Ways to Correct the Errors in Posture of Multi-beam Sounding Resulted from Water Flow

Xin Wang¹, Chengkai Feng¹, Jiayong Yu¹, Maoyi Tian¹∗ and Pingwei Fu²

¹College of Geomatics, Shandong University of Science and Technology, Qingdao, Shandong, 266000, China
²Sanya Land Resources and Mapping Geographic Information Center, Sanya, Hainan, 572000, China
* Corresponding author’s e-mail: tianmaoyi_zhy@126.com

Abstract. Multi-beam bracket deformation is caused by factor like water flow and speed of ship. Such deformation also leads to the axle offset of relative attitude indicator of transducer, which may influence the accuracy of results. As for this phenomenon, the paper proposes a method that calculates water velocity and output speed of ship according to the navigation data, in order to fit the attitude deviation and correct the results of depth measurement. First of all, water velocity and output speed of ship of two adjacent stripes without abnormal sounding results in the testing zone in good sea condition are calculated respectively according to navigation data, and then the errors in posture of these two stripes in different time are worked out respectively based on discrepancy in elevation of the overlapping portions of the stripes; secondly, a modifier formula of water velocity, output speed of ship and errors in posture is formulated; finally, this formula is applied to solving errors in posture and correcting the sounding data of stripes in the testing zone. According to the experimental results, the proposed method can eliminate errors in posture effectively, with the average of discrepancy in elevation reduced from 0.188m (before) to 0.032m (after). The stripe splicing effect is improved and the data accuracy is enhanced enormously.

1. Introduction
Multi-beam sounding system, a submarine topographic measurement technology developed in the 1960s, with a variety of sensors such as transceiving transducer, GNSS positioning system and attitude determination system, boasts advantages such as large detection range, high speed and high precision. Multi-beam sounding technology has become a key means of underwater topographic survey.

With multiple sensors involved in, Multi-beam sounding system is highly complicated, and its results are subject to the influence of multiple error sources for the complex ocean environment for measurement [1]. Errors in posture refers to the phenomenon where the posture of attitude indicator measurement is inconsistent with the actual posture of transducer resulted from the axle offset of attitude indicator and transducer caused by multi-beam bracket deformation resulted from causes such as water flow, wave and ship speed. Different from accidental errors in the measurement process of attitude indicator, such errors in posture are systematic errors with long change circle. The impact of errors in posture on the edge beam is greater than that on the central beam, as tens of centimeters of error may emerge at the edge beam in poor sea conditions, so the stripe splicing effect is affected tremendously. It will has a great impact on the accuracy and aesthetics of the final measurement results if it remains uncorrected.
Zhang Deng et al. analyzed the impact of installation deviation on the sounding results[2], Ma Kai et al. studied the profile error correction of sound velocity[3], John E. Hughes Clarke analyzed errors in posture resulted from integral errors and their manifestations[4], Yang Fanlin analyzed the characteristics of errors in posture caused by sensor offset and its influence on beam homing[5-6] and Li Jiabiao summarized the empirical model of the relationship between ship speed and dynamic draft[7]. In short, for the principles of installation deviation, sound velocity profile error and the impact of errors in posture and the influence of ship speed and water flow on draught, some experts at home and abroad already carried out systematic research, but correction of errors in posture caused by water flow has been less studied. A method to calculate water velocity and output speed of ship for fitting errors in posture and correction of sounding results according to navigation data is proposed in this paper. Experiments prove that correction with this method can reduce the discrepancy in elevation of adjacent stripes resulted from errors in posture and improve the stripe splicing effect.

2. Calculation of Water Velocity and Output Speed of Ship with Navigation Data

Different from the resultant velocity of ship relative to the land, the speed of ship relative to water is called the output speed of ship, which is determined by the output power of the ship’s engine. The speed provided by the GNSS system is the resultant velocity of ship relative to the land and no ADCP is matched to measure flow rate simultaneously in general multi-beam operations, but since the resultant velocity of ship relative to the land can be regarded as the vector sum of water velocity and output speed of ship, so water velocity and output speed of ship can be worked out according to the direction of the bow and the actual movement of the ship.

