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Towards Optimization and Assessment of the Chinese New-generation VLBI Network for Earth Orientation Parameters Monitoring

Hao Xiang[1], Zhong-Kai Zhang[1,2,3], Lan Du[1], Ze-Jun Liu[1], and Xu-Qiao Wang[1]
[1] College of Geospatial Information, Information Engineering University, Zhengzhou 450001, China; zhongkai@ashn.org.cn
[2] Henan Industrial Technology Academy of Spatio-Temporal Big Data, Zhengzhou 450046, China
[3] College of Geography and Environmental Science, Henan University, Kaifeng 475004, China
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Abstract

The Earth Orientation Parameters (EOP) provide a time-varying transition relationship between the International Terrestrial Reference Frame and the International Celestial Reference Frame. To support deep space exploration and the Beidou Navigation Satellite System, the Chinese New-generation Very Long Baseline Interferometry Network (CNVN) is under construction for independent monitoring of the EOP. This paper evaluates the performance of existing 4-antenna CNVN through a batch generated observation schedules followed by extensive Monte Carlo simulations. The optimal positions of the fifth and sixth antennas of CNVN are found from 24 hypothetical antenna positions uniformly distributed in China. In this process, the weighted parameters are optimized, which not only reduce the possibility of large error of EOP estimation accuracy due to unreasonable combination, but also greatly reduce the calculation cost.

Key words: methods: analytical – techniques: interferometric – reference systems

1. Introduction

The Earth Orientation Parameters (EOP) hold significant importance in the fields of geodesy, astronomy, and astronautics owing to its provision of a time-varying transformation relationship between the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF; Charlot et al. 2020). Its high-accuracy estimation is facilitated through the employment of the Very Long Baseline Interferometry (VLBI) technique (Schuh & Böhm 2013). The VLBI principle relies on the observation of radio sources from multiple radio telescopes. By using a cross-correlation technique, the difference in arrival times of radio signals at various telescopes can be calculated, enabling the estimation of EOP (Nothnagel 2019). Typically, a VLBI observing session includes coordinating the involvement of several radio telescopes (Sovers et al. 1997).

In order to achieve more precise observational results, it is imperative to consider various factors including the geometric configuration of the VLBI antenna network, specifications of radio antennas, visibility of radio sources, and observation duration. Among them, the geometry of the VLBI antenna network plays a crucial role. For instance, the east–west baseline facilitates precise estimation of the difference between universal Time (UT1) and Coordinated universal Time (UTC), known as dUT1 (UT1-UTC) (Schartner et al. 2021). Similarly, the north–south baseline enables accurate estimation of Earth's rotational axis in terms of its the east–west direction (XPO) and its motion or offset in the north–south direction (YPO). Moreover, longer baselines enhance parameters estimation accuracy; however, they also limit the common visible sky area among radio antennas (Schartner et al. 2020).

Therefore, arranging a suitable VLBI observation network that satisfies diverse scientific objectives is of utmost importance and presents significant challenges. The International VLBI Service (IVS; Nothnagel et al. 2017) orchestrates observing sessions on a global scale to delineate the framework for VLBI observations. Furthermore, driven by the Global Geodetic Observing System (GGOS) in monitoring global transformations, IVS proposes a new-generation VLBI global observing system known as VGOS to meet the precision demands of GGOS (Rothacher et al. 2009). The construction of VGOS antennas is underway worldwide (Petrachenko et al. 2012). Selecting appropriate locations to establish VGOS antennas becomes crucial for both global and regional networks as it facilitates connectivity with existing networks, thereby forming optimal network configurations.

With different approaches a number of investigations on possible new VGOS antenna locations in terms of their expected precision were performed. For instance, the investigations by Pavlis et al. 2008 compared of different network designs through simulations. A most remote point method was used to iteratively define a homogeneous network based on Delaunay triangulation by Hase & Pedreros (2014).

Schartner & Böhm 2019 investigated the impacts of adding a new antenna in Africa through simulation analysis. Kareinen et al. (2017) analyzed possible tag-along antenna locations for Intensive networks. Glaser et al. (2017) performed investigations by adding antennas to existing global VLBI networks. Iles et al. (2018) extended the Australian AuScope array with dynamic scheduling techniques to obtain EOP with current global accuracy. Schartner et al. (2020) investigated optimal antenna locations of VGOS for the estimation of EOP with large scale simulations based on optimal observing schedules by adding a new antenna to different existing VGOS networks. Huda et al. (2021) reduced repeatability of EOP by 20% by adding Indonesian antennas to existing network configurations.

For the Chinese VLBI networks specifically, attaining independent capability in providing stable, regular, rapid, and high-precision EOP assumes paramount significance for deep space exploration missions and satellite navigation service. The Chinese VLBI Network (CVN), currently comprises four VLBI antennas strategically located in Shanghai (Sh), Beijing (Bj), Urumqi (Ur), Kunming (Km). These antennas are primarily employed for astrometry and deep space tracking purposes. Besides these there exist other antennas such as Tianma (Tm), Jiamusi (Jm), Kashi (Ks) mainly for astrometry and deep space tracking. However, currently there are no regular VLBI sessions scheduled for monitoring and estimating EOP in China independently. In light of this limitation, a proposal was put forth in 2015 to establish the Chinese New-generation VLBI Network (CNVN) adhering to VGOS standards. A preliminary draft plan for this network expansion has been proposed with an aim to include six antennas for comprehensive EOP monitoring and evaluation. Li et al. (2010) proposed a plan of the new VLBI network with 10 antennas located in China for comprehensive applications in geodesy, astrometry and deep space explorations. Fan (2018) assessed the accuracy of the estimation of EOP by new networks with adding several new antennas to the CVN. Currently, four VGOS antennas of CNVN have been announced in Sh, Ur, Sanya (Sy) and Harbin (Hb). Subsequent stages of CNVN construction will necessitate the installation of two more antennas alongside the aforementioned four.

Therefore, in this paper, based on the existing 4-antenna CNVN, we try to find the optimal geographical positions of the remaining two antennas in hypothetical antenna locations to form the optimal 4+1 and 4+2 antenna network. The "Experiments" section describes in detail the processes and methods we used to find the optimal 4+1 antenna network and 4+2 antenna network using batch processing technology, and provides detailed information on the parameter settings used in the simulation experiments. In the "Results" section, we evaluate the performance of the initial 4-antenna CNVN and determine the optimal configurations of the 4+1 and 4+2 antenna network from a large number of Monte Carlo experiments. In the "Discussion" section, we explain the reasons for choosing the optimal antenna positions and provide comprehensive explanations regarding the correlation between experimental parameter settings and realistic antenna construction. Finally, a concise summary of the entire paper is presented in the "Conclusion" section.

2. Experiments

2.1. Methods

The workflow of our study is illustrated in Figure 1.

As mentioned in the introduction, planning a schedule needs to consider scientific objectives and network characteristics. Therefore, in all network analysis and evaluation processes, we pay attention to the four key optimization criteria and their weight parameters, so as to avoid the accuracy reduction of EOP estimation due to unreasonable parameter configurations. This will be reflected in the "Results and Discussion." The four key optimization criteria and their weight parameters are sky-coverage, number of observations, duration and idle time. Sky-coverage ensures uniform coverage at each station to enhance tropospheric delay estimation. The purpose of the number of observations is to maximize the redundant observations to improve the accuracy of EOP estimation. Duration minimizes antenna switching, calibration work and overhead time. Idle time is a precautionary measure to ensure that all antennas can perform regular observations (Schartner & Böhm 2019).

