Research on Improvement Method of Systematic Deviation of Autonomous Navigation Message of BDS

Qiuli Chen[1(✉)], Haihong Wang[1(✉)], Xu Zhang[1(✉)], Yu Ding[1(✉)], and Weisong Jia[2(✉)]

[1] Institute of Telecommunication and Navigation Satellites, CAST, Beijing, China
[2] Beijing Institute of Spacecraft System Engineering, Beijing, China

Abstract. Beidou navigation satellite system (BDS) is a global navigation satellite system independently constructed and operated by China. An important function of BDS is to have autonomous navigation capability. Satellite autonomous navigation is a kind of satellite navigation technology that can operate autonomously without the support of ground system. Based on the inter-satellite ranging information, the navigation message information is generated independently and broadcast to users, so as to realize real-time navigation, positioning and timing. The systematic deviation of autonomous navigation message is the deviation between the calculated value of ephemeris and clock and the observed value, which is recorded as o-c. It reflects the matching degree between navigation message and inter-satellite observation. Theoretically, the smaller the better. Aiming at the systematic deviation of autonomous navigation message, this paper proposes a calculation method to eliminate the systematic deviation. Experiments show that this method can effectively reduce the message system error of autonomous navigation, that improve the performance of autonomous navigation.

Keywords: BDS satellite · Autonomous navigation · Navigation message · Systematic deviation

1 Introduction

Beidou navigation satellite system (BDS) is a global navigation satellite system independently constructed and operated by China. By June 2020, the BDS has been completed global networking. The space segment of the system includes 24 MEO satellites: Walker 24/3/1, 3 geo satellites and 3 IGSO satellites [1]. An important function of BDS is to have autonomous navigation capability. Satellite autonomous navigation is a kind of satellite navigation technology that can operate autonomously without the support of ground system. Based on inter satellite ranging, the navigation message is generated and transmitted to the ground, so as to realize real-time navigation and time service [2–4].

Based on the data of the inter-satellite link and data of the ground tracking station, the average RMS of the orbital radial overlap is better than 0.2 m [5]. The relationship between GEO satellite orbit error and differential positioning accuracy, and simulation

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orbit determination based on inter satellite link data were also studied [6]. In this paper, a solution was given to the error of the autonomous navigation message system based on inter satellite link.

The systematic deviation of autonomous navigation message based on inter-satellite link is the deviation between the calculated value and the observed value of ephemeris and clock, which is recorded as o-c. It reflects the matching degree of navigation message and inter satellite observation data. Theoretically, the smaller the systematic deviation, the higher the accuracy of navigation message. For the systematic deviation of autonomous navigation message, this paper presented a method to eliminate the systematic deviation of message. Experiments show that this method can effectively reduce the error of autonomous navigation message system, and further improve the accuracy and service performance of autonomous navigation message.

2 Source Analysis of Systematic Deviation of Message

As mentioned above, the systematic deviation of autonomous navigation message not only reflects the matching between autonomous navigation broadcast message and inter-satellite observation data, but also represents the on orbit service performance of autonomous navigation. According to the principle of autonomous navigation message solution and data processing flow, the factors causing systematic deviation of navigation message include phase centroid correction, relativistic effect correction and channel delay correction [7–9]. In this section, based on the correction method of three factors, the difference between the maximum correction error and the error of autonomous navigation message system was analyzed. And the source of the error has been given.

2.1 Correction of Satellite Centroid and Antenna Phase Center

The precise measurement value of the antenna phase center in the antenna single machine coordinate system, the installation position of the antenna reference point in the satellite mechanical coordinate system, and the precise value of the centroid in the mechanical coordinate system are the input of the antenna phase center and satellite centroid correction. The vector of antenna phase center in satellite body coordinate system was shown in Formula (1).

$$r_{ka} = r_p + r_t + r_m \tag{1}$$

Where, r_p is the vector of the antenna phase center in the antenna single machine coordinate system, r_t is the vector of the antenna single machine coordinate origin in the mechanical coordinate system, r_m is the vector of the satellite mechanical coordinate origin in the satellite body coordinate system, r_{ka} is the vector of the antenna phase center in the satellite body coordinate system.

The error of phase center correction was shown in Formula (2).

$$\Delta_1 = r_{ka} \cdot \cos(\gamma + \delta) \tag{2}$$

Where, γ is the theoretical value of antenna pointing angle, δ and is the pointing angle error.

