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Acoustic Seaglider: PhilSea10 Data Analysis

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ABSTRACT

Broadband acoustic source transmissions recorded on Seagliders at ranges up to 700 km are used to estimate subsurface glider position. Estimates of a posteriori errors ranged from 78–105-m rms and from 9.1–11.6-cm/s rms for glider position and velocity, respectively. Data residuals were on the order of 50-m rms. These results demonstrate the potential for (more) precise long range underwater acoustic navigation, with the understanding that the navigation and the ocean sound speed and currents be jointly determined.

LONG-TERM GOALS

Within the Ocean Acoustics Deep Water program, the long-term goals are to understand the physics of long-range, broadband propagation in deep water and the effect of oceanic variability on acoustic propagation.

The project will seek to develop new techniques and technologies to improve the ability to measure and characterize the highly dynamic ocean environment and understand the effect of ocean variability due to mesoscale eddies, tides, currents, and internal waves on the acoustics. An accurate characterization of the ocean improves the predictability of acoustic propagation through it and, in

turn, enables inversions for oceanic properties from acoustic receptions. The long-term goal is to use multiple platforms and techniques, old and new, acoustic and oceanographic, moored and mobile, to sense the ocean environment, and to understand the effect of oceanic fluctuations on deep-water acoustic propagation.

OBJECTIVES

Six transceiver moorings were deployed in a pentagon shape as part of a large-scale tomography array in the northern Philippine Sea with an extensive distributed vertical line receiving array (DVLA) moored within the pentagon. Gliders recording acoustic data as well as measuring temperature and salinity were deployed (Figure 1). General objectives of the experiment are to understand the acoustic propagation in the Philippine Sea, an oceanographically complex and dynamic region, and to use the acoustic receptions to learn about the time-evolving nature of the oceanic environment, and thus, the effect of the latter on the acoustic propagation and coherence.
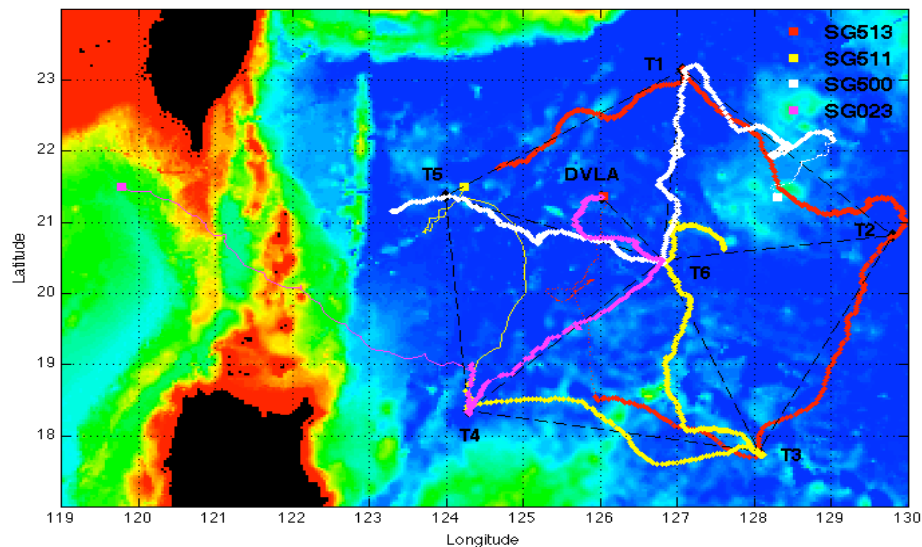

Figure 1. Plan view of the PhilSea10 mooring geometry, with six acoustic transceivers (T1, T2, … T6) and the DVLA. Four acoustic Seagliders (SG) were deployed and followed the indicated paths. Heavy dots indicate surface positions of gliders while collecting data. Light dots for SG500 and SG513 indicate the glider is diving but not collecting data. Light solid lines for SG023 and SG511 indicate surface-drift paths. Squares indicate recovery positions.

