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Carrier Phase Common-View Single-Differenced Time Transfer via BDS Penta-Frequency Signals

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Abstract: The BeiDou Navigation Satellite System (BDS-3) has officially provided services worldwide since July 2020. BDS-3 has added new signals for B1C, B2a and B2b based on old BDS-2 B1I and B3I signals, which brings opportunities for achieving high-precision time transfer. In this research, the BDS-3/BDS-2 combined penta-frequency common-view (CV) single-differenced (SD) precise time transfer model is established with B1I, B3I, B2I, B1C, B2a and B2b signals, including dual-, triple-, quad- and penta-frequency (abbreviated as DF, TF, QF and PF) ionosphere-free (IF) combination CV SD models. Taking four long baseline time links (from 637.6 km to 1331.6 km) as examples, the accuracy and frequency stability of the BDS-3/BDS-2 combined DF, TF, QF and PF SD time transfer models were evaluated. The experimental results show that the frequency stability of the TF, QF and PF SD models were improved by 2.5%, 5.3% and 8.5%, on average, over the DF SD model. Compared with the traditional DF (B1I/B3I IF combination) SD model, the standard deviation (STD) of the multi-frequency SD model was reduced by 5.9%, on average, and the frequency stability was improved by 4.0% on average, which had the most apparent effect on the improvement of short-term frequency stability. Specifically, the DF1 (B1C and B2a DF IF combination), TF1 (B1C, B2a and B2b TF IF combination), QF1 (B1C, B1I, B2a and B2b QF IF combination) and PF4 (B1C, B1I, B2a, B2b and B3I PF IF combination) SD models had better performance in timing, and the PF4 SD model had the best performance. Considering that the PF4 (one PF signal IF combination) SD model does not require an estimated inter-frequency bias and that its noise factor is minor compared with the PF1 (four DF signal IF combination), PF2 (three TF signal IF combination) and PF3 (two QF signal IF combination) SD models, we recommend the PF4 SD model for multi-frequency time transfer and the use of the PF2, PF2 or PF3 SD model to supplement the PF4 SD model in cases of penta-frequency observation loss.

Keywords: BDS; penta-frequency; common-view; single-differenced; time transfer

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1. Introduction

As a constellation transmitting penta-frequency signals, the BeiDou Navigation Satellite System (BDS-3) has provided positioning, navigation and timing (PNT) services since July 2020. It is compatible with old BDS-2 B1I and B3I signals and adds B1C, B2a and B2b new signals [1–4] (the frequencies of BDS-3 B2b and BDS-2 B2I are the same, but the modulation methods are different). The penta-frequency signals of BDS have created conditions for high-precision time transfer and provided opportunities for the maintenance and implementation of spatiotemporal benchmarks in the era of precision measurement.

Regarding the potential advantages of multi-frequency signals in further observation, ionosphere-free (IF) combinations, fixing ambiguity and cycle slip detection, scholars have conducted research on the model of BDS multi-frequency signals, tested and evaluated its

performance in various fields and assessed the advanced performance of multi-frequency signals [5–9]. IGS analysis centers (such as Wuhan University (WHU)) have been able to provide code and phase bias products for BDS multi-frequency signals [10], as well as providing conditions for the application of BDS-3 penta-frequency (PF) signals. Scientists have conducted extensive experiments on the reliability of BDS-3 multi-frequency precise point positioning (PPP) in response to the advantages of multi-frequency-signal minimum noise and quickly fixing undifferenced ambiguity [11–15]. Since then, the application of multi-frequency signals has gradually expanded to the time-frequency field, and a large number of technologies in multi-frequency precision positioning have also been continued in time transfer [16–18]. Now, the Global Navigation Satellite System (GNSS) PPP time transfer accuracy and frequency stability can reach sub-ns and sub- 10^{-16} @10 day [19–21]. At the same time, extensive research has evaluated the models and performance of BDS-3 triple-frequency (TF), quad-frequency (QF), and PF undifferenced (UD) IF combination PPP time transfer, and the accuracy and frequency stability advantages of multi-frequency signals over traditional dual-frequency (DF) signals in UD PPP timing have been demonstrated, especially in short-term frequency stability [22–30].

Furthermore, considering that the carrier phase single-differenced (SD) (also known as carrier phase common-view (CP-CV)) model [31] can further weaken the satellite-related errors compared with the UD PPP model, the SD model with BDS multi-frequency observations may have more advantages than the PPP model in time transfer. However, perhaps due to the influence of SD usage distance and the difficulty of processing long baselines, there is relatively little research on SD time transfer, and all the relevant studies focus on GPS and short baselines [32–36]. These studies have demonstrated that SD has certain accuracy advantages over UD PPP in timing, especially in the case of a short baseline. Hence, the BDS multi-frequency long baseline SD time transfer model is still worth studying, exploring and evaluating. The current high-precision multi-frequency and multi-GNSS satellite products, the refinement of error models and the large number of common-view satellites make the precise solution of a long baseline possible, guaranteeing the realization of precise SD time transfer.

Previous studies have focused more on BDS UD PPP or GPS SD time transfer, and there has been no research on establishing the BDS-2/BDS-3 combined multi-frequency SD timing model. Moreover, with the rapid development of BDS multi-frequency signals, the previous SD time transfer research has had difficulty in adapting to the current environment. BDS multi-frequency signals will bring more IF combination space, smaller noise coefficients, more observations, and advantages to SD models, so the BDS multi-frequency SD time transmission will have more significant potential. This research proposes BDS-3/BDS-2 combined CV SD time transfer models with BDS-2 B1I, B2I and B3I and BDS-3 B1I, B2b, B3I, B1C and B2a multi-observations, and a comprehensive analysis and an evaluation of the performance of BDS multi-frequency SD time transfer were conducted.

The structure of this research includes the following: Firstly, the function model and stochastic model of the PF CV SD time transfer of BDS-2/BDS-3 combination are studied, and the coefficients of the DF to PF IF combination are given. Secondly, four-time transfer links with high-precision atomic clocks are selected to compare and evaluate the performance of the DF to PF SD time transfer models. Finally, the research work is discussed, and the conclusion is given.