The maximum pointing error is 0.5°. According to the precision measurement, the correction error under the maximum pointing error is about 1 cm. It can be concluded that the systematic deviation of broadcast message larger than 1 cm is not caused by centroid phase center correction.

2.2 Relativistic Effect Correction

The fully autonomous navigation operating mode refers to the situation where the ground operation control system, measurement and control system, and anchoring station are unable to inject the space-time reference information required for the operation of the navigation constellation. The system only relies on a working mode in which satellites automatically generate full constellation clock difference and ephemeris data. The operating mode is shown in Fig. 2.

Relativistic effects in data processing include gravitational delay of electromagnetic wave and frequency variation of satellite clock caused by relativistic effects. The time delay correction of relativistic effect was shown in Formula (3) [10].

$$\Delta t^{RC} = \frac{2\vec{R} \cdot \vec{V}}{c^2} \tag{3}$$

Where, Δt^{RC} is the relativistic time delay (in seconds) caused by the non-zero eccentricity of the satellite's elliptical orbit, $\vec{R}$ is the radial vector of the satellite's orbit, $\vec{V}$ is the inertial velocity vector of the satellite's orbit, and c is the speed of vacuum light, with the value of 299792458 m/s.

From the orbit and velocity accuracy of Beidou satellite, the maximum error of time delay correction of relativistic effect is equivalent to less than mm.

2.3 Channel Transmit Receive Delay Correction

The transmit and receive delay of inter satellite link was measured and calculated on the ground, and then injected to the satellite as the input of channel delay correction.

Measurement error, space environment change, calculation processing and other factors would lead to a certain deviation of time delay. The correction error caused by this will further cause systematic deviation of autonomous navigation message. Based on the above analysis and the actual engineering situation, this paper attempted to correct the maximum error source of the channel delay which is the worst in the system, and obtained a better result.

Figure 1 showed the difference of autonomous navigation message system in a certain test period. Based on the above analysis, it was considered that the channel delay correction error is the biggest error source of the message system error of autonomous navigation.

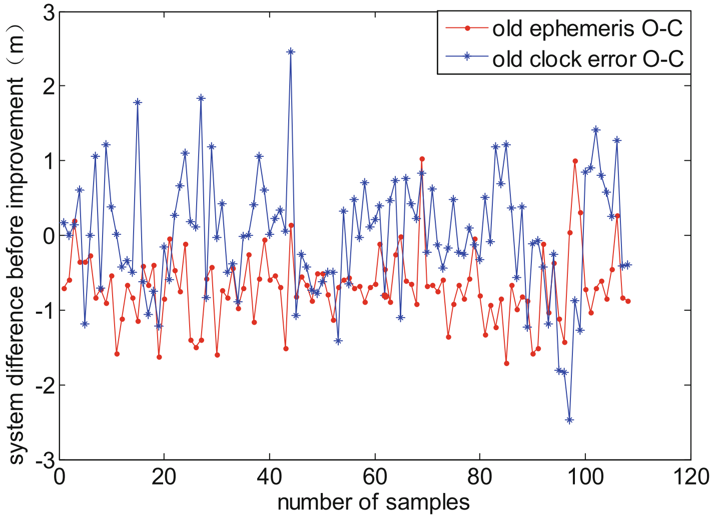

Fig. 1. Systematic deviation of autonomous navigation message in 2020

3 Solution of Channel Transmit and Receive Delay Correction Error

Through the epoch reduction of the ephemeris and clock observations, that differs from the calculated value, the relationship between time delay correction error and systematic error could be obtained through.

For any pair of two-way transmitting and receiving satellites, t_{ot-de}, $t_{\text{or - de}}$, $t_{\text{sr - de}}$, $t_{\text{st - de}}$, was defined as the input value of the delay of other satellite transmitting, other satellite receiving, local satellite transmitting and local satellite receiving. $t^*_{\text{ot - de}}$, $t^*_{\text{or - de}}$, $t^*_{\text{sr - de}}$, $t^*_{\text{st - de}}$ was define the real values of the time delay of other satellite transmitting, other satellite receiving, local satellite transmitting and local satellite receiving. Furthermore, δt_{ot-de}, $\delta t_{\text{or - de}}$, $\delta t_{\text{sr - de}}$, $\delta t_{\text{st - de}}$ was defined as the delay error of other satellite transmitting, other satellite receiving, local satellite transmitting and local satellite receiving. Their relationships were described in the following formula.

