Evaluation of an Off-the-Shelf Acoustic System for Precision Positioning of Seabed Transponders

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***Abstract*- In this study, a commercial off-the-shelf acoustic system with ranging accuracy of 20 centimeters is employed to conduct an experiment of positioning seabed transponders. The feasibility of using a GPS/acoustic system with off-the-shelf transponders to achieve centimeter-level positioning accuracy was evaluated. In order to verify the relative positioning accuracy between seabed transponders, a seafloor acoustic transponder (SAT) system was developed. Three transponders were mounted on the SAT system to form a triangle with known baselines. In addition, a data acquisition and logging system was developed to integrate with a motion reference unit (MRU) and a fiber optic gyro (FOG) for collecting the heading information of the SAT system. A field experiment to verify the relative positioning accuracy between transponders was carried out. The collected GPS/acoustic observations and sensor data were then used to estimate the positions of the three transponders based on an optimization technique combined with ray trace calculations. The transponder positioning result shows that the root mean square slant range residuals are in good agreement with the inherent ranging accuracy of the acoustic system. The experimental results also show that the mean value of the acoustic slant range residuals is about 3 centimeters and the relative positioning error between transponders is less than 3 centimeters. Furthermore, the heading of the SAT system derived from the position estimates of the three transponders is in good agreement with the measurement obtained by the MRU and FOG on the SAT system.**

I. INTRODUCTION

Observation of crustal deformation is crucial for understanding geodynamical properties at plate boundaries. Usually, crustal deformation on land is observed directly from the measurements of space-based geodetic techniques such as interferometric synthetic aperture radar (InSAR) and global positioning system (GPS). However, unlike the measurement of crustal deformation on land, measurement of seafloor crustal deformation can not be accomplished by InSAR or GPS alone. Detecting and monitoring seafloor crustal deformation is often composed of GPS positioning and acoustic ranging techniques, which involves positioning of seabed transponders [1-5].

Since the plate motions averaged over the past few million years are on the order of 1-10 centimeters per year [6], the GPS/acoustic system is usually equipped with specific precision acoustic transponders in order that the round trip travel time can be determined to within a few microseconds [1, 4-5]. The cost of a GPS/acoustic system with specific precision transponders, however, is substantial. Instead of using a specific precision transponder, if a commercial off-the-shelf transponder can be used to achieve satisfactory positioning accuracy, the cost of the acoustic system will be significantly reduced. In addition, the precision of a transponder coordinate estimates is conventionally evaluated in terms of slant range residual. To the best of our knowledge, except for slant range residual, there is no study that provides other credible indication to verify the positioning accuracy of seabed transponders.

The major purpose of this paper is to investigate the feasibility of using an off-the-shelf acoustic system for precision positioning of seafloor transponders. In addition to use of slant range residual to verify the transponder positioning accuracy, another evaluation method that can verify the relative positioning accuracy between transponders is proposed in this study. In this proposed method, a Seafloor Acoustic Transponder (SAT) system is designed to install instruments including three transponders, a heading data acquisition and logging system, a CTD logger, and a dual acoustic release mechanism. The baselines between transponders installed on the SAT system can be measured reliably by direct means, such as a calibrated ruler. The heading logger mounted on the SAT system is designed to collect heading data of the SAT system. After the positions of the three transponders are estimated based on GPS/acoustic measurements, the transponder position estimates will be used to calculate the heading of the SAT system and the relative distances between transponders. The transponder position derived heading and relative distances will be compared with the measurements to evaluate the relative positioning accuracy of the acoustic system.

The paper is organized as follows. In Section II, we introduce the optimization method used to estimate the position of a transponder. In Section III, the system configuration of the SAT system for installing transponders and instruments is presented. The field experiment and its results are described in Section IV, and conclusions of our works are given in the final section.