Specific objectives of this project are:
1. Deploy, operate, and recover four acoustic seagliders as part of PhilSea10.
2. Estimate the positioning precision and accuracy of the gliders underwater using the received signals from the various distant moored sources to determine whether precision is adequate for tomographic inversions.
3. Utilize acoustic transmissions from fixed acoustic sources to mobile receivers to map the acoustic arrival pattern as a function of range and depth. Observe wavefront scattering at these various positions in conjunction with the complementary full-ocean depth observations obtained on the DVLA.
4. Identify ray arrival peaks from the glider acoustic travel-time data. These ray identifications will be used in the joint navigation and tomographic reconstruction solution.

Within the preceding project, objective 1 was accomplished and the second task begun. Objective 3 is being pursued by LVU in another ONR project. In this particular project, we have accomplished most of objective 2 and the beginnings of objective 4. The joint navigation and tomographic reconstruction solution will have to await further funding and effort.

The results pertaining the work of this grant have been published in two sequential papers; highlights of the second are given here.

TECHNICAL APPROACH

Overview
The seven moorings were deployed in April 2010 and were in-place for one year. Seagliders were deployed November 2010 – April 2011 (two recovered early). Each glider was equipped with an acoustic recording system (ARS) to record the moored source transmissions, as well as temperature, salinity and pressure sensors (from which sound speed is calculated). The ARS data provide the travel times for use in the initial navigation solutions and ultimately the joint navigation-tomographic inversions; the latter will provide a time-evolving characterization of the variable upper ocean between the transceivers. Objective mapping and (simple) Kalman filtering techniques will be explored to utilize the unique time-space sound speed sampling of the Seagliders to generate snapshots of the time-evolving oceanic environment.

This estimation of the oceanic environment will form the basis of acoustic propagation calculations for comparison with received acoustic data. A solid understanding of the acoustic propagation will enable inversions for the structure of the ocean volume encompassed by the transceivers, i.e., acoustic tomography. The acoustic Seagliders will supplement the moored sensors, serving as additional nodes in the tomographic array, and thereby multiplying the number of cross-sectional acoustic paths in the study area (Cornuelle, 1985; Gaillard, 1985; Cornuelle et al., 1989; AMODE-MST Group, 1994; Duda et al., 1995).

WORK COMPLETED

The gliders were operated successfully in PhilSea10, although two were recovered prematurely. Glider temperature and salinity profiles have been processed, outliers removed, and the data set made publically available.

The acoustic data clearly show tomography source signals with high SNR. Data have been processed to obtain arrival patterns. Measured arrival peaks have been unambiguously identifed with predicted ray arrivals. Travel time offsets between the measured and predicted arrivals have been obtained for the entire data set; the latter offset has been attributed to glider position errors and interpreted as a measure of the range uncertainty. The full ray-identification process has not been apprioled to the data set.

Estimates of range uncertainty for signals from sources T1-T5 have been combined using the method of least squares to estimate glider position uncertainty.

Initial results from just-after-recovery were presented at the Kona Oceans11 meeting (Howe et al., 2011) and at the Underwater Acoustics Measurements conference in June 2011. Continuing analysis results have been presented at the subsequent Acoustical Society of America (ASA), International Congress on Acoustics, 1st International Conference and Exhibition on Underwater Acoustics, and MTS/Oceans conferences. The initial positioning results, assuming all five sources transmit at the

same effective time, have been published in the special issue on Deep water acoustics JASA (October 2013). In a subsequent paper published in the IEEE Journal of Oceanic Engineering (2015), the actual source transmission schedule (9 minutes apart) and the gilder velocity (assumed constant) during the 36 minute spread of arrivals was taken into account explicitly. The following results summarize those in these two papers, with more weight to the more recent one.