$$t_{ot-de} = t^*_{ot-de} + \delta \mathrm{t}_{ot-de} \tag{4}$$

$$t_{or-de} = t^*_{or-de} + \delta \mathrm{t}_{or-de} \tag{5}$$

$$t_{sr-de} = t^*_{sr-de} + \delta \mathrm{t}_{sr-de} \tag{6}$$

$$t_{st--de} = t^*_{st-de} + \delta \mathrm{t}_{st-de} \tag{7}$$

3.1 Epoch Reduction of Inter Satellite Distance Observations

Any link satellite is a two-way transceiver link. To the transmission of this satellite and the reception of other satellites link, the transmit time of this satellite was defined as t_{st}, and the reception time of other satellites was defined as t_{or}. To other satellites transmit and local satellite receive link, other satellites transmit time was defined as t_{ot} and local satellite receive time was t_{sr}. As shown in Fig. 2, L1 was the observation of the transmission of this satellite and the reception of other satellites link. And L_2 was the observation of the transmission of other satellite and the reception of this satellites link. In order to calculate the difference with the calculated value of inter satellite distance, it is necessary to reduce the observed value to the specified epoch time t_z. L1' and L2' were the observed values reduced to t_z.

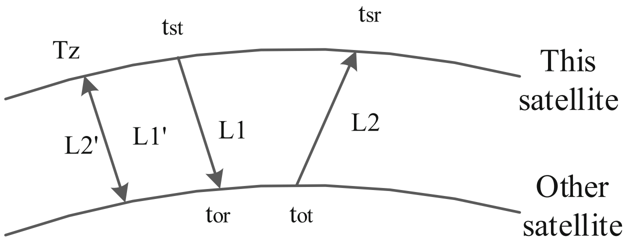

Fig. 2. Inter satellite observation and epoch reduction process

Observation of this satellite transmission and other satellite reception L_1(unidirectional link):

$$L_1 = L_{o,st,or} = [(t_{or} - (\mathrm{t}^*_{or-de} + \delta\mathrm{t}_{or-de}) - \mathrm{a}_0^{or}) - (t_{st} + (\mathrm{t}^*_{st-de} + \delta\mathrm{t}_{st-de}) - \mathrm{a}_0^{st})] \cdot c \tag{8}$$

Where, t_{or} is the clock time received by other satellite, a_0^{or} is the clock difference received by other satellite, t_{st} is the clock time transmitted by this satellite, and a_0^{st} is the clock difference transmitted by this satellite.

Observation of other satellite transmission and this satellite reception L_2(unidirectional link):

$$L_2 = L_{o,ot,sr} = [(t_{sr} - (\mathrm{t}^*_{sr-de} + \delta\mathrm{t}_{sr-de}) - \mathrm{a}_0^{sr}) - (t_{ot} + (\mathrm{t}^*_{ot-de} + \delta\mathrm{t}_{ot-de}) - \mathrm{a}_0^{ot})] \cdot c \tag{9}$$

Where, t_{sr} is the clock time received by this satellite, a_0^{sr} is the clock difference received by this satellite, t_{ot} is the clock time transmitted by other satellite, and a_0^{ot} is the clock difference transmitted by other satellite.

Adding the two-way pseudo range measurements to the same epoch time can eliminate the satellite clock error, only including the satellite distance [11]. The calculation of the inter satellite observations lo and EP of the ephemeris is shown in Formula (10) (reduction time tz).

$$
\begin{aligned}
L_{o,ep} &= (L_2' + L_1')/2 \\
&= \{[(t_{sr} - t^*_{sr-de} - a_0^{sr}) - (t_{ot} + t^*_{ot-de} - a_0^{ot})] \cdot c/2\}(t_z) - (\delta t_{sr-de} + \delta t_{ot-de}) \cdot c/2 \\
&+ \{[(t_{or} - t^*_{or-de} - a_0^{or}) - (t_{st} + t^*_{st-de} - a_0^{st})] \cdot c/2\}(t_z) - (\delta t_{or-de} + \delta t_{st-de}) \cdot c/2 \\
&= (L_2(t_z) - (\delta t_{sr-de} + \delta t_{ot-de}) \cdot c + L_1(t_z) - (\delta t_{or-de} + \delta t_{st-de}) \cdot c)/2
\end{aligned} \tag{10}
$$

Where, L_1', L_2' is the observed value of L_1, L_2 for epoch reduction, and δt_{sr-de}, δt_{ot-de}, δt_{or-de}, δt_{st-de} has nothing to do with epoch reduction.