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II. Estimation of Transponder Positions

In the GPS/acoustic measurement, observations of GPS and travel time between the transceiver and the transponder are collected at a variety of locations. The position of the transceiver at every location can be known from GPS and attitude sensors. Let the position of a seafloor transponder be denoted as $\mathbf{P}_T = [P_{Tx}, P_{Ty}, P_{Tz}]^T$ with respect to the world coordinate. At the ith epoch, the position of the transceiver is $\mathbf{P}_i = [P_{ix}, P_{iy}, P_{iz}]^T$ and the measured acoustic one-way travel time is t_{mi}. On the other hand, based on ray tracing technique, the one-way travel time, t_i, of the sound wave between the transceiver and the transponder can be calculated:

$$t_i = f\left(\mathbf{P}_T, \mathbf{P}_i, c\right) \quad (1)$$

where f is a nonlinear function of ray tracing and c is the sound speed profile of the water column. Ideally, if the estimate of the transponder position is absolutely correct, the calculated acoustic travel time from (3) should be identical to the measured one (i.e., $t_i = t_{mi}$). As the transponder coordinate estimates are incorrect, there exists a difference, ε_i, between the calculated and measured travel times:

$$\varepsilon_i = t_{mi} - t_i\,. \quad (2)$$

The estimation of a transponder position can be regarded as a minimization problem, which involves a process to minimize the difference between the measured and calculated slant ranges (or, precisely, one-way travel times). Several optimization algorithms, such as genetic algorithm and simulated annealing, have been developed to provide global solution of minimization problems. Therefore, this study utilizes the optimization approach to estimate the position of a transponder. We wish to determine the best values for the transponder coordinates P_{Tx}, P_{Ty}, and P_{Tz} so that the difference between the measured and calculated acoustic travel times can be minimized. Therefore, the objective function for this problem can be defined as the sum of squared errors between the measured and calculated acoustic travel times:

$$\textit{Minimize} \quad F\left(P_{Tx}, P_{Ty}, P_{Tz}\right) = \sum_{i=1}^{n}\left(\varepsilon_i\right)^2 = \sum_{i=1}^{n}\left(t_{mi} - t_i\right)^2 \quad (3)$$

Subject to:

$$x_l \le P_{Tx} \le x_u$$
$$y_l \le P_{Ty} \le y_u$$
$$z_l \le P_{Tz} \le z_u$$

where n is the number of epochs, (x_l, y_l, z_l) and (x_u, y_u, z_u) are the lower and upper bounds, respectively, of the design variables (P_{Tx}, P_{Ty}, P_{Tz}). Thus, based on the objective function F and the constraints presented in (3), the position of a transponder can be estimated using a variety of constrained optimization algorithms.

III. The Seafloor Acoustic Transponder (SAT) System

In order to evaluate the relative accuracy of an off-the-shelf acoustic system in positioning seafloor transponders, it is necessary to have absolute values of the baselines between transponders. The SAT system was therefore developed to quantitatively evaluate the relative positioning accuracy of an off-the-shelf acoustic system. The SAT system was designed to fulfill the following requirements:

(1) The system should be able to accommodate three transponders.
(2) The system should be able to collect heading information of the SAT system when it rests on the sea floor.
(3) The system should be able to be recovered.

A picture of the developed SAT system is presented in Fig. 1 while a schematic of the SAT system is shown in Fig. 2. Three commercial transponders, denoted by T_1, T_2, and T_3, in a triangular array are mounted on the SAT system. The baselines are measured directly between each transponder as 150.5 centimeters, 150.5 centimeters, and 116.0 centimeters, respectively, as shown in Fig. 2. In order to evaluate the relative poisoning accuracy of the acoustic system, the measured baselines will be compared to those derived from the position estimates of the three transponders. A motion reference unit (MRU) with fiber optic gyro (FOG) is accommodated in the SAT system. The MRU and FOG are used to provide heading information of the SAT system when it rests on the seafloor. To collect the heading data, a MSP430-based ultra-low power data logger [7] was developed. The data logger consisted of recording electronics and batteries are contained in a cylindrical aluminum pressure housing. The pressure housing has two end cap connector penetrations for the MRU and a serial communication interface. As well as the baselines, the heading of the SAT system can be derived from the position estimates of the three transponders. Therefore, the given heading measurement from the MRU will be compared to the transponder position derived heading to evaluate the relative positioning accuracy of the acoustic system.

