RESEARCH IMPLEMENTATION OF BEIDOU DATA FAST PROCESSING OF LARGE-SCALE GNSS REFERENCE STATION NETWORK

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KEY WORDS: BDS, GNSS, Large network processing, orbit determination, geodetic reference framework.

ABSTRACT：

GNSS reference station network is the core infrastructure for the establishment ,maintenance, renewal and service of national geodetic reference framework. At present ,nearly 3000 reference stations have been constructed in the national resources system ,of which about 2500 stations have the continuous observation capacity of BDS signal. In the face of daily massive observation data, the traditional sub-network and fully combined baselines can not meet the needs of rapid data processing for the maintenance of geodetic coordinate framework.

In this paper, the high-precision and fast processing of BDS observation data of large-scale GNSS reference station network (≥ 300 stations) is realized through modular design, non difference model, parameter management to be estimated and flexible ambiguity processing. Through the whole network calculation of the 7-day BDS observation data of about 500 MGEX stations and national reference stations that selected all around the world from 211 to 217 days in 2017, the positioning results show that the average RMS values of the coordinates in the three directions of station N,E and U are ± 2.3mm, ± 2.8mm and ± 4.6mm respectively. The orbit determination results show that the average accuracy of GPS satellite orbit in three directions is better than ±2cm; BDS MEO / IGSO track accuracy is better than ±20cm and GEO track accuracy is better than ±200cm.

1. BACKGROUND

1.1 Introduction

GNSS reference station network is the core infrastructure for the establishment, maintenance, renewal and service of national geodetic reference framework. At present, nearly 3000 reference stations have been constructed by resource sectors, of which about 2500 stations have the continuous observation capacity of BDS signal. In the face of daily massive observation data, the traditional sub-network and fully combined baselines method can not meet the needs of rapid data processing for the maintenance of geodetic coordinate framework.

Now, the high-precision processing strategy for large-scale GNSS reference station network data is mainly partition processing or distributed processing(Ge M et al,2006),(Jiang Weiping et al,2011),(Chen Zhengsheng et al,2015) and (Cheng chuanlu et al,2014). Such as the high-precision GNSS data processing software GAMIT, when processing the observation data of the reference station network of more than 100 stations, the software is based on the double difference principle for baseline calculation, and uses the full combination method; considering that the pressure on the computing power increases exponentially with the increase of stations, the software is designed for no more than 100 stations per computing subnet. Although the EPOS software of GFZ can compute 400 stations, it requires high-performance computers and a lot of time, which lags behind the current situation of the product to a large extent. Therefore, it is generally recommended that the number of stations be less than 250(Lv Hao et al, 2015). BERNESE software adopts the single baseline combination mode, and its baseline solution adopts the "n-1" algorithm, which can realize the synchronous data processing of more than 100 stations, but it usually uses the non-difference mode for the data of large-scale reference station network. Generally, under the standalone default configuration of BERNESE software, the number of PPP stations is limited to 200, and the software solution time increases significantly with the increase of the number of stations, which limits its application in the rapid and high-precision processing of large-scale GNSS reference station network data. (Lv Hao et al, 2015).

In view of this, based on the advantages of the current non difference processing method, this paper introduces the parameter elimination recovery method to realize the high-precision and rapid processing of Beidou and other GNSS observation data of large-scale reference station network, which is verified with the measured data.