2.1.1. Evaluation of 4-antenna CNVN

The EOP estimation accuracy of 4-antenna CNVN first evaluated in this paper corresponds to the first step in Figure 1. 4-Antenna CNVN is shown in Figure 2. As previously mentioned, during the evaluation of this network, we carefully assessed the influence of four weighting parameters on the estimation results: sky coverage, number of observations, duration, and idle time. To determine the combined impact of these weighting parameters on the estimation results, we varied each parameter from 0 to 1 in increments of 0.25. This resulted in a total combination of 625 weighting parameters for this network ($5 \times 5 \times 5 \times 5$). However, it is suggested that the effect of these weighting parameters depends primarily on their relative proportions. The combinations of weighting parameters as Equation (1) will generate the same observation schedules (Here, we use the Equation sign not to mean that the vectors are numerically equation, but to mean that the vectors will result in

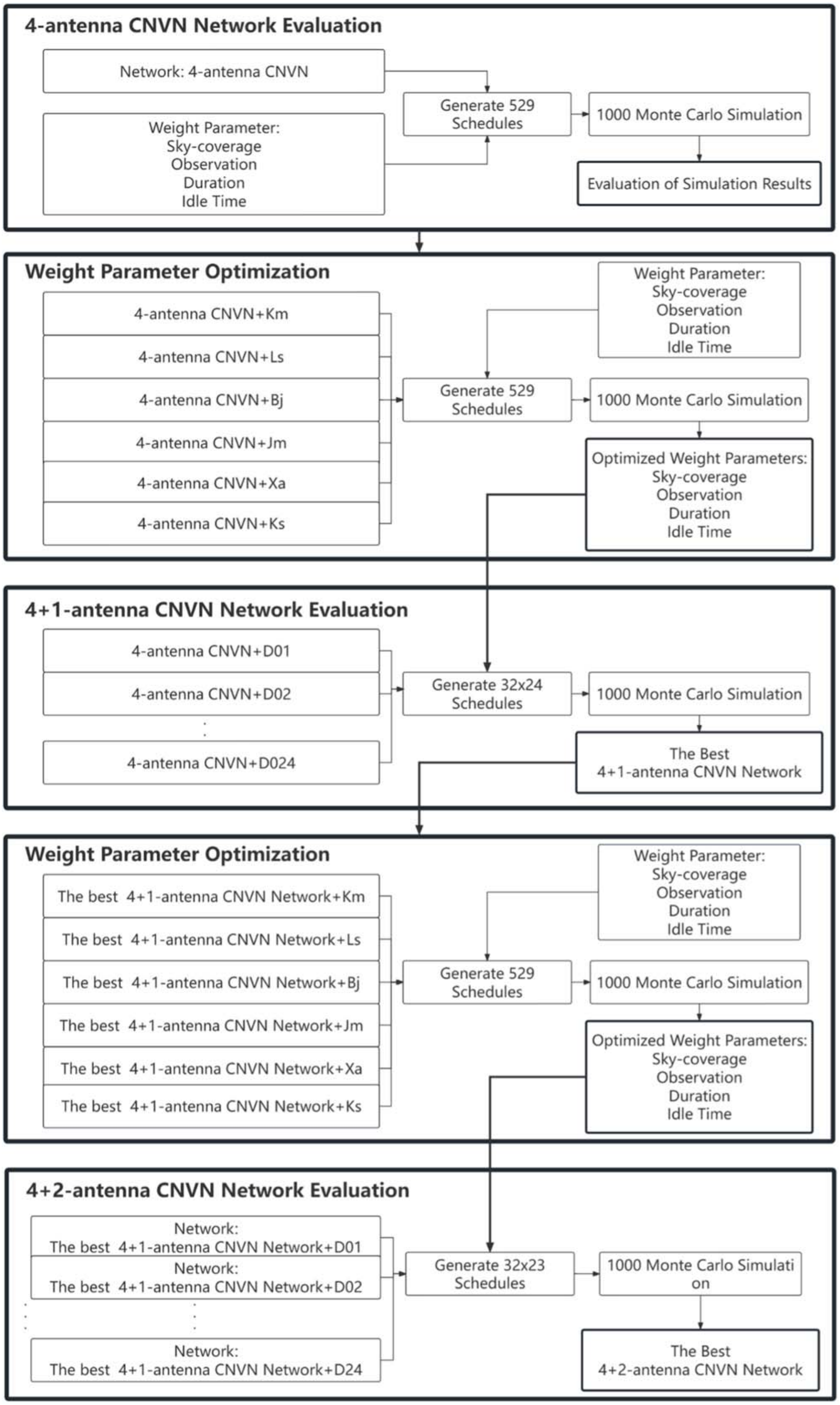

Figure 1. Workflow of this article.

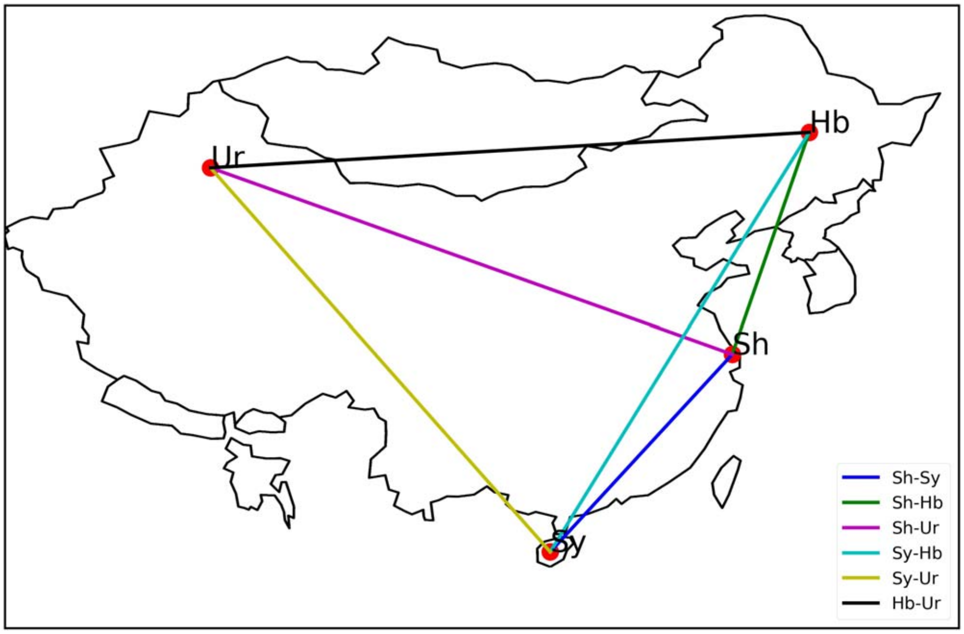

Figure 2. 4-antenna CNVN.

the same weight ratio).

$$\begin{pmatrix} w_{\text{sky-coverage}} \\ w_{\text{observation}} \\ w_{\text{duration}} \\ w_{\text{idletime}} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.25 \\ 0.25 \\ 0.25 \\ 0.25 \end{pmatrix} = \begin{pmatrix} 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \end{pmatrix} = \begin{pmatrix} 0.75 \\ 0.75 \\ 0.75 \\ 0.75 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$
$$\begin{pmatrix} w_{\text{sky-coverage}} \\ w_{\text{observation}} \\ w_{\text{duration}} \\ w_{\text{idletime}} \end{pmatrix} = \begin{pmatrix} 0.25 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.5 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0.75 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \quad . \tag{1}$$
$$\begin{pmatrix} w_{\text{sky-coverage}} \\ w_{\text{observation}} \\ w_{\text{duration}} \\ w_{\text{idletime}} \end{pmatrix} = \begin{pmatrix} 0 \\ 0.25 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0.5 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0.75 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \ldots$$

Consequently, the 4-antenna CNVN will yield a total of 529 distinct combinations of weight parameters, thereby generating an equivalent number of observation schedules. Subsequently, we conduct 1000 Monte Carlo simulation experiments for each of these 529 observation schedules to assess the estimation capability of the 4-antenna CNVN regarding EOP.