In addition to the sensors mentioned above, a CTD logger is accommodated on the SAT system. During the descending and ascending of the SAT system, CTD observations are collected and therefore the sound speed profile of the water column can be derived from the CTD measurements. In addition, when the SAT system rests on the sea floor, the depth measurements of the CTD logger can be employed to correct tidal effect on the estimation of the transponder position.

For recovery, two spherical floats, mounted at the top of the system, provide 50 kilograms of total flotation. A dual acoustic release mechanism was employed to connect the SAT system to the anchor. When recovery, the SAT system is released from the anchor using the dual acoustic release and allowed to float to the sea surface. A radio beacon and a flashing light are attached on the system to help retrieve the SAT system during recovery.

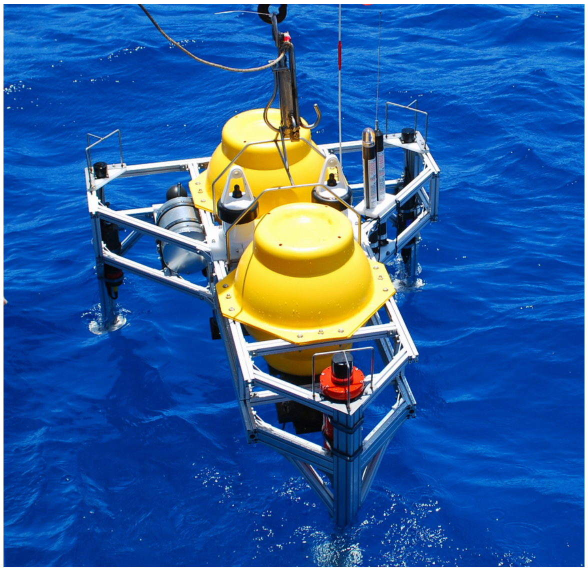
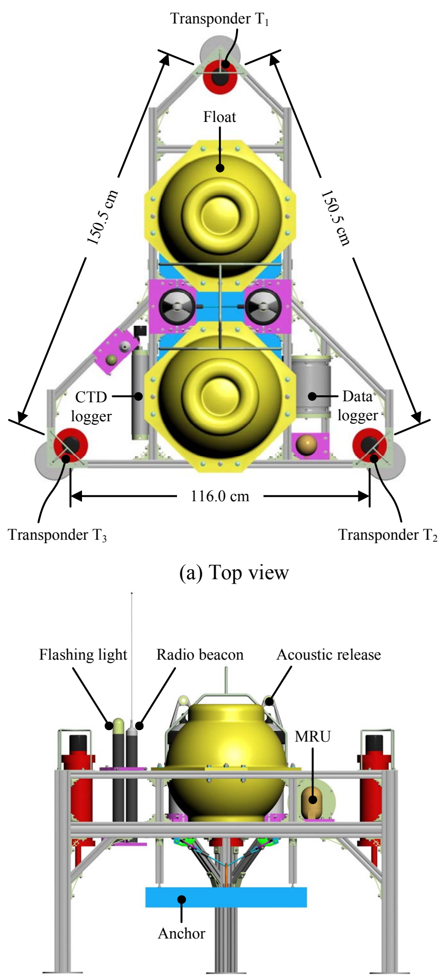


Figure 1. The Acoustic Seafloor Transponder (SAT) system.



(b) Back view

Figure 2. Schematic of the SAT system.

IV. Field Experiment and Results

In May 2009, an experiment was conducted off the coast of Kaohsiung Harbor, Taiwan, to investigate the accuracy of an off-the-shelf acoustic system in positioning seafloor transponders. The off-the-shelf acoustic system and sensors employed for the field experiment are listed in Table I. In this experiment, a LinkQuest TrackLink USBL tracking system with ranging accuracy of 0.2 meters was used. The acoustic transceiver was mounted on a pole over the side of the vessel OR3 Researcher and three transponders were mounted on the SAT system. The SAT system was deployed from OR3 Researcher to a depth of about 300 meters, as shown in Fig. 3. After the SAT system rested on the sea floor, the vessel was moved around the top of the SAT system to interrogate the transponders and record time-of-flight measurements to individual transponders. Fig. 4 presents the trajectory of the vessel around the SAT system. The position of the vessel was measured with a Sokkia GPS with a precision of 1 meter. The attitude of the vessel was measured with a TSS gyrocompass (Meridian Surveyer) and a TSS motion sensor (DMS-05). Then, the position of the transceiver was calculated using the measurements of GPS, gyro compass, and motion sensor.

