RELIABLE ACOUSTIC PATH TOMOGRAPHY AT THE ALOHA CABLED OBSERVATORY

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Abstract: *Using a mobile ship platform (R/V Kilo Moana) with an acoustic source transmitting to a fixed bottom hydrophone at the ALOHA Cabled Observatory, we are investigating the feasibility of "RAP tomography" (Reliable Acoustic Path). This will allow the spatial mapping of a path integrated sound speed (temperature) over a 60-km diameter "teacup" volume of the ocean. We see this as a pilot project that may lead to more sophisticated acoustic measurements and configurations, e.g., spatially distributed arrays of vector sensors to provide improved performance for tomography, as well as for other purposes and replacing the ship with multiple autonomous surface vehicles such as wave gliders. Here we report on work in progress, including measurements and simulations.*

Keywords: *Reliable Acoustic Path, Ocean Tomography*

1. INTRODUCTION

Measuring oceanic properties and dynamics continues to be an area of active research interest, with many challenges. In the past, most data were collected on-site (in-situ) often requiring the use of a ship and hands-on work of skilled technicians and scientists. Technology has been helping to automate the collection of data. Here, reliable acoustic path (RAP) tomography involves transmitting from a surface craft to a cabled, bottom hydrophone to determine sound speed. Similar experiments have been conducted using different instrumentation for sources and receivers [1] [2]. While initially we are using a manned ship for the surface craft, we see autonomous surface vehicles (ASVs) being used in the future.

For these experiments an acoustic transmission can be received in a direct path (RAP, Fig. 1). Within the RAP volume with surface diameter equal to a complete surface limited ray loop (~60 km, 1 convergence zone CZ) and centered on the ACO hydrophones, rays can propagate without surface or bottom bounces (thus "reliable"). With the associated travel times we can then build up a 2-D map of path/depth integrated sound speed (temperature) as a function of ship (or ASV) position as it moves around on the surface within a radius of ½ CZ. This can be considered an extension of an inverted echosounder (from a vertical to near horizontal path) combined with the precise positioning and timing of seafloor geodesy, where their noise (sound speed variation) is our signal [3].

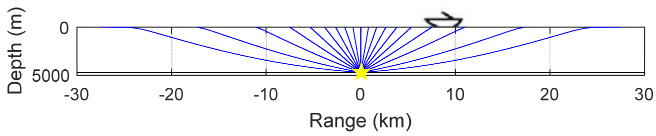

Fig. 1: Reliable acoustic paths for ranges extending outwards to ~30 km. Each path corresponds to a different initial launch angle.

Our field site is Station ALOHA 100 km north of Oahu with water depth 4728 m. Since 1988 on a quasi-monthly schedule, the Hawaii Ocean Time-series (HOT) project has been collecting ship and mooring based oceanographic data. The ALOHA Cabled Observatory (ACO) installed in 2011 supports this and other innovative scientific research at Station ALOHA. These data, together with those from associated process studies, form a unique, multivariate long-term data set of the ocean – and acoustic – state centered at one location. See http://aloha.manoa.hawaii.edu and http://aco-ssds.soest.hawaii.edu [4] [5].

An estimate of the expected travel time signals can be obtained from inverted echosounder (IES) results given by Chiswell, 1994 [5]. In terms of travel time, Chiswell found a peak-to-peak round-trip value of 5 ms or approximately 1 ms rms one way. This is consistent with either a 0.5 m/s depth-averaged sound speed perturbation, or, more realistically, a 5 m/s (1 °C) change in the main thermocline/upper 500 m. Further, Chiswell presented time series data from several geographically distributed IESs (over about 1 CZ) indicating eddy propagation. These are small signals; ideally, we want to resolve a tenth of this. Synchronizing at both ends to GPS time and correcting for ship position/motion is essential, along with a substantial amount of $\sqrt{N}$ averaging to obtain errors < 0.1 ms (0.15 m). Tides are both signal and noise for this application; the associated 0.8 m p-p surface elevation variation can be used for validation.