2.1.2. Optimal 4+1 Network

A preliminary draft plan for CNVN has been presented, which includes six antennas. To determine the best position for the fifth antenna, we selected 24 evenly distributed land-based sites across China with a latitude and longitude difference of 6° while avoiding the Altai Mountains and the Taklamakan Desert as illustrated in Figure 3. We partitioned a 6° × 6° square grid centered on each hypothetical antenna location to represent the approximate estimated accuracy for that particular area. These 24 hypothetical locations' antennas were sequentially added to CNVN one by one to form different 4+1-antenna networks. The above work corresponds to step 3 in Figure 3.

As with the evaluation of 4-antenna CNVN, before evaluating these 4+1 antenna networks, it was necessary to optimize the combinations of weighted parameters to reflect the optimal performance of these networks in estimating EOP. Assuming that each 4+1-antenna network considers weight parameters as (0, 0.25, 0.5, 0.75, 1), this would result in a total of 12,696 (24 × 529) observation schedules for the 24 networks. Performing 1000 Monte Carlo experiments for each schedule would lead to around 130 million simulations and significant computational costs. So, we added a second step to Figure 1. Based on the method proposed by Schartner et al. (2020), in this paper, antennas located at Bj, Km, Ls, Xa, Jm and Ks were added to the 4-antenna CNVN to form a training

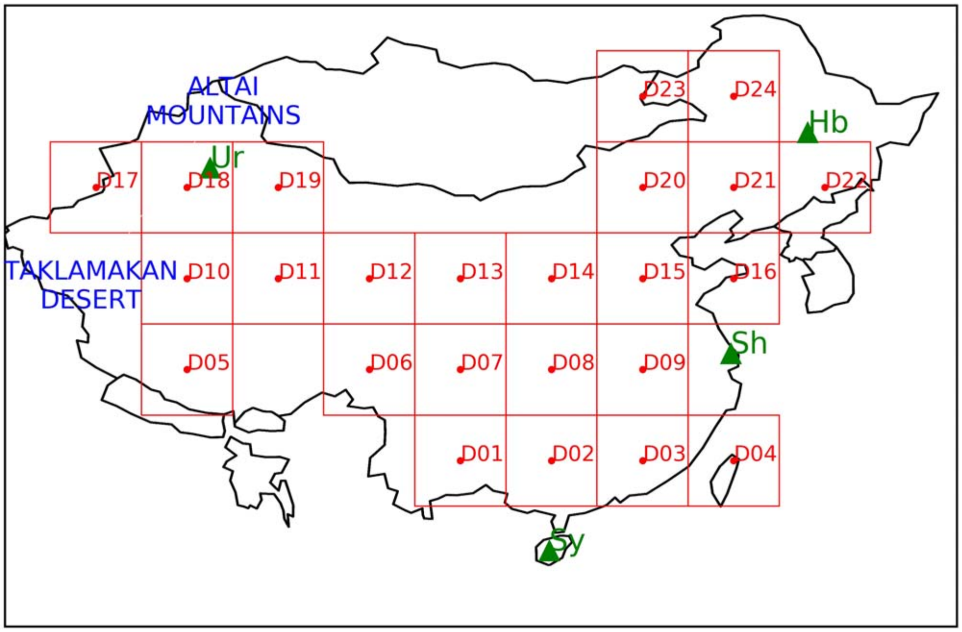

Figure 3. Hypothetical location of 24 antennas. (The blue font indicates the geographical location of the Altai Mountains and the Taklamakan Desert; the green triangle and green font represent the configuration of the 4-antenna CNVN; the red dots and red font denote the 24 hypothetical antenna positions studied in this study.)

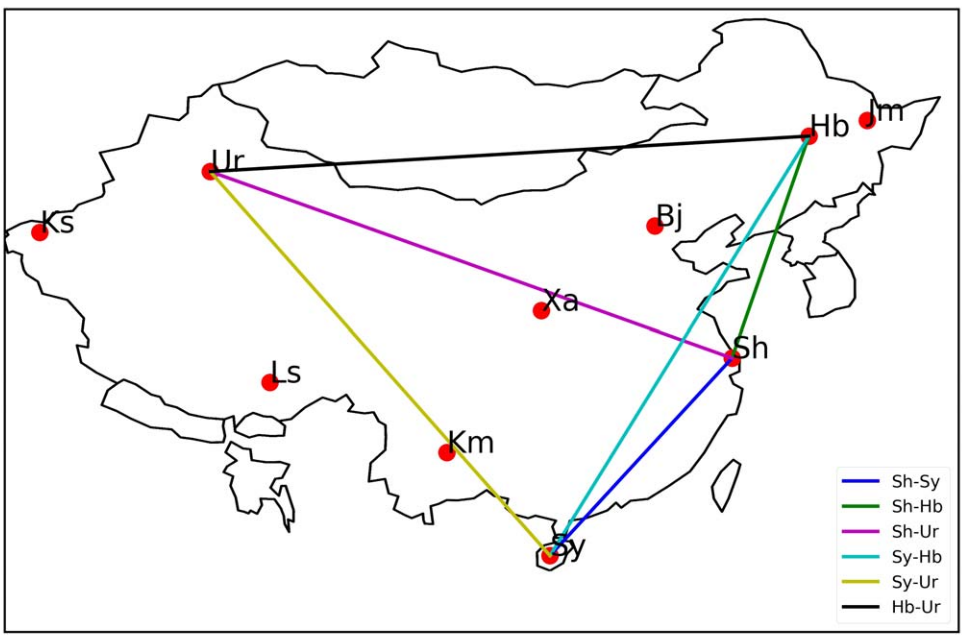

Figure 4. Distribution of locations of antennas added to the 4+1 training network.

network of six 4+1 antennas to determine a more accurate range of each weight parameter and reduce the calculation cost. These specific training networks were selected due to their existing corresponding antennas or conditions suitable for deep space observations and their even distribution across China as depicted in Figure 4.

We conducted simulation experiments on six training networks and evaluated them to determine the optimal range of values for the four weighting parameters, effectively reducing the parameter space and decreasing computational costs. Another reason to optimize the weight parameter space was to avoid the unreasonable combinations of weight parameters that cannot obtain the optimal level of EOP estimation.

2.1.3. Optimal 4+2 Network

The accuracy of the EOP is closely linked to the geometric configuration of the antenna network. For instance, an east–west baseline facilitates precise estimation of dUT1, while a north–south baseline enables accurate estimation of XPO and YPO. Therefore, it is probable that selecting a fifth optimal antenna location to enhance EOP accuracy would still be situated in either the eastern, western, southern or northern regions of China. However, it should be noted that the previously discussed 4-antenna CNVN already includes antennas located in Sh, Ur, Sy and Hb which correspondingly represent these four cardinal directions within China. Consequently, it is likely that any selected 5th best antenna location would be in close proximity to these existing locations. Additional 23 hypothetical location antennas were added to the optimized 4+1 antenna network to form the optimal 4+2 antenna network configuration.

2.2. Simulation

2.2.1. Software

In this study, we used the VieSched++ software developed by Vienna University of Technology to assess the accuracy of EOP estimated by antenna networks with different geometries (?). The software generates numerous observation schedules for VLBI sessions based on different scientific objectives and selects optimal schedules using nine optimization criteria and statistical results from extensive Monte Carlo experiments. These optimization criteria are assigned corresponding weight parameters.

2.2.2. Parameters

With reference to the VGOS standard (Gipson 2018) and combined with the current CNVN construction status, the relevant parameters of the CNVN system involved in the simulation were as follows:

1. Antenna Diameter: 13 m.
2. Antenna axis type: Az–El.
3. Slew rate: Az (720° minutes^{-1}), El (450° minutes^{-1}).
4. Limits of axis: Az (10° 270°), El (7°–89°).
5. Work bands and SEFDs: X (3000), S (3000).
6. Data System: MARK6 (Whitney & Lapsley 2012).