The resultant velocity of ship is subject to the influence of multiple factors such as wind speed, water velocity and wave, the following assumptions is made to simplify the issue:
1. The direction and speed of water flow are consistent in a short time;
2. As shown in figure 1, the resultant velocity of ship can be regarded as the vector sum of water velocity and output speed of ship, and water velocity, output speed of ship and resultant velocity are in line with the parallelogram rule, namely:

\[
\begin{align*}
|V_{\text{water}}| \sin \alpha &= |V_{\text{ship}}| \sin \beta \\
|V_{\text{water}}| \cos \alpha + |V_{\text{ship}}| \cos \beta &= |V|
\end{align*}
\]

In the formula, \(V_{\text{water}}\) represents water velocity, \(V_{\text{ship}}\) represents the output speed of ship and \(V\) represents the resultant velocity given by the GNSS system, \(\alpha\) represents the acute angle formed by the direction of water flow and the resultant velocity of ship, \(\beta\) represents the acute angle formed by the output speed of ship and the resultant velocity of ship derived from the calculation of real-time heading and line azimuth of the attitude indicator, and both \(\alpha\) and \(\beta\) are positive values.

Hypothesis 1 and Hypothesis 2 are in line with the actual situation in most cases.
The steps to calculate water velocity and the output speed of ship, are as follows:
As shown in figure 2, the motion state of the ship measured at a certain time is decomposed. Specifically, Point A and Point B represent two points on the same line, and the state of the ship measured at Point A is decomposed; \( H \) represents the heading of the ship measured at point A given by the inertial navigation system; \( H_{\text{line}} \) represents the coordinate azimuth of the line from Point A to Point B worked out according to the coordinates of these two points; \( \gamma \) represents the coordinate azimuth of the direction of water flow at point A; \( V_{\text{water}}, V_{\text{ship}} \) and \( V \) represent water velocity, the output speed of the ship measured and the actual resultant velocity of the ship measured, respectively.

The following formulas can be set based on Hypothesis 2:

\[
V_{\text{ship}} \times \sin(H_{\text{line}} - H) - V_{\text{water}} \times \sin(\gamma - H_{\text{line}}) = 0
\]  
\( V_{\text{water}} \) can be set based on Hypothesis 2:

\[
V_{\text{ship}} \times \cos(H_{\text{line}} - H) + V_{\text{water}} \times \cos(\gamma - H_{\text{line}}) - V = 0
\]

The following conditions should be met at the same time:

\[
V_{\text{ship}} + V_{\text{water}} > V
\]  
\[
V_{\text{ship}} + V > V_{\text{water}}
\]  
\[
V_{\text{ship}} + V > V_{\text{water}}
\]

For the least squares solution of the formula worked out in a period of time based on Hypothesis 1, \( V_{\text{water}}, V_{\text{ship}} \) and \( \gamma \) are worked out.

3. Characteristics and Solutions of Errors in Posture

3.1. Generation and Characteristics of Errors in Posture Resulted from Water Flow

Embedded, mounted and ceiling mounted installations are commonly applied to multi-beam transducer. Compared with other installation methods, there is a certain distance between the transducer and the bottom of the ship in ceiling mounted installation, protecting the acoustic performance of the transducer from impact of the turbulent layer and air bubbles under the bottom of the ship [8] to endow the multi-beam with higher imaging quality. However, the hull resistance in this installation will increase significantly and the draught depth and the maneuverability of the ship will also be affected, and the possible deformation of the bracket will affect normal operation of the equipment [9]. Great velocity and speed of ship in ceiling mounted installation of the transducer may bend the bracket and cause axis deflection of the transducer, which will result in errors in posture.

