomous recorders is often used for detecting marine mammals over large areas ; however, localization is more difficult because non-linear recorder clock drift desynchronizes underwater recorders and precludes correlation-based localization methods that use time difference of arrival (TDOA) data. In this paper, we localize bowhead whales using Bayesian inversion of calls detected on asynchronous hydrophones in the Chukchi Sea north of Alaska. The shallow water environment acts as a dispersive waveguide and supports a limited number of propagating modes. The mode arrival times depend on the whale location, water sound-speed profile (SSP), seabed geoacoustic properties, and relative recorder clock drift, all of which are treated as unknown parameters estimated in the inversion. The Bayesian formulation also provides rigorous uncertainty estimates for the model parameters.

2 Methods

2.1 Data Processing

Bowhead whales make low-frequency calls that propagate tens of kilometres as normal modes in the shallow waters of the Chukchi Sea. The modes propagate with different group speeds (i.e., they disperse) but it can be difficult to distinguish mode arrivals in a spectrogram if, for example, the whale-hydrophone range is small or the instantaneous frequency (IF) of the call is slowly-varying with time. Recently, Bonnel *et al.* [1] developed a method to apply mode-warping to frequency-modulated (FM) bowhead calls for filtering modes from each other. We use the same approach here to filter the modes and define arrival times as the time of maximum amplitude for each frequency and mode using a spectrogram of the mode-filtered signal.

2.2 Bayesian Inversion

The frequency-dependent mode arrival times depend on the whale location, source IF, environment, and relative recorder clock drifts as given by

$$t_{wam}(f) = \frac{\sqrt{(x_w - x_a)^2 + (y_w - y_a)^2}}{v_m(f)} + \tau_w(f) + \Delta_a, \quad (1)$$

where x_w and y_w are the easting and northing coordinates of whale w, x_a and y_a are the coordinates of recorder a (considered known in this paper), $v_m(f)$ is the group speed for mode m, $\tau_w(f)$ is the source IF, and Δ_a is the recorder clock drift relative to a reference recorder. We use a trans-dimensional (trans-D) Bayesian formulation for the unknown range-independent environmental properties [2] which determine the mode group speeds. The environmental model for the water column has unknown depth and SSP that is defined by an unknown number of depth/sound-speed nodes. The seabed model consists of an unknown number of homogeneous layers overlying a halfspace. The seabed properties (layer thickness, sound speed, and density) are considered unknown. The normal-mode code ORCA [3] is used to calculate the mode group speeds for a given environment and are converted to predicted modal arrival times using the whale location, source IF, and relative recorder clock drift [Eq. (1)], all of which are unknown parameters in the inversion. In a Bayesian formulation the solution consists of properties of the posterior probability density (PPD) of the model parameters given the measured data and prior information. The PPD is approximated numerically for non-linear problems using a reversible-jump Markov-chain Monte Carlo [4] algorithm where model transitions are accepted with a probability that depends on the prior, proposal, and likelihood ratios. See Warner *et al.* [2] for details on the implementation of this algorithm in a related inverse problem that uses the same trans-D environmental model.

2.3 Likelihood

In this paper, we assume residual errors between measured and predicted data are uncorrelated and Gaussian-distributed for each whale call (with standard deviation σ_w). If $\mathbf{d}_{wam}$ is a vector of modal arrival times at N_{wam} frequencies, the likelihood function is the product

$$L(\mathbf{m}) = \prod_{w=1}^{W} \prod_{a=1}^{A} \prod_{m=1}^{M_{wa}} \frac{1}{(2\pi\sigma_w^2)^{N_{wam}/2}} \times \exp\left[-\frac{|\mathbf{d}_{wam} - \mathbf{d}_{wam}(\mathbf{m})|^2}{2\sigma_w^2} \right], \quad (2)$$

where W is the total number of whale calls, A is the total number of recorders that detected a call, and M_{wa} is the number of modes for call w on recorder a. A maximum-likelihood estimate for the inter-recorder clock drift Δ_a can be derived by substituting Eq. (1) into this equation and setting $\partial L / \partial \Delta_a = 0$, giving :

$$\hat{\Delta}_a(\mathbf{m}) = \left[\sum_{w}^{W} \sum_{m}^{M_{wa}} N_{wam}/\sigma_w^2 \right]^{-1} \times \sum_{w}^{W} \sum_{m}^{M_{wa}} \sum_{f}^{N_{wam}} \left[d_{wam}(f) - \tau_w(f) - \frac{|\mathbf{r}_{wa}|}{v_m(f)} \right] / \sigma_w^2, \quad (3)$$

where $\mathbf{r}_{wa}$ is $(x_a - x_w, y_a - y_w)$. Equation (3) provides an estimation of unknown Δ_a without having to explicitly sample

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this parameter. This formulation assumes the clock drifts do not change significantly in the time interval between the inverted whale calls (3.25 mins).

