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LBL Seabed Datum Transfer without Acoustic Ray Correction

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Abstract:

This paper focuses on LBL seabed datum transfer as the research object. Long Baseline underwater acoustic positioning system (LBL) is applied to locating various submersible vehicles. Transmission of the LBL seabed datum is one of the key factors, which have impact on positioning accuracy of system. With the development of marine science and engineering technology, it has become a basic problem to transmit water surface or land datum to seabed accurately by use of LBL in deep-sea scientific research. Traditional seabed datum transfer method is of low accuracy, which adopts slant range observation and linear navigation observation or uses USBL/SBL directly. Based on ray theory, this paper combined the underwater acoustic broadband signals ranging technology with Global Navigation Satellite System (GNSS) precise positioning technology effectively. By using circular voyage to observe symmetrically and using classic adjustment theory to eliminate sound velocity systematic error, this paper realized the transmission with high precision between the seabed surveying and mapping datum and the land surveying and mapping datum without velocity of sound correcting. Experimental results showed that the accuracy of the reference point on the seabed can reach centimeter order, which is equal to the CNSS positioning accuracy. The proposed method has been verified by the experiment in Songhua Lake.

***Keywords**: Seabed datum, GNSS positioning, Ray theory, Broadband positioning.*

I. INTRODUCTION

The long baseline acoustic positioning system (LBL- Long Baseline) plays a significant role in the use of various underwater vehicles, and LBL seabed datum transfer is one of the key technologies that affect the system positioning accuracy. In addition, with the development of ocean science such as oceanic plate research, marine sediment research, submarine landslide monitoring, ocean engineering technology [1-4], precise transmission of water surface (land) surveying and mapping datum to the sea floor by LBL has become the basic problem in deep-sea research.

Traditional seabed datum transfer depends on slant-range observation and straight-line navigation observation method [5-7], or use ultra-short baseline (USBL) positioning system and short baseline (SBL) positioning system for datum transmission [8-12], all of which cannot prevent the deviation caused by acoustic ray bending, and the accuracy of seabed control point shall be at 0.5~1% magnitude of water depth. References [13] and [14] studied the positioning of single underwater transponder and its coordinate depends on limited layered medium model; comparison by actual measurement has not been carried out yet. This paper, based on Songhua Lake test, analyzes the effect of acoustic velocity error on range finding of the LBL system and put forward the transmission method for seabed surveying and mapping datum without acoustic ray correction.

II. BASIC PRINCIPLE

At present, Global Navigate Satellite System (GNSS) is widely used in establishing and maintaining high-accuracy three-dimensional geocentric coordinate system, establishing new ground control network, studying and refining geoid etc.[15]; but in highly conductive water, the energy of electromagnetic wave used by GNSS may lose about $1400 f^{1/2} dB / km$ (f in kHz) [16] in propagation with the increase of distance and thus cannot be used to build the seabed surveying and mapping datum. Different from electromagnetic wave, acoustic wave has excellent propagation performance in the ocean; range finding by acoustic broadband signal can reach centimeter accuracy. And with the advent of Global Positioning System Real-time Kinematic (GPS RTK), Post-processing Kinematic (PPK) and Precise Point Positioning (PPP) technologies, sea surface positioning has entered the era of high centimeter accuracy positioning. High-accuracy seabed surveying and mapping datum transmission can be realized by effectively combining ranging technology by underwater acoustic broadband signal with GNSS precise positioning technology.

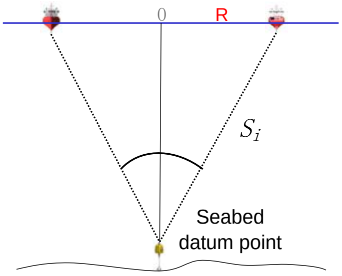

Fig. 1. The basic principle of LBL seabed datum transfer

As shown in Fig.1, the seabed datum point is fixed on the sea floor; the survey vessel, which sails on the sea, sends acoustic signal by a transducer, and measures the round-trip time τ with the transponder mounted at the seabed datum point through the way of “interrogation-reply”; and acoustic velocity C is obtained by Sound Velocity Profiler (SVP), then the slant range can be determined by:

$$S_i = C \times \tau / 2 . \tag{1}$$

The three-dimensional coordinate of transducer X_T is surveyed in real time by PPP or RTK, the three-dimensional coordinate of seabed datum point is X_B, then there is:

$$(X_B - X_T)^2 = S_i^2 \tag{2}$$

Equation (2) is used to form a system of equations according to the space intersection principle, and X_B is determined by adjustment computation. This is the basic principle for the realization of seabed surveying and mapping datum transmission.

