Accuracy Analysis of Earth Rotation Parameters Combining with VLBI Observations in CONT17 and GNSS Observations

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Accuracy Analysis of Earth Rotation Parameters Combining with VLBI Observations in CONT17 and GNSS Observations

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Abstact

The Earth rotation parameters (ERP) mainly including the displacement and rate of the earth's poles, UT1-UTC, length of day are estimated by processing the thirty-one IGS stations data from November 28, 2017 to December 12, 2017 with GAMIT. The ERP are obtained with VieVS3.2 by processing VLBI data observed on CONT17 campaign. The ERP results of GNSS and VLBI are combined in a weighted way, based on the Helemert variance component estimation and weighting method is proposed. The results show that the Root Mean Square(RMS) of the polar shift component in the X-direction is 0.000985 mas, the RMS of the polar shift component in the Y-direction is 0.000286 mas, and the RMS of UT1-UTC is 0.000690 ms, and the weighted accuracy is significantly better than that of the separate solutions of GNSS and VLBI, which can make up for the shortcoming of the single technique as GNSS and VLBI.

Keywords VLBI · GNSS · ERP · CONT17 · Helemert

1. Introduction

Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite System (GNSS) are both important space geodetic techniques, ERP mainly include the displacement and rate of the earth's poles, UT1-UTC, length of day (Wei et al. 2015). The ERP are the main conversion parameter linking the Earth and celestial reference frames and are also necessary for the precise orbiting of artificial satellites, autonomous navigation of deep space probes and high-precision timing services(Wei et al. 2013).

VLBI and GNSS are of great importance in improving the accuracy of the ERP(Liu, Wei and Wang 2017). The Earth Rotation Parameters play an important role in Earth astronomy, atmosphere and dynamics and plays a unique role in the implementation and maintenance of the International Celestial Reference Frame (ICRF), as well as contributing to the development of the International Terrestrial Reference Frame (ITRF)(Diamantidis, Kłopotek and Haas 2021; Boisits, Landskron and Bohm 2020). The advantages of GNSS, which includes GPS, BDS, GLONASS and GALILEO, are its ability to provide continuous, all-weather, high-precision observations, the uniform distribution of stations around the world, the availability of sufficient high-precision observations, and the low cost of equipment, but its disadvantages are mainly system bias and the need to improve stability(Glaser et al. 2015). It is by far the highest resolution astronomical technique with very high goniometric accuracy, but because of its large and expensive equipment, there are fewer stations worldwide and observations are not continuous(Nilsson et al. 2014).

The majority of the current experiments using various space geodetic techniques to solve the Earth's rotation parameters are solved using single techniques such as GNSS and VLBI(Karbon et al. 2018; Mayer et al. 2017). The single space geodetic technique reference frame is generally determined by prescribed and real-time protocols and therefore does not have all the necessary information, so that the orientation of the reference frame cannot be determined precisely by the various space techniques(Brumberg and Ivanova 2007; Moghilnitsky and Tolstikov 2002; Gordon et al. 2014). The earth rotation parameters are calculated by using the XA and XB frequencies continuously encrypted by CONT17 campaign in VLBI. The accuracy of VLBI calculation data is verified by processing the GNSS data in the same period. After calculation, it is found that the stability and accuracy are improved(Qian et al. 2021). In the calculation of earth rotation parameters by GNSS, if the stations are evenly distributed all over the world, it will help to improve the accuracy and stability of the calculation results (Wei et al. 2017). Improving the prediction accuracy of ERP is one of the current research hotspots. Different methods to predict the accuracy of ERP mainly include root mean square error, mean error, median error, etc. In short-term prediction, the combination of several methods is conducive to high-precision prediction, but the weighting model is not reflected, Therefore, based on the above research, The Helmert variance component estimation legal right is proposed for the first time. The results show that the Helmert variance component estimation method can effectively improve the accuracy of ERP prediction(Malkin and Tissen 2022). The joint solution of VLBI and GNSS technology is used to make up for the defects of insufficient density of VLBI observation data and unstable GNSS solution results, so as to improve the stability and reliability of the solution results (Wei et al. 2016). There are differences in the processing methods, models and determination of the different parameters of the reference frame used by the analysis centers of the various technologies, and there are systematic differences between the reference frames due to the limitations of the technologies, suggesting that the georeferencing frame established by a single technology is not the optimal choice(Schlüter and Behrend 2007; Beutler et al. 2020). The GNSS and VLBI techniques, as representatives of the kinetic and kinematic geometry techniques in geodesy respectively, can adequately define the required reference frame based on their joint solution, which can well compensate for this discrepancy phenomenon(Zajdel et al. 2020; Collilieux et al. 2010).