The satellite orbit can be eliminated by subtracting the two-way pseudo range measurements at the same epoch, only including the satellite clock error [12]. The observed value of clock Lo,cl_a. The calculation method of a (reduction time TZ) is shown in Formula (11).

$$
\begin{aligned}
L_{o,cl\_a} &= (L_2' - L_1')/2 \\
&= \{[(t_{sr} - t^*_{sr-de} - a_0^{sr}) - (t_{ot} + t^*_{ot-de} - a_0^{ot})] \cdot c/2\}(t_z) - (\delta t_{sr-de} + \delta t_{ot-de}) \cdot c/2 \\
&- \{[(t_{or} - t^*_{or-de} - a_0^{or}) - (t_{st} + t^*_{st-de} - a_0^{st})] \cdot c/2\}(t_z) + (\delta t_{or-de} + \delta t_{st-de}) \cdot c/2 \\
&= (a_0^2(t_z) - (\delta t_{sr-de} + \delta t_{ot-de}) \cdot c - a_0^1(t_z) + (\delta t_{or-de} + \delta t_{st-de}) \cdot c)/2
\end{aligned} \tag{11}
$$

The definition of each parameter in the formula was the same as that in Formula (10).

3.2 Calculated Value of Inter Satellite Distance

The ephemeris calculated value (time TZ) is shown below.

$$
L_{c,ep} = |r_1(t_z) - r_2(t_z)| \tag{12}
$$

Where, $r_1(t_z)$, $r_2(t_z)$ is the calculated value of inter satellite distance at epoch time. Calculated value of satellite clock error (tz time)

$$
L_{c,cl\_a} = a_0^{(2)}(t_z) - a_0^{(1)}(t_z) \tag{13}
$$

Where, $a_0^{(1)}(t_z)$, $a_0^{(2)}(t_z)$ is the clock difference of epoch time.

3.3 Calculation of the Difference Between the Observed and Theoretical Values of Ephemeris and Clock

By calculating the difference between the observed and theoretical values of ephemeris and clock, the relationship between the systematic deviation shown in Formulas (14) and (15) and the time delay error of the link building satellite was obtained.

$$
\Delta L_{O-C,ep} = L_{o,ep} - L_{c,ep} = -\frac{[(\delta t_{ot-de} + \delta t_{or-de}) + (\delta t_{st-de} + \delta t_{sr-de})]}{2} \cdot c \tag{14}
$$

$$
\Delta L_{O-C,cl} = L_{o,cl} - L_{c,cl} = -\frac{[(\delta t_{ot-de} - \delta t_{or-de}) - (\delta t_{st-de} - \delta t_{sr-de})]}{2} \cdot c \tag{15}
$$

In the formula, the meaning of parameters were the same as the above.

4 Simulation Calculation of Channel Transmit and Receive Delay Error

Based on the third part of the relationship between the receiving and transmitting delay and the systematic deviation of ephemeris and clock, the systematic deviation of a fixed period was selected as the input data of simulation solution, which is recorded as the system difference matrix B. The contents of systematic deviation matrix include the code of transmitting satellite, receiving satellite, clock O-C and ephemeris O-C of two-way link. The coefficient matrix A of the time period has been constructed from the chain building relationship corresponding to the input matrix and Formulas (14) and (15), as shown in Formula (16) [13].

$$\begin{cases} [n1, n2] = size(B) \\ A = zeros(2 * n1, 2 * B(n1, 1)) \\ A(2i-1, 2\cdot OC(i,1)-1) = -\frac{1}{2} \\ A(2i-1, 2\cdot OC(i,2)-1) = \frac{1}{2} \\ A(2i-1, 2\cdot OC(i,2)-1) = \frac{1}{2} \\ A(2i-1, 2\cdot OC(i,2)) = \frac{1}{2} \\ A(2i, 2\cdot OC(i,1)-1) = -\frac{1}{2} \\ A(2i, 2\cdot OC(i,1)) = -\frac{1}{2} \\ A(2i, 2\cdot OC(i,2)-1) = -\frac{1}{2} \\ A(2i, 2\cdot OC(i,2)) = -\frac{1}{2} \end{cases} \tag{16}$$

Where n1 and n2 are the number of rows and columns of input matrix B, and i = 1, n1.