III. LBL SEABED DATUM TRANSFER

3.1 Ranging Error Caused by Acoustic Velocity Measurement Error

By analyzing equation (1) and (2), we know that the accuracy of x_T can reach centimeter level; therefore, the accuracy of x_B is determined by the survey precision of s_i. When acoustic broadband signal is used in survey, the accuracy of time delay τ can reach 10^{-6}s and it would affect ranging error by only 4 mm [17]; therefore, the accuracy of x_B is determined by survey accuracy of c. The acoustic velocity in the seawater is not a constant and changes with depth, thus the acoustic wave may bend during propagation in the water; therefore, the slant range is not a straight line. The current accuracy of acoustic velocity measurement can reach up to 0.05 m/s. Under certain incidence angle, ranging error caused by acoustic velocity measurement error is proportional to the water depth, as shown in Fig.2. If range finding is carried out several thousands of meters underwater, its ranging error shall be over several meters. It is obvious that error effect caused by acoustic ray bending must be eliminated to realize high-accuracy transmission between seabed surveying and mapping datum and land datum.

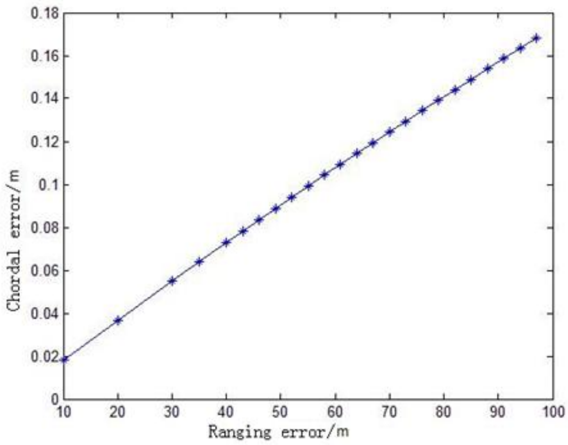

Fig. 2. The ranging error caused by the velocity measurement error

3.2 Snell Law of Refraction

In underwater acoustics engineering, approximate treatment method is often used in ray acoustics. The sound velocity profile in the seawater is divided into several layers along the depth, and relative sound velocity gradient in each layer equals constant, namely layered medium model [18]. As shown in Fig. 3, the propagation of acoustic wave in the seawater shall meet the Snell law:

$$\frac{\cos\alpha}{c} = \frac{\cos\alpha_0}{c_0} = Constant \tag{3}$$

Where α is the included angle of acoustic propagation direction to the horizontal plane and is called grazing angle, c is the acoustic velocity at that position, α_0 and c_0 are the corresponding values of the acoustic ray emission.

3.3 Symmetrical Observation Method Based on Circlenavigation

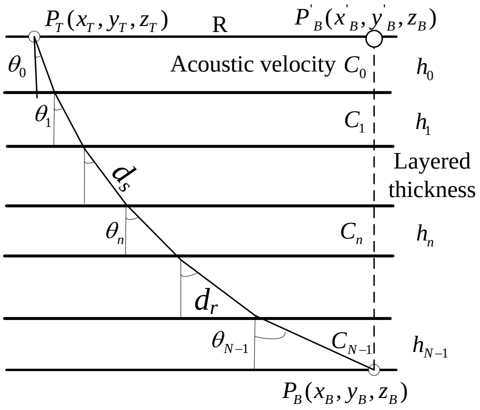

Fig. 3. The approximation acoustic ray of layered medium model

As shown in Fig.3, in three-dimensional plane coordinate system $O(x,y,z)$, the positions of transducer and seabed datum point are expressed by $P_T=(x_T,y_T,z_T)$ and $P_B=(x_B,y_B,z_B)$ respectively. $P_T=(x_T,y_T,z_T)$ is provided by GNSS and $P_B=(x_B,y_B,z_B)$ is to be determined. $P'_B=(x'_B,y'_B,z_T)$ is the point where $P_B=(x_B,y_B,z_B)$ is vertical upward projection to the plane of $P_T=(x_T,y_T,z_T)$. The horizontal distance between the two is denoted as R, and the observed slant range of transducer to the seabed transponder is denoted as S. According to the Snell law, there is:

$$d_{s_n} = \frac{h_n}{\cos\theta_{mn}} \tag{4}$$

$$d_{r_n} = h_n \tan\theta_{mn} \tag{5}$$

Then there is:

$$S = \sum_{n=0}^{N-1} d_{sn} \tag{6}$$

$$R = \sum_{n=0}^{N-1} d_{rn} = \sqrt{(x'_B - x_T)^2 + (y'_B - y_T)^2} \tag{7}$$

In the limited space, parameters of working sea area such as temperature and salinity are relatively constant [19]. Therefore, the sound velocity profile is constant; the ranging error caused by sound ray error is system error and is denoted as ε_c .The linear distance of transducer to seabed transponder is denoted as D_S , and then there is:

$$D_S = S + \varepsilon_c$$

$$\sqrt{(x'_B - x_T)^2 + (y'_B - y_T)^2 + (z'_B - y_T)^2} = S + \varepsilon_c \qquad (8)$$

As shown in Fig.1, the mother vessel uses circular navigation observation with horizontal-projected point of seabed transponder *O* as center and *R* as radius to synchronously collect the position of the transducer $P_{T_m}(x_{T_m}, y_{T_m}, z_T)$ and its slant range with seabed transponders $S_m (m = 1, 2, 3, 4 \ldots, M)$. P_{T_m} and S_j form data pairs, which are mutually-independent observation quantities. Given that P'_B is known, there are many data pairs symmetrical with the circle that uses P'_B as center and *R* as radius, and the system error ε_c of the surveyed value of S_m caused by acoustic ray bending are equal. Therefore, ε_c would only effect the depth value of seabed datum point and the depth value is provided by pressure sensor. During real-time observation, because P'_B is unknown, it is very difficult for the mother vessel to navigate in the identical radius. If GNSS data at the time of deploying the seabed transponder is used as the initial coordinate of P'_B, then there is always some data symmetrical with the initial coordinate as center in the observed data, and ranging error can be eliminated by repeat observation. The method is as follows:

Use seabed tripod to deploy the transponder used as the seabed datum point on the sea floor; the tripod can make sure the seabed datum point does not have any displacement, meanwhile, use the GNSS position at the time of deploying as the original coordinate of seabed datum point and denote it as $P_B^G = (x_B^G, y_B^G, z_T)$ .With reference to Fig.1, observation is performed symmetrically by circle navigation and the mother vessel makes one circuit with P_B^G as center and R_0 (R_0 takes the water depth H of seabed datum point) as radius to synchronously collect the coordinate of the transducer $P_{T_m}^G (m = 1, 2, 3, 4 \ldots, M)$, the slant range of the transducer to the transponder of seabed datum point $S_m^G (m = 1, 2, 3, \ldots, M)$ and values of pressure sensors on the transponders $Z_{B_m}^G (m = 1, 2, 3, \ldots, M)$ .Given that the coordinate of seabed datum control point is $P_B^0 = (x_B^0, y_B^0, Z_B^0)$, set up *M* pieces of equations according to equation (1) to form the following equation (M≥4):

$$\begin{cases} \sqrt{(x_B^0 - x_{T_0}^G)^2 + (y_B^1 - y_{T_0}^G)^2 + (z_B^G - z_{T_0}^G)^2} = S_0^G \\ \sqrt{(x_B^0 - x_{T_1}^G)^2 + (y_B^1 - y_{T_1}^G)^2 + (z_B^0 - z_{T_1}^G)^2} = S_1^G \\ \ldots \\ \sqrt{(x_B^0 - x_{T_M}^G)^2 + (y_B^1 - y_{T_M}^G)^2 + (z_B^0 - z_{T_M}^G)^2} = S_M^G \end{cases} \qquad (9)$$

Use the least square method to solve the equation (9) and obtain $P_B^0 = (x_B^0, y_B^0, Z_B^0)$, which is used as the

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initial values of observation and iteration calculation. The mother vessel shall make *L* circuits clockwise and counter-clockwise respectively by using $P_B^0 = (x_B^0, y_B^0, Z_T)$ as center and water depth value of seabed datum point as radius $R_i(i = 1, 2, 3, 4, \cdots, 2L)$. The clockwise navigation is expressed in odd and the counterclockwise in even, and vice versa. The coordinate of the transducer $P_{T_m}^i(x_{T_m}^i, y_{T_m}^i, z_{T_m}^i)(m = 1, 2, 3, 4, \dots, M)$, the slant range of the transducer to the transponder of seabed datum point $S_m^i(m = 1, 2, 3, 4, \cdots, M)$ and $z_{B_m}^i(m = 1, 2, 3, 4, \dots, M, \mathrm{M} \geq 4)$ are synchronously collected in each circuit.