During the observation process, the relevant parameters are set as follows:

7. Observation duration: 24 hr.
8. Sample rate: 1024 MHz.
9. Sample bits: 2.
10. Total recording rate: 16,384 Mbps.
11. Correction factor due to approximations made in the correlation process: 0.97.
12. Observation bands: A (3.2564 GHZ), B (5.4694 GHZ), C (6.6164 GHZ), D (10.4564 GHZ).
13. Min scan length: 60 s.
14. Sources and flux version: 2024 MAY06_igsfc (https://raw.githubusercontent.com/nvi-inc/sked_catalogs/main/flux.cat).
15. Min SNR: X band (20.41), S band (20.41).

The minimum SNR can be set as Equations (2)–(6):

$$\mathrm{SNR} = \eta\rho\sqrt{\mathrm{NumSample}} \quad (2)$$

$$\rho = \frac{F}{\sqrt{\mathrm{SEFD}_2 \times \mathrm{SEFD}_1}} \quad (3)$$

$$F == \text{observed flux density} = 0.1\ \mathrm{Jy} \quad (4)$$

$$\mathrm{NumSample} = \mathrm{Totalrecordingrate} \times \mathrm{Scanlength} \quad (5)$$

$$\eta = \mathrm{bit}_{\mathrm{eff}} \times \mathrm{corr}_{\mathrm{eff}} \quad (6)$$

Here $\mathrm{bit}_{\mathrm{eff}}$ is the degradation in SNR due to digital sampling and the value is 0.6366 (2-bit). $\mathrm{corr}_{\mathrm{eff}}$ is a correction factor due to approximations made in the correlation process and the value is 0.97 (MARK6). The parameters related to the error during the simulation were set as follows:

16. Standard deviation of Gaussian white noise: 2.83 ps.
17. Structural constant of the refractive index of the troposphere: $1.8 \times 10^{(-7)}$.
18. Clock Allan's standard deviation (ASD): $1 \times 10^{(-14)}$.
19. Equivalent time of clock ASD: 50 minutes.
20. Easterly wind speed: 8 m s^{-1}.
21. Additional const weight zenith dela: 150 mm.
22. Tropospheric time increasement in hours: 2 hr.
23. Tropospheric time increasement in meters: 200 m.
24. Tropospheric height: 2000 m.

Among them, the clock drift was simulated by the sum of the random wandering and the integral random wandering. Finally, in all the experiments, 1000 Monte Carlo simulations were used and the results were calculated statistically.

2.3. Evaluation Criteria

According to the basic principles of VLBI, the Least Squares Method (LSM) is used to minimize the weighted sum of squares of the difference between the observed time delay and the theoretical time delay (the so-called residual) to estimate the unknown parameter. In this paper, the accuracy of EOP was evaluated by the mean formal error and repeatability. When a Monte Carlo experiment is performed, LSM is used to solve the EOP, the formal error is defined as the square root of the covariance matrix corresponding to the diagonal elements, and the mean formal error is defined as the average of the formal error of a large number of Monte Carlo experiments. Repeatability is defined as the standard deviation of an estimate

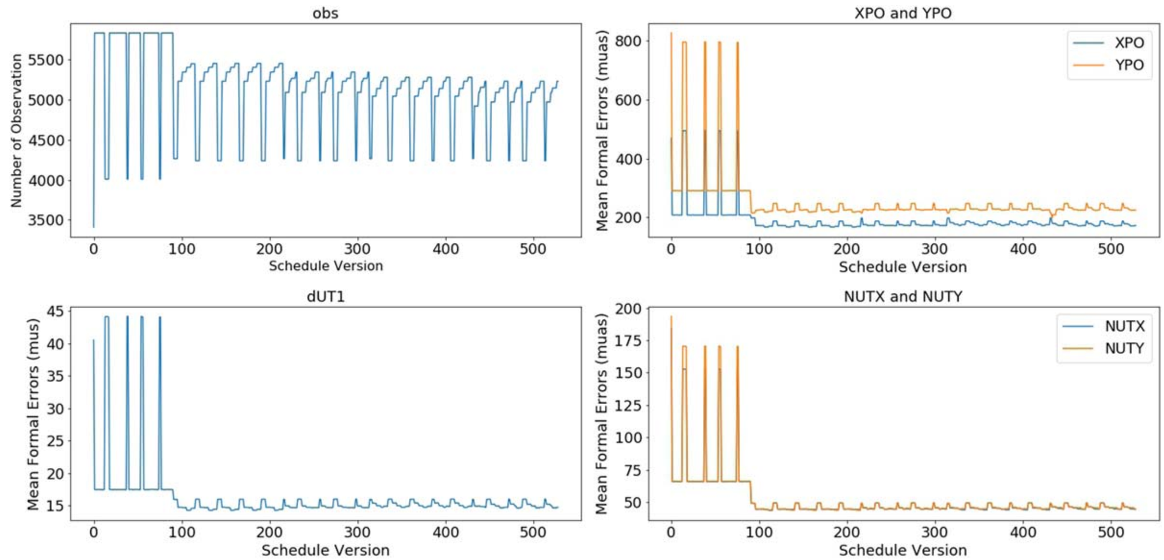

Figure 5. Mean formal errors for estimating EOP for 4-antenna CNVN.

Table 1
Parameters Weight Combination of Different Versions

Schedule Version	Parameters Combination (Sky Coverage × Number of Observations × Duration × Idle Time)
1	(0 × 0 × 0 × 0.25)
2	(0 × 0 × 0.25 × 0)
3	(0 × 0 × 0.25 × 0.25)
4	(0 × 0 × 0.25 × 0.5)
5	(0 × 0 × 0.25 × 0.75)
6	(0 × 0 × 0.25 × 1)
7	(0 × 0 × 0.5 × 0.25)
8	(0 × 0 × 0.5 × 0.75)
9	(0 × 0 × 0.75 × 0.25)
...	...
529	(1 × 1 × 1 × 0.75)

for a single simulation. A general rule of thumb is that the mean formal error and repeatability should account for 30% and 70% respectively in the overall assessment of EOP accuracy, although this can be adjusted for different scientific objectives.

3. Results

3.1. Evaluation of the 4-antenna CNVN

We assessed a total of 529 observation schedules for the 4-antenna CNVN depicted in Figure 2, and the statistics pertaining to the estimation of EOP are presented in Figures 5 and 6.

The horizontal coordinate of each subgraph represents the different version of the observation schedule obtained by combining weighted parameters. The specific parameter combinations are shown in Table 1. The vertical coordinate represents the estimated accuracy of the EOP.

Table 2
4-antenna CNVN Optimal EOP Estimation Accuracy and Weight Parameter Combination

EOP	Mean Formal Errors	Repeatability
XPO (as)	175.8	280.6
YPO (as)	225.9	438.4
dUT1 (s)	14.9	24.1
NUTX (as)	44.1	71.0
NUTY (as)	45.0	72.9

Note. Schedule Version (sky coverage × number of observations × duration × idle time): 0.75 × 0.25 × 1 × 0.75. Score: 0.9185.