Therefore, based on the above research, this paper uses the VLBI observation data of CONT17 Campaign and the GNSS data of IGS in the same period to calculate the Earth rotation parameters, which is different from the IERS14 C04 series provided by IERS. For the first time, Helmert variance component estimation legal weight is used to verify the accuracy of ERP parameters. The integration of spatial measurement technology can give full play to their advantages, and make up for the defects of different spatial geodetic technology to solve the differences of ERP model, the non-uniformity of observation stations, the discontinuity of observation time. This paper is expected to solve the continuous ERP parameter sequence and provide a reference for deep space exploration and other fields.

2. Principle of ERP solution based on VLBI and GNSS

2.1 Principle of ERP solution based on GNSS

For GNSS estimation of ERP, the GNSS carrier phase observations are expressed as a functional mode of the parameters to be estimated. the GNSS observation equation can be written as(Wang, Dang and Xu 2013, He et al. 2010)

$$L = M(t\ , X_{sp}, X_T, X_N, X_{erp}, X_{atm}) + \varepsilon \tag{1}$$

Where M represents a model of the observations as a function of the solution parameters. t represents the time. X_{sp} represents the number of orbital roots and the ingestion parameters at the initial moment. X_T represents the station coordinates, the X_N represents the carrier phase ambiguity, the X_{erp} represents the Earth's rotation parameters, and X_{atm} represents the atmospheric delay, and ε represents the observation noise.

After linearizing(1), the partial derivative of ERP is

$$\frac{\partial R}{\partial X_{erp}} = \frac{\partial M}{\partial R}\frac{\partial R}{\partial R_1}\frac{\partial R_1}{\partial X_{erp}} = \frac{(r-R_1)}{R}\frac{\partial R_1}{\partial X_{erp}} \tag{2}$$

where R represents the star station distance, and R_1 represents the position of the station in the inertial coordinate system, and r represents the position of the satellite in the inertial coordinate system. Where $\frac{\partial R_1}{\partial X_{erp}}$ contains the polar shift in X component of $\frac{\partial R_1}{\partial x_p}$ and the polar shirt in Y component on $\frac{\partial R_1}{\partial y_p}$, and $UT1 - UTC$ the first order rate of change of $\frac{\partial R_1}{\partial D_R}$ and $UT1 - UTC$ the second order rate of change of $\frac{\partial R_1}{\partial \widetilde{D}_R}$:

$$\frac{\partial R_1}{\partial x_p} = PNS\frac{\partial D}{\partial x_p}R_T(t) = PNS\begin{bmatrix} -Z \\ 0 \\ x \end{bmatrix} \tag{3}$$

$$\frac{\partial R_1}{\partial y_p} = PNS\frac{\partial D}{\partial y_p}R_T(t) = PNS\begin{bmatrix} -x_p y \\ x_p x + z \\ -y \end{bmatrix} \tag{4}$$

$$\frac{\partial R_1}{\partial D_R} = \frac{\partial R_1}{\partial \theta_g}\frac{\partial \theta_g}{\partial D_R} \tag{5}$$

$$\frac{\partial R_1}{\partial \widetilde{D}_R} = \frac{\partial R_1}{\partial D_R}(t - t_0) \tag{6}$$

Its equation (5) reads

$$\frac{\partial R_1}{\partial \theta_g} = PN\frac{\partial S}{\partial \theta_g}D^T = PNSD\begin{bmatrix} -y - y_p z \\ x - x_p z \\ y_p x + x_p y \end{bmatrix} \tag{7}$$

$$\frac{\partial \theta_g}{\partial D_R} = 2\pi(1+k)\frac{\partial UT1}{\partial D_R} = 2\pi(1+k)(t - t_0) \tag{8}$$

The above calculation process is the principle of GNSS to solve ERP. In this paper, GPS and BDS network data are used to solve ERP, where it should be noted that the coordinate system of the dual system data needs to be unified when solving, i.e. the spatial and temporal datum needs to be unified when data is fused.