2. RESEARCH CONTENTS

2.1 Modular design

GNSS data processing modules mainly includes data preparing, data pre-processing, parameter estimation, residual error editing, ambiguity fixation and result output. The specific processing flow is shown in Figure 1:

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https://doi.org/10.5194/isprs-archives-XLIII-B4-2022-203-2022

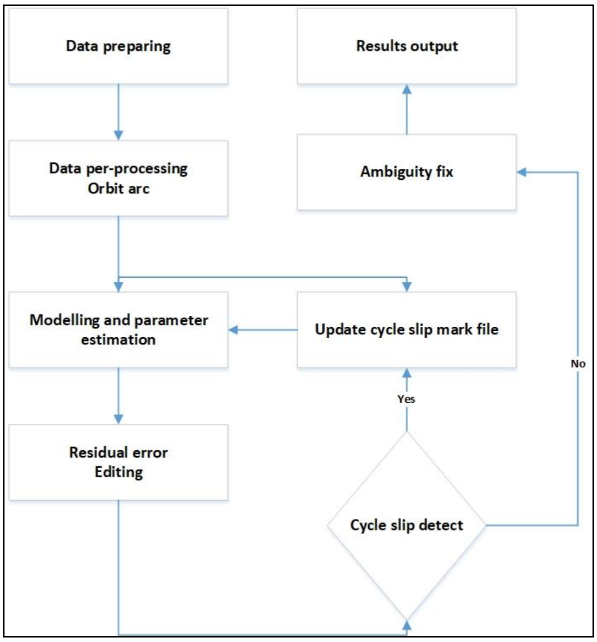

Figure 1. Data processing modules.

2.1.1 Data preparing: The control files preparing required for data processing, including processing time period, sampling interval, list of pre-adopted satellites and related information, list of pre-adopted stations, initial coordinates of stations, receiver information, antenna information, DCB correction file, ephemeris file, list of positions of sun, moon and celestial bodies, nutation precession, etc.

1.Obtain rinex format files, including observation files, navigation files, precision ephemeris, etc.

2.Obtain precession, nutation parameters and earth rotation parameter files and convert them into the format supported by the software.

3.Obtain satellite and receiver antenna phase correction files.

4.Obtain the ocean load correction file.

2.1.2 Data pre-processing: In order to obtain clean GNSS observation data, Beidou / GPS observation data need to be pre-processed before parameter estimation. Data pre-processing specifically includes: first, repairing the millimetre jumping of receiver clock error contained in the original data; second, determine the cycle slip and gross difference in the original observation data by means of wide-lane cycle slip check and ionospheric residual check, in which the cycle slip detection limit can be set according to experience.

Detect the wide-lane cycle slip with MW Combined observation value, as shown in the following formula:

$$\langle b_{wl}\rangle_i = \langle b_{wl}\rangle_{i-1} + \frac{1}{i}\left(b_{wl,i} - \langle b_{wl}\rangle_{i-1}\right) \quad (1)$$

$$\sigma_i^2 = \sigma_{i-1}^2 + \frac{1}{i}\left\{\left(b_{wli} - \langle b_{wl}\rangle_{i-1}\right)^2 - \sigma_{i-1}^2\right\} \quad (2)$$

In the formula， $\langle b_{wl}\rangle_i$ is a smooth wide lane ambiguity of i epoch， $b_{wl,i}$is the ambiguity of wide lane in epoch i， σ_i^2 is the variance of< $b_{wl,i}$ >， if $b_{wl,i} - \langle b_{wl}\rangle_i > 4\sigma_i$， it is considered that there is cycle slip or gross error.

Detect cycle slip with ionospheric combined observations
The carrier phase ionospheric combination observations are as follows:

$$L_1 = L_1 - L_2 = I + \lambda_1 b_1 - \lambda_2 b_2 = I + \lambda_1 b_{wl} - \lambda_1 b_2 \quad (3)$$

where I = ionosphere influence
b_1,b_2 = ambiguity of L_1, L_2 carrier phases respectively
$\lambda_1 = (\lambda_2 - \lambda_1) \approx 0.54cm$

in practical application, linear fitting or high-order difference method is used to detect cycle slip.
Considering that the repair of cycle slips in non-differential phase data is more difficult than detection, or even impossible to repair accurately, so here only detects cycle slips in data processing, and does not repair the cycle slips. For each place where cycle slip occurs, a new ambiguity parameter is added. If the effective arc segment between two adjacent cycle jumps of a satellite is less than the pre-set threshold (the size of the threshold depends on the sampling rate of the data), the observation data of the short arc segment will be eliminated.