We report on data collected on two cruises of the *R/V Kilo Moana* around the ALOHA Cabled Observatory (ACO). The first, 22–26 January 2017, was a cruise of opportunity with the HOTS project. The second was 7–12 June 2017.

2. EXPERIMENTAL SETUP

On the first cruise, transmissions were made using two configurations of the on-board 3.5 kHz Knudsen echosounder: either as a single transducer (Massa TR-1075A) or with the full array of 16 elements. On the second cruise, only the single element was used. In the first configuration, an adjacent array element is used as a receiving reference hydrophone. A GPS pulse per second is recorded as a time reference along with the voltage and current to the transducer and the reference hydrophone signal. The bottom hydrophone at ACO samples at a rate of 96 kHz and a subsampled 24 kHz file is used in processing. It too is synchronized to GPS time via the cable system at the 1 μs level.

The *R/V Kilo Moana's* coordinates are given by Applanix's Position and Orientation System for Marine Vessels (POS MV). It uses an inertial measurement unit combined with positioning data provided by the Global Navigation Satellite System. Services of FUGRO Marinestar™ (G2) correction service is used. The estimated position uncertainties for the two cruises were about 15 cm and 5 cm, respectively.

3. EXPERIMENTAL RESULTS

Two separate waveforms were tested: a linear frequency modulated (LFM) sweep and a maximal length sequence (m-sequence). They were generated with identical parameters: center frequency of 4134.375 Hz, bandwidth 1378.125 Hz, and 22.5 ms duration. They were transmitted at 30 s intervals to prevent any overlap/interference between the direct arrival and other bottom-surface arrivals. For the second cruise, the LFM signal was used as there appeared to be slightly less clutter in the replica correlation. Also on the second cruise, 2-minute m-sequences of 23.777 s period were sent, these will be analysed to determine coherent processing times and the effect of changing Doppler thereon.

Using data collected on the first cruise, the left plot in Fig. 2 shows the travel time perturbations (actual vs. estimated travel times) for each recorded transmission and the right plot shows the corresponding vessel position. Estimated travel times are calculated using ray tracing (including earth curvature correction) [6] given by the equations in *Sounds in the Sea* [7]. The ray tracing is computed with an a priori sound speed profile derived from a CTD cast taken at 2 m intervals during the cruise.

It is evident the travel time perturbations varied mostly between ±10 ms which correspond to a ±3 m/s depth averaged sound speed difference when compared to the a priori sound speed profile. The travel time differences have structure according to vessel location, but do not have any dependence on the ships heading. Note for these measurements, the GPS error was approximately 0.15 m rms, still not a contributing source of uncertainty on this scale. Of course, hydrophone position uncertainty (estimated to be 10 m) is still a contributing factor.

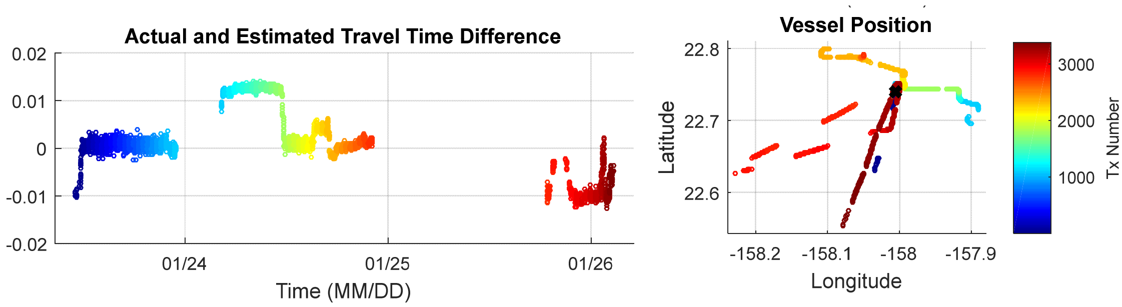

Fig. 2: (Left) Plot of actual vs. estimated travel times perturbations (ms). (Right) Plot of the vessel's position during the cruise, where the black X denotes the estimated hydrophone position. Color scale represents the transmission number for both plots.

