POSITION ESTIMATING TECHNOLOGY OF SUBMERGED ACOUSTIC ARRAY BASED ON ERROR ANALYSIS FOR OAT IN DEEP SEA

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Abstract: The data precision of deep sea acoustic tomography system is derived from the acoustic element position error, the time measuring error when the acoustic signal travels from the source to the receiving array of the acoustic tomography, and the error caused by the timing system of the submerged acoustic array during the long period of working in deep sea as well. The position of the transmitting transducer is precisely obtained by using the long baseline positioning system. The high-precision magnetic sensor data is combined with the position data of the transmitting transducer and their relative position data to calculate the position of the submerged receiving array elements, using high-precision clock to reduce the timing, time-keeping, and time measuring error of the system to obtain the deep sea acoustic tomography experiment data simultaneously. The technology was applied in the first acoustic tomography experiment of the South China Sea in 2016 to verify that the positioning precision of the transmitting transducer is less than 3 meters compared with DGPS result. The results show that the technology can be used to calculate element's position of submerged acoustic array in deep sea to obtain effective experimental acoustic tomography data. The result of sound speed inversion based on experimental data reaches the specified precision range.

Keywords: Ocean Acoustic Tomography, deep sea, submerged acoustic array, high-precision, positioning system, South China Sea.
1. INTRODUCTION

In 1979, Munk and Wunch proposed the classic ocean acoustic tomography theory, discussed the acoustic requirement and inversion method of mesoscale ocean description [1]. In the classical theory, the scale range of oceanic acoustic tomography can reach more than 1000km [2], which is a very efficient method of ocean observation. It uses a low frequency and high power level transducer to transmit acoustic pulses and a wide range vertical sound receiving array for acoustic signal reception. The sound speed perturbation due to temperature and current change is extremely small, therefore theoretical acoustic tomography experiment requires a pretty accurately measurement of the transducer position on the very transmitting starting point and the receiving time of the vertical receiver array elements [3] to gain a high-precision inversion results for sound speed field, temperature field, current speed field [1] [4].

Most areas of the earth are covered by the ocean with a water depth more than 4,000 meters. The well-designed acoustic tomography equipment has the great significance for deep-sea stereoscopic observation in mesoscale ocean. However, there are still many technical problems. For instance, the deep-sea mooring acoustic tomography system cannot provide enough information accurately, due to lack of technique for underwater transducer or receiving array element position information, lack of real-time underwater calibration technique of long-term time keeping during the entire tomography experiment [1]. It has been considered as the place where the temperature field and current field error of acoustic tomography inversion are coming from.

Using the existing techniques to design the acoustic tomography experiment, although it is not possible to achieve the perfect inversion results required by the acoustic tomography theory, it is still important to obtain acceptable acoustic tomography inversion accuracy under limited conditions. Last year, May 21, 2016 - August 25, we conducted an OAT experiment with 2 mooring system in the South China Sea to validate the feasibility of the deep sea mooring OAT experimental equipment that designed by Hangzhou Applied Acoustic Research Institute.

2. ERROR ANALYSIS

For South China Sea’s OAT experiment, we were interested only in changes with time, no need to know the absolute separation of the instruments in mooring system, but only the changes in range from measurement to measurement (i.e., the relative mooring displacement) [1]. Therefore, the main error of the inversion precision comes from three aspects which is the position error of the transmitting transducer measurement, the arrival time measurement error and the time keeping error.

The error caused by inversion model can also be significant. The improvement for inversion model error not only depends on steady OAT algorithm, abundant empirical data, the system sound noise ratio and signal bandwidth, but also connected to the position error of the transmitting transducer measurement and the arrival time measurement error.

The problem of time keeping error is mainly solved by high precision clock. The time keeping error of the selected high-precision clock is less than 3ms/month. Specifically, the two clocks for 2 mooring system are recovered after three months’ experiment and compared with GPS time on deck and found the error were -2.7ms and 9ms respectively. Assuming that the time error is linear during 3 months’ time keeping, we obtained even
more accurate result by using linear interpolation as the time keeping error correction method.

The positioning of the transmitting transducer is carried out using a long baseline system [7] and its accuracy is determined comparing with the positioning of the DGPS. The results show that the true position interval of the long baseline positioning system is a circle with a diameter of 1.51 m which caused only 0.0776 m/s of the sound speed perturbation error according to [6].

Using the high-precision compass and tilt sensor (with a precision of 1°) to locate the vertical array with the long baseline positioning results of the transmitting transducer, the results show that the position interval of the remote hydrophone element is is a circle with a diameter of 11.98 m which caused a 0.311 m/s of the sound speed perturbation error according to [6].

The final results are given in the subsequent inversion results.

3. POSITION ESTIMATING TECHNIQUE

The deep sea mooring acoustic tomography experimental system design needs to balance the underwater energy supply, equipment scale, measurement accuracy and economy and many other factors. The design of the mooring system in last year's acoustic tomography experiment has the following structural form [5], and constructs two nodes of the mooring system at a distance of 56 km in southwest of Taiwan to validate the feasibility of the design. The transducer is placed in the measuring acoustic channel axis (depth 1050 m). Three high precision compasses and tilt sensors were installed separately near the first hydrophone with a 430 m water depth, the last hydrophone with a 1670 water depth and the transducer with a 1070 m water depth. A long baseline positioning device is installed at 20 meters below the transmitting transducer to measure the transducer position.