2. Methodology

2.1. DF IF Combination SD Time Transfer Function Model

Take the B1I and B3I signals as examples, and select the BDS-3 receiver clock offset is the datum. The linearized BDS-3/BDS-2 combined DF IF combination SD model can be written as

$$\begin{cases} \Delta p_{rb,IF_{13}}^{C_{2/3,i}} = -\mathbf{u}_r^{C_{2/3,i}} \cdot \mathbf{x}_r + c\Delta\tilde{t}_{rb}^{C_3} + M_b^{C_{2/3,i}} Z_b - M_r^{C_{2/3,i}} Z_r + \Delta ISB_{rb,IF_{13}}^{C_2} + \Delta\zeta_{rb,IF_{13}}^{C_{2/3,i}} \\ \Delta I_{rb,IF_{13}}^{C_{2/3,i}} = -\mathbf{u}_r^{C_{2/3,i}} \cdot \mathbf{x}_r + c\Delta\tilde{t}_{rb}^{C_3} + M_b^{C_{2/3,i}} Z_b - M_r^{C_{2/3,i}} Z_r + \lambda_{IF_{13}}^{C_{2/3,i}} \Delta\tilde{N}_{rb,IF_{13}}^{C_{2/3,i}} + \Delta\zeta_{rb,IF_{13}}^{C_{2/3,i}} \end{cases} \quad (1)$$

with

$$\begin{cases} c\Delta\tilde{d}_{rb}^{C_3} = c\Delta d_{rb}^{C_3} + \Delta d_{rb,IF_{13}}^{C_3} \\ \Delta ISB_{rb,IF_{13}}^{C_2} = \Delta d_{rb,IF_{13}}^{C_2} - \Delta d_{rb,IF_{13}}^{C_3} \\ \lambda_{IF_{13}}^{C_{2/3}} \Delta\tilde{N}_{rb,IF_{13}}^{C_{2/3},i} = \lambda_{IF_{13}}^{C_{2/3}} \left(\Delta N_{rb,IF_{13}}^{C_{2/3},i} + \Delta b_{rb,IF_{13}}^{C_{2/3}} \right) - \Delta d_{rb,IF_{13}}^{C_3} \end{cases} \quad (2)$$

where the p and l are code and phase observed minus computed values, respectively; subscripts r and b denote rover and base stations, respectively; the symbol Δ represents the SD operator, defined as $\Delta(\cdot) = (\cdot)_b - (\cdot)_r$; the superscripts C_2 and C_3 denote BDS-2 and BDS-3, respectively; the superscript i denotes PRN number of satellite; the subscript “IF” denotes the IF combination of multi-frequency signals; the subscript numbers (such as 13) of “IF” indicate the frequency used by the IF combination, with 1 to 5, respectively, for the B1I, B2b or B2I, B3I, B1C and B2a signals of BDS; $\mathbf{u}$ and $\mathbf{x}$, respectively, represent the vector of coefficient and vector increment for coordinates; c represents the speed of light; Δd_{rb} denotes clock offset between two stations; M and Z denote the troposphere mapping function and zenith wet delay, respectively; λ is wavelength; N represents ambiguity parameter; d and b denote the un-calibrated code delay and un-calibrated phase delay, respectively; ISB denotes inter-system bias (ISB) between BDS-2 and BDS-3; ζ and $\tilde{\zeta}$ represent the code and phase observation noises, respectively; and the symbol “ $\sim$ ” at the head of parameter is the reparametrized estimate.

2.2. Four DF IF Combination SD Time Transfer Function Model

The BDS-2 (B1I and B3I) and (B1I and B2I) signals are selected to form two DF IF combination SD equations, and the BDS-3 (B1C and B2a), (B1C and B2b), (B1C and B3I) and (B1I and B2a) signals are selected to form four DF IF combination SD equations. Three additional SD inter-frequency bias (IFB) parameters [37] are required to maintain consistency between the four DF IF combination SD code equations of BDS-3. For ease of expression, we named this model PF1. The linearized PF1 SD model can be written as follows:

$$\begin{cases} \Delta p_{rb,IF_{13/12}}^{C_{2,i}} = -\mathbf{u}_r^{C_{2,i}} \cdot \mathbf{x}_r + c\Delta\tilde{d}_{rb}^{C_3} + M_b^{C_{2,i}} Z_b - M_r^{C_{2,i}} Z_r + \Delta ISB_{rb,IF_{13/12}}^{C_2} + \Delta IFB_{rb,IF_{12}}^{C_2} + \Delta\tilde{\zeta}_{rb,IF_{13/12}}^{C_{2,i}} \\ \Delta l_{rb,IF_{13/12}}^{C_{2,i}} = -\mathbf{u}_r^{C_{2,i}} \cdot \mathbf{x}_r + c\Delta\tilde{d}_{rb}^{C_3} + M_b^{C_{2,i}} Z_b - M_r^{C_{2,i}} Z_r + \lambda_{IF_{13/12}}^{C_2} \Delta\tilde{N}_{rb,IF_{13/12}}^{C_{2,i}} + \Delta\tilde{\zeta}_{rb,IF_{13/12}}^{C_{2,i}} \\ \Delta p_{rb,IF_{45/24/34/15}}^{C_{3,i}} = -\mathbf{u}_r^{C_{3,i}} \cdot \mathbf{x}_r + c\Delta\tilde{d}_{rb}^{C_3} + M_b^{C_{3,i}} Z_b - M_r^{C_{3,i}} Z_r + \Delta IFB_{rb,IF_{24/34/15}}^{C_3} + \Delta\tilde{\zeta}_{rb,IF_{24/34/15}}^{C_{3,i}} \\ \Delta l_{rb,IF_{45/24/34/15}}^{C_{3,i}} = -\mathbf{u}_r^{C_{3,i}} \cdot \mathbf{x}_r + c\Delta\tilde{d}_{rb}^{C_3} + M_b^{C_{3,i}} Z_b - M_r^{C_{3,i}} Z_r + \lambda_{IF_{45/24/34/15}}^{C_3} \Delta\tilde{N}_{rb,IF_{45/24/34/15}}^{C_{3,i}} + \Delta\tilde{\zeta}_{rb,IF_{45/24/34/15}}^{C_{3,i}} \end{cases} \quad (3)$$

with

$$\begin{cases} c\Delta\tilde{d}_{rb}^{C_3} = c\Delta d_{rb}^{C_3} + \Delta d_{rb,IF_{13}}^{C_3} \\ \Delta ISB_{rb,IF_{13}}^{C_2} = \Delta d_{rb,IF_{13}}^{C_2} - \Delta d_{rb,IF_{13}}^{C_3} \\ \Delta IFB_{rb,IF_{12}/IF_{24/34/15}}^{C_{2/3}} = \Delta d_{rb,IF_{12}/IF_{24/34/15}}^{C_{2/3}} - \Delta d_{rb,IF_{13}/IF_{45}}^{C_{2/3}} \\ \lambda_{IF}^{C_{2/3}} \Delta\tilde{N}_{rb,IF}^{C_{2/3},i} = \lambda_{IF}^{C_{2/3}} \left(\Delta N_{rb,IF}^{C_{2/3},i} + \Delta b_{rb,IF}^{C_{2/3}} \right) - \Delta d_{rb,IF_{45}}^{C_3} \end{cases} \quad (4)$$

where the secondary subscript symbol “/” in subscript IF means “or”, and the clock offset estimated by the PF1 model absorbs the UCD of the B1C/B2a IF combination between the two stations.