Using the least square method, the correction of delay difference is obtained as Formula (17).

$$\delta x = (A^T A)^{-1} A^T \cdot B \tag{17}$$

Using the above formula, we can get the channel delay difference correction of the whole constellation. The improved channel delay is shown in Formula (18).

$$t_{de}^{*} = t_{de} - \delta \mathrm{t}_{de} \tag{18}$$

The centroid antenna phase center correction, relativistic correction, and the improved time delay value were replaced into the simulation software. And the navigation message, ephemeris and clock system error were carried out again. The comparison

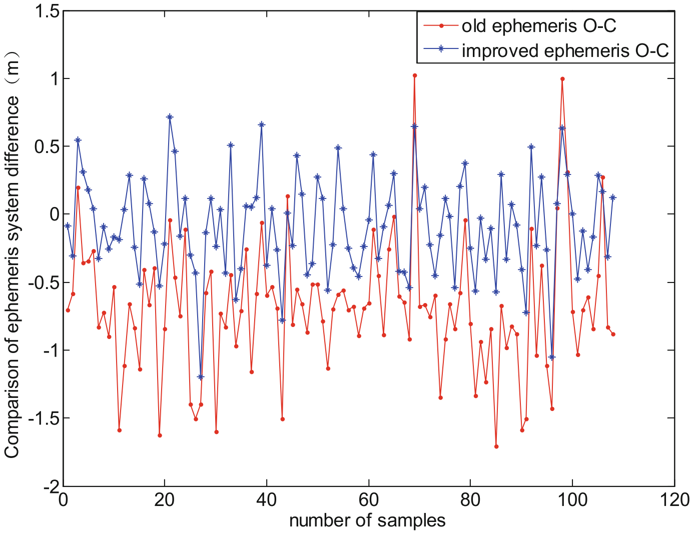

Fig. 3. Comparison of ephemeris O-C before and after improvement

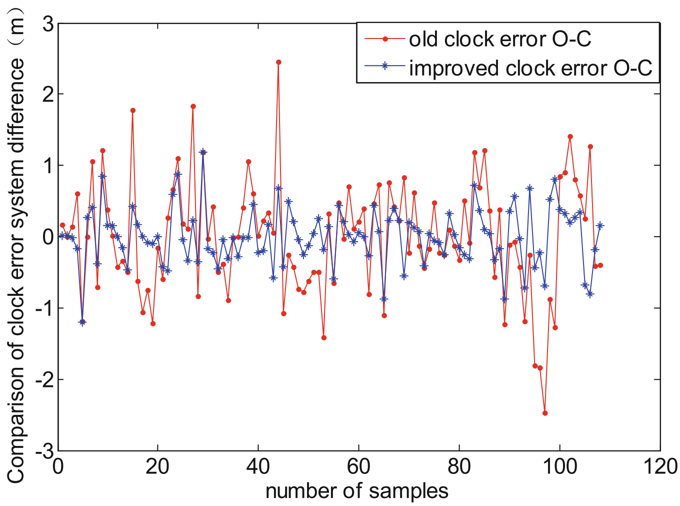

Fig. 4. Comparison of O-C of satellite clock before and after improvement

of the improved system was shown in Fig. 3 and Fig. 4. The experimental results show that the improvement effect was still obvious in the following period of time. The mean value of O-C system difference of ephemeris before correction was −0.690 m, root mean square was 0.842 m. And the mean value after correction was −0.0926 m, root mean square was 0.371 m. The mean value of O-C system clock error before correction was −0.003 m, root mean square was 0.806 m. And the mean value after correction was − 0.003 m, root mean square was 0.404 m.

5 Conclusion

Autonomous navigation is one of the characteristics of modern GNSS system. Based on the inter satellite measurement and information interaction, the generation and broadcast of autonomous navigation message can be completed, so as to realize the autonomous operation of the system, which will greatly reduce the ground operation cost of the system. The accuracy of autonomous navigation message will directly affect the accuracy of navigation, positioning and time service during the autonomous operation of the system. For the systematic deviation of autonomous navigation message, this paper analyzes the factors that cause the systematic deviation. It is proved that the method can effectively reduce the error of autonomous navigation message system and further improve the performance of autonomous navigation.

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