Long-range glider localization using broadband acoustic signals and a linearized model of glider motion

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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. Because the sources transmitted at 9-minute intervals the glider moved appreciably between source receptions. Source-glider ranges estimated from acoustic arrivals were combined using least-squares analysis to estimate a single glider position and velocity offset during the reception period. The analysis was applied to 387 sets of source transmissions and resulted in data residuals of 73 m rms. The estimated offsets were 845 m rms and 16.6 cm/s rms with *a posteriori* error estimates of 106 m rms and 11.7 cm/s rms, respectively. Overall glider speed is estimated at 21.1 cm/s rms.**

I. Introduction

Gliders are powerful tools for ocean measurements, with applications ranging from collecting oceanographic temperature measurements to military surveillance. Seagliders are capable of diving to depths of 1000 m, acquiring position from GPS at surfacing events between dives. A Seaglider is underwater for several hours at a time and can travel several kilometers during a single dive, during which time the glider is unable to obtain a position from GPS. The glider uses a kinematic model to estimate its position throughout the dive.

For ocean acoustic applications, gliders equipped with acoustic recording devices can complement or be used in place of more traditional, and more expensive, moored systems or ship-based receivers. It is important to be able to accurately and precisely position the glider in order to resolve the fundamental ambiguity between position and sound speed. Narrowband RAFOS signals have been used to navigate gliders under the ice in the Arctic with travel-time residuals on the order of 2-3 seconds, which result in positioning uncertainties of a few kilometers [1], [2]. Broadband source signals commonly used in acoustic tomography experiments offer significantly higher travel-time resolution, which further reduce the positioning uncertainty [3], [4].

During a tomography experiment performed in the Northern Philippine Sea in 2010-2011 (PhilSea10), four Seagliders, each equipped with an Acoustic Recorder System (ARS), were deployed at various locations around a pentagonal array of moored acoustic tomography sources. The ARS on each glider recorded over 2000 transmissions from five acoustic sources at ranges of up to 700 km.

Acoustically-derived ranges from sets of five sequential source transmissions, spaced at 9-minute intervals, were combined using the stochastic inverse method of least squares to estimate a single glider position. Least-squares estimated solutions for glider position differed by 914 m rms from the positions produced by the glider kinematic model, with estimated uncertainty of 106 m rms in horizontal position and data residuals of 178 m rms [5].

Here an improved least-squares positioning model incorporates a linearized model of glider motion to account for distance traveled by the glider between source receptions, as they did not transmit simultaneously and the glider can move appreciably between source receptions. Estimates of glider velocity are produced in this analysis. The experiment is described in more detail in Section II. The linearized model of glider motion and results for glider positioning and velocity are presented in Section III. Conclusions are given in Section IV.

II. PhilSea10 Experiment

A. Moored Tomography Experiment

Six acoustic transceivers (T1-T6) were deployed in the Philippine Sea from April 2010 to March 2011 as part of the ONR-sponsored PhilSea10 Experiment. The moorings were positioned in a pentagonal arrangement with a radius of approximately 330 km (Figure 1). Each transceiver mooring supported an acoustic source [6], [7] moored at nominally 1050 m, the approximate depth of the sound channel axis. The source was navigated throughout the deployment using a long-baseline navigation system of three bottom-mounted acoustic transponders.

The sources sequentially transmitted 135-s linear frequency modulated (LFM) sweeps from approximately 200-300 Hz, although the start and stop frequencies of the sweeps varied slightly from one source to the next. The source transmissions in a sequence were separated in time by 9 minutes. The sequence of source transmissions was repeated every three hours on odd-numbered yeardays beginning at 0000, 0300, 0600, ... 2100 UTC throughout the duration of the deployment.

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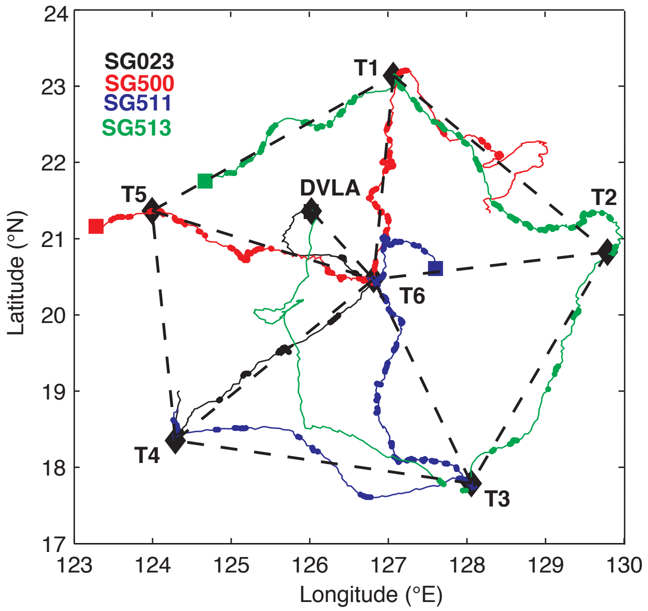


Fig. 1. Acoustic Seaglider tracks in the Philippine Sea. Heavy dots indicate positions of gliders while collecting data. Squares indicate deployment positions. Black diamonds indicate positions of the moorings. (Reproduced from [5].)