2.1.3 Parameter estimation: Parameter estimation is mainly to read the original observation value, apply various required error corrections, form the observation value equation, and superimpose the observation equation of each satellite at each time into the unified normal equation, and finally solve it to obtain the final solution result. The specific parameter estimation process is shown in Figure 2 below:

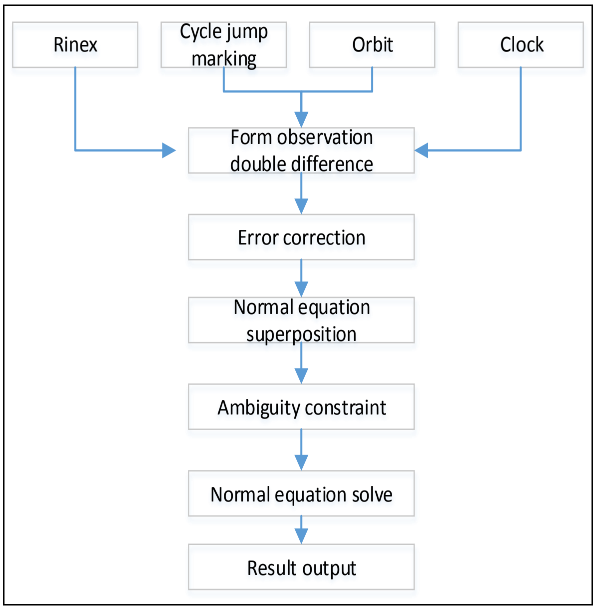

Figure 2. Parameter estimation processes.

The error models applied in parameter estimation mainly include receiver clock error correction, receiver antenna phase center deviation correction, earth tide correction, ocean load tide correction, satellite clock error and orbit correction

2.1.4 Residual error editing: After the normal equation is solved, the residual error needs to be further analyzed to detect the possible small cycle slip or gross error, and then update the original data pre-processing results;

Residual editing is an important step in quality control. In residual editing, if the jump of the residuals of two consecutive epochs in the time series exceeds a certain limit, it is generally considered that there is cycle slip. The editing results will be updated to the original cycle slip mark file for the next parameter estimation. The specific process of residual error editing is shown in Figure 3:

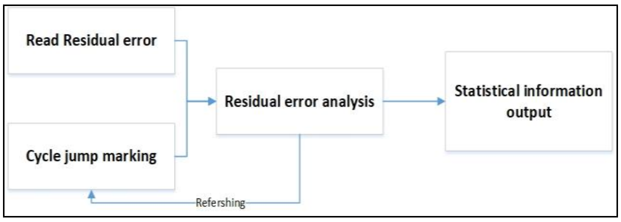

Figure3. Residual error editing process

2.1.5 Ambiguity fixation:

2.1.5 Ambiguity fixation: The fixed ambiguity mainly determines the integer solution of ambiguity. Non-difference ambiguity does not have integer characteristics and cannot be fixed directly. It is necessary to form double difference ambiguity first, and then fix the ambiguity. The ambiguity fixing module of the software reads out the non-difference ambiguity results of parameter estimation, selects the independent ambiguity, forms the double difference ambiguity, and finally fixes the ambiguity. The software design process is shown in Figure 4:

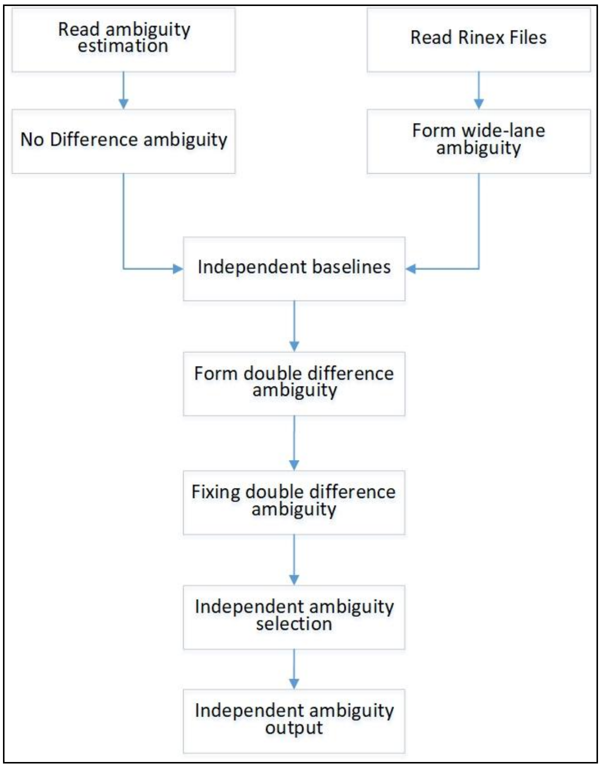

Figure4. Ambiguity fixing process

2.2 Key methods

In order to realize the high-precision and rapid processing of Beidou observation data of large-scale satellite navigation and positioning reference station, this paper introduces the non-difference data processing method, parameter elimination recovery method and the optimal management and setting of ambiguity parameters in the original traditional high-precision data processing process.

2.2.1 Non-difference data processing method: Double difference method is a common method in the early stage of GNSS data processing. It mainly makes two differences between the original observation value between the reference station and the navigation satellite, eliminates the clock difference between the receiver and the satellite, and greatly weakens the atmospheric correlation error. The double difference method is to establish the double difference observation equation based on the double difference observation value. However, this observation value cannot be used when only one of the two stations observes a satellite. The non-difference method is to establish the observation equation directly on the non-difference observation value, estimate the clock error between the satellite and the receiver at the same time, and do not make any form of difference between stations or satellites, so it has higher data utilization than the double difference method.

2.2.2 Parameter elimination and recovery method: In the GNSS non-differential positioning model, the general station coordinates, troposphere, ERP parameters, orbit, receiver and satellite clock error, ambiguity and other parameters need to be estimated together. Among them, the satellite and receiver clock error parameters generally need to be estimated every epoch, and there are many ambiguity parameters. If all these parameters are left in the normal equation to be solved together, the dimension of the normal equation will be too large and the calculation speed will be very slow. This is also a problem that has not been well solved in GNSS data processing. The method of parameter elimination alleviates this contradiction to a certain extent. Its main idea is to eliminate those inactive parameters from the normal equation at the end of each epoch, so as to reduce the dimension of the normal equation, and then recover these parameters after the inversion of the normal equation. This method can effectively improve the computational efficiency, and has been implemented in the internationally famous software EPOS and PANDA. The following is a brief introduction to the parameter elimination and recovery method.

In GNSS positioning algorithm, parameter elimination is mainly to eliminate clock error parameters, inactive ambiguity parameters and inactive tropospheric parameters from the normal equation, so as to reduce the dimension of the normal equation and improve the calculation efficiency. After the inversion of the normal equation, these parameters need to be restored. The clock error parameters thus obtained can provide precise clock error correction for other users, tropospheric parameters can provide tropospheric products, and the ambiguity parameters can be fixed after recovery. The whole process of parameter elimination and recovery is shown in Figure 5.