2.2 Principle of ERP estimation based on VLBI observation

The basic principles of VLBI for solving ERP are(Krasna et al. 2021; Schartner et al. 2021)

$$aA = c\tau = \left|\vec{b}\right| \cos\theta = \vec{b} \cdot \vec{s} \tag{9}$$

Where τ is the time of arrival of the radio signal at the radio telescope, and $\vec{s}$ is the unit vectorin the direction from the radio telescope to the radio source, and θ is the $\overrightarrow{s}$ and $\vec{b}$ the angle between The unknown parameters are $\vec{b}$ are the two radio telescope baseline vectors as well as the direction of the radio source.

If the effects of the Earth's rotation are taken into account, the $\vec{b}$ no change. α_G Amount of change occurring.

$$\Delta a_G = \omega \cdot \tau = c \cdot \tau = \vec{b} \cdot \vec{s} = \cos\delta \cos(\alpha - \alpha_G)\,\Delta X + \cos\delta \sin(\,\alpha - \alpha_G)\Delta Y + \sin\delta \Delta Z \tag{10}$$

$$\frac{d\tau}{d\alpha_G} = \frac{1}{c}[\cos\delta \sin(\alpha - \alpha_G)\,\Delta X - \cos\delta \cos(\,\alpha - \alpha_G)\Delta Y] \tag{11}$$

$$\Delta\tau = \frac{d\tau}{d\alpha_G} \cdot \Delta a_G = \frac{\omega\tau}{c}[\cos\delta \sin(\alpha - \alpha_G)\,\Delta X - \cos\delta \cos(\,\alpha - \alpha_G)\Delta Y] \tag{12}$$

The observation equation is therefore

$$\begin{aligned}\Delta\rho &= c(\tau + \Delta\tau)\\ &= c \cdot \tau + c \cdot \Delta\tau\\ &= \cos\delta \cos(\alpha - \alpha_G)\,\Delta X + \cos\delta \sin(\,\alpha - \alpha_G)\Delta Y + \sin\delta \Delta Z\\ &\qquad + \omega \cdot \tau[\cos\delta \sin(\alpha - \alpha_G)\,\Delta X - \cos\delta \cos(\,\alpha - \alpha_G)\Delta Y]\end{aligned} \tag{13}$$

This paper assumes that the astronomical coordinates of a quasar α、δ are accurately determined with as few as three unknown parameters ΔX、ΔY、ΔZ

Therefore, linearizing the above equation (13) and expressing it in matrix form, we get

$$V = B\hat{X} - l \tag{14}$$

and by the least squares principle, assuming that the weight of the observation is P, the solution of the observation is obtained as

$$\hat{X} = (B^T P B)^{-1} B^T P l \tag{15}$$

For the above solution, the error sources are corrected by adding instrument corrections, ionospheric corrections, tropospheric corrections, radio source structure, thermal deformation, and axis offset to obtain the corrected observation time delay. The theoretical time delay is also obtained by adding the a priori station coordinates and a priori radio source coordinates to the error sources such as Earth deformation, a priori geoid parameters and relativistic effects. The least squares solution is obtained by computing the corrected observed time delay with the theoretical time delay.

3. GNSS and VLBI solutions and analysis

3.1 GNSS solutions

3.1.1 GNSS Observation

The software GAMIT is used to process the GNSS data from November 28, 2017 to December 12, 2017. Thirty-one stations were selected for the solution, evenly distributed around the world. IGS stations with suitable station locations are selected as reference stations for data interpretation, i.e. BJFS, ALCO, SANT, GRAZ and ALIC are used as reference stations. The selected IGS stations are shown in the Fig.1, with the base station locations in red.