B. Acoustic Seagliders

Four Acoustic Seagliders (SG023, SG500, SG511, and SG513) were deployed in November 2010 in various positions around the array; they then transited different paths, roughly clockwise around the array (Figure 1). The Seagliders are buoyancy-driven autonomous underwater vehicles (AUVs) [10]. The pitch and roll of the Seagliders are adjusted by shifting an internal mass, and their effective buoyancy is altered by pumping oil between internal and external bladders. The gliders were programmed to dive to 1000 m depth.

Each glider was equipped with an Acoustic Recorder System (ARS) that collected data from a single High-Tech Inc. HTI-92-WB hydrophone at a sampling rate of 4 kHz for 3200 s beginning at the nominal transmit time for the T1 source ([5], [8], and [9]).

Each recording period included receptions from up to five sources (T1-T5). The T6 source had ceased transmitting prior to the glider deployment, so no transmissions were received by the gliders. In all, 2111 usable receptions were collected during the duration of the glider deployment.

III. Subsurface Glider Localization

Although the Seagliders can only obtain GPS fixes during surfacing events between dives, the glider position during a dive is estimated by a kinematic flight model that incorporates the roll, pitch, heading, buoyancy, and depth of the glider, in conjunction with dead-reckoning based on GPS position fixes at the beginning and end of each dive. A Kalman filter uses information on the difference between predicted and actual surfacing locations for navigational control [10].

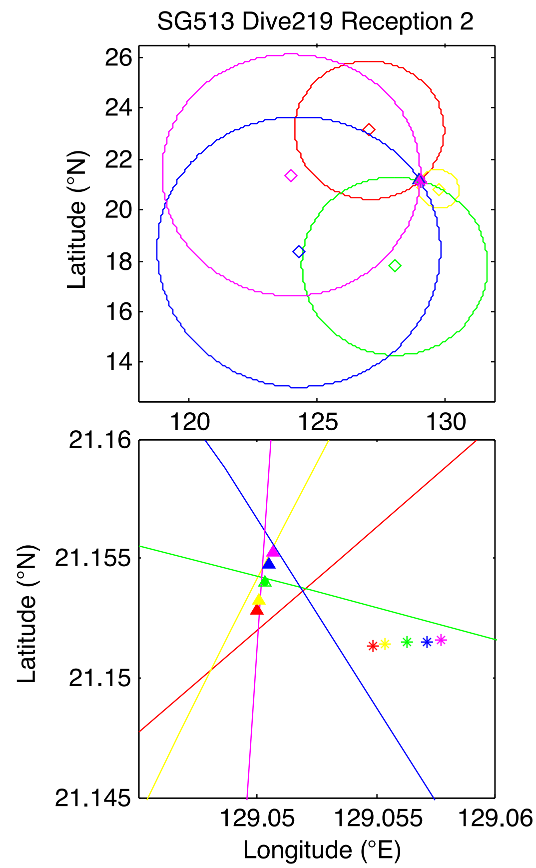


Fig. 2. Acoustically-derived ranges from sources T1 (red), T2 (yellow), T3 (green), T4 (blue), and T5 (magenta) for SG513 Dive 219, Reception 2 (top). Diamonds of the same colors indicate source positions. On this scale, the circles appear to cross at the measured glider location. An expanded view of the region near the intersection of the circle arcs is shown with the glider-estimated positions for each source reception (stars corresponding in color with those listed above) and least-squares estimated positions (triangles).

A. Determination of source-glider range

Temporal acoustic arrival structure was obtained using matched filter processing, taking account of the measured effective sweep times and frequencies of the LFM source signals. For the longer ranges between the source and glider, the acoustic arrivals are spread out over on the order of about 4 seconds. These patterns of arrivals were time-aligned with acoustic ray arrival predications at the depth of the glider for the ranges between the transmitting source and the latitude and longitude predicted by the glider kinematic model at the time of the acoustic reception. Range offsets were obtained by multiplying the travel-time offsets of the arrival patterns time by a sound speed of 1500 m/s. Since the source positions are well known from the mooring motion corrections applied from the long baseline acoustic tracking, the range offsets were applied to the glider positions and constitute the data used here (Figure 2, top).