Errors in the placement parameters and the real-time posture will lead to the overall deviation of the sounding points and affect the splicing of adjacent stripes. For the difference between them, the placement parameters are fixed values, the stripe splicing problem caused by the placement parameter errors have consistent performance if there is no other error and the discrepancy values in elevation are positive or negative constantly, so the resulted stripe splicing problem will be manifested as that a certain stripe is always higher than the other stripe; after errors in installation are corrected, accidental errors in the measurement of the attitude indicator may cause “wrinkles” on the underwater terrain, and since errors in posture resulted from axis offset may lead to long-period shift of the underwater terrain, stripe splicing may have different performance at different positions of the survey line (as shown in figure 3); moreover, as the discrepancy values in elevation have no fixed symbol, the resulted stripe splicing problem will be manifested as that the adjacent stripes are on the top alternatively.
As shown in figure 3, the symbols of discrepancy values in elevation resulted from errors in posture at different positions of the line may be opposite. For two identical lines, the elevation of the stripe on the right side of the upper area is higher, and the elevation of the stripe on the left side of the lower area is higher. If the attitude indicator and the transducer still have a deflection angle $\alpha$ around the z-axis after installation deviation correction, then the relationship between the actual roll and pitch of the transducer and the roll and pitch measured by the attitude indicator is:

\[
\begin{align*}
\sin r' &= \sin \alpha \sin p + \cos \alpha \sin r \\
\sin p' &= \cos \alpha \sin p - \sin \alpha \sin r
\end{align*}
\]

(7)

In the formula, $\alpha$ is the deflection angle around the z-axis of the attitude indicator and the transducer after installation deviation correction; $r$ is the actual roll; $p$ is the actual pitch; $r'$ is the measured roll; $p'$ is the measured pitch.

Formula (7) indicates that errors in posture are related to the true attitude and the deflection angle.

The approximation of the impact of errors in posture on water depth without considering the ray refraction:

\[
E_V=Z \left[ 1- \frac{\cos (\theta + \delta_r)}{\cos (\theta)} \right]
\]

(8)

\[
E_V=Z (1-\cos (\delta_p))
\]

(9)

In the formula, $E_V$ is the water depth error; $\theta$ is the beam angle; $\delta_r$ is the roll deviation; $\delta_p$ is the pitch deviation; $Z$ is the measured water depth.

According to formula (8) and formula (9), the influence of roll deviation on the measurement accuracy of edge beam exceeds that on the center beam, and the difference will cause that the submarine topography will rotate around the x-axis by a certain angle[10]; moreover, the influence of pitch deviation on water depth is similar to sinkage and the impact on all depth points in the same ping. It is assumed that the ocean floor is flat, the water depth is 25m, the opening angle is 120° and the error in attitude measurement is 0.3°, then the error in depth caused by pitch deviation is less than 1 mm and the error in depth caused by roll deviation at the edge beam is up to 22cm. For the edge beam, the impact of pitch deviation on water depth is greater than that of roll deviation and sinkage error, and the impact of errors in posture on splicing of adjacent stripes is mainly embodied on roll deviation.

3.2. Solution of Errors in Posture

According to formula (8), the following equation can be set for discrepancy in elevation caused by roll deviation for adjacent stripes:

\[
Z_1 \times \left[ 1- \frac{\cos (\theta_1 + \delta_r)}{\cos \theta_1} \right] - Z_2 \times \left[ 1- \frac{\cos (\theta_2 + \delta_r)}{\cos \theta_2} \right] = 0
\]

(10)
In the formula, $Z_1$ and $Z_2$ represent the water depth values measured at the two stripes for sampling, respectively. $\delta_{r1}$ and $\delta_{r2}$ represent the roll deviation of the two stripes at this moment and $\theta_1$, $\theta_2$ represent the beam angles of the two stripes at the sampling point.

For a certain sampling point, the change of $\delta$ can be regarded as subtle in a very short time, and $\delta_{r1}$ and $\delta_{r2}$ can be obtained by solving equation (10) for the least squares solution in the neighbourhood.

4. Fitting of Errors in Posture with Water Velocity and Output Speed of Ship and Correction of Sounding Results

Equation (7) indicates that errors in posture are related to the true attitude and the deflection angle. Water velocity and output speed of ship are key factors with influence on attitude and the deflection angle and a functional relationship with errors in posture. Two representative adjacent survey lines with quality data are chosen in the testing zone with respective water velocity and output speed of ship solved with navigation data, and errors in posture are solved with discrepancy in elevation of the overlapping region of the two stripes. Function fitting is carried out for water velocity, output speed of ship and errors in posture. Correction of the elevation of all stripe sounding points in the testing zone with this functional relationship can solve the problem of stripe splicing resulted from errors in posture caused by water velocity and ship speed.