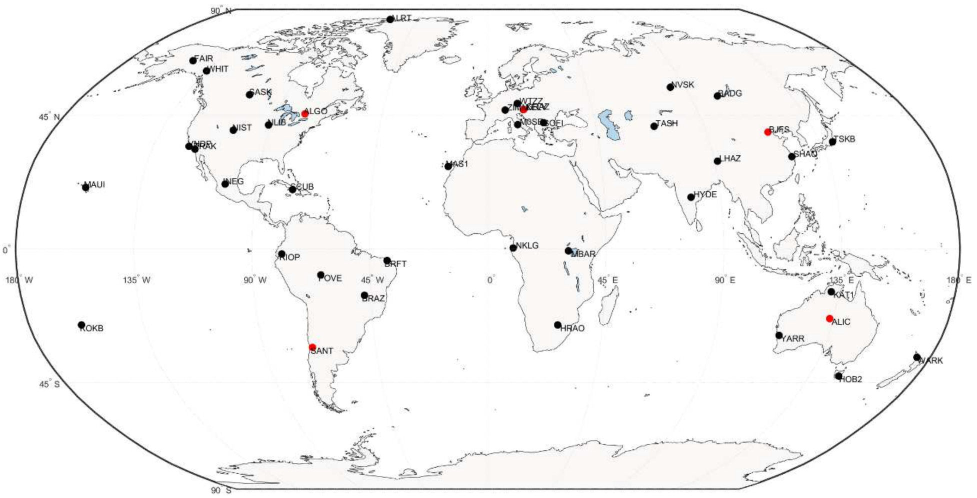


Fig.1 IGS sites distribution map

3.1.2 Data Interpretation and Analysis

When GAMIT solved ERP, The standard root mean square of baseline solution of GNSS data in this paper is about 0.25cm, which meets the accuracy requirements.

Considering the influence of the number of observation stations and the uniformity of the number of observation stations in the world on the accuracy of ERP solution, Thirty-one evenly distributed sites were selected in this paper, high accuracy and relatively stable in the world to solve ERP using

GAMIT, and calculates the difference between the ERP data solved and the results of IERS14 C04 series provided by IERS. The root mean square of the absolute value of the difference is used as the external coincidence precision, as shown in Table 1 and Fig.2.

Table 1 External coincidence accuracy of GNSS ERP solutions

ERP parameters	RMS	MEAN	MAX	MIN
Xpol/mas	0.001152	0.113316	0.129963	0.096587
Ypol/mas	0.000275	0.235215	0.237040	0.233456
UT1-UTC/ms	0.000590	0.242533	0.252179	0.233046