B. Linearized model of glider motion

Simple triangulation for glider position is not optimal as the PhilSea10 acoustic sources did not transmit simultaneously. As

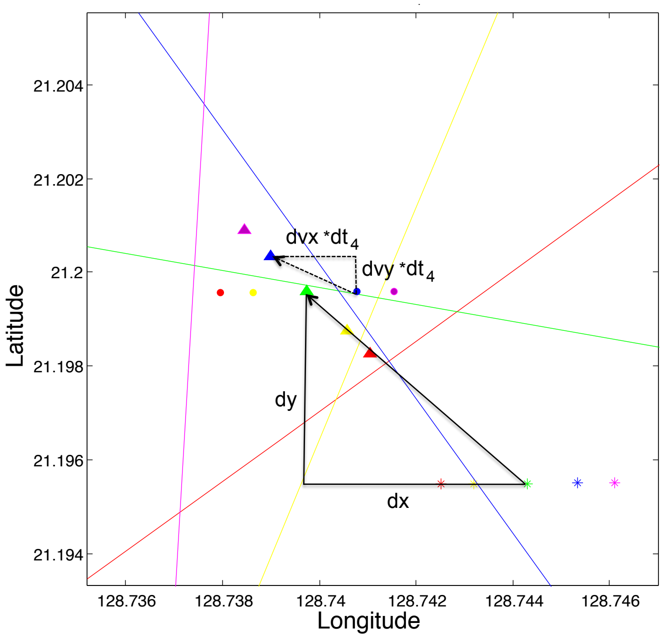


Fig. 3. Acoustically-derived ranges from sources T1 (red), T2 (yellow), T3 (green), T4 (blue), and T5 (magenta) for SG513 Dive 204, Reception 1. Stars in corresponding colors indicate the position estimated by the glider kinematic model at the time of the five source receptions. The circles of the same color indicate the glider position adjusted by the position offsets from the least-squares analysis. These positions are further dilated and rotated using the glider velocities estimated from the least-squares analysis and the triangles indicate the resulting glider position.

a first step, the ranges estimated from each of the receptions in a sequence of source transmissions were combined using the stochastic inverse method of least squares to estimate a single position (nominally the position at the time of the reception from the T3 source) in [5]. The least-squares solutions indicate that the acoustically-derived range offsets in a set of sequential source receptions are consistent, but they do not account for the motion of the glider between acoustic source receptions.

Here, the glider position is calculated at the time of each source reception, assuming that the glider has a constant velocity offset during the reception period. Glider positions estimated by the kinematic model are first translated in latitude and longitude (Figure 3). A constant velocity offset is determined that rotates and dilates the the position offsets to obtain a final estimate that best (in the least squares sense) aligns the glider trajectory with the measured range offsets. The least squares solution for position and velocity offset is done simultaneously.

C. Stochastic Inverse method of Least Squares incorporating Glider model

Glider position estimates were calculated using the stochastic inverse method of least squares [13] for each of the 387 Seaglider receptions with 3 or more source transmissions using the linearized observation equation:

$$d = Em + n \tag{1}$$

where d is the data vector, consisting of the range offsets that are the differences between the acoustically-derived ranges and those inferred from the distance between the sources and the glider-estimated latitude and longitude at the time of the acoustic reception. The model vector, m, represents the x (east) and y (north) displacement of the glider positions, as well as the velocity vectors in the x and y direction; both are relative to the position and velocity determined with GPS and the kinematic glider model. The observation matrix, E, relates the range offsets to the glider position and velocity using the source-receiver geometry.

TABLE I. STATISTICS OF LEAST-SQUARES POSITION ESTIMATES AND ERRORS.

Data		rms
	R (Data error)	15 m (Pattern matching) 69 m (Doppler) 105 m (Sound speed)
	Total R	127 m (T3)
	d (Innovation)	630 m
	Residuals	73 m
Model		
	S_d (*a priori* error)	1020 m
	S_v (*a priori* error)	17 cm/s
	P_d (*a posteriori* error)	106/107 m (x/y)
	P_v (*a posteriori* error)	11.6/11.8 cm/s (x/y)
	$\hat{m}$	845 m

The inverse of E is denoted by B and depends on the data error covariance, $R =< nn^T >$, and the *a priori* model error covariance, $S =< mm^T >$:

$$B = SE^T(ESE^T + R)^{-1} \tag{2}$$

giving the model estimate $\hat{m}$ and its associated *a posteriori* model error covariance, P:

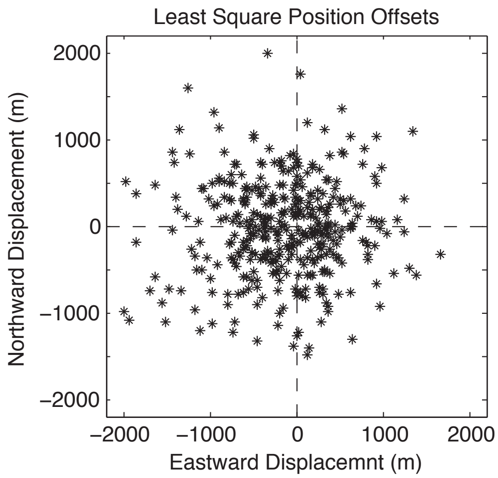
$$\hat{m} = Bd \tag{3}$$

$$P = (S^{-1} + E^T R^{-1} E)^{-1} \tag{4}$$

The diagonal terms of S represent the *a priori* error in the glider position estimate due to the length of time between a surface GPS position fix and the acoustic reception as well as the approximate adjustment to glider velocity. The average time to a GPS position fix was 100 minutes and the average glider speed was estimated at 17 cm/s and these were used to obtain a measure of glider position error (Table I).

The data covariance matrix, R, is a combination of measurement and representation errors including the uncertainty in range due to eigenray pattern matching, estimated to be $(10\ ms \times 1500\ m/s)^2$, uncertainty due to ocean sound-speed variability estimated to be $(70\ ms \times 1500\ m/s)^2$, and the error due to Doppler effects on travel time estimated using the PhilSea10 source signal parameters to be $(46\ ms \times 1500 m/s)^2$ for a glider traveling at 17 cm/s directly towards a source [12, equation 16], a conservative estimate as the orientation of the glider with respect to the source will vary.

Glider position and velocity estimated by the kinematic model were adjusted according to the position offsets in longitude and latitude and constant velocity estimated by the least squares analysis (Figures 2 and 3). Compiled results for the 387 sequences consisting of 3, 4, or 5 source receptions indicated a position offset of 845 m rms from the estimated glider positions, and overall glider speeds of 21.1 cm/s rms (Figure 4). Perturbations to the glider speed estimated by the



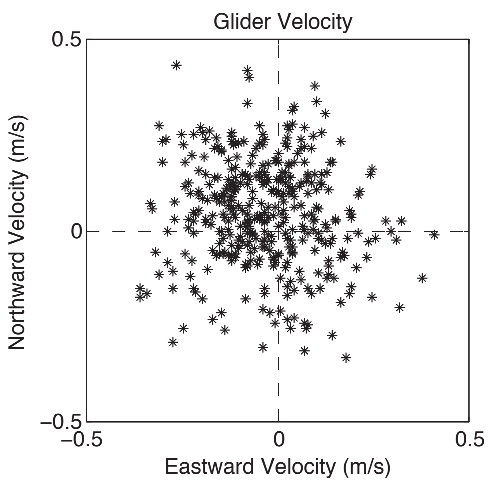


Fig. 4. A compilation of the position offsets (top) and glider velocities (bottom) estimated from least-squares analysis for 387 glider data records with 3, 4, or 5 source receptions.

model were 16.6 cm/s rms and *a posteriori* error estimates for the velocity perturbations were on the order of 11 cm/s rms. These can be compared with the *a priori* (kinematic model) velocity of 18 cm/s rms and the associated *a priori* error of 17 cm/s (Table I). The analysis resulted in data residuals of 73 m rms and *a posteriori* displacement error estimates of approximately 106 m rms in the horizontal.

IV. Concluding Remarks

A posteriori error estimates of 106 m rms were almost identical to those estimated in [5], which did not incorporate a constant velocity adjustment model for glider motion. However, that analysis only included data receptions with 5 source receptions, whereas the analysis here was extended to include all data records with 3, 4, or 5 source transmissions. When the analysis described here was performed for only those data records with 5 acoustic receptions, the resulting *a posteriori* errors were reduced to 91 m rms in the horizontal. When those cases with only 3 or only 4 receptions were isolated, the estimated *a posteriori* errors were on the order of 158 m rms and 117 m rms, respectively.

The *a posteriori* error estimates were reduced by incorporating the linearized model of glider motion, but the perhaps the greatest advantage of incorporating a constant velocity adjustment model is the reduction of the residuals. The residuals of 178 m rms from the analysis described in [5] were reduced to 73 m rms using the model presented here.

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