RESULTS

An example of a raw acoustic reception showing the LFM signals form the five sources is shown in Figure 2.
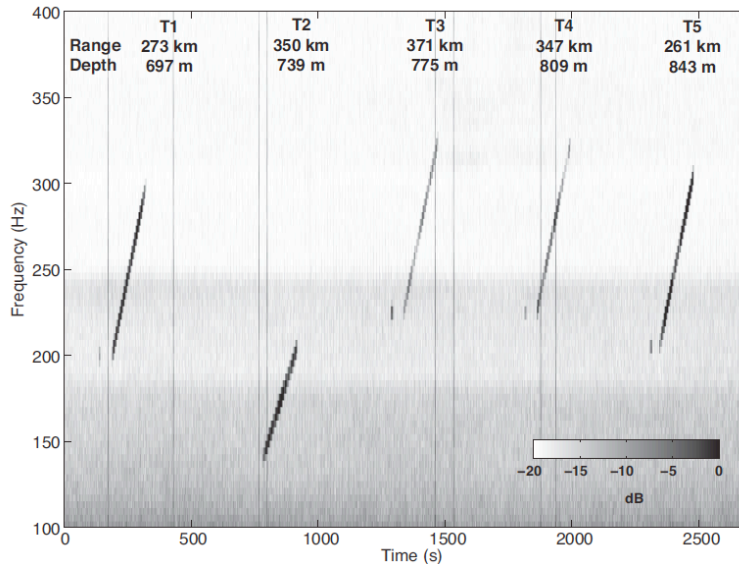

Figure 2. Sample Seaglider PhilSea10 spectrogram.

Because every reception on the glider is for a unique range and depth, the tracking over time of ray arrivals that is common for fixed-path tomography is not possible. We have found though that the measured arrival patterns (especially the dispersion of arrivals) are close enough to predicted ray arrivals that an unambiguous ray identification can be made (Figure 3). This particular example is "rich" in arrivals because of relatively large range and deep receiver depth. Clear in this figure are strong diffracted arrivals associated with late arriving rays that nominally turn below the receiver.

Three kinematic models (DR, GSM and HDM) for the glider underwater position and velocity as a function of time were corrected for the depth averaged current (DAC) and were used to estimate the latitude, longitude, and depth of the gliders at the time when they received the acoustic transmissions. These positions served as first guess positions for the least squares inversions, and are designated as dynamically estimated positions. Ranges from the source to the dynamically estimated positions are likewise designated as dynamically estimated ranges.

The patterns of measured acoustic arrivals were aligned with acoustic eigenray predictions by shifting them in time to obtain the best visual alignment. The eigenray predictions were obtained by performing acoustic ray simulations between the transmitting source position, corrected for mooring motion, and the latitude, longitude, and depth estimated from the DR, GSM, and HDM models at the time of the most intense arrival peak of the acoustic reception. A single sound-speed profile was used for all acoustic predictions. This temporally and spatially averaged sound-speed profile was constructed from

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temperature and salinity measurements collected from the gliders throughout the PhilSea10 deployment in the upper ocean and World Ocean Atlas climatology in the deep ocean.
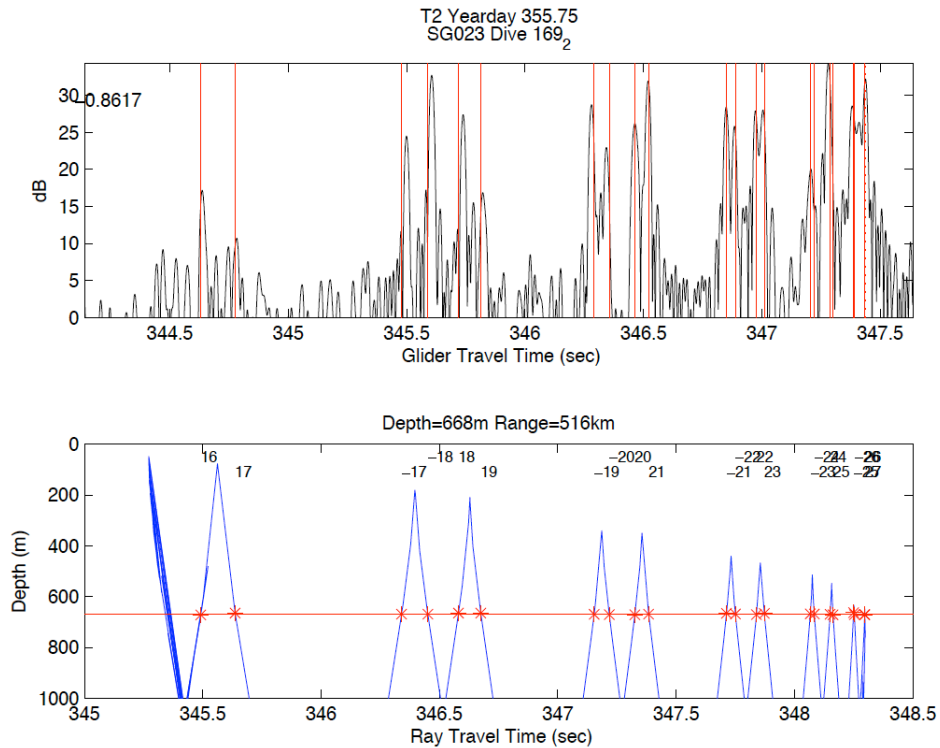