TABLE I
THE ACOUSTIC SYSTEM AND SENSORS EMPLOYED FOR THE EXPERIMENT

Sensor/Instrument	Update rate	Precision
LinkQuest USBL	–	Range: 0.2 meter
Sokkia GPS	1 Hz	1 meter
TSS Gyrocompass	10 Hz	Heading: 0.1°
TSS Motion sensor	20 Hz	Pitch: 0.04° Roll: 0.04° Heave: 5 cm
Tritech iGC & iFG	20 Hz	Heading: 1°
RBR CTD logger	1 Hz	Conductivity: 0.003 mS/cm Temperature: 0.002 °C Depth: 0.05% Full scale

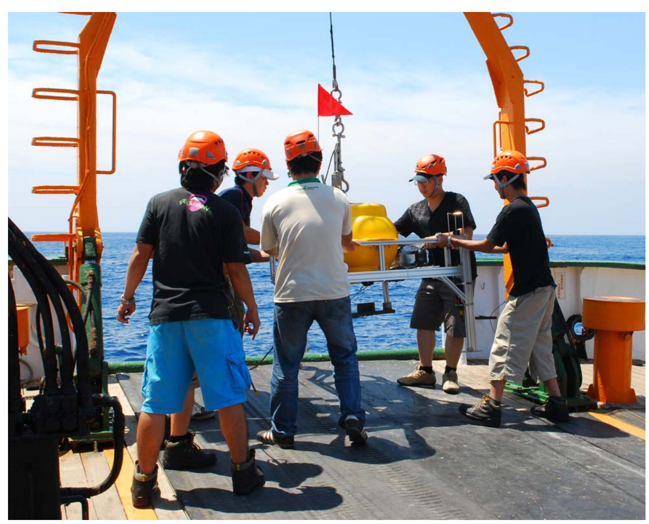


Figure 3. Deployment of the SAT system.

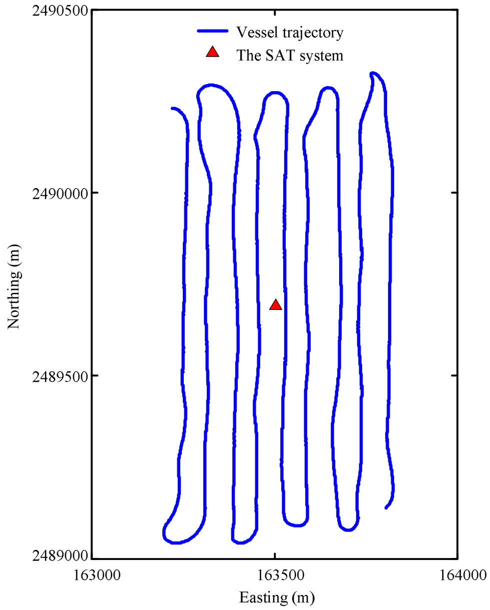
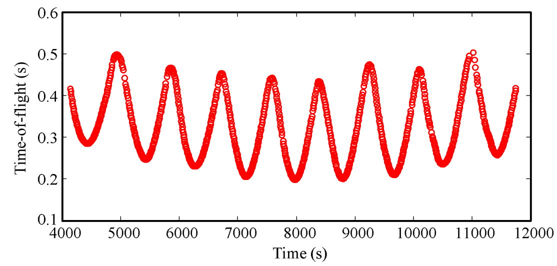


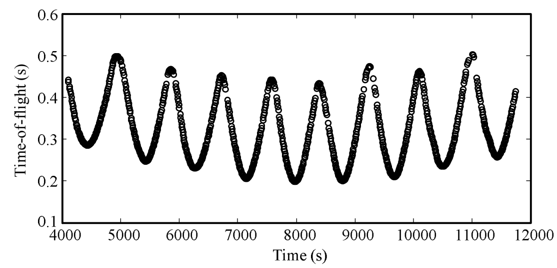
Figure 4. Vessel trajectory for survey line runs on May 2009.

