Analysis of Baseline Length Selection of Beidou RTK in Attitude Determination of Special Vehicle

Chuanqiang Yu, Fan Yang* and Bowen Zhang
Xi’an Hi-tech Institute, Xi’an 710025, China

*Corresponding author e-mail: yfan20130904@163.com

Abstract. With the completion of the Beidou satellite navigation system, its single Beidou RTK technology has become a new technical means for the pose measurement of special vehicles. This article first introduced the advantages and related principles of Beidou RTK technology. The experimental platform was set up for testing and analysis on the basis of the relationship between baseline length and measurement accuracy, and the optimal baseline length of practical installation was obtained in combination with the outline dimensions of the special vehicle.

1. Introduction
In the process of special vehicle driver’s field training examination, the position and posture of vehicles in the field are the important basis to judge the driver's driving skills, so the measurement of the vehicle's attitude is an important content. As the development direction of modern measurement technology, satellite positioning technology has been widely used in driving training institutions and vehicle management institute, which also provides reference for the troops to apply it to the position measurement of large launching vehicles.

The Beidou satellite navigation system (BDS) is a satellite navigation system with independent construction, independent operation and openness, which is focus on national security and economic and social development needs. It provides all weather, all day positioning and navigation services. It has high precision, high reliable positioning, navigation and time service, and has a short message communication capability [1]. The measurement of Real Time Kinematic (RTK), which can obtain the accuracy of centimeter or millimeter level positioning in real time, is a major milestone in the high precision application of satellite navigation. Its appearance has greatly enhanced the performance of various high precision measurement applications such as project lofting, topographic mapping and so on.

2. The attitude measurement principle of the Beidou System

2.1. Definition of attitude angle and conversion of relative coordinate system

The attitude of the carrier generally refers to the angle relation of the carrier coordinate relative to the various axes of the local geographic coordinate system [3]. The attitude of the carrier is determined by three attitude angles, which are the pitching, the rolling and the yaw. There are three coordinate systems for the attitude measurement of the carrier: the earth-centered-earth-fixed, the body frame system and the geographic coordinate system.
The Earth-Centered-Earth-Fixed (ECEF) is located in the earth's mass center, the Z axis points to the earth's North Pole, and the X axis points to the intersection of the original meridian surface and the earth equator, and the Y axis and the X and Z axis constitute the right hand coordinate system. The Beidou system uses the 2000 national geodetic coordinate system (CGCS2000) [4].

The geographical coordinate system is also called the local level system (LLS). In general, its origin coincides with the origin of the body frame system. In order to eliminate the origin shift of the coordinate system, the X axis points to the local North meridian, the Y axis is perpendicular to the X axis, and the Z axis is orthogonal to the X axis and the Y axis to form the right hand coordinate system, which is often referred to as the "northeast" geographical coordinate system.

The Body Frame System (BFS) generally takes the phase center of the main antenna as the original point [5], the X axis is right along the carrier transverse axis, the Y axis is forward along the carrier longitudinal axis, the Z axis is perpendicular to the X axis and the Y axis, and the right hand coordinates are formed vertically along the carrier.

For M at any point in space, the relationship between CGCS2000 coordinates and local level system is written in matrix form:

\[
\begin{bmatrix}
X_M \\
Y_M \\
Z_M
\end{bmatrix}_{LLS} =
\begin{bmatrix}
-\sin B \cos L & -\sin L & -\cos B \cos L \\
-\sin B \sin L & \cos L & -\cos B \sin L \\
-\cos B & 0 & -\sin B
\end{bmatrix}
\begin{bmatrix}
X_M - X_H \\
Y_M - Y_H \\
Z_M - Z_H
\end{bmatrix}_{CGCS2000}
\]

In the formula, B and L are geodetic latitude and longitude respectively at the origin H of the local level system. \([X_H \ Y_H \ Z_H]_{CGCS2000}\) and \([X_M \ Y_M \ Z_M]_{CGCS2000}\) are coordinates of H points and M points in CGCS2000 coordinate system, respectively.

The origin of the local level system and the body frame system are the same, all in the phase center of the main antenna, and the transformation parameters between the two are actually three Eulerian angles. In the initialization stage of the attitude measurement, the coordinates of the CGCS2000 coordinates are obtained. As the initial known data of the attitude calculation, the attitude angle can be calculated by the above two coordinate transformation.