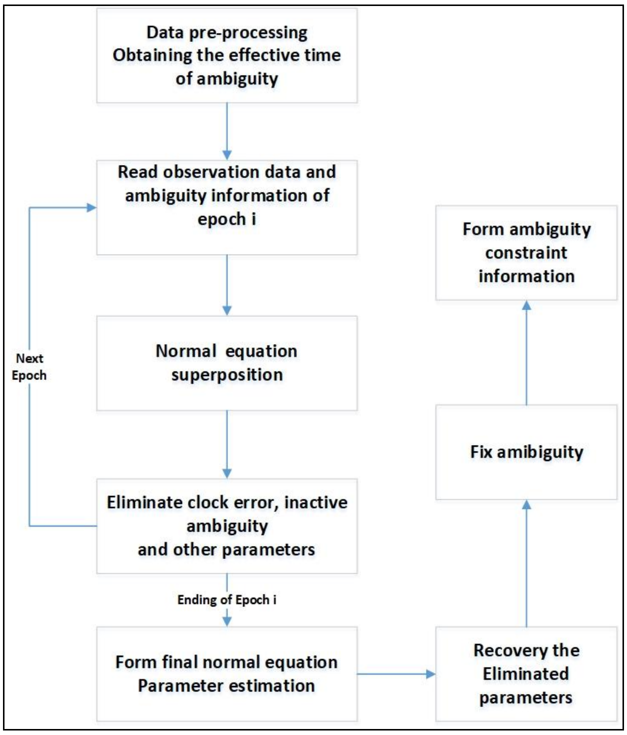

Figure 5. Parameter eliminated-recovery and Ambiguity fix process

Firstly, obtain the effective time of ambiguity on each station through data pre-processing, and then read the observation data of the first epoch and the corresponding ambiguity information to form the observation equation and superimpose the normal equation. Then, remove the clock error parameters, inactive ambiguity parameters and tropospheric parameters from the normal equation one by one, and write the relationship between the eliminated parameters into the temporary file, and then read the observation data and ambiguity information of the second epoch until all epochs are traversed. Then solve the whole normal equation, and then recover the eliminated parameters one by one. The estimated parameters are consistent with the results obtained without parameter elimination method. At last, fix the ambiguity.

Parameter elimination is mainly to eliminate inactive parameters from the normal equation to reduce the dimension of the normal equation. If the normal equation is:

$$\begin{bmatrix} N_{11} & N_{12} & N_{13} \\ N_{21} & N_{22} & N_{23} \\ N_{31} & N_{32} & N_{33} \end{bmatrix} \begin{bmatrix} X \\ Y \\ P \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} \qquad (4)$$

Where P is the parameter to be eliminated.
In order to eliminate p from the normal equation, it will be expressed as a function of X and Y:

$$P = N_{33}^{-1}(w_3 - N_{31}X - N_{32}Y) \qquad (5)$$

Bring (5) into (4):

$$\begin{bmatrix} \tilde{N}_{11} & \tilde{N}_{12} \\ N_{12} & \tilde{\mathrm{N}}_{22} \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \tilde{w}_1 \\ \tilde{w}_2 \end{bmatrix} \qquad (6)$$

In which：

$$\begin{aligned} \tilde{N}_{11} &= N_{11} - N_{13}N_{33}^{-1}N_{31} \\ \tilde{N}_{12} &= N_{12} - N_{13}N_{33}^{-1}N_{32} \\ \tilde{N}_{22} &= N_{22} - N_{23}N_{33}^{-1}N_{23} \\ \tilde{w}_1 &= w_1 - N_{13}N_{33}^{-1}w_3 \\ \tilde{w}_2 &= w_2 - N_{23}N_{33}^{-1}w_3 \end{aligned} \qquad (7)$$

And from formula (4)：

$$V^TPV = L^TPL - X^Tw_1 - Y^Tw_2 - P^Tw_3 \qquad (8)$$

After parameter P is eliminated, the above formula becomes:

$$V^TPV = L^TPL - X^T\tilde{w}_1 - Y^T\tilde{w}_2 - P^TN_{33}^{-1}w_3 \qquad (9)$$

The meaning of parameters is shown in equation (7).

In this way, the parameters can be eliminated, so as to reduce the dimension of the normal equation without affecting the final result.