4. SOUND SPEED MODEL AND INVERSION

The following model and inversion process uses stochastic inverse theory [8] to compute the sound speed perturbation relative to an a priori sound speed field. The field is discretized as two-dimensional pixels in latitude/longitude. It has one vertical mode, the first mode empirical orthogonal function (EOF) that describes the sound speed profile perturbations at ACO, with rms sound speed uncertainty 3.8 m/s at the peak of the mode (~250 m). There is a Gaussian covariance between each location in the field with a length scale of 20 km. This was chosen as a conservative estimate and to allow for more spatial variability, in contrast to typical length scales of ocean phenomena are on the order of 100 km. In addition, an uncertainty for the hydrophone position is included and a new estimated position is calculated.

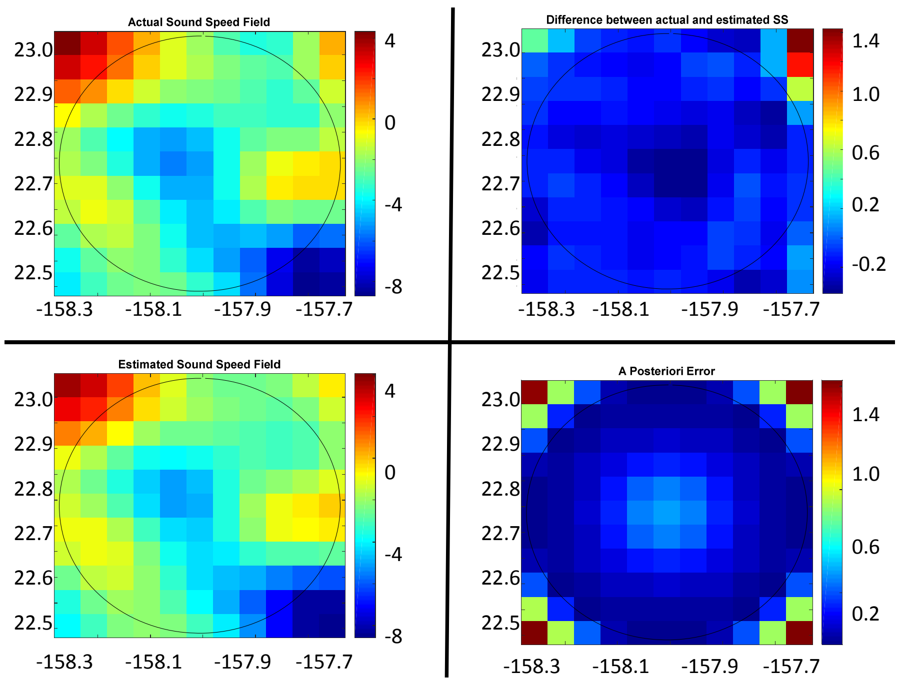

Fig. 3: (Top left) Simulated sound speed field. (Bottom left) Estimated sound speed field. (Top right) Actual vs. estimated sound speed field. (Bottom right) A posterior error.

Fig. 3 shows a sample simulated sound speed field, where the colors represent the perturbations from the a priori field at 250 m (peak of first mode EOF) and the circle encloses all locations with transmissions (data) present. The estimated sound speed field (from the stochastic inverse) and the difference between these two are also given. Lastly, the rms a posterior errors are plotted for each location. It is clear the inversion reproduces the actual sound speed field best where there is data present and errors increase the further away from the data. There is a somewhat larger error in the center as compared to the outer regions, due to the uncertainty in the hydrophone position having a larger effect when in closer pixels.