For each parameter of EOP, we use Equations (7) and (8) to select the optimal version among many observation schedules, where the 7:3 ratio is based on the experience of real-world observational scheduling (Schartner et al. 2021). The one with the highest score is the optimal schedule.

$$\text{Score}_{\text{network}} = \frac{1}{5}\sum \text{Score}_{\text{EOP}} \tag{7}$$

$$\text{Score}_{\text{EOP}} = 0.7 \cdot \text{Score}_{\text{EOP}-\text{Repeatability}} + 0.3 \cdot \text{Score}_{\text{EOP}-\text{MeanFormalError}} \tag{8}$$

In Equation (8), take $\text{Score}_{\text{EOP}-\text{Repeatability}}$ as an example, the schedule with the highest repeatability accuracy is 1, and the schedule with the worst accuracy is 0. Linear interpolation is adopted between them. Finally, the optimal schedule and combinations of weight parameters are shown in Table 2.

At present, although the network deployment of the four CNVN stations has been announced, the joint test capability of the four stations is not yet fully formed. In order to verify the reference of the simulation conditions and a series of experimental results in this paper, we compared the actual

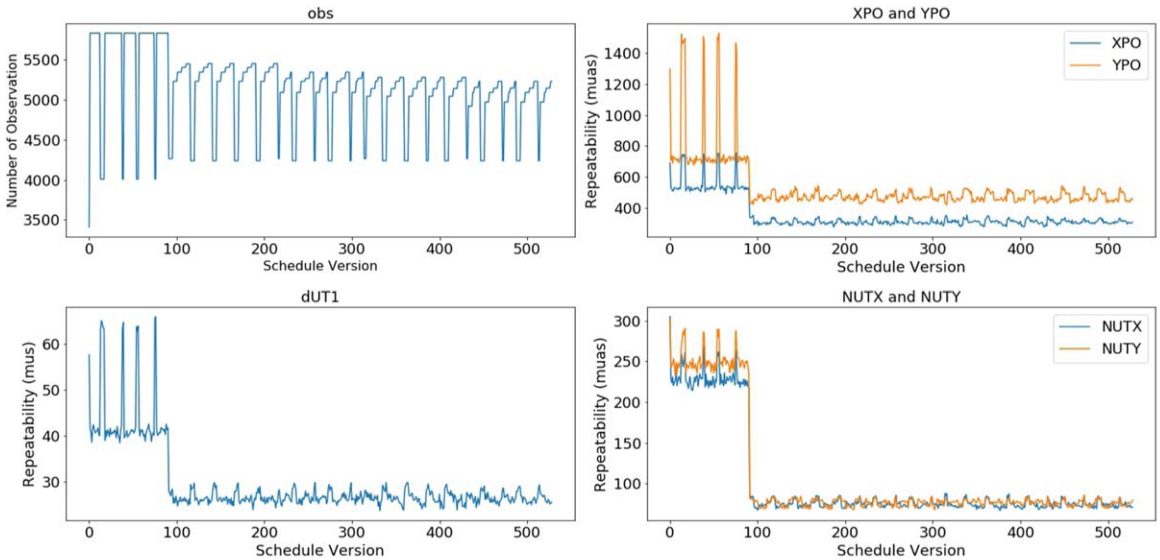

Figure 6. Repeatability of estimated EOP for 4-antenna CNVN.

Table 3
The dUT1 Result of S6-U6 in 2021

Time	Formal Error (Actual Measurement)/μs	Mean Formal Error (Simulation)/μs
04-12 18:30—19:30	26.0	19.92
05-13 18:30—19:30	12.9	18.93
05-17 18:30—19:30	18.3	18.56
05-27 18:30—19:30	12.3	17.41
05-31 18:30—19:30	20.5	19.01
06-10 18:30—19:30	26.0	20.49
06-14 18:30—19:30	11.2	19.76
06-21 18:30—19:30	14.3	19.82
Mean	17.7	19.24

measurement results of Sh 13 m VGOS antenna (S6) and Ur 13 m VGOS antenna (U6) dUT1 in 2021 (Yao et al. 2023). The one-hour intensive observation simulation was carried out under the conditions in Section 2.2.2, and the comparison results are shown in Table 3. It should be added that the measured data comes from the results of one observation, so the formal error is used to measure the accuracy of the results. In order to show the consistency of simulation results, 1000 Monte Carlo experiments were used, so the mean formal error is used to measure the accuracy of the solution results. In addition, since the measured data comes from one observation, we believe that repeatability is meaningless, and there is in fact no indicator to measure the good or bad results of an actual observation. Therefore, we only compare the mean formal error results obtained from the simulation data with those obtained from the measured data.

In contrast, the results obtained in this paper according to the set simulation conditions have certain reference significance. Therefore, the 4-antenna CNVN network studied in this section is expected to achieve the estimated accuracy of the approximate simulation results after fully forming the observation capability.

However, the estimated accuracy needs to be further improved. From Figures 5 and 6, it also can be observed that due to the improper configuration of weighted parameters, the EOP estimation accuracies of different schedules are very different. As described in Section 2.1, different combinations of weight parameters need to be considered in order to achieve the best performance for network estimation accuracy. Therefore, it is necessary to eliminate these unreasonable weight parameter combinations to optimize the parameter space, which can not only reduce the estimation accuracy of EOP, but also effectively save the calculation cost.

3.2. Optimal 4+1-antenna Network

Prior to conducting the evaluation of the optimal 4+1-antenna network, as mentioned in the preceding section, it is imperative to ascertain the range of variation for weighting parameters and thereby narrow down the parameter space. We strategically added antennas at Bj, Km, Ls, Jm, Xi'an (Xa), and Ks locations respectively to augment the existing 4-antenna