Figure 3. Received acoustic data (top) on SG023 from the 1800 transmission of source T2 on 2010 Yearday 355 at a range of 516 km and glider depth of 668 m. Vertical lines indicate alignment with predicted eigenrays, with an offset of 0.8617 seconds. Stars mark the intersection of the predicted timefront pattern in the upper ocean (bottom) with a horizontal line indicating the depth of glider at the time of the reception. The Ray ID for these identified eigenrays are indicated.

The glider position is calculated at the time of each source reception, assuming that the glider has a constant horizontal velocity offset during the reception period. The acoustically derived range offsets from dynamically estimated positions translate the dynamically estimated positions in latitude and longitude. As the offsets are small, a local rectangular coordinate system is assumed. Constant horizontal velocity offsets are determined that further rotate and dilate the dynamically estimated positions to obtain an estimate that best (in the least squares sense) aligns the glider trajectory with the measured travel-time (range) offsets to obtain the acoustically derived position. The least squares solution for position and velocity offset is done simultaneously. The results for one acoustic transmission/reception are shown in Figure 4, with the translation and dilation mapping the original estimated positions to the final ones shown.

Figure 5 shows similar results but for two transmissions during one dive. Once can graphically see that the various kinematic glider models are in error by up to 1000 m.
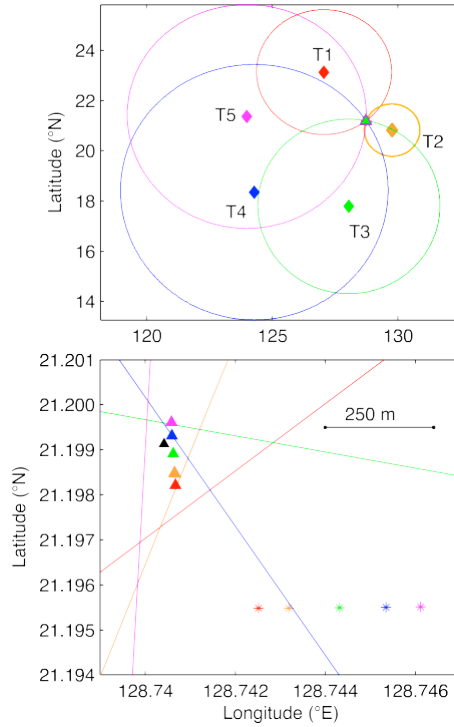
Figure 4: Circles indicate acoustically derived ranges from sources T1 (red, 275.6 km), T2 (orange, 115.4 km), T3 (green, 384.6 km), T4 (blue, 563.0 km), and T5 (magenta, 493.5 km) for SG513 Dive 204, Reception 1 (top). Diamonds of the same colors indicate source positions. On this scale, the range circles appear to cross at the measured glider location. An expanded view of the region near the intersection of the circle arcs (bottom) shows the DR dynamically estimated positions for each source reception (stars corresponding in color with those listed above) and corresponding acoustically derived positions resulting from the least squares inversion (triangles). The black triangle indicates the corresponding position from the case which neglects the glider motion between transmissions.
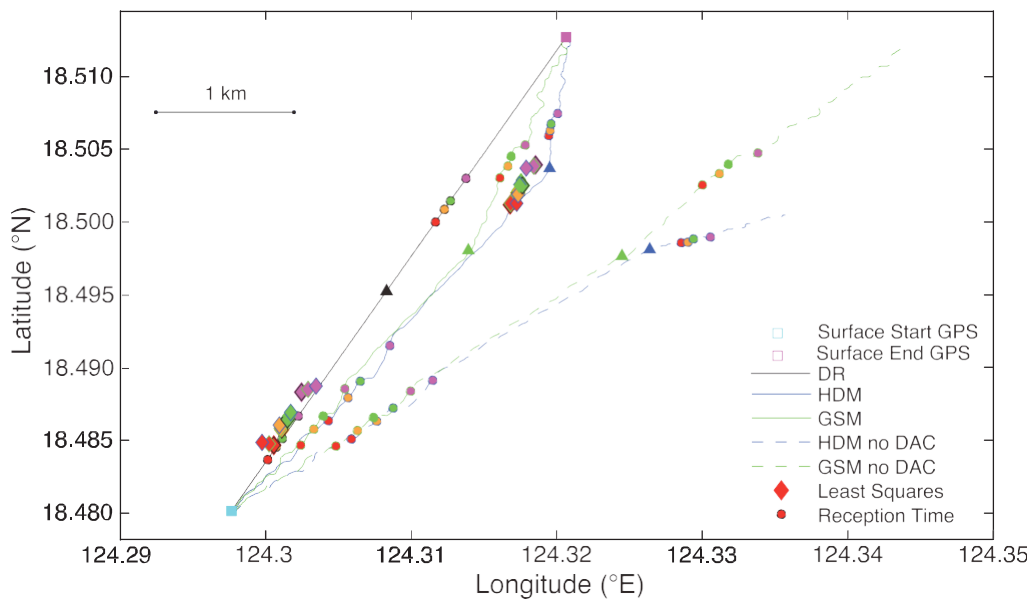
Figure 5. Dive profiles for SG511 Dive 385, collected on February 15, 2011, according to DR (black), GSM (green), and HDM (blue). Dashed lines indicate profiles uncorrected for the DAC. Triangles of the same color along the dive profiles indicate the apogee of the dive, where the glider transitions from a dive to a climb. Colored dots indicate dynamically estimated positions along each path at times corresponding to acoustic receptions for T1 (red), T2 (orange), T3(green), T4 (blue, absent in this case), and T5 (magenta). Two sets of source transmissions were received during this dive, one at midnight GMT on the descent and one three hours later on the climb, indicated by the lower and upper sets of dots, respectively. Acoustically derived least squares positioning results are shown as diamonds, colored according to the color scheme used in Fig. 2. Positioning results are differentiated by the outline color of the diamonds for the DR (black), GSM (green), and HDM (blue) models. The results are very close and often overlap, indicating that the first guess position does not have a large effect on the outcome of the least squares inversion.