2.2. Principle of baseline vector measurement

The baseline length of the dipper on the carrier is usually meter level, and the baseline vector is measured accurately by the carrier phase difference method, and the phase difference almost eliminates all the error sources of the existing spatial correlation [6]. Take a single baseline as an example, as shown in the picture 1. The Beidou satellite can be seen as a parallel wave when it reaches more than 20000km of the ground and reaches the two Beidou antenna. The phase difference between the two antennas is.

\[
\varphi = eb + \lambda N
\]

The e is the unit vector of the Beidou antenna to the satellite. The position coordinates of the antenna are obtained from the pseudo range positioning, and the coordinates of the satellite are obtained from the satellite ephemeris. \(b = [x \ y \ z]^T\) is the coordinates of the unknown baseline vector in the earth coordinate system. For carrier wavelength, N is a whole week ambiguity.
If \( n \) satellites are observed at a certain time, the \( N \) group baseline vector coordinates are obtained and the observation equations are obtained.

\[
\begin{bmatrix}
\varphi_1 \\
\varphi_2 \\
\vdots \\
\varphi_N
\end{bmatrix} = \begin{bmatrix}
e_1 \\
e_2 \\
\vdots \\
e_N
\end{bmatrix} \begin{bmatrix}X \\ Y \\ Z \end{bmatrix} + \lambda \begin{bmatrix}N_1 \\ N_2 \\
\vdots \\
N_n \end{bmatrix}
\] (3)

From the formula (3), we can see that only the correct integer ambiguity \( N \) is required, the baseline vector \( b \) can be solved. Ambiguity resolution is not the object of this paper and the process is complex. It can be consulted in document [7]. The baseline vector \( b \) is converted into coordinate transformation, and the transformation matrix of baseline vector \( b^c \) (carrier coordinate system), \( b^l \) (geographic coordinate system) and two baseline vector is obtained, and the attitude angle can be solved.

3. The relationship between the length of the baseline and the measurement accuracy

What is the relationship between baseline length and attitude accuracy? This paper will deduce this problem. It is assumed that the vector of the base line in the carrier coordinate system is \( b_i = [x_i^b ~ y_i^b ~ z_i^b]^T \), and its corresponding vector in the geographic coordinate system is \( l_i = [x_i^l ~ y_i^l ~ z_i^l]^T \), which satisfies the previous transformation relation, that is,

\[
b_i = R_x(r)R_y(p)R_z(y)l_i
\] (4)

If \( v \) is the difference between the observed value and the true value, then there is.

\[
v = \tilde{b}_i - b_i = \tilde{b}_i - R(r,p,y)l_i
\] (5)

It is assumed that the estimation value of the attitude angle is \( \tilde{x} = [\tilde{y} ~ \tilde{p} ~ \tilde{f}]^T \), and there is a relational \( \tilde{x} = x_0 + \delta x \), and the delta x is the difference, so that a new relation about \( v \) and \( \tilde{x} \) is established according to formula (5):

\[
f(\tilde{x},v) = b_i + v - \tilde{b}_i = R(r,p,y)l_i + v - \tilde{b}_i = 0
\] (6)

By Taylor series, ignoring the polynomial above the second power, the formula (6) can be rewritten as.

\[
f(\tilde{x},v) = f(x_0,v_0) + \left. \frac{\delta f}{\delta x} \right|_{x_0,v_0} \delta x + \left. \frac{\delta f}{\delta v} \right|_{x_0,v_0} \delta v = W_i + A \delta \tilde{x} + B \delta v = 0
\] (7)

In the form:
\[ W_i = f(x_0, v_0) = R(y_0, p_0, r_0)l_i - b_i, R(r, p, y) = R(y_0, p_0, r_0). \]

\[ A = \delta f \mid _{x_0, v_0} = \frac{\delta R}{\delta x} \mid _{x_0, v_0} = \left( \begin{array}{cccc} \frac{\delta R}{\delta y} l_i & \frac{\delta R}{\delta p} l_i & \frac{\delta R}{\delta r} l_i \end{array} \right)_{x_0, v_0}, \]

\[ B = \frac{\delta f}{\delta v} \mid _{x_0, v_0} = 0, \delta \hat{x} = [\delta \hat{\phi}, \delta \hat{\theta}, \delta \hat{\psi}]^T, \]

\[ \delta v = -R(y_0, p_0, r_0) \delta l_i + \delta \hat{b}_i = [K_i, I][\delta l_i \  \delta \hat{b}_i]^T \]

Therefore, formula (7) can be rewritten as.

\[ f(\hat{x}, v) = W_i + A \delta \hat{x} + [K_i, I][\delta l_i \  \delta \hat{b}_i] = 0 \quad (8) \]

The least squares method can be used to calculate the \( \delta \hat{x} \):

\[ \delta \hat{x} = -(A^T C^{-1} A)^{-1}(A^T C^{-1})(W + K) \quad (9) \]

The formula is: \( C = \text{diag}(K C, C_0) \), \( C_0 \) is the covariance matrix of \( \delta l \), \( C_0 \) is the covariance matrix of \( \delta b \). The covariance matrix of \( \delta \hat{x} \) is as follows:

\[ C_{\hat{x}} = (A^T C^{-1} A)^{-1} \quad (10) \]

The \( A_i \) reflects the influence of the antenna baseline length on the accuracy of attitude measurement, and the following formula can be obtained in the case of single baseline.

\[ C_{\hat{x}} \propto (J J^T)^{-1}, J = [b_1, b_2, \cdots, b_n]^T \quad (11) \]

The accuracy of the attitude measurement is proportional to the square of the baseline length. This conclusion is derived from the mathematical formula to ignore the influence of the multipath effect and so on. Next, through building RTK measurement platform, the relationship between baseline length and attitude measurement accuracy is detected in practical application, and the appropriate baseline length is found.