2.3. Three TF IF Combination SD Time Transfer Function Model

The BDS-2 B1I, B3I and B2I signals are selected to form TF IF combination SD equation, and BDS-3 (B1C, B1I and B2a), (B1C, B1I and B2b) and (B1C, B2a and B3I) signals are selected to form another three TF IF combination SD equations. The TF IF combination coefficient can be obtained from Zhou and Xu’s research [38]. We named this model PF2, which can be linearized and expressed as follows:

$$\begin{cases} \Delta p_{rb,IF_{123}}^{C_{2,i}} = -\mathbf{u}_r^{C_{2,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{2,i}} Z_b - M_r^{C_{2,i}} Z_r + \Delta ISB_{rb,IF_{123}}^{C_2} + \Delta \zeta_{rb,IF_{123}}^{C_{2,i}} \\ \Delta l_{rb,IF_{123}}^{C_{2,i}} = -\mathbf{u}_r^{C_{2,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{2,i}} Z_b - M_r^{C_{2,i}} Z_r + \lambda_{IF_{123}}^{C_2} \Delta \tilde{N}_{rb,IF_{123}}^{C_{2,i}} + \Delta \zeta_{rb,IF_{123}}^{C_{2,i}} \\ \Delta p_{rb,IF_{145/124/345}}^{C_{3,i}} = -\mathbf{u}_r^{C_{3,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{3,i}} Z_b - M_r^{C_{3,i}} Z_r + \Delta IFB_{rb,IF_{124/345}}^{C_3} + \Delta \zeta_{rb,IF_{145/124/345}}^{C_{3,i}} \\ \Delta l_{rb,IF_{145/124/345}}^{C_{3,i}} = -\mathbf{u}_r^{C_{3,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{3,i}} Z_b - M_r^{C_{3,i}} Z_r + \lambda_{IF_{145/124/345}}^{C_3} \Delta \tilde{N}_{rb,IF_{145/124/345}}^{C_{3,i}} + \Delta \zeta_{rb,IF_{145/124/345}}^{C_{3,i}} \end{cases} \quad (5)$$

with

$$\begin{cases} c\Delta \tilde{d}t_{rb}^{C_3} = c\Delta dt_{rb}^{C_3} + \Delta d_{rb,IF_{145}}^{C_3} \\ \Delta ISB_{rb,IF_{123}}^{C_2} = \Delta d_{rb,IF_{123}}^{C_2} - \Delta d_{rb,IF_{145}}^{C_3} \\ \Delta IFB_{rb,IF_{124/345}}^{C_3} = \Delta d_{rb,IF_{124/345}}^{C_3} - \Delta d_{rb,IF_{145}}^{C_3} \\ \lambda_{IF_{123}/IF_{145/124/345}}^{C_{2/3}} \Delta \tilde{N}_{rb,IF_{123}/IF_{145/124/345}}^{C_{2/3,i}} = \lambda_{IF_{123}/IF_{145/124/345}}^{C_{2/3}} \left(\Delta N_{rb,IF_{123}/IF_{145/124/345}}^{C_{2/3,i}} + \Delta b_{rb,IF_{123}/IF_{145/124/345}}^{C_{2/3}} \right) - \Delta d_{rb,IF_{145}}^{C_3} \end{cases} \quad (6)$$

2.4. Two QF IF Combination SD Time Transfer Function Model

Considering the noise amplification factor after combination, this study selected BDS-3 (B1C, B1I, B2a and B2b) and (B1C, B1I, B2a and B3I) signals for the IF combination and named this model PF3. The QF IF combination coefficient can be obtained from Jin and Su's study [22]. The linearized PF3 SD model can be expressed as follows:

$$\begin{cases} \Delta p_{rb,IF_{123}}^{C_{2,i}} = -\mathbf{u}_r^{C_{2,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{2,i}} Z_b - M_r^{C_{2,i}} Z_r + \Delta ISB_{rb,IF_{123}}^{C_2} + \Delta \zeta_{rb,IF_{123}}^{C_{2,i}} \\ \Delta l_{rb,IF_{123}}^{C_{2,i}} = -\mathbf{u}_r^{C_{2,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{2,i}} Z_b - M_r^{C_{2,i}} Z_r + \lambda_{IF_{123}}^{C_2} \Delta \tilde{N}_{rb,IF_{123}}^{C_{2,i}} + \Delta \zeta_{rb,IF_{123}}^{C_{2,i}} \\ \Delta p_{rb,IF_{1245/1345}}^{C_{3,i}} = -\mathbf{u}_r^{C_{3,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{3,i}} Z_b - M_r^{C_{3,i}} Z_r + \Delta IFB_{rb,IF_{1345}}^{C_3} + \Delta \zeta_{rb,IF_{1245/1345}}^{C_{3,i}} \\ \Delta l_{rb,IF_{1245/1345}}^{C_{3,i}} = -\mathbf{u}_r^{C_{3,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{3,i}} Z_b - M_r^{C_{3,i}} Z_r + \lambda_{IF_{1245/1345}}^{C_3} \Delta \tilde{N}_{rb,IF_{1245/1345}}^{C_{3,i}} + \Delta \zeta_{rb,IF_{1245/1345}}^{C_{3,i}} \end{cases} \quad (7)$$

with

$$\begin{cases} c\Delta \tilde{d}t_{rb}^{C_3} = c\Delta dt_{rb}^{C_3} + \Delta d_{rb,IF_{1245}}^{C_3} \\ \Delta ISB_{rb,IF_{123}}^{C_2} = \Delta d_{rb,IF_{123}}^{C_2} - \Delta d_{rb,IF_{1245}}^{C_3} \\ \Delta IFB_{rb,IF_{1345}}^{C_3} = \Delta d_{rb,IF_{1345}}^{C_3} - \Delta d_{rb,IF_{1245}}^{C_3} \\ \lambda_{IF_{123}/IF_{1245/1345}}^{C_{2/3}} \Delta \tilde{N}_{rb,IF_{123}/IF_{1245/1345}}^{C_{2/3,i}} = \lambda_{IF_{123}/IF_{1245/1345}}^{C_{2/3}} \left(\Delta N_{rb,IF_{123}/IF_{1245/1345}}^{C_{2/3,i}} + \Delta b_{rb,IF_{123}/IF_{1245/1345}}^{C_{2/3}} \right) - \Delta d_{rb,IF_{1245}}^{C_3} \end{cases} \quad (8)$$