This model formalism can be used to estimate the expected travel time variation (Fig. 4). In the absence of receiver position uncertainty, the expected travel time perturbation grows with range from about 1 ms to 2.5 ms rms. With the position uncertainty included, the expected travel time perturbation is larger near the center (because the z value is poorly constrained, being observed from just one side) and decreases with range. Much of the data fall outside the expected range of values. When inversions are done, the results are not plausible, with normalized residuals of 5 std dev, and a-physical sound speeds (not shown). The reasons for this are under investigation. The model will need to be revisited as it only includes the first mode EOF and higher modes may need to be included to model the volume more accurately. Also, time dependence may need to be included especially when dealing with datasets occurring over longer periods of time.

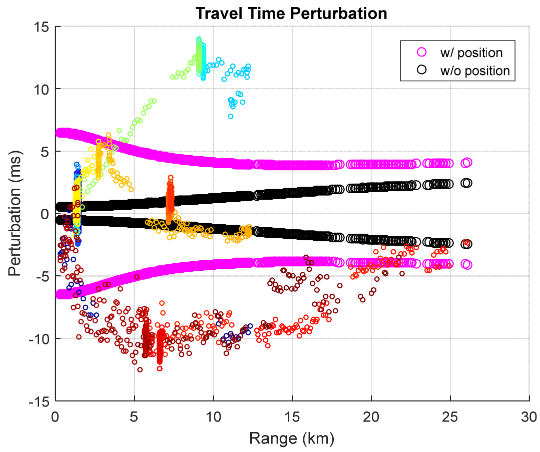

Fig. 4:Travel time perturbations with respect to range between the source and receiver (color indicates time as above). The black dots represent the expected rms travel time in the absence of hydrophone position uncertainty, while the magenta dots include this uncertainty for rms travel time.

5. RECENT MEASUREMENTS

We shift now to briefly describing the new data collected 7–12 June 2017. The ship track during the cruise is shown in Fig. 5. Circles were run twice (5, 15, 25 km radius) and radials were run four or five times. A continuous 36 hours was spent directly over the ACO hydrophone. Some 59 XBTs were deployed.

During the entire cruise within the operational area, a LFM chirp was transmitted (per above, with source level 260 W acoustic, 195 dB re 1 μPa at 1 m). During daylight hours, the 2-minute m-sequence signal was transmitted (3-hour interval minimum, 26 W acoustic, 185 dB re 1 μPa at 1 m). With this very data set we expect to resolve the problems and inconsistencies of the first data set.

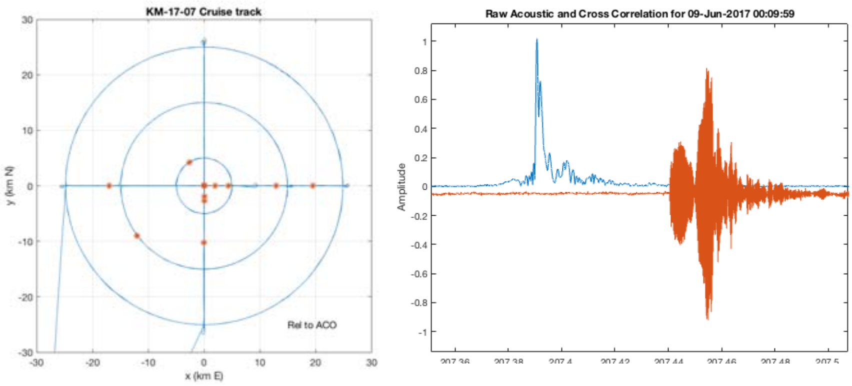

Fig. 5: (Left) Cruise track for full operational area. The multiple tracklines are difficult to see at this scale. Expected position uncertainty is 5 cm rms. Red stars show locations of 2-minute transmissions. (Right) The raw signal (shifted right 50 ms and down) and correlation envelope plotted together. The null in the middle of the raw signal envelope is attributed to the interference of the direct and bottom bounce signals.

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