4. Construction of RTK measurement experimental platform

RTK measurement is a real-time dynamic relative positioning technique based on high precision carrier phase measurement. The radio data transmission chain needs to be set up. The carrier phase observation data observed by the reference station receiver or the position information of the base station is transmitted to the mobile receiver in real time in a certain data communication format, and the mobile receiver combines with the observed data by itself, and calculates the position and attitude information of the carrier in real time [8].

The experimental platform adopts the M300 receiver designed and developed by Shanghai Sinan satellite Navigation Company, and it has the inertial navigation module, which provides a short time inertial navigation positioning by the inertial navigation module when the satellite signal is lost. The base station is set up first. The base station is mainly used to provide RTK difference correction to the mobile station. It includes two parts: one is the base station receiver, the antenna, the accessories and so on, and another is the communication equipment of the wireless transmission data chain. Select the location of the open field, the ground reflection is weak, the higher position of the ground to conduct signal quality test to see whether the search situation is good. After the signal intensity and the number of observable satellites meet the requirements, the base stations, radio and mobile stations will be configured to complete the construction of the platform.
5. Experimental test analysis
In this paper, the single baseline measurement is adopted, so the attitude angle detected is yaw angle and pitch angle. Figures 3 to 4 are the comparison diagrams of the measurements of the yaw angle and pitch angle of the Beidou's single baseline length of 0.43 m, 1.8 m, 3.2 m, 4.5 m, 6 m, and 8.4 m.

Figure 2. Experimental test platform

Figure 3. Comparison of yaw measurements under different baseline lengths
Figure 4. Comparison of pitch measurements under different baseline lengths

During the experiment, the main antenna is fixed and the length of the baseline is changed by moving the auxiliary antenna. Because there is no absolute plane, moving the auxiliary antenna is sure to cause a slight change in the pitch angle, and it is difficult to ensure that the connection of the main and auxiliary antennas (the yaw) is exactly the same as the previous one. These effects show a slight shift along the longitudinal axis, but their volatility and dispersion are not affected. Therefore, the standard deviation and the maximum error of statistical analysis can still show the accuracy and stability of the yaw and pitch under different baseline lengths, and the data statistics are shown in the following table.
Table 1. Statistical information of attitude angle calculation results at different baseline lengths

| attitude angle | Baseline length | average | standard deviation | maximum error |
|----------------|-----------------|---------|--------------------|---------------|
| Yaw            | 0.43m           | 100.683 | 0.11203            | 0.28361       |
|                | 1.8m            | 100.649 | 0.05148            | 0.16992       |
|                | 3.2m            | 100.664 | 0.03654            | 0.10525       |
|                | 4.5m            | 100.530 | 0.01913            | 0.05984       |
|                | 6.0m            | 100.600 | 0.01280            | 0.04038       |
|                | 8.4m            | 100.641 | 0.01191            | 0.03976       |
| Pitch          | 0.43m           | −0.0458 | 0.13401            | 0.42116       |
|                | 1.8m            | 0.0354  | 0.07162            | 0.26524       |
|                | 3.2m            | −0.0607 | 0.06783            | 0.21457       |
|                | 4.5m            | −0.1423 | 0.03877            | 0.14234       |
|                | 6.0m            | −0.0135 | 0.03190            | 0.09647       |
|                | 8.4m            | −0.0867 | 0.03021            | 0.09502       |

In summary, the standard deviation of attitude angles measured at different baseline lengths is shown in the following figure.

Figure 5. Standard deviation of attitude angle measurement with different baseline length

According to the table and figure 5, it can be found that the measurement accuracy increases with the increase of the baseline length, but the baseline length is more than 5 meters, and the improvement effect of the measurement accuracy is no longer significant. When the baseline length is too long, the multipath error will increase and the reliability of data will be reduced.

6. Conclusion

In this paper, the relationship between the baseline length of the dipper and the measurement precision is deduced and the experimental platform is set up to verify. It is found that the measurement accuracy of the short distance is increased with the increase of the baseline length. At the same time, combining the effect of the actual measurement error to the precision, the suitable baseline length is obtained, which is of certain reference significance for the selection of baseline length of the special vehicle by using RTK technology.

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