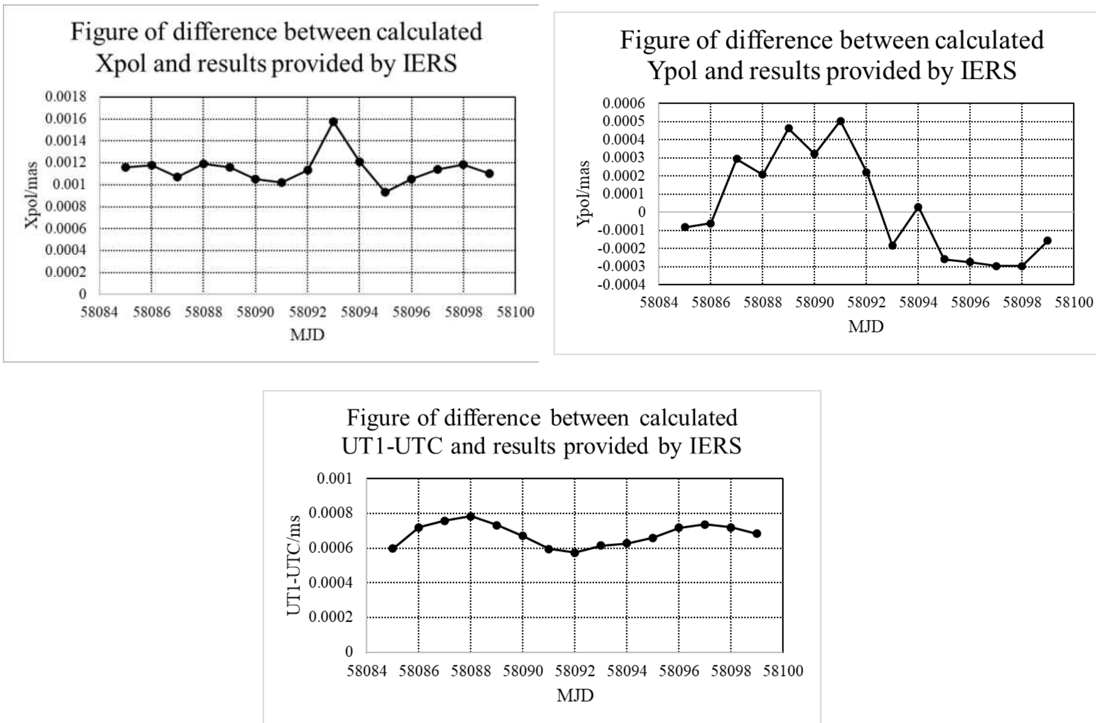


Fig.2 Difference between ERP processed data and results provided by IERS in GNSS

Based on the GNSS data of the same period under the observation of CONT17 campaign, the root mean square of the pole shift component in the X direction is 0.001152 mas, and the root mean square of the pole shift component in the Y direction is 0.000275 mas. The root mean square of $UT1-UTC$ is 0.000590 ms. According to the above ERP data analysis, it can be seen that the root mean square of pole shift component in X and Y directions and the root mean square of $UT1-UTC$ are small, which means that the solution accuracy is high. The main reason is that the selected stations are evenly distributed in the world, the number is suitable and the stability is high.

3.2 VLBI solutions

3.2.1 VLBI Observation

The software VieVS is used to process the observation data of CONT17 campaign in VLBI from November 28, 2017 to December 12, 2017. During the observation, three independent VLBI observation networks: two traditional S / X bands and 14 global radio telescopes were used for independent observation for 15 days in the same period, and the global observation data of VLBI during this period were continuously recorded(Behrend et al. 2020). The distribution of CONT17 campaign observation stations is shown in Fig.3.