As described above, the eliminated parameters cannot be solved explicitly in the final solution of the normal equation, that is, the clock error parameters and inactive ambiguity parameters cannot be obtained explicitly. Many of the eliminated parameters are useful parameters. For example, the clock error can be provided to other users as a product, and the ambiguity can also participate in the fixation of ambiguity to improve the accuracy and reliability of the results. Therefore, these parameters need to be recovered after the solution of the normal equation.

In the process of parameter elimination, generally, formula (5) can be saved in a temporary file. Record and read it one by one after the inversion of the normal equation, and calculate the estimation of the eliminated parameters according to formula (5). At this stage, in order to save time, its variance is generally not restored. The ambiguity parameters obtained after restoration can still be used in ambiguity fixation. This effectively reduces the dimension of the normal equation and improves the calculation efficiency.

2.2.3 Ambiguity setting and management method: In GNSS parameter estimation, the effects of station coordinates, receiver clock error, orbit and troposphere on pseudo range and phase observations are consistent, and these parameters have the same effects on pseudo range and phase observations. However, there is ambiguity in the phase observation, which is inconsistent with the pseudo range. In general parameter estimation, the clock error and ambiguity parameters are the most. It takes short to eliminate the clock error parameters by epoch, but the ambiguity parameters are time-consuming because they are closely related to other parameters. Therefore, reasonable setting and management of ambiguity parameters plays a key role in computer memory and computing efficiency. In this paper, the ambiguity is marked in the temporary file. In the parameter estimation, the ambiguity is added only when the ambiguity mark in the temporary file is encountered, and all the inactive ambiguity is eliminated from the normal equation. This not only ensures the dimension of the normal equation, but also ensures that the normal equation does not occupy unnecessary memory space.

3. RESULTS

In order to verify the effect of this method on the rapid processing of large-scale and high-precision GNSS data, this paper selects the Beidou measured data of 500 stations from MGEX project and China's regional reference stations, carries out positioning and orbit determination processing, and carries out accuracy statistics. The specific results are as follows:

3.1 Orbit determination accuracy results

The orbit determination results show that the average accuracy of GPS satellite orbit in three directions is better than 2cm; BDS MEO / IGSO satellite orbit accuracy is better than 30cm and GEO satellite orbit accuracy is better than 400cm.

3.1.1 Repeated orbit error: The repeatability of tracks between different days at the junction of two days is the standard to measure the quality of tracks. In this paper, the orbits of each day are integrated forward and successively for extra 30 minutes. That is, the daily integral arc section starts at 23:30 of the previous day and ends at 00:30 of the next day, totalling 25 hours. In this way, there is an hour of repeated arc every two days. The comparison results of repeated arc segments are shown in Figure 6 below:

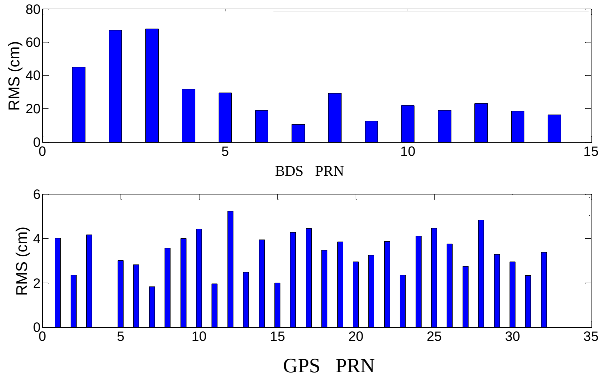

Figure 6. RMS value of repeated orbit at the junction of days

It can be seen that the average RMS value of GPS repetitive orbit is only 3.3cm, which is equivalent to the repetitive orbit quality of the current international IGS analysis center. The Beidou orbit is of slightly lower quality. The average RMS of GEO repeated orbit is 48.3cm and IGS / MEO is 18.8cm. This may be mainly due to the imperfect model of station distribution, optical pressure and antenna phase center.