3 Bowhead Whale Call Data

JASCO Applied Sciences recorded thousands of bowhead whale calls in the Chukchi Sea on several Autonomous Multichannel Acoustic Recorders (AMARs) during Aug.–Oct. 2013 [5]. In this paper, we invert mode arrival times for nine whale calls recorded on up to seven AMARs (herein named A–G) over a 3.25 min period on 11 Oct. Figure 1 shows spectrograms of whale call 1 on three selected AMARs with the mode arrival time picks ; the relative modal time separation indicates the whale was closest to AMAR D since that recording showed the least dispersion.

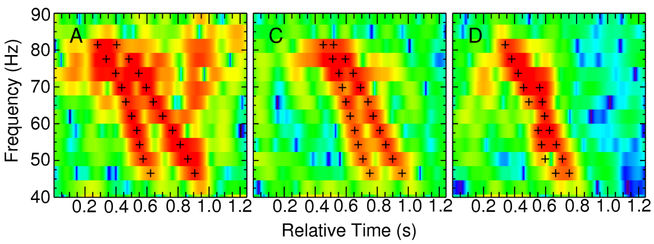

Figure 1 : Example spectrograms of whale call 1 recorded on AMARs A, C, and D. Data picks are shown with + symbols.

4 Inversion Results

Nine whale calls were inverted independently (scenarios S1–S9) and then jointly for one multi-call inversion (S10). Figure 2 shows the two-dimensional marginal probability distributions for whale locations for S1–S3, S9, and S10 (results for S4–S8 are similar to those of S3 and are omitted here for brevity), with the recorders that detected calls shown with × symbols. Scenario 10 clearly shows the localization improvements from joint inversion of multiple whale calls. Whale locations in S10 are estimated to accuracies of 30–160 m.

The clock drift uncertainty estimates varied between 8 and 728 ms for the single-call inversions. Uncertainties were correlated with distance from the reference recorder and strongly reflected localization uncertainty. The corresponding drift uncertainty estimates for the multi-call scenario varied between 3 and 26 ms (a reduction of up to 96% compared to the single-call scenarios).

5 Discussion and Conclusions

Each recorded call provides a whale range estimate through the amount of modal dispersion, and having more estimates from a distributed cluster of recorders better constrains the location of the whale, which in turn improves estimated clock drifts. Localization and clock drift results significantly improved when jointly inverting multiple calls. Multi-call inversions require all data to be fit simultaneously, which effectively requires an averaging of the clock drifts. The benefit is greatest when the whales are spread out among the hydrophone cluster. The Bayesian inversion was applied to bowhead whale call modal dispersion data recorded on asynchronous hydrophones and accounted for unknown whale location, source IF, water SSP, subbottom geoacoustic properties, and relative recorder clock drifts. The synchronization provided by the inversion may allow other localization methods to be applied to other types of marine mammal calls.

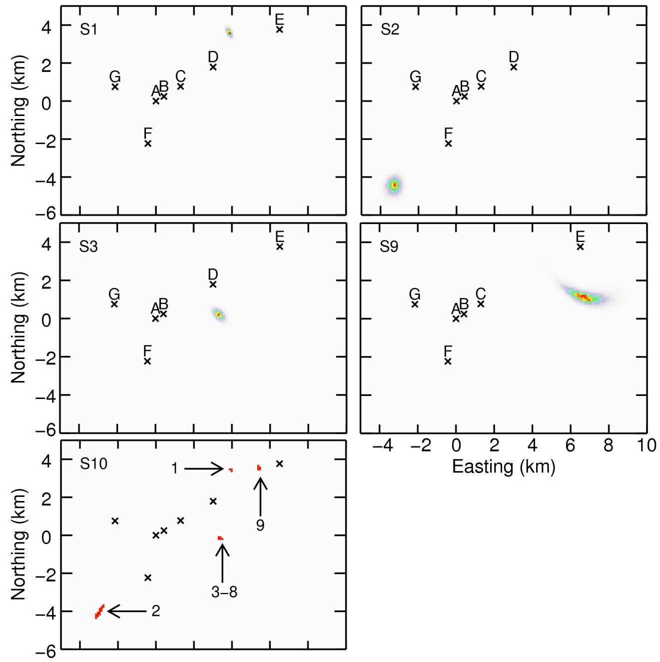

Figure 2 : Marginal probability densities for bowhead whale location(s) for selected scenarios. Probability distributions for S10 are quite compact and are shown as a binary image for clarity.

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References

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