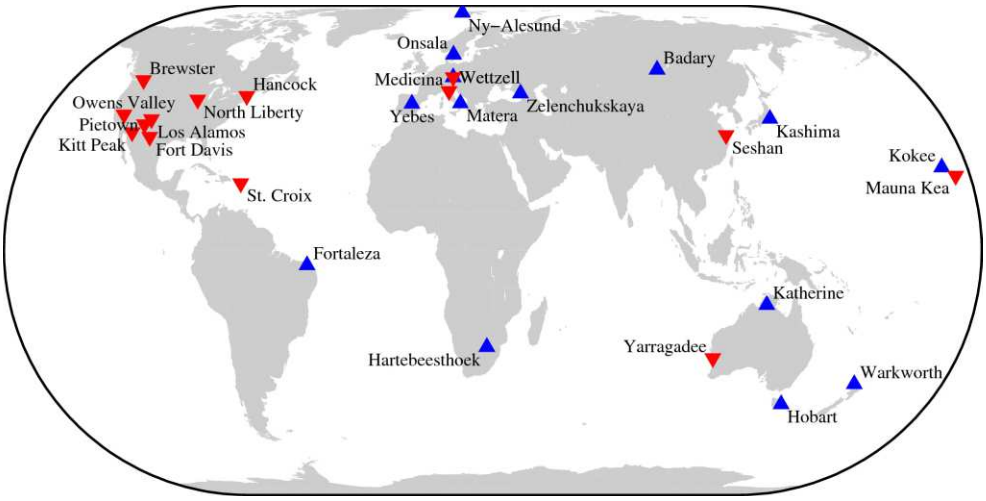


Fig.3 Map of the CONT17 observation sites

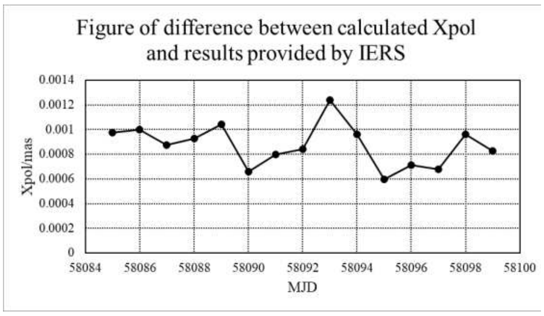
3.2.2 Data Interpretation and Analysis

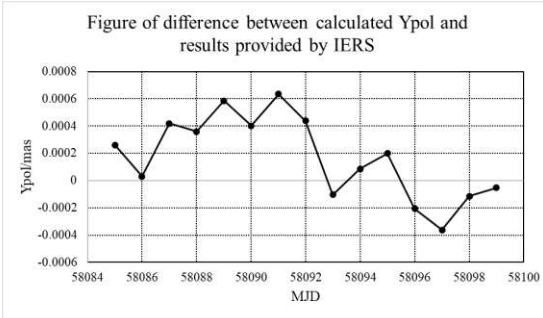
In this paper, VLBI continuous encrypted observations in VgosDB format from rom November 28, 2017 to December 12, 2017 were processed using the VieVS3.2 developed by the Vienna University of Technology, Austria(Behrend et al. 2020). Firstly, when solving the ERP for the Earth rotation parameters, ITRF2014 is selected for the reference frame, JPL421 is selected for the ephemeris, and all other settings are for the default parameters(Böhm et al. 2018).

This paper is based on VLBI data in VgosDB format under the CONT17 campaign observations, processed using VieVS3.2, and the series processed to obtain ERP results for difference analysis with the IERS published IERS14 C04 series results. The root-mean-square of the absolute value of the difference was used as the out-conformity precision. As shown in Table 2 and Fig.4 are shown.

Table 2 External coincidence accuracy of VLBI ERP solutions

ERP parameters	RMS	MEAN	MAX	MIN
Xpol/mas	0.000888	0.113587	0.130151	0.096861
Ypol/mas	0.000339	0.235068	0.236908	0.233190
UT1-UTC/ms	0.000702	0.242513	0.252145	0.233015





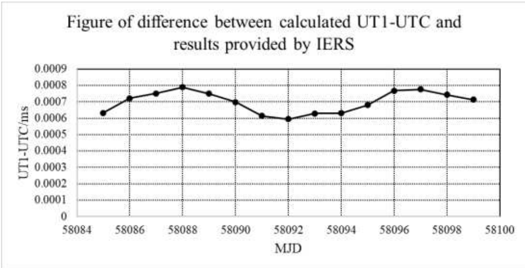


Fig.4 Difference between ERP processed data and results provided by IERS based on VLBI under CONT17

Based on the observation of CONT17 campaign, the root mean square of pole shift component in X direction is 0.000888 mas, and the root mean square of pole shift component in Y direction is 0.000339 mas. The root mean square of $UT1-UTC$ is 0.000702 ms. It can be seen from the above analysis of ERP solution results that the sequence of VLBI solution results is relatively flat, which means that there is no systematic error in the ERP parameters solved, and it can be seen that the solution accuracy of the pole shift component in the X direction and Y direction is better than 0.5mas, and the solution accuracy of $UT1-UTC$ is 0.05ms. However, the accuracy of the pole-shift component in the Y direction fluctuates, which indicates that the stability and continuity of VLBI observation technology still need to be improved.

4. A stochastic model for joint solution of ERP by VLBI and GNSS

4.1 Reciprocal weighting model of ERP root mean square

When VLBI and GNSS jointly solve ERP, even if the a priori normal equations in the two spatial geodetic technologies are completely known, the accuracy difference between each technology is usually unknown and needs to be determined through a posteriori information. This also means that when the parameter is eliminated and the unit weight variance factor is no longer accurate, it needs to use the Helmert variance component estimation method for iterative calculation to re-establish the unit weight variance factor. At present, the reciprocal weighting model based on the square of the root mean square of ERP is commonly used in multi technology joint solution of ERP, and its main calculation formula is as follows:

$$RMS_{GNSS} = \sqrt{\frac{\sum_1^n (ERP_{GNSS} - ERP_{IERS})^2}{n}} \tag{16}$$

$$RMS_{VLBI} = \sqrt{\frac{\sum_1^n (ERP_{VLBI} - ERP_{IERS})^2}{n}} \tag{17}$$

$$ERP_{GNSS+VLBI} = \frac{RMS_{VLBI}^2 ERP_{GNSS} + RMS_{GNSS}^2 ERP_{VLBI}}{RMS_{VLBI}^2 + RMS_{GNSS}^2} \tag{18}$$

$$RMS_{GNSS+VLBI} = \sqrt{\frac{\sum_1^n (ERP_{VLBI+GNSS} - ERP_{IERS})^2}{n}} \tag{19}$$