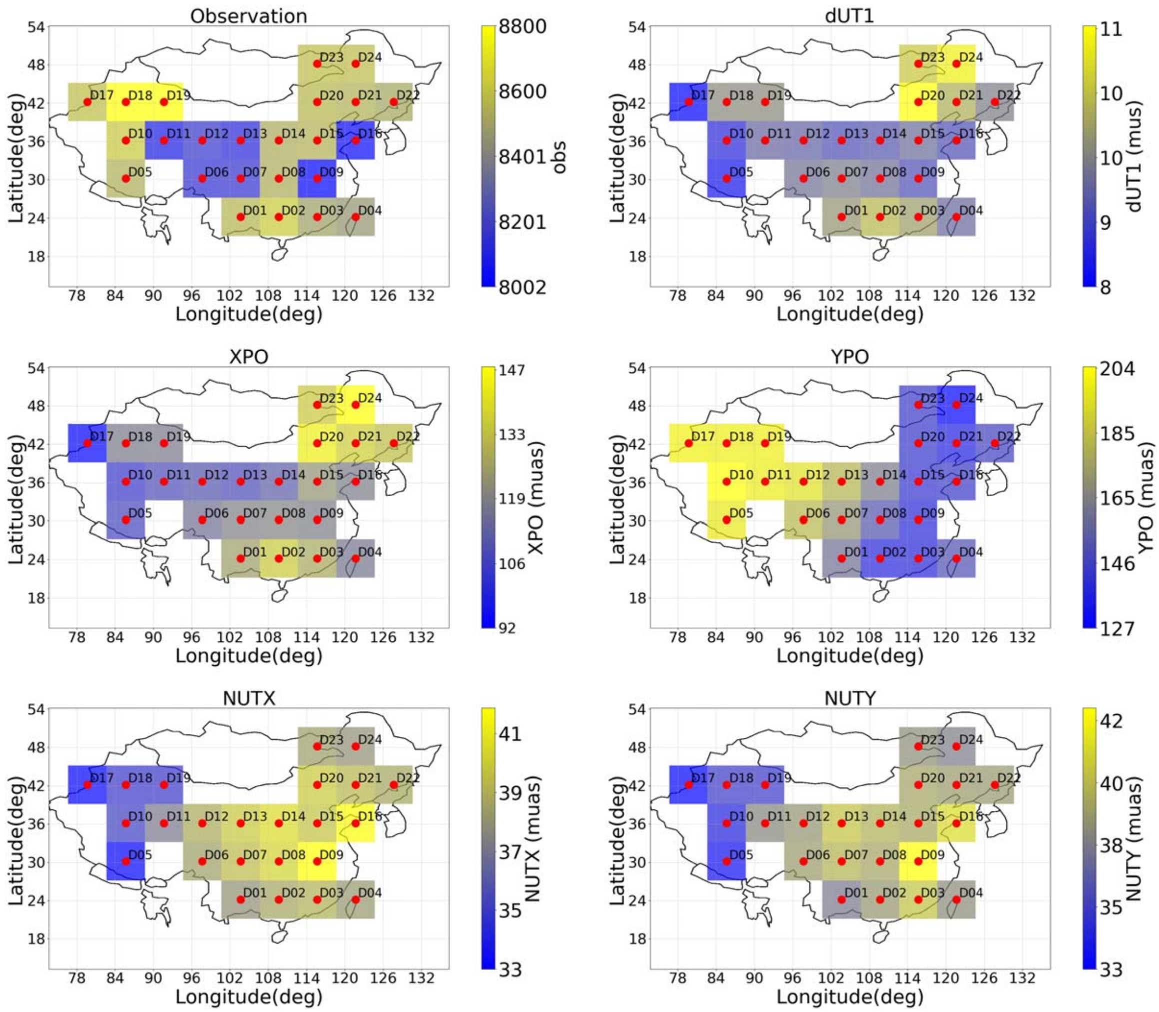

Figure 7. Mean formal errors of 24 4+1-antenna networks for estimating EOP under optimal observational schedule conditions.

Table 4
Range of Weighting Parameters Based on the Evaluation Results of the 4-antenna CNVN and the Six 4+1 Training Networks

Network	Sky-coverage	Observation	Duration	Idle Time	Score	Version
4+Bj	0.75	0	0	1	0.9601	322
4+Jm	0.25	0	0	1	0.8232	96
4+Km	0.25	0	0	0	0.9724	92
4+Ls	1	0	0	0.75	0.9651	433
4+Xa	0.5	0	0	0.5	0.9756	221
4+Ks	0.5	0	0	0.75	0.8938	218
Range	0.25 ∼ 1	0	0 ∼ 0.25	0 ∼ 1		

CNVN (as depicted in Figure 4). These selected locations possess favorable observation conditions and ensure a more uniform coverage across China's territory. By evaluating the training networks of 4+Bj, 4+Xa, 4+Jm, 4+Km, 4+Ls, and 4+Ks through a comprehensive set of 3174 schedules (6 × 529), we subsequently apply Equations (7) and (8) to identify high-scoring schedules and determine the optimal weighted parameter space, as detailed in Table 4.

Through optimization, the weight factors for sky-coverage are limited to 0.25 ∼ 1, observation to 0, duration to 0 ∼ 0.25, and idle time to 0 ∼ 1; reducing the space of weighting parameters from 529 to 32 and computational cost by nearly

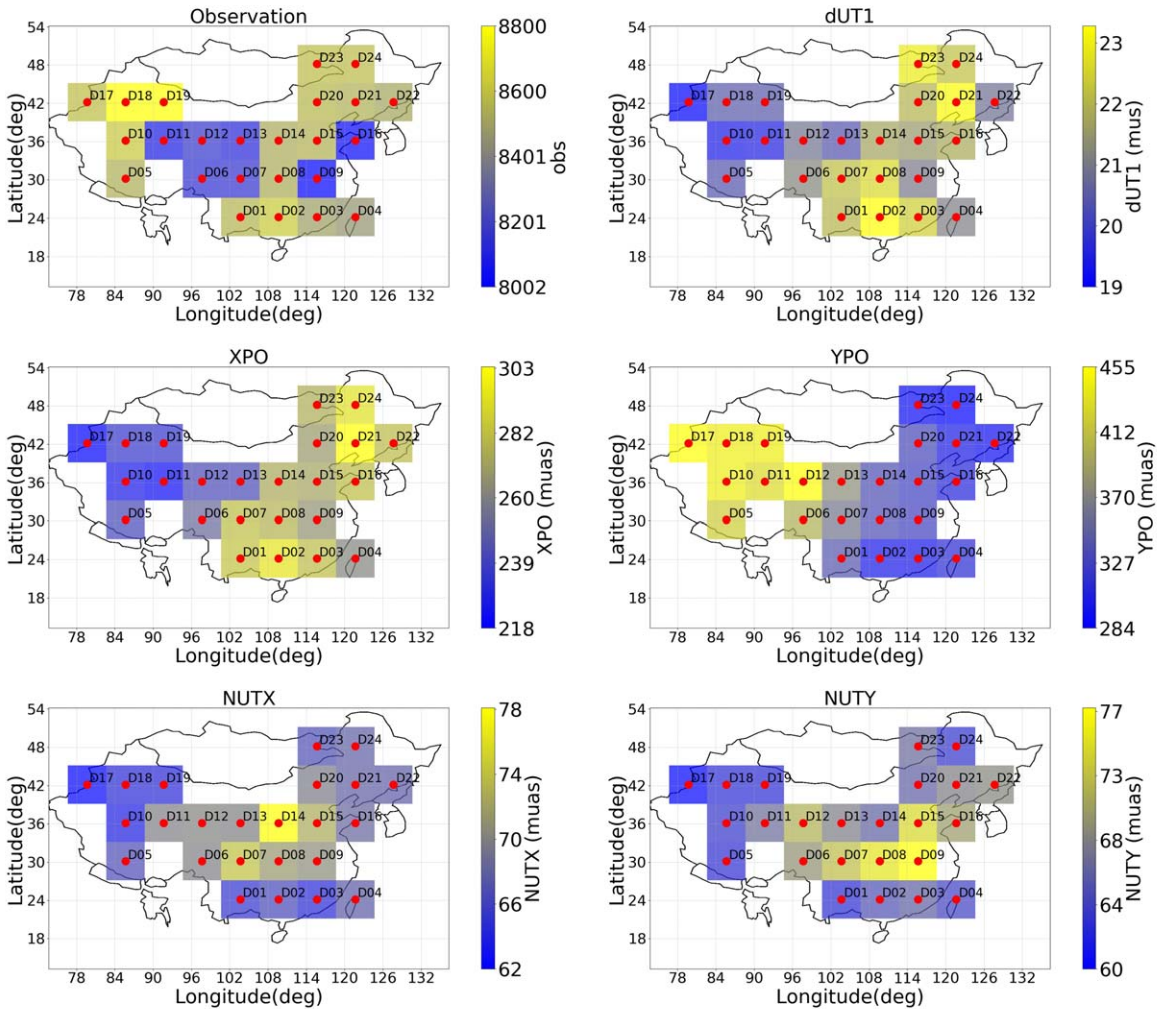

Figure 8. Repeatability of the estimated EOP for a network of 24 4+1 antennas under the optimal observation schedule conditions.

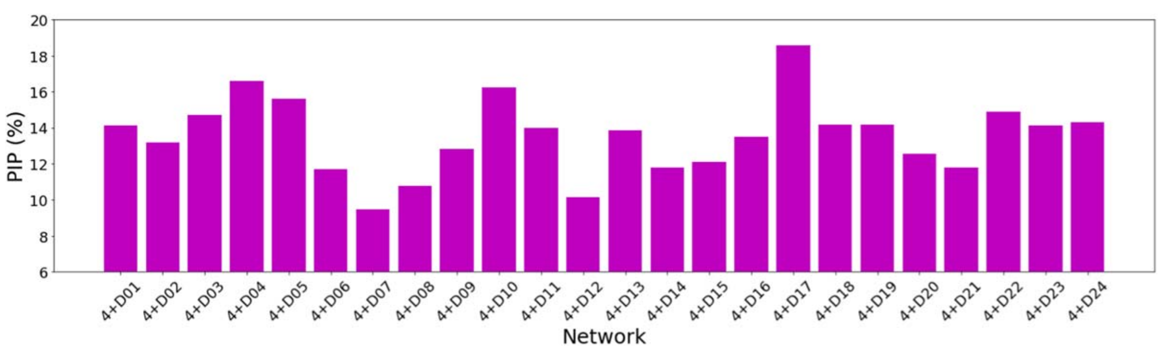

Figure 9. PIPs for the 24 4+1-antenna networks.