3.4 Iteration Calculation of Coordinate of Seabed Array Elements

Use the least square method to calculate, and data used for calculation shall be more than 4 sets. The steps for iteration calculation of observation data for the *i* circuit are as follows:

Step 1: Given that $P_B^j = (x_B^j, y_B^j, z_B^j)$ ($j = 0, 1, 2, \dots, k$ as iteration times) and $P_{T_m}^{i_j} = (x_{T_m}^{i_j}, y_{T_m}^{i_j}, z_{T_m}^{i_j})$ $(m = 1, 2, 3 \dots, M - 4j)$ of the *i* circuit are known conditions, form the system of equations according to equation (1), and use the least square method to obtain $S_m'^{i_j}(m = 1, 2, 3, \dots, M - 4j)$. Analyze statistically and calculate the standard difference σ and best estimation $\overline{S'}^{i_j}$ of $S_m'^{i_j}$.

Step 2: Use the standard of 2σ and 3σ to compare $\overline{S'}^{i_j}$ and $S_m'^{i_j}(m = 1, 2, 3, \dots, M - 4j)$ of the *i* circuit, and cancel some data to obtain $S_m'^{i_{j+1}}$ and $P_{T_m}^{i_{j+1}}(x_{T_m}^{i_{j+1}}, y_{T_m}^{i_{j+1}}, z_{T_m}^{i_{j+1}})(m = 1, 2, 3, 4, \cdots, M - 4(j+1))$. $S_m'^{i_{j+1}}$ and $P_{T_m}^{i_{j+1}}$ are known conditions, form system of equation by equation (2) to obtain $P_B^{j+1} = (x_B^{j+1}, y_B^{j+1}, z_B^{j+1})$ by adjustment calculation.

Step 3: Repeat Step 1 and Step 2 for iteration calculation to finally work out the coordinate of seabed datum point $P_B^i(x_B^i, y_B^i, z_B^i)$ that meets the accuracy requirement.

According to the above steps, 2L pieces of coordinates of seabed array transponders $P_B(x_B, y_B, z_B)$ are obtained. By statistically analyzing those coordinates, the best estimation of the coordinate of seabed datum point can be finalized.

IV. BUILDING OF HIGH-ACCURACY LBL SEABED DATUM

Coordinates of other seabed datum points can be obtained according to the above method. In addition, trilateration control network similar to land survey can be obtained through mutual range finding between all transponders of LBL seabed array. The baselines of control network are mutually independent and are connected into a closed triangulation network or array network made up of polygon control networks. Carry out adjustment in one cast by least square method to eliminate the discrepancy of those conditions for closure and build the datum for array network, namely position, direction and dimension datum of the network. Then, according to the typical adjustment theory of control network, carry out adjustment calculation by using the surveyed coordinates (2-3 pieces) of the seabed control point obtained by the above method as constraint condition and work out coordinates of other datum points [20,21].

In actual work, the seabed transponder is integrated with high-accuracy pressure sensors, so it can project the point onto the designated plane for two-dimensional network adjustment calculations. In short, there are precise control points and trilateration network in the datum network, and calculation can also be carried out by using other methods in modern adjustment theory; in this way a high-accuracy seabed surveying and mapping datum is built.

V. EXPERIMENTAL VERIFICATION

According to the above principle and method, field data observation was carried out with the 6G LBL underwater acoustic positioning system of British Sonardyne in Songhua Lake, Jilin, and data processing and computation was also carried out.

During the experiment, the flow velocity is slow, the passing vessels are relatively few, and the bottom of the lake is muddy sand, which is conducive to the development of the experiment. Based on the topographic map of the lake bottom, the depth of the lake water and the fluctuation of the lake bottom, the area of array projection with a total area of about 1.5 square kilometers is selected, which is within the red frame shown in Fig 4. The terrain of this region is relatively flat and the water depth is about 64 meters.