The ranging operation lasted for about two hours and then the SAT system was recovered. Fig. 5 shows the time series plots of the acoustic time-of-flight measurements. After the SAT system was recovered, the heading data of the system was retrieved from the data logger and the results are presented in Fig. 6. It can be observed from Fig. 6 that the heading of the SAT system was 123.0 degrees when the SAT system rested on the sea floor. The data of salinity and temperature corresponding to water depth was retrieved from the CTD logger on the SAT system and the derived sound speed profiles are shown in Fig. 7.

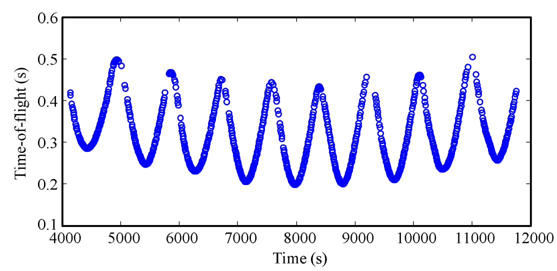
Based on the optimization technique along with ray trace calculations, positions of the three transponders on the SAT system were estimated from the data collected during the experiment. The position estimates and the corresponding histograms of acoustic slant range residuals of the three transponders are presented in Table II and Fig. 8, respectively. The estimation result shows that the root mean square value of the slant range residuals for the three transponders are 26, 28, and 31 centimeters, respectively, which are in good agreement with the ranging accuracy (20 centimeters) of the acoustic system. In addition, the mean values of the slant range residuals for the three transponders are –1.7, –2.3, and –2.2 centimeters, respectively. To evaluate the relative accuracy in transponder position, we calculated the relative distances between transponders based on the obtained transponder position estimates. As shown in Table III, the position estimates of the three transponders form a triangle with sides 152.8, 150.7 and 117.2 centimeters, which demonstrates that, comparing with the true baselines, the relative positioning error between transponders is less than 3 centimeters. Based on the position estimates of the three transponders, we also calculate the heading of the SAT system when it rested on the sea floor. With the consideration of the Earth's magnetic field [8], the transponder position derived heading of the SAT system is 120.1 degrees which is in agreement with the measurement from the heading sensor on the SAT system.



(a) Transponder T_1



(b) Transponder T_2



(c) Transponder T_3

Figure 5. Time series of the acoustic one-way travel time.

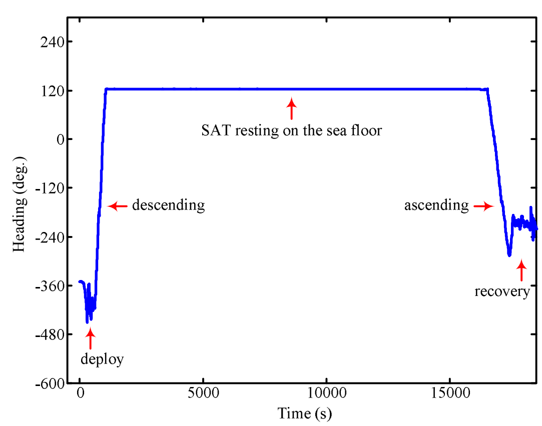


Figure 6. Heading of the SAT system during the period of the experiment.