94%. This also prevented large errors caused by irrational parameter configurations. We then evaluated hypothetical locations for a total of 24 antennas uniformly distributed in China based on optimized weighting parameters from six training networks and a 4-antenna network generating a total of 768(32 × 24) observation schedules with each 4+1-antenna network selecting optimal schedules based on EOP's mean formal errors and repeatability while performing 1000 Monte Carlo simulations. The statistics results are shown in Figures 7 and 8.

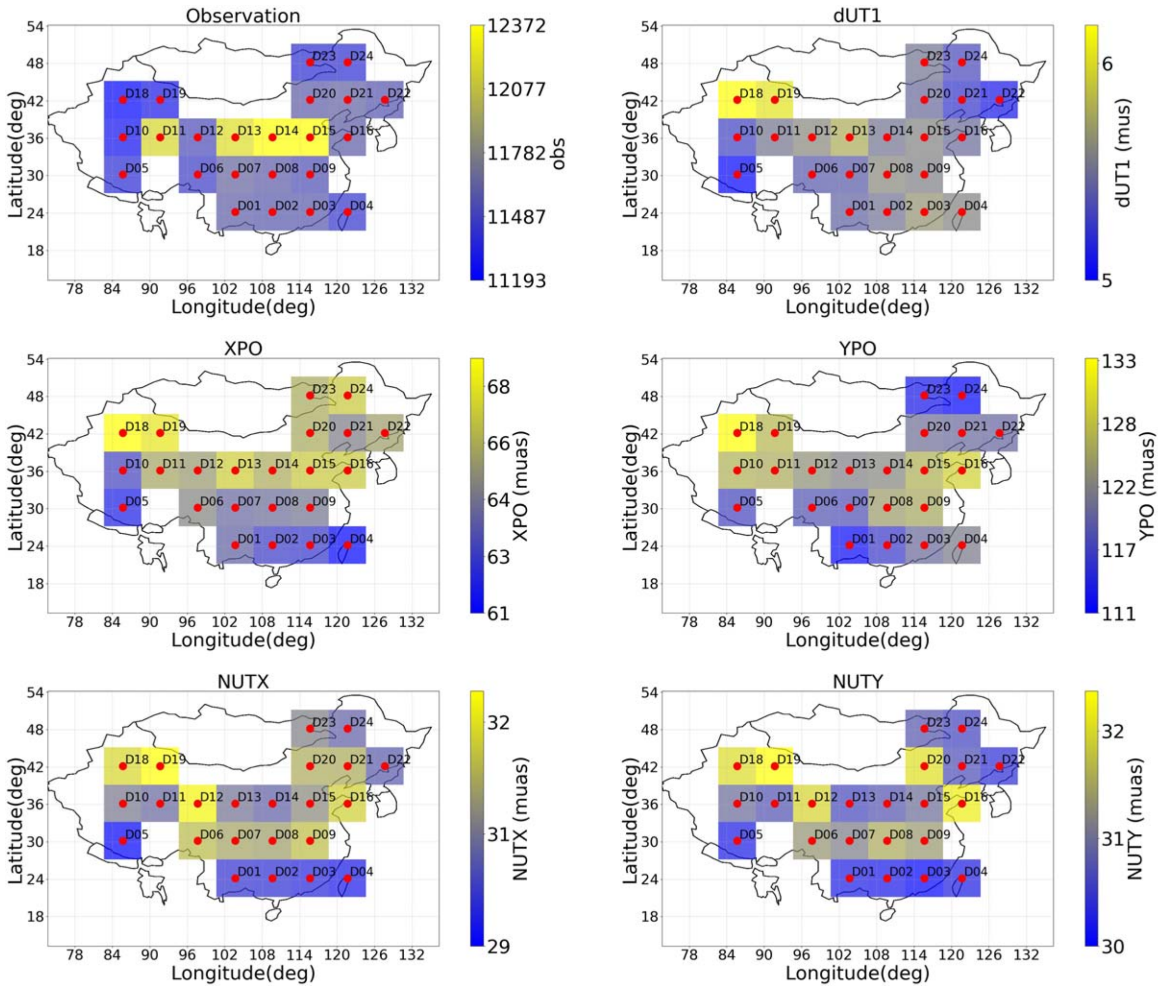

Figure 10. Mean formal errors of 23 4+D17+1 antenna networks for estimating the EOP under the optimal observation schedule conditions.

Figures 7 and 8 present the statistical results of mean formal errors and repeatability in EOP estimation for these networks based on the optimal observation schedules, respectively. We use Equations (9) and (10) to calculate the performance gain of these networks compared to 4-antenna CNVN, expressed as percentage of performance improvement (PIP). The result is shown in Figure 9.

$$\mathrm{PIP}_{\mathrm{NETWORK}}(\%) = \frac{1}{5}\sum \mathrm{EOPPIP}(\%) \tag{9}$$

$$\begin{aligned}\mathrm{EOPPIP}(\%) = 0.3 \cdot \mathrm{EOPPIP}_{\mathrm{MeanFormalError}}(\%) \\ + 0.7 \cdot \mathrm{EOPPIP}_{\mathrm{Repeatability}}(\%)\end{aligned} \tag{10}$$

Figure 9 shows the overall performance improvement of the network's estimated EOP accuracy with the addition of different antennas to the 4-antenna CNVN. Obviously, the inclusion of D17 antenna will significantly enhance the overall estimated line performance of the 4-antenna CNVN, resulting in an approximate increase of 18%. Therefore, we propose that 4-antenna CNVN + D17 represents optimal choices for a 4+1-antenna network configuration.

3.3. Optimal 4+2-antenna Network

In the preceding section, we constructed 24 4+1-antenna networks by amalgamating 4-antenna CNVN with 24 antenna hypothesis locations and systematically evaluated them, resulting in 4-antenna CNVN + D17 emerging as the optimal 4+1-antenna networks. Similarly, we combined 4-antenna CNVN + D17 with Bj, Jm, Km, Ls, Xa and Ks respectively to form a training network and obtained the range of variation of the four weight parameters. The weight factors for sky-coverage were limited to 0.75 ∼ 1, observation to 0 ∼ 0.25, duration to 0.5 ∼ 0.75, and idle time to 0 ∼ 0.75; reducing the space of weighting parameters from 529 to 32 and computational cost by nearly 94%. In this section, we further consider the best 4+2-antenna network from the remaining 23 antenna hypothetical locations based on 4-antenna CNVN + D17, thus