2.5. Single PF IF Combination SD Time Transfer Function Model

A single PF IF combination can form a BDS-3 PF SD model, and the IF combination coefficient formula can be obtained from Su and Jin's research [25]. Since the BDS-2 only provides observations of B1I, B2I and B3I frequencies, we only perform B1I, B2I and B3I IF combination in BDS-2. For ease of expression, we named this model PF4. The linearized PF4 SD model can be expressed as follows:

$$\begin{cases} \Delta p_{rb,IF_{123/12345}}^{C_{2/3,i}} = -\mathbf{u}_r^{C_{2/3,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{2/3,i}} Z_b - M_r^{C_{2/3,i}} Z_r + \Delta ISB_{rb,IF_{123}}^{C_2} + \Delta \zeta_{rb,IF_{123/12345}}^{C_{2/3,i}} \\ \Delta l_{rb,IF_{123/12345}}^{C_{2/3,i}} = -\mathbf{u}_r^{C_{2/3,i}} \cdot \mathbf{x}_r + c\Delta \tilde{d}t_{rb}^{C_3} + M_b^{C_{2/3,i}} Z_b - M_r^{C_{2/3,i}} Z_r + \lambda_{IF_{123/12345}}^{C_{2/3}} \Delta \tilde{N}_{rb,IF_{123/12345}}^{C_{2/3,i}} + \Delta \zeta_{rb,IF_{123/12345}}^{C_{2/3,i}} \end{cases} \quad (9)$$

with

$$\begin{cases} c\Delta \tilde{d}t_{rb}^{C_3} = c\Delta dt_{rb}^{C_3} + \Delta d_{rb,IF_{12345}}^{C_3} \\ \Delta ISB_{rb,IF_{123}}^{C_2} = \Delta d_{rb,IF_{123}}^{C_2} - \Delta d_{rb,IF_{12345}}^{C_3} \\ \lambda_{IF_{123/12345}}^{C_{2/3}} \Delta \tilde{N}_{rb,IF_{123/12345}}^{C_{2/3,i}} = \lambda_{IF_{123/12345}}^{C_{2/3}} \left(\Delta N_{rb,IF_{123/12345}}^{C_{2/3,i}} + \Delta b_{rb,IF_{123/12345}}^{C_{2/3}} \right) - \Delta d_{rb,IF_{12345}}^{C_3} \end{cases} \quad (10)$$

2.6. Comparison of BDS-3/BDS-2 Combined DF and PF SD Models

Table 1 summarizes the combined signals, combination coefficients, and noise factor of DF, TF, QF and PF IF SD time transfer models adopted in this study. Among them, there are a total of 24 SD models, including DF1-DF6, TF1-TF9, QF1-QF5 and PF1-PF4. It should be noted that due to space limitations, the TF and QF models lack detailed formula introductions, but they can be derived from the PF model. In addition, since BDS-2 only has TF signals, only the BDS-2 B1I, B2I and B3I TF signals were used in the QF1-QF5 and PF2-PF4 SD models of the BDS-2/BDS-3 combination to form a single IF combination equation. The B1C, B1I, B2a, B2b and B3I IF combination presents a minimum noise amplification factor. The B1I and B3I IF combination has the maximum noise amplification factor. With the increase in the number of IF combination signals, the corresponding noise factor

also decreases gradually, and the decrease in noise factor also shows a decreasing trend. Although the PF1, PF2, PF3 and PF4 models are all fully applicable to the PF observations of BDS-3, when the multi-frequency observations are lost, the PF4 model will be completely unusable. In contrast, PF1, PF2 and PF3 models are more likely to be used.

Table 1. Summary of BDS-3-and-BDS-2 combined SD time transfer model.

System	Model	Signal and IF Combination Coefficient					Noise Factor
		B1C	B1I	B2a	B2I/b	B3I	
BDS-2	DF1-6/PF1	/	2.944	/	/	−1.944	3.527
	TF1-9/QF1-5/PF2~4	/	2.566	/	−1.229	−0.337	2.865
BDS-3	DF1	2.261	/	−1.261	/	/	2.588
	DF2	2.422	/	/	−1.422	/	2.809
	DF3	2.844	/	/	/	−1.844	3.389
	DF4	/	2.314	−1.314	/	/	2.663
	DF5	/	2.487	0	−1.487	/	2.898
	DF6	/	2.944	0	/	−1.944	3.527
	TF1	1.172	1.114	−1.287	/	/	2.067
	TF2	1.262	1.191	/	−1.453	/	2.263
	TF3	1.503	1.388	/	/	−1.891	2.786
	TF4	2.315	/	−0.836	−0.479	0	2.507
	TF5	2.290	/	−1.196	/	−0.094	2.586
	TF6	2.497	/	/	−1.168	−0.33	2.777
	TF7	/	2.372	−0.874	−0.497	/	2.577
	TF8	/	2.343	−1.254	/	−0.089	2.659
	TF9	/	2.566	/	−1.229	−0.338	2.865
	QF1	1.199	1.525	−0.788	−0.563	/	1.924
	QF2	1.224	1.171	−1.058	/	−0.336	2.025
	QF3	/	2.335	−0.923	−0.544	0.132	2.572
	QF4	1.255	1.317	0	−1.058	−0.514	2.167
	QF5	2.282	/	−0.880	−0.521	0.120	2.504
	PF1	2.261	/	−1.261	/	/	2.588
		2.422	/	/	−1.422	/	2.809
		2.844	/	/	/	−1.844	3.389
	PF2	/	2.314	−1.314	/	/	2.662
		1.172	1.115	−1.287	/	/	2.067
		1.262	1.191	/	−1.453	/	2.263
	PF3	2.290	/	−1.196	/	−0.094	2.586
		1.224	1.171	−1.058	/	−0.336	2.025
		1.199	1.525	−0.788	−0.563	/	1.924
	PF4	1.216	1.170	−0.742	−0.520	−0.123	1.919

3. Implementation of SD Time Transfer and Data Processing Strategies

3.1. Implementation Process of PF SD Time Transfer

Figure 1 shows the implementation flow of PF SD time transfer. The remote GNSS timing receiver (R_P and R_Q) is connected to the remote local clock (C_P and C_Q) downwards and the remote GNSS antenna (A_P and A_Q) upwards, and the local clocks C_P and C_Q generate 1 PPS and 10 MHz signals to the remote GNSS timing receiver, R_P and R_Q . At this time, a long baseline time transfer link is formed between the receiver R_P and R_Q . After gross error and cycle slip detection by BDS PF code and phase observations, the correlation error can be eliminated or weakened by precision satellite orbit, satellite clock offset, ANTEX, code bias products and error models (for instance, the phase windup model, tides model and Sagnac model). At this time, based on the proposed BDS PF SD time transfer model, the local time difference or clock offset dt_{CPCQ} can be obtained by parameter estimation using an extended Kalman filter (EKF), and then the goal of time transfer can be achieved.