![Figure 1](image)

Figure 1. (a) Mooring system design and position of devices (b) Location map of 2 nodes OAT experiment in 2016

In each positioning cycle of the long baseline system, the subsystem installed in the mooring system can measure the acoustic two-way propagation delay of each "challenge-response" signal, and each set of delay measurements determines a sphere centered by the subsystem. With several transponders we are able to calculate the intersection of the spherical surfaces which is the real position of the subsystem installed 20 meters below the transmitting transducer. The positioning equation is:
\[(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2 = \frac{1}{4} c^2(t_i - t_0)^2\]

Where \((x_i, y_i, z_i)\) and \(t_i\) are the spatial position of the \(i\)-th transponder and the time of the \(i\)-th response signal with respect to the challenge time, \(t_0\) is the response delay of the \(i\)-th transponder, \((x_s, y_s, z_s)\) is the spatial position of subsystem installed in the mooring system, \(c\) is the sound speed.

The basic principle of the transponder position measurement is to measure the ship’s position under the guidance of DGPS, and take the DGPS position data of the measuring ship and the ranging data of the transponder in the corresponding position, and then use the sphere intersection model to solve the transponder position coordinates on seabed.

The position of the long baseline positioning system matches DGPS quite well. With a DGPS positioning accuracy of 0.05 m, the corresponding long baseline position error is 1.51 m, as shown in Table 1.

![Figure 2. (a) Long Baseline positioning (b) Transponder position measuring procedure](image)

![Figure 3. (a) Long baseline positioning and DGPS comparison results (b) Position of the LBL devices in mooring system changes in 3-months results](image)

<table>
<thead>
<tr>
<th>Positioning Root mean square error</th>
<th>Positioning error average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (X/m)</td>
<td>RMSE (Y/m)</td>
</tr>
<tr>
<td>0.81</td>
<td>1.27</td>
</tr>
</tbody>
</table>

The error of the long baseline position and the tilt sensor are input to simulate the received array of 640 meters above the transmitting transducer. If the position of the transmitting transducer is within the probability circle of diameter \(r\), Then the receiving hydrophone at 640 meters above the transducer should be located within the probability
circle of diameter R (assuming that the array is in a stretched state under the tension of 430 kg of buoyancy), the equation of error calculation is:

\[ R = r + \sin \left( \frac{\delta \theta}{2} \right) \times L \times 2 \]

Where \( R \) is the remote hydrophone position probability circle diameter, \( r \) is the transducer position probability circle diameter, \( \delta \theta \) is the maximum value of error of tilt sensor, \( L \) is the vertical distance between the transducer and hydrophone.

The simulation results (the blue part in the figure) given by the hydrophone positioning results are highly consistent with the actual received signal delay results (red part of the way) received by the hydrophone. As shown in Figure 4(b).

![Figure 4](image)

(a) Experimental results of arrival sound signal (b) Simulation results of arrival sound signal (blue) and experimental received signal delay results (red) comparison

4. SOUND SPEED INVERSION RESULTS

The sound velocity profile is decomposed into the weighted sum of multiple empirical orthogonal functions, and the dimension of the solution to be solved is reduced. Considering the situation that the speed of sound is independent of the distance, the acoustic rays modeling and the constrained least squares method are used in inversion. The results are shown in Figure 5. We can see the maximum error is about 1.3m/s, most errors are less than 0.5m/s.

![Figure 5](image)

(a) sound speed profile (b) inversion error

Figure 5: (a) Showing the sound speed profile where the green one is the sound speed profile from the CTD installed in the mooring system and the red one is for the estimated results (b) Inversion error
5. CONCLUSIONS

It is feasible to positioning the transmitting transducer and the receiving array elements in the deep sea mooring acoustic tomography system by using the long baseline positioning combined with the compass and the tilt sensor at the time of transmitting and receiving the acoustic pulse. The arrival time value of the acoustic signal received by the mooring system matches the theoretical simulation value.

The results of the inversion for sound speed show that the maximum error is about 1.3m/s. the error is less than 0.5m / s in average. The corresponding temperature inversion accuracy is within 0.12 degrees.

The use of compass and magnetic sensors is limited by its measurement accuracy, the error increases with the increasing length of the receiving array. Using array elements to receive long baseline system transponder positioning signal and solve the array position combine with compass and tilt sensor is intended to be carried out in the next step to validate the previous compass and tilt sensor results in deep sea acoustic tomography experiment in the near future.

ACKNOWLEDGEMENTS

This study was supported by the National Key Research and Development Program of China (2016YFC1400101); We will also give our sincere gratitude to Prof. Zhao Hangfang from Zhejiang University for her great job of data analysis and Prof. Liang Guolong from Haerbin Engineering University for supporting the long-baseline positioning technique in our first OAT experiment in deep sea.

REFERENCES