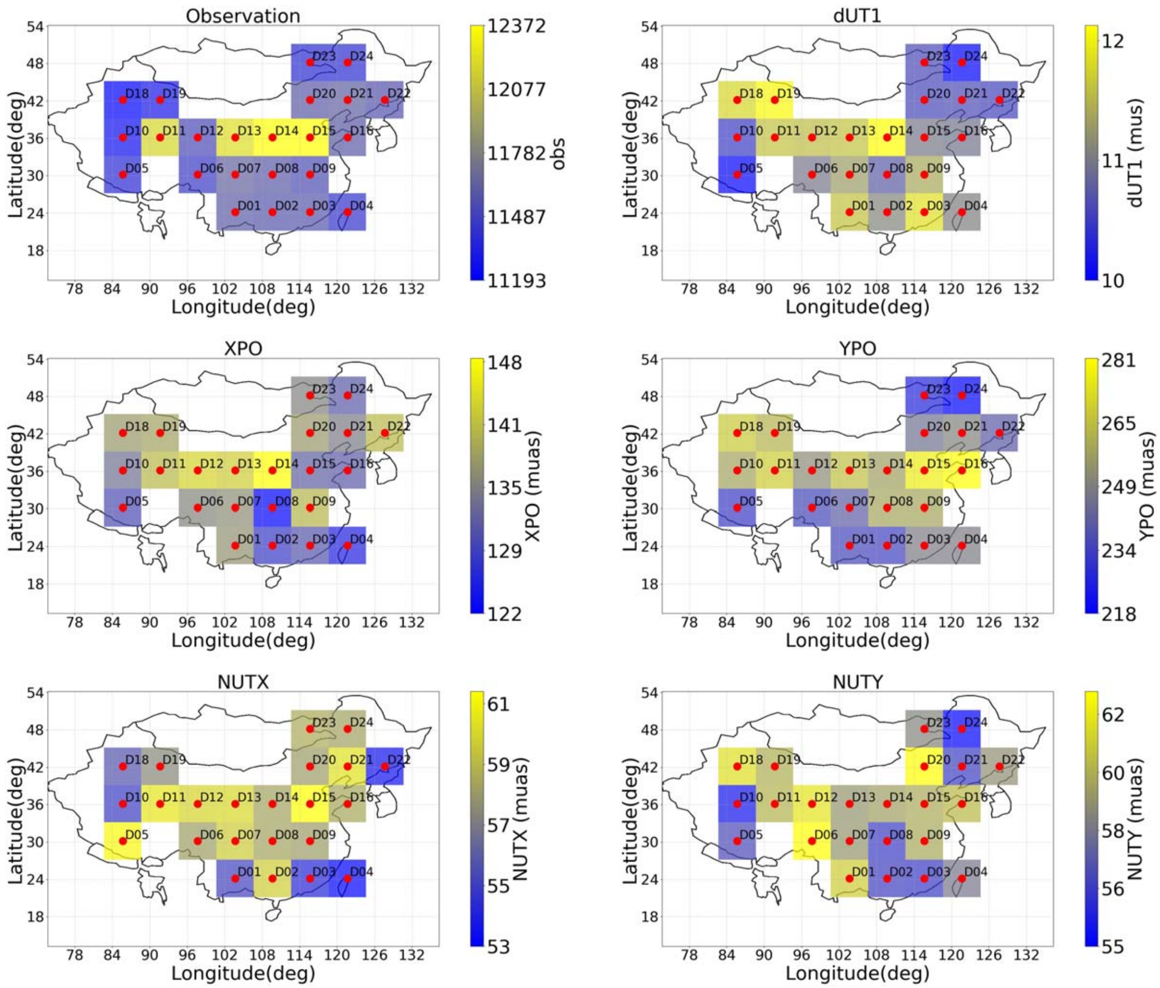

Figure 11. Repeatability of 23 4+D17+ 1 antenna networks for estimating EOP under optimal observation schedule conditions.

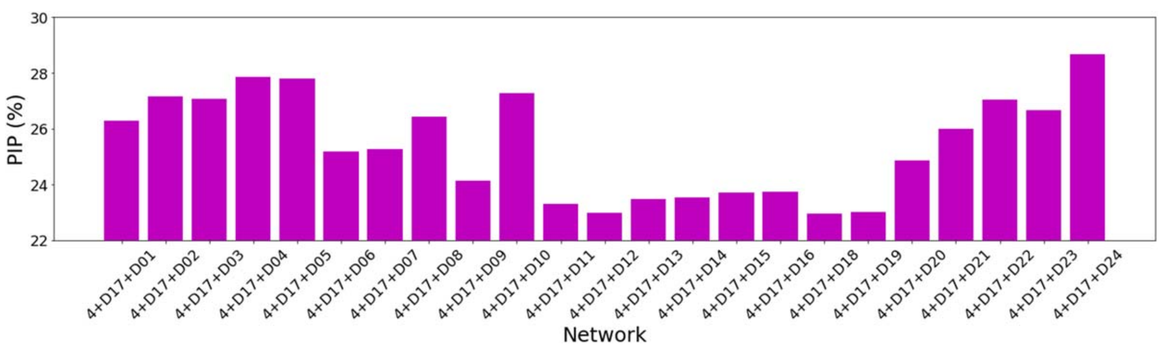

Figure 12. PIPs for the 23 4+D17+1-antenna networks.

a total of 736 observation schedules (32 × 23) are generated. Similarly, the 4+2 antenna networks are evaluated according to Equations (7) and (8).

Figures 10 and 11 present the statistical results of mean formal errors and repeatability in EOP estimation for these networks based on the optimal observation schedules, respectively. We use Equations (9) and (10) to calculate the performance gain of these networks compared to 4-antenna CNVN+D17 network. The result is shown in Figure 12.

The addition of antennas will further improve the overall estimated line performance of the network. The best is 4+D17 +D24, with an increase of 28.6%, and the worst is 4+D17 +D18, with an increase of 23%. Therefore, we propose that 4-antenna CNVN + D17+D24 is the best choice for 4+1 antenna network configuration.

4. Discussion

There is no doubt that with the addition of antennas, the accuracy of estimation of EOP will gradually improve, mainly due to changes in geometry. The addition of D17 and D24 significantly increases the baseline component of the 4-antenna CNVN in east–west and north–south directions. At the same time, the increase of redundant observations also helps to improve the accuracy. According to the simulation results, the selected antenna No. 5 and No. 6 are near Ur and Hb respectively. In the actual network construction, in order to save a certain cost, it can be considered to build a dual antenna system on the basis of the existing 4-antenna CNVN, so as to achieve the effect of east–west extension and north–south extension of the baseline component after adding D17 and D24. However, when considering the actual network construction, we must pay attention to the error caused by the tropospheric delay, which is actually an important reason for affecting the accuracy. In the simulation process, we have considered the tropospheric delay ideally, trying to determine the optimal network geometry in geographical position. Due to the vast area of China, the next step should also consider the annual meteorological change law of the region when the actual antenna is built. Second, the weight parameters of different networks should be considered more finely in practice to reflect the ultimate performances. However, in the actual observations, the ratio between the weight parameters is not invariable, such as when only the subnets observe or when the observations are made in different seasons throughout the year. Finally, it should be noted that when evaluating network performance in this paper, a point is selected to represent the approximate level of the square area, and this result may vary in or around the area. When considering network performance, the PIPs of different EOP are weighted with equal weight. When the scientific objectives are different or some EOP already have prior information, the weighting of PIPs for different EOP will be adjusted.

5. Conclusion

The initial plan for CNVN network is to construct six antennas, with the purpose of supporting deep space exploration missions and providing services for the Beidou Navigation Satellite System (BDS). Considering the VGOS antennas already announced in Sh, Ur, Hb, Sy, this study analyzes the potential VGOS antennas using VieSched++. The preliminary capability of the 4-antenna CNVN has been analyzed from simulations, which matches with former researches. In order to explore potential possibility of CNVN, we conducted a series of simulations and analyzed with 4+1-antenna network and 4 +2-antennas network. The simulation results demonstrate that maximizing the east–west and north–south baseline components is a viable approach. Meanwhile, the estimation accuracy of EOP can be significantly improved with the increase of antennas. Furthermore, this paper optimizes the parameter space for weighting, enabling its application in future studies involving additional hypothetical antenna locations or consideration of more weighting parameters. This optimization effectively reduces computational costs and mitigates the risk of inaccurate estimation of EOP caused by unreasonable combinations of weighting parameters.

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ORCID iDs

Zhong-Kai Zhang https://orcid.org/0000-0001-8293-7400

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