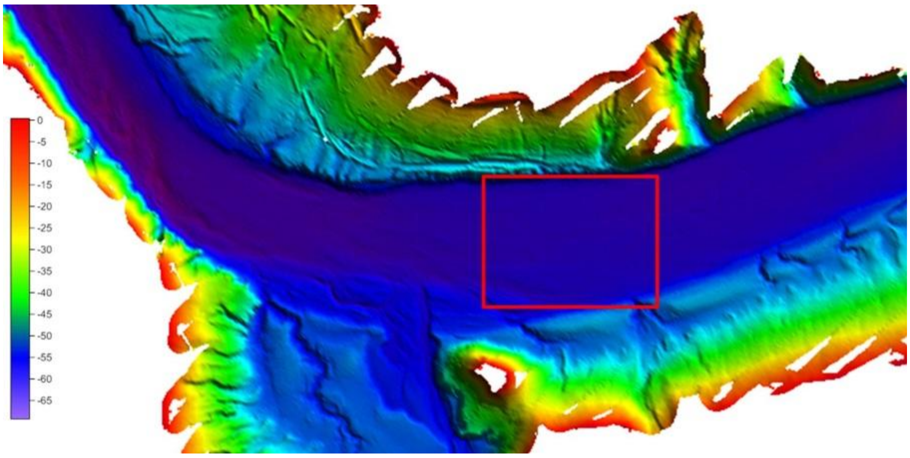

Fig. 4. Test area

The 6G LBL underwater acoustic positioning system used in this experiment includes five elements and their floating bodies, one tracking and positioning transceiver (including telemetry transducer) and deck units. The subsea target tracking accuracy independent of depth of 6G LBL is centimeter level and the ranging accuracy is better than 0.015m.

When carrying out observation, five transponders acted as control points were put into the lake basin and GPS RTK was used to calculate the coordinate of the transducer. According to the method of this paper, observation and calculation of the absolute positions of those five points were carried out, and the trilateration network of datum network was observed at the same time. Algorithm experiment is realized based on matlab.

Through statistical analysis of the observation data, data that are twice the standard deviation are chosen and those with larger errors are removed. TABLE I shows the calculation results of 5 array elements, TABLE II shows the calculation results of different iteration times of C8. Due to difference in observation sequence, calculation is carried out for clockwise, counterclockwise and all data, and the results are shown in TABLE III.

TABLE I. Adjustment results of seabed array elements

CONTROL POINT	X/M	Y/M	Z/M	σP/±M
c8	4841896.685	315736.449	60.378	0.007
c5	4841864.983	315792.608	59.834	0.006
c2	4841955.114	315690.413	60.955	0.005
c4	4841835.066	315697.764	59.964	0.004
c6	4841969.620	315787.096	60.562	0.007

TABLE II. Adjustment results of different iterations

ITERATION TIMES	X/M	Y/M	Z/M	σP/±M
1	4841892.357	315730.709	60.419	0.015
2	4841896.683	315736.365	60.726	0.010
3	4841896.698	315736.376	60.340	0.010
4	4841896.698	315736.376	60.340	0.010

TABLE III. Adjustment results of different observation

DATA	X/M	Y/M	Z/M	σP/±M
CLOCKWISE DATA	4841896.698	315736.376	60.340	0.010
COUNTERCLOCKWISE DATA	4841896.671	315736.522	60.463	0.010
ALL DATA	4841896.685	315736.449	60.378	0.007

VI. CONCLUSION

Based on the relatively stable characteristics of marine environment, this paper demonstrates that LBL seabed datum transfer can be realized without acoustic ray correction by effectively combining underwater precise ranging technology with GNSS precise positioning technology, with conclusions as follows:

(1) Based on symmetrical observation of circular navigation, the ranging error caused by acoustic measurement error is effectively eliminated.

(2) LBL underwater array element positional precision can be improved by counterclockwise and clockwise observations.

(3) The results of Songhua Lake test show that the accuracy of control points underwater is amount to

GNSS positioning accuracy, which realizes the high-accuracy transmission of LBL seabed datum from land datum.

The theoretical method can be further verified in the deep-sea environment.

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