3.1.2 IGS orbit comparison: Compare the results with -MGEX products provided by GFZ. The results are shown in Figure 7. It can be seen that the GPS track is in good agreement with the GBM track provided by GFZ, and the average RMS value of the two results is only 1.6cm. In Beidou, IGSO/GEO compliance is also good, only 18.1cm. GEO satellite is slightly worse, with an average of 184.7cm, which may be mainly caused by different Beidou tracking station data.

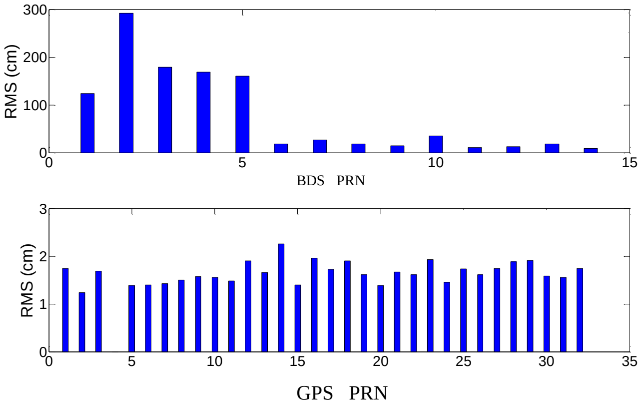

Figure 7. Comparison between satellite orbit and GBM orbit products released by GFZ.

3.2 Positioning accuracy results

The positioning results show that the average RMS values of the coordinates in the three directions of station N,E and U are ±2.3mm, ±2.8mm and ±4.6mm respectively.

3.2.1 The coordinate repeatability between different days solution: The coordinate repeatability between different days is one of the standards to measure the positioning accuracy. This paper uses the results of 214 days as the datum, compares the results of other days with them, and calculates the RMS values in N, E and U directions respectively, as shown in Figure 8.

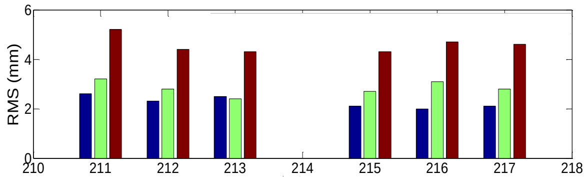

Figure 8. Statistical results of coordinate repeatability based on 214-day results

The average values of coordinate RMS in N, E and U directions are 2.3mm, 2.8mm and 4.6mm respectively.

3.2.2 Comparison with IGS weekly solution: Compare the positioning results of MGEX station with the weekly solution provided by IGS, and the RMS values in N, E and U directions are shown in Figure 9.

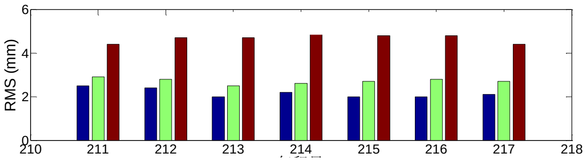

Figure 9. RMS statistical results compared with IGS orbit

It can be found that the average values of RMS in N,E and U directions are ±2.3mm, ±2.8mm and ±4.6mm respectively. According to the weekly solution accuracy published by IGS, the N, E and U directions are ±3mm, ±3mm and ±6mm respectively, which shows that the project positioning results are basically equivalent to the results of IGS analysis center.

4. CONCLUSION

In this paper, the rapid solution of BDS observation data of large-scale GNSS reference station network of more than 500stations is realized through optimization processing module and non difference model, parameter management and flexible ambiguity processing. The accuracy of positioning and orbit determination is equivalent to that of the current mainstream processing software.

5. ACKNOWLEDGEMENT

This article is supported by the project of “key technology research of BDS navigation system in railway” (K2020x017). Thanks to the MGEX project for the station data.

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https://doi.org/10.5194/isprs-archives-XLIII-B4-2022-203-2022