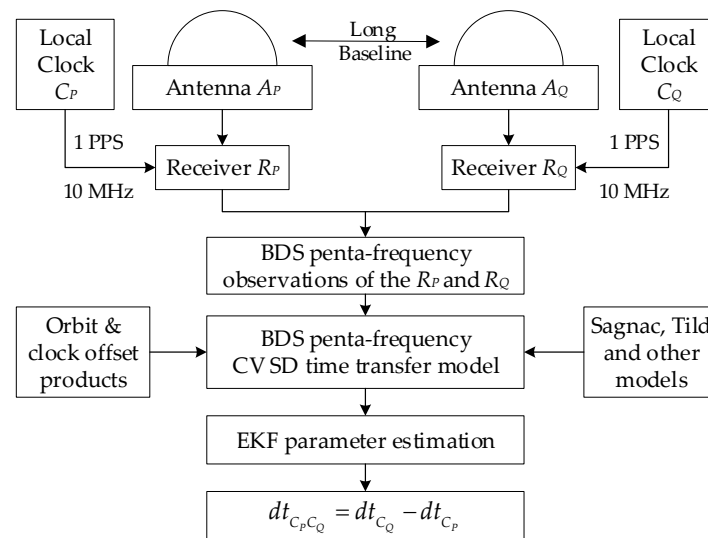


Figure 1. Float chart of BDS penta-frequency SD time transfer.

3.2. Experimental Data Sources and Processing Methods

The BRUX, CEBR, ONSA, SPT0 and WTZS stations (equipped with Hydrogen-Maser (H-Maser) or Cesium-Maser (C-Maser)) support BDS B1C, B1I, B2a, B2b, B2I and B3I observations from the multi-GNSS experiment (MGEX) network, which was selected for PF CV SD time transfer experiment. Among these stations, the BRUX, SPT0 and WTZS refer to the Universal Time Coordinated (UTC) Punctuality Laboratory ORB (Observatoire Royal de Belgique), RISE (Research Institutes of Sweden AB) and IFAG (Institut für Angewandte Geodaesie), respectively. In addition, all the experimental stations are equipped with the same GNSS timing receivers (Septentrio PolaRx5TR), which helps to avoid the impact of receiver-type differences on time transfer results. The experiment period is the day of the year (DOY) 337 to DOY 343 in 2021, totaling one week. With BRUX as the central node, the BRUX-CEBR (1331.6 km), BRUX-ONSA (883.8 km), BRUX-SPT0 (947.4 km) and BRUX-WTZS (637.6 km) long baseline time links are established. Figure 2 and Table 2 show the geographical locations and basic information, respectively, of BRUX, CEBR, ONSA, SPT0 and WTZS stations.

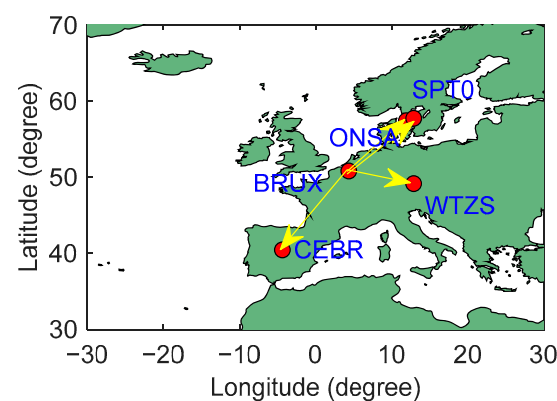


Figure 2. Location distribution for BRUX, CEBR, ONSA, SPT0 and WTZS.

Table 2. Stations information for BRUX, CEBR, ONSA, SPT0 and WTZS.

Station	Latitude	Longitude	Country	Clock Type	Antenna	Distance
BRUX	50.798°	4.359°	Belgium	IMASER 3000	JAVRINGANT_DM	/
CEBR	40.453°	−4.368°	Spain	H-MASER	SEPCHOKE_B3E6	1331.6 km
ONSA	57.395°	11.926°	Sweden	H-MASER	AOAD/M_B	883.8 km
SPT0	57.715°	12.891°	Sweden	H-MASER	TRM59800.00	947.4 km
WTZS	49.145°	12.879°	Germany	C-MASER	LEIAR25.R3	637.6 km

Table 3 illustrates the processing strategies for the BDS-3/BDS-2 combined PF SD time transfer. To simplify data processing, this research carries out equal weight processing between the B1C, B1I, B2a, B2b, B2I and B3I frequencies. The weight ratio of BDS-2 GEO, BDS-2 IGSO and MEO: BDS-3 satellites was set as 1:10:10 [39]. Considering that the experiment is in the ionospheric quiet period and the stations are all in the middle latitude, relevant studies [40] show that the high-order ionospheric delay in this case has little effect on the time transfer. Therefore, the IF combination is used in this study to eliminate the first-order term of ionospheric delay and ignore the impact of higher-order ionospheric delay. The modified GNSS open-source data processing software RTKLIB 2.4.3 b34 [41] (<https://www.rtklib.com/>, accessed on 10 April 2024) meets the needs of the BDS multi-frequency CV SD time transfer experiment. We use GeoForschungsZentrum (GFZ) rapid precise products and station coordinates fixed by IGS weekly solution file to perform the BDS-3-and-BDS-2 combined DF B1I and B3I IF combined PPP solution to evaluate the performance of SD solution. In addition, the Allan deviations (ADEV) are calculated to assess the frequency instability of the time transfer link.

Table 3. Details of SD and PPP time transfer processing strategies.