Including the constant-velocity offset in the least squares inversion resulted in a drastic reduction of residuals from 178- to 53-m rms for the most conservative model, and a posteriori position error remained about the same. If we further refine the data errors, the a posteriori errors are also reduced from 105- to 85-m rms, and to 78-m rms if Doppler is neglected. In future experiments, the use of Doppler-sensitive signals such as m–sequences or up–down LFM could be used to directly measure vehicle velocity, further reducing uncertainties.

Future work includes using using independent internal tide current estimates to better resolve glider absolute velocity (with J. Colosi), to further investigate the Doppler effect on the swept-frequency signals, and use of individual ray data. Simulations of the joint estimation problem have begun (but are too immature to report here), to be followed by the integration of the glider acoustic data set into the tomography solution, when funding permits.

IMPACT/APPLICATIONS

Results to date support the validity of "underwater GPS" / RAFOS-2, namely that precise, O(~100 m), long-range navigation and positioning is achievable using multiple low frequency broadband acoustic sources and the resulting multipath arrivals (Duda et al., 2007). The larger community interested in "positioning, navigation, timing" (PNT) is becoming more engaged in this underwater arena. This will open up a host of new applications, just as space/terrestrial GPS has done with corresponding very major impact.

TRANSITIONS

DARPA has started a program call POSYDON - Positioning System for Deep Ocean Navigation – that builds directly on the results we have obtained.

RELATED PROJECTS

This project is just one of many associated with the ONR PhilSea10 experiment and the PI and co-PIs of this project have contributed to other publications.

Earlier acoustic Seaglider data (from 2006) were analyzed to demonstrate the ability to use long-range ATOC acoustic signals for communications; acoustic signal from distinctly separate dives was combined coherently to obtain high SNR results.

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