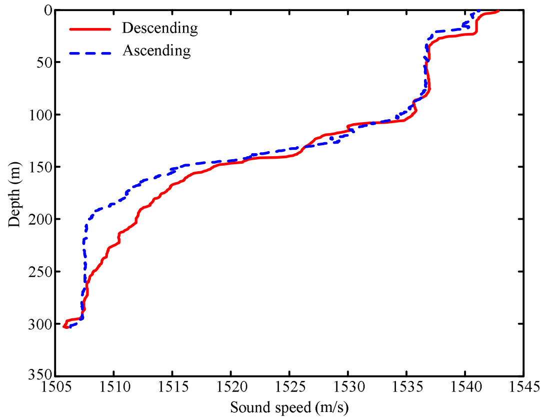
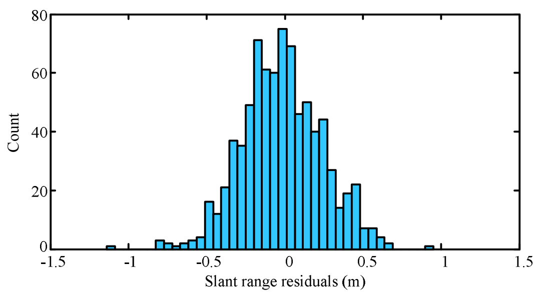
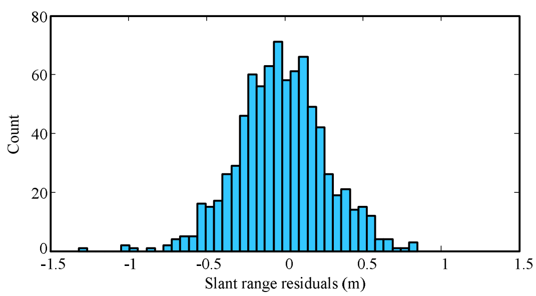


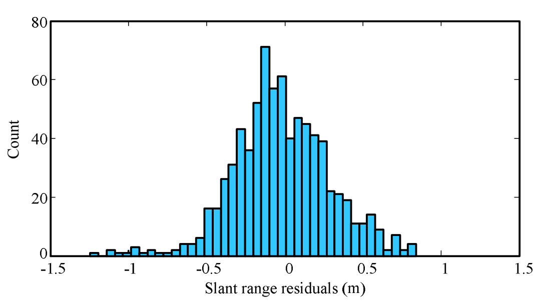
Figure 7. Sound speed profiles of the water column were obtained from the SAT's CTD measurements. The CTD data used for deriving sound speed was collected during the descending and ascending periods of the SAT system.



(a) Transponder T_1



(b) Transponder T_2



(c) Transponder T_3

Figure 8. Histograms of the acoustic slant range residuals. The RMS values are approximately 30 cm and the mean values are approximately –2 cm.

TABLE II
POSITION ESTIMATES OF THREE TRANSPONDERS

Transponder	P_{Tx} (m)	P_{Ty} (m)	P_{Tz} (m)
T_1	163504.669	2489688.678	–304.733
T_2	163503.188	2489688.769	–305.098
T_3	163503.724	2489689.809	–305.048

TABLE III
RELATIVE POSITIONING ACCURACY BETWEEN TRANSPONDERS

Transponders	Baseline		Error (cm)
	True value (cm)	Estimate (cm)	
T_1–T_2	150.5	152.8	2.3
T_1–T_3	150.5	150.7	0.2
T_2–T_3	116.0	117.2	1.2

V. CONCLUSIONS

This study presented the results of a transponder positioning experiment conducted with an off-the-shelf acoustic system. A SAT system was developed to accommodate three transponders and a heading data acquisition and logging system for verify the positioning accuracy of the acoustic system. In this experiment, a commercial acoustic system with ranging accuracy of 20 centimeters was employed and the SAT system was deployed on the sea floor at a depth of about 300 meters. The transponder positions were estimated by the optimization technique along with ray trace calculations. The experimental results indicate that, from the point of view of slant range residual, the transponder positioning accuracy is approximately 30 centimeters. Apparently, the transponder positioning accuracy is mainly due to the inherent ranging accuracy of the acoustic system. Even though the standard deviation of the slant range residual is limited to the inherent accuracy of the acoustic system itself, the experimental results show that both the mean value of the slant range residual and the relative positioning error between transponders are within 3 centimeters. The relative positioning accuracy between transponders was further confirmed through the measurements observed from the heading sensor on the SAT system. The position estimates of the three transponders were used to calculate the heading of the SAT system, and the calculated result is in agreement with the measured one. Therefore, the experimental results demonstrate that the optimization technique along with ray trace calculations is practical for precisely estimating the transponder position. In particular, the results also reveal that, using an off-the-shelf acoustic system, it is possible to achieve centimeter-level relative accuracy in positioning seabed transponders.

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