Where ERP_{GNSS}、ERP_{VLBI}、$ERP_{GNSS+VLBI}$ denote the ERP sequences obtained from GNSS, VLBI, GNSS+VLBI based on the weighted IERS14 C04 sequence, respectively. RMS_{GNSS}、RMS_{VLBI} 、 $RMS_{GNSS+VLBI}$ denote the root mean square of the difference between GNSS,VLBI,GNSS+VLBI and IERS14 C04 sequence, respectively.

4.2 Helmert variance component estimation

VLBI and GNSS jointly calculate Helmert variance component estimation steps of ERP:

(1) According to the ERP of single spatial geodetic technology, the initial empirical weight ratio between different technologies is set to $P_V = P_G = 1$, the weight is determined by the reciprocal of ERP root mean square in the same technology. The formula is:

$$P_i = \frac{1}{(RMS_i)^2} \tag{20}$$

Where: P represents the weight, RMS represents the root mean square of ERP after calculation, and i represents different spatial geodetic technologies.

(2) Adjust the observation equation and calculate the correction number V of the parameter;

(3) The Helmert variance component is estimated, and the unit weight variance factors of different spatial geodetic techniques are calculated θ： $\theta = S^{-1}W$; Of which:

$$S = \begin{bmatrix} n^V - 2tr(N^{-1}N^V) + tr(N^{-1}N^V)^2 & tr(N^{-1}N^V N^{-1}N^G) \\ tr(N^{-1}N^V N^{-1}N^G) & n^G - 2tr(N^{-1}N^V) + tr(N^{-1}N^V)^2 \end{bmatrix} \tag{21}$$

$$W = [V_V^T P_V V_V \quad V_G^T P_G V_G]^T \tag{22}$$

$$\theta = [\theta_V^T \quad \theta_G^T]^T \tag{23}$$

$$N = N^V + N^G \tag{24}$$

$$N = A^T P A \tag{25}$$

Where: n^V 、 n^G represent the number of observed values of VLBI and GNSS.

(4) Using the calculated unit weight variance factor θ, Re-assign the weight matrix between different spatial geodetic technologies:

$$P_j = \frac{MP_j}{\theta_i^2} \tag{26}$$

Where: M is a constant, which can be expressed by$(\theta_V^2 + \theta_G^2)/2$ instead;

(5) If $\theta_V^2 \approx \theta_G^2$, it can replace the corrected weight matrix and re calculate the ERP. Otherwise, repeat steps (2), (3) and (4) until it is met $\theta_V^2 \approx \theta_G^2$, terminate the iteration and output the result.

4.3 ERP data analysis of VLBI and GNSS joint solution

Single spatial geodetic technology is often limited by the difference of calculation model, the inhomogeneity of observation stations, the discontinuity of observation time and so on. Therefore, it is necessary to carry out multi-technology joint calculation to make up for this part of the deficiency. In this paper, GNSS and VLBI spatial geodesy techniques are used to solve ERP, and the Helmert variance component estimation method is proposed for the first time to solve the ERP weighting, which is expected to achieve all-weather high-precision continuous ERP sequence acquisition. The following are the results of the joint ERP solution, as shown in Table 4 and Fig.5.

Table 4 External coincidence accuracy of the joint VLBI and GNSS ERP solutions

ERP parameters	VLBI	GNSS	VLBI+GNSS
Xpol/mas	0.000888	0.001152	0.000985
Ypol/mas	0.000339	0.000275	0.000286
UT1-UTC/ms	0.000702	0.000590	0.000690