Item	Strategy
Estimator	Extended Kalman filter
Observation	PPP solution: BDS, B1I and B3I SD solution: BDS B1C, B1I, B2a, B2b, B2I and B3I
Sampling interval	30 s
Cut-off angle	7.0°
Weight scheme	Sin (elevation) [42]
Satellite orbit and clock	GFZ rapid precise products
Satellite DCB	PPP solution: Corrected by Chinese Academy of Sciences (CAS) Bias-SINEX (BSX) product; SD solution: uncorrected
Earth rotation	International Earth Rotation Service (IERS) 2010 model [43]
Relativistic effect	Corrected: elliptical orbit and Shapiro effect [44]
Phase windup effect	Corrected by model [45]
Tide effect	Corrected [43,46]
Satellite PCO and PCV	PPP solution: corrected, igs14.atx file; CV SD solution: uncorrected
Receiver PCO and PCV	Corrected, igs14.atx file
Inter-system bias	Estimated as white noises ($10^4 \text{ m}^2/\text{s}^2$) [47,48]
Inter-frequency bias	Estimated as constants [49]
Station coordinates	Fixed by IGS weekly SNX file
Receiver clock	Estimated as white noises ($10^4 \text{ m}^2/\text{s}^2$) [50]
Ionospheric delay	First-order-eliminated by IF combination, and ignore the influence of higher-order terms [51]
Zenith dry tropospheric	Corrected by Saastamoinen model [52]
Zenith wet tropospheric	Estimated with Global Mapping Function (GMF) [53]

4. Results

Firstly, we evaluated the number of satellites (NSats), time dilation of precision (TDOP) and multipath combination (MPC) noises of the experimental station. Next, the time transfer performance of four DF, nine TF and five QF SD models composed of BDS B1I, B2I, B2b, B3I, B1C and B2a observations were compared. Finally, the properties of IFB and time transfer stability of four PF SD models were evaluated.

4.1. Quality Analysis of BDS Multi-Frequency Observations

As shown in Figure 3, the NSats in the BDS-2/BDS-3 combination are significantly higher than those in BDS-2 and BDS-3. Compared with BDS-2, the BDS-3 NSats increased by 1.95 times, on average. The NSats of BRUX-CEBR, BRUX-ONAS, BRUX-SPT0 and BRUX-WTZS were 9.8, 12.4, 12.4 and 11.2, on average, respectively, and the corresponding TDOP values were 0.89, 0.75, 0.76 and 0.85, on average, respectively. The TDOP values of BRUX-CEBR and BRUX-WTZS were bigger than those of BRUX-ONSA and BRUX-SPT0 because of the poor quality of the CEBR and WTZS observations.

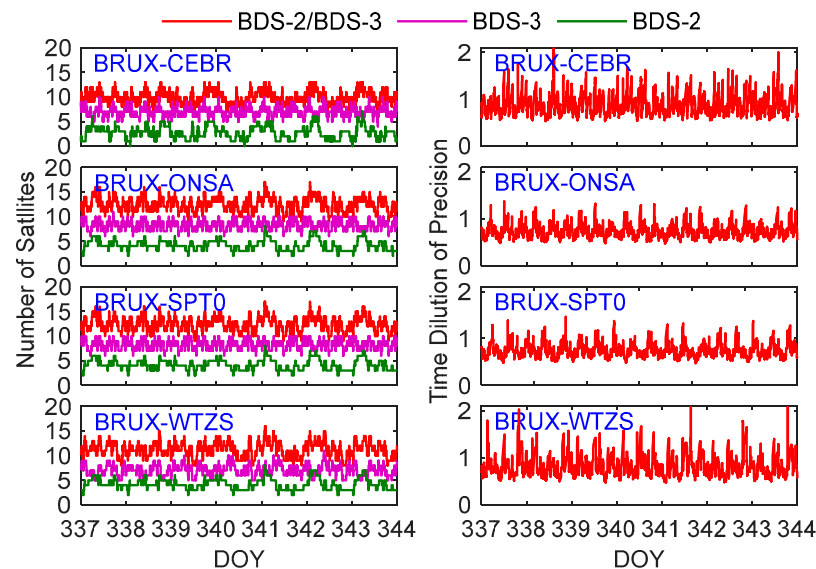


Figure 3. The number of satellites (NSats) (left) and time dilution of precision (TDOP) (right) at BRUX-CEBR, BRUX-ONSA, BRUX-SPT0 and BRUX-WTZR links.

As shown in Figure 4, the MPC noises of each frequency are all within ± 2.0 m. According to the statistics, the RMSs of B1C, B1I, B2a, B2b and B3I MPC noises are 0.347 m, 0.388 m, 0.222 m, 0.238 m and 0.220 m, on average. The B1I single has the highest MPC noise, and those of the B2a and Bb singles are similar. This indicates that BDS multi-frequency signals can provide higher-quality observations compared to traditional DF signals, making them more conducive to achieving high-precision time transfer. The average MPC noise of CEBR (0.356 m) is greater than in other stations (BRUX, ONSA, SPT0 and WTZR, which are 0.250 m, 0.254 m, 0.255 m and 0.299 m, respectively), and the B2a, B2b and B3I signals also reach 0.3 m, indicating that the data quality of CEBR is slightly poor.

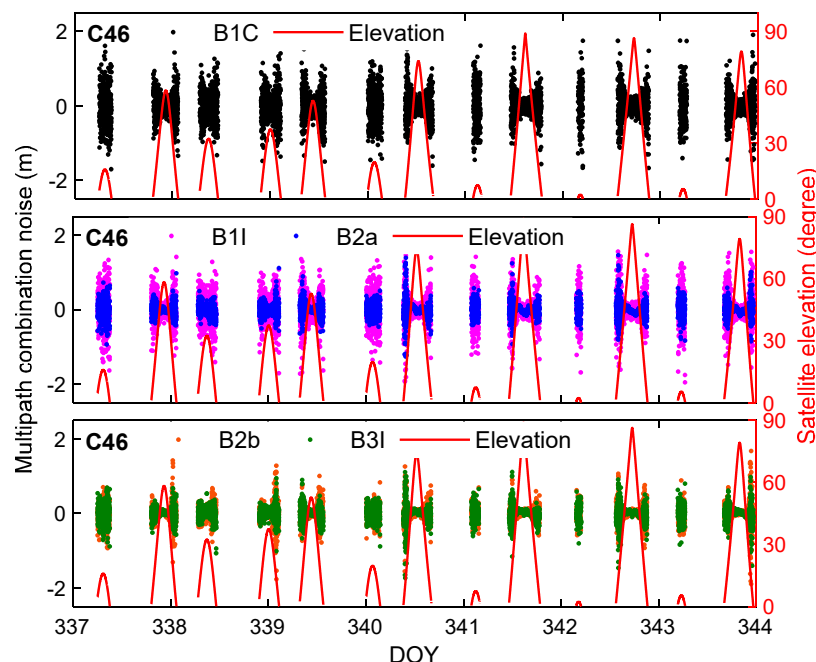


Figure 4. B1C, B1I, B2a, B2b and B3I frequencies multipath combination (MPC) noises at BRUX.