5. Experimental Analysis

The experimental data was collected with EM2040 multi-beam & Trimble SPS351 beacon, OCTANS high-precision fiber inertial navigation, AML SV Plus V2 sonic velocity profiler and DCX-25 tide gauge; the surveying vessel is 20.6 meters long and 4 meters wide; as shown in figure 4, the transducer was installed in a hoisting manner with a 2-meter long bracket. The data was collected in a certain sea area of Zhejiang Province from May to June 2018.

$\sigma$ is set as $V_{ship} \times \cos(H_{line} - heading)$, where $V_{ship}$ represents the actual output speed of the ship, $H_{line}$ represents the coordinate azimuth of heading of the ship and heading represents the coordinate azimuth of the bow direction. According to the test, $\delta_r$ can be fitted better in the quadratic function form of $\sigma$, with the fitting result shown in figure 5.

As shown in figure 6 and figure 7, $V_{water}$, $V_{ship}$ and $\gamma$ are obtained from equations 2-6 based on hypothesis 1, and the sounding points are corrected by the roll error $\delta_r$ obtained by quadratic function fitting, with the stratification of stripes improved significantly and a good effect of correction achieved. The average discrepancy in elevation is reduced from 0.188m to 0.032m.
6. Conclusion

The calculation approach of water velocity with navigation data proposed in this paper is used to calculate water velocity and output speed of ship without ADCP, and function fitting is carried out for errors in posture based on velocity information and discrepancy in elevation of stripes. The sounding result is corrected with the correction formula obtained by fitting with an ideal effect achieved, as the average discrepancy in elevation drops from 0.188m to 0.032m. With the data accuracy and the appearance of drawing improved, it is beneficial for solving the problem of stripe splicing caused by water flow.

Acknowledgments

Funding: This research was funded by National Science and Technology Major Project of the Ministry of Science and Technology of China (No.2013YQ120343, No.040326010701).

References

[1] Zhao, J.H., Zhang, H.M., Yan, J., Zhang, Y.Q. (2013) Study on the Method of Attenuating the Combined Influence of Residual Errors on Multi-Beam Sounding. Journal of Wuhan University (Information Science Edition), 38(10):1184-1187.

[2] Zhang, D., Zhu, Y.L., Zhang, T., Zhang, Y.Y., Wu, B.J. (2019) Calibration Method of Sea Beam 3012 Deepwater Multi-beam Sounding System. Geomatics & Spatial Information Technology, 42(04): 144-149.

[3] Ma, K., Xu, W.M., Xu, J., Dong, Z.Y. (2019) A Multi-beam Sound Velocity Profile Inversion and Submarine Terrain Correction Technique. Journal of Wuhan University (Information Science Edition), 44(04): 525-531+600.

[4] Clarke, J. (2003) Dynamic Motion Residuals in Swath Sonar Data: Ironing out the Creases. International Hydrographic Review, 4(1):6-23
[5] Yang, F.L., Lu, X.S., Li, J.B., Guo, J.Y. (2010) Ways to Correct Multi-beam Surveying Motion Sensor Offset. Journal of Wuhan University (Information Science Edition), 35(07): 816-820.

[6] Yang, F.L., Li, J.B., Wu, B.Y., Zhao, L.H., Ai, B. (2009) Ways to Correct the Instantaneous Errors in Posture of Multi-beam Sounding. Journal of Surveying and Mapping, 38(05): 450-456.

[7] Li, J.B. (1999) Multi-beam Survey Principles & Technology and Methods. Ocean Press, Beijing.

[8] Cao, R., Tian, Y.F., Chen, D.D., Li, Z.Y., Tan, H.C. (2016) Selection of Ways to Install Multi-beam Transducer for an Oceanographic Vessel. China Water Transport (Second Half), 16 (01): 129-131.

[9] Chen, R. (2014) Comparison of Performance of Ways to Install Multi-beam Transducer. Ship Science and Technology, 36 (S1): 79-82.

[10] Zhang, Y.C., Zhang, B. (2010) Correlation Analysis of Various Parameters in Multi-beam Installation Calibration. Marine Charting, 30 (01): 53-55+58.