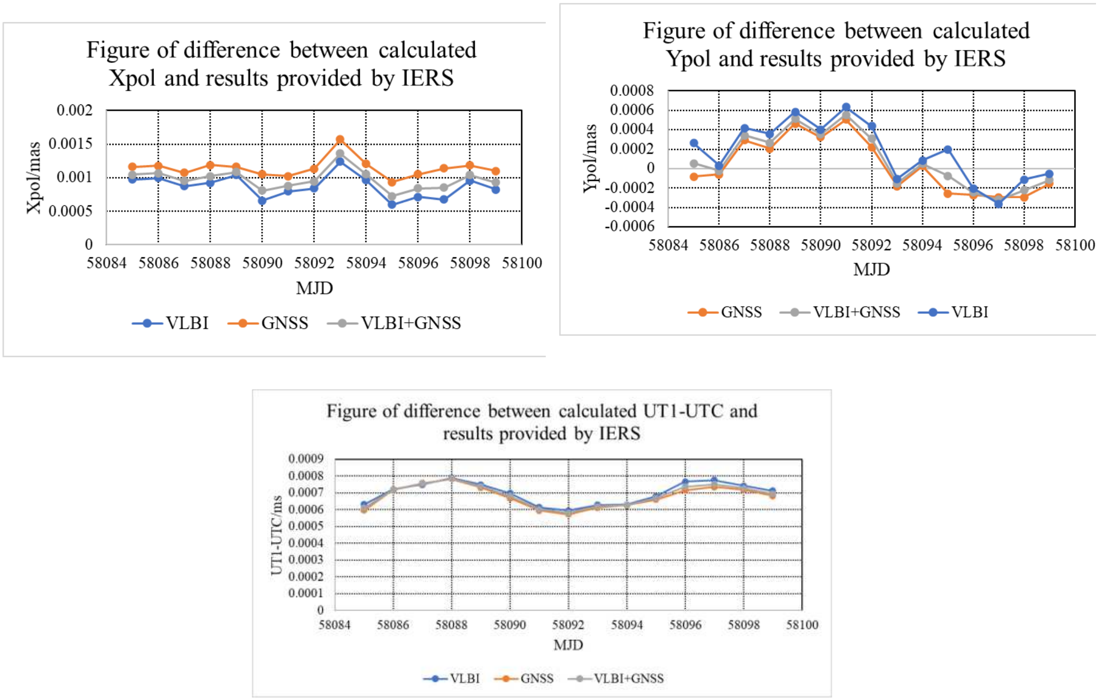


Fig.5 Difference between ERP data and results provided by IERS based on the joint VLBI and GNSS solution

Based on the observation of CONT17 campaign, the root mean square of the pole shift component in the X direction is 0.000985 mas and the root mean square of the pole shift component in the Y direction is 0.000286 mas. The root mean square of $UT1-UTC$ is 0.000690 ms. It can be seen from the analysis that the results obtained after VLBI and GNSS weighting based on the IERS14 C04 sequence provided by IERS are between GNSS and VLBI, and the accuracy of root mean square pole shift component in X and Y directions and $UT1-UTC$ is slightly higher than the RMS accuracy of GNSS and the individual accuracy of VLBI.

The result shows that the calculation of earth rotation parameters by VLBI technique meets the requirement of high precision. The results obtained in this paper are compared with the earth rotation parameters calculated by GNSS observation data in the same period. The results show that there is a small gap between VLBI technique and GNSS technique, which is probably related to the selected time period, the uniform distribution of GNSS stations in the world, high stability and continuous observation data.

5. Conclusions

In this paper, based on VLBI data observed by CONT17 campaign, using VieVS3.2 processed VLBI data, and uses GAMIT to process GNSS data in the same period. The ERP fusion solution is obtained by Helmert variance component estimation based on IERS14 C04 sequence provided by IERS. The root mean square of pole shift component in X direction is 0.093462mas, and the root mean square of pole shift component in Y direction is 0.074871mas. The root mean square of UT1-UTC is 0.069255ms. The results show that GNSS and VLBI can effectively improve the reliability and stability of ERP solutions, and compensate for the differences of ERP models, the inuniformity of observation stations and the discontinuity of observation time of different spatial geodetic techniques.

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Kehao Yu, Mengqi Sun performed the experiment;

Lihua Li, Kehao Yu contributed to the conception of the study;

Kehao Yu, Lihua Li, Mengqi Sun contributed significantly to analysis and manuscript preparation;

Kehao Yu performed the data analyses and wrote the manuscript;

Lihua Li helped perform the analysis with constructive discussions.