4.2. Performance Analysis of DF SD Time Transfer

Figure 5 shows the results of the PPP and SD DF IF combined time transfer. Due to spatial limitations and the similarity between the SD time transfer results, Figure 5 only shows the results of the epoch-differenced clock offset for the PPP and SD DF1 models. It can be found that the time transfer results of the PPP, DF1, DF2, DF3, DF4, DF5 and DF6 models tend to be consistent, verifying

the correctness of the established SD model. In particular, the clock offset variation amplitude of the BRUX-SPT0 and BRUX-WTZZ links is relatively small, which is related to the physical characteristics of the external clocks of the BRUX, SPT0 and WTZZ stations. There are varying sizes of jumps in PPP at the daily boundary, and the jumps on each link are inconsistent (with a maximum value of about 0.1 ns). However, due to the weakening or elimination of the impact of daily boundary jumps in satellite clock offset products by the SD model, the time transfer results of SD are more stable compared to PPP, and these results are basically not affected by daily boundary jumps, which reflects the advantage of the SD model over the PPP model in time transfer. Furthermore, some of the jumps in non-daily boundary areas (such as around time 343.7) may be caused by the data quality of the satellite products or stations. In addition, due to the external clock of WTZZ being a cesium clock, the epoch-differenced clock offset variation amplitude of the BRUX-WTZZ link is slightly larger than in the other three links.

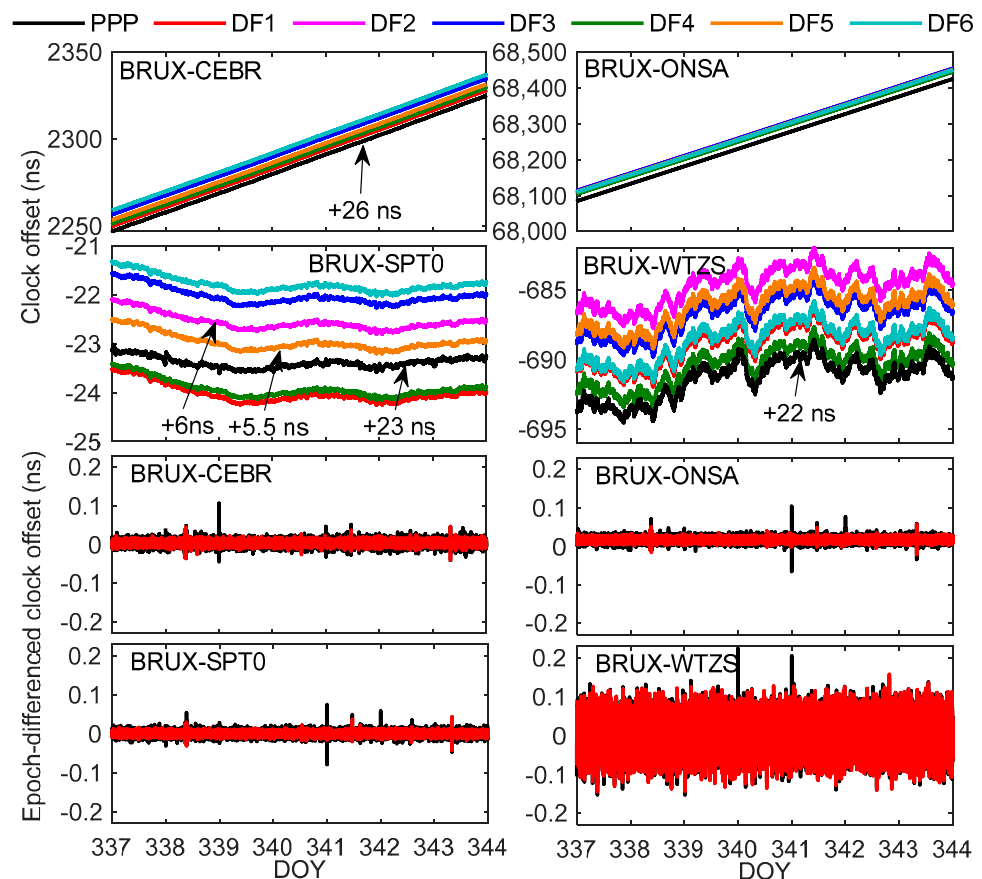


Figure 5. Clock offset and epoch-differenced clock offset for the dual-frequency (DF) precise point positioning (PPP) and single-differenced (SD) time transfer results of the BRUX-CEBR, -ONSA, -SPT0 and -WTZ links formed in the experiment.

Figure 6 shows the difference between the time transfer results of the DF SD and PPP and the IGS final product. Since the differences between the schemes are small and have a certain overlap, the clock offset difference is shifted in this study to distinguish each scheme clearly. The variation trends of each DF model are entirely consistent. Due to the combination of different dual-frequency observations, the receiver clock offset will absorb different UCDs, resulting in a bias between the clock offsets of each DF model. The bias STDs between DF1, DF2, DF3, DF4, DF5 and DF6 are 18.6 ps, 16.4 ps, 11.6 ps, 14.2 ps and 11.6 ps, on average, respectively. These values prove that the biases between each DF SD model are very stable and meet the prerequisite for the time link calibration. The clock offset of each model has a jump at the daily boundary, caused by the IGS final product [54–56]. In addition, due to the loss of the CEBR clock offset provided by the IGS at some times, the result of the clock offset difference in the BRUX-CEBR link is discontinuous. We note that the clock offsets of SD are more stable than those of PPP, especially at the daily boundary (such as BRUX-WTZZ in DOY 340), which is related to the SD algorithm's weakening of satellite-related errors. By comparison, the

fluctuation of the BRUX-CEBR clock offsets is significantly greater than in the other three links, which may be related to the fewer Nsats of BRUX-CEBR and the poor data quality of CEBR.

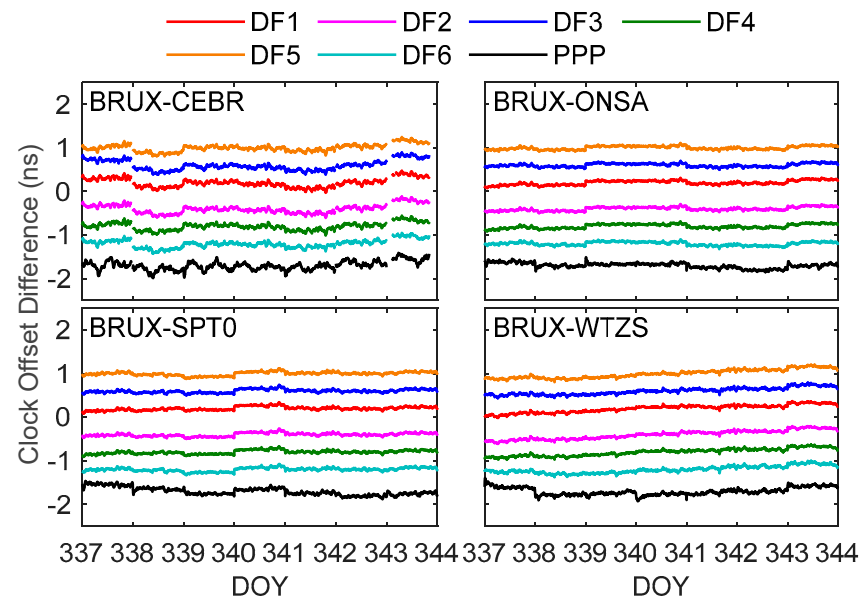


Figure 6. Clock offset differences between the DF PPP and SD time transfer results of the BRUX-CEBR, -ONSA, -SPT0 and -WTZ links formed in the experiment and IGS reference value.

As shown in Table 4, the standard deviation (STD) values of the DF1, DF2, DF3, DF4, DF5 and DF6 solutions are basically the same. In order to reduce the impact of daily boundary jumps on accuracy evaluation, this study calculated the STD for each day and took the average of the STD as the result for the entire experimental period. Compared with PPP, the STDs of SD were reduced to different degrees, with maximum, minimum and average decreases of 48.2%, 25.3% and 36.5%, respectively, indicating that SD has apparent advantages in time transfer performance over PPP. In addition, compared with the traditional DF6 (B1I and B3I IF combination), the STD values of DF1, DF2, DF3, DF4 and DF5 also decreased, with maximum, minimum and average decreases of 18.8%, 0.4% and 8.0%, respectively, which is related to the smaller noise amplification coefficient of the DF1, DF2, DF3, DF4 and DF5 models. Among these models, the mean STD decrease of DF1 was the largest (9.8%), while that of DF3 was the lowest (3.3%), relating to the small noise amplification factor of DF1 and the large noise amplification factor of DF3. The mean STD reduction of BRUX-WTZS was the largest (15.5%), while BRUX-ONSA's was the smallest (3.6%).

Table 4. Standard deviation (STD) of the dual-frequency (DF) (SD) solutions when differenced from the IGS final product (ps).

Link	PPP	DF1	DF2	DF3	DF4	DF5	DF6
BRUX-CEBR	66.93	34.64	35.89	36.38	35.04	34.75	36.96
BRUX-ONSA	25.78	16.81	16.65	17.52	16.83	16.97	17.59
BRUX-SPT0	28.31	19.02	19.38	20.54	18.80	18.66	21.16
BRUX-WTZS	35.08	21.53	22.30	24.20	21.49	21.85	26.35
Mean	39.03	23.00	23.56	24.66	23.04	23.06	25.52

As shown in Figure 7, in the BRUX-CEBR, BRUX-ONSA and BRUX-SPT0 links, the frequency stabilities of DF1, DF2, DF4 and DF5 are significantly improved compared with PPP before 30,000 s. The short-term frequency stabilities of DF3 and DF6 are close to those of PPP but slightly worse than those of DF1, DF2 and DF5 due to the significant noise amplification factor. The frequency stability of BRUX-SPT0 is the best, reaching about 1×10^{-15} @ 1.2×10^5 s. Due to the limited performance of the external cesium atomic clock of WTZS, the frequency stability of BRUX-WTZS is the worst (about 1×10^{-14} @ 1.2×10^5 s), and the frequency stability differences of PPP, DF1, DF2, DF3, DF4, DF5 and DF6 are small.

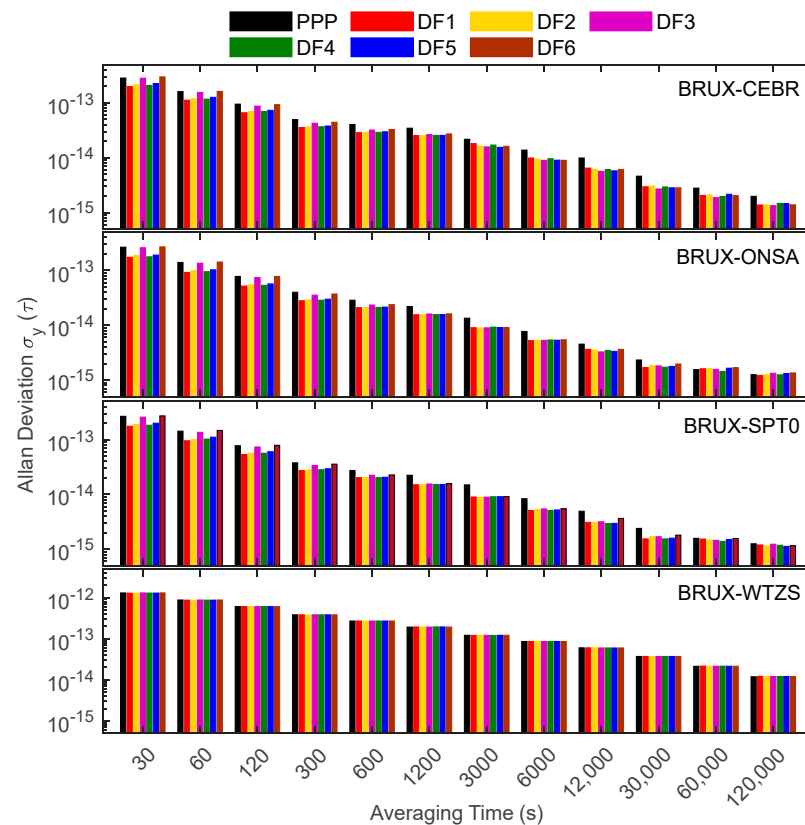


Figure 7. Frequency instabilities of the four links formed in the experiment for the DF SD solution.

Figure 8 shows a specific difference (less than 1×10^{-12}) in short-term frequency stability between the PPP and SD solutions, but there is little difference in the long-term frequency stability. DF1, DF2, DF4 and DF5 have smaller noise amplification factors, making their short-term frequency stability better than those of DF3 and DF6. The frequency stability of DF1, DF2, DF3, DF4 and DF5 was improved compared to that of PPP, but DF6 is still inferior to PPP at 30 s and 60 s, indicating the disadvantage of traditional B1I/B3I DF6 IF combinations compared to BDS new signal IF combinations. Compared with DF PPP and DF6, the multi-frequency DF solutions' stabilities are increased by 6.5% and 2.7%, on average, proving the advantage of multi-frequency in SD time transfer. It should be noted that the fluctuation (1200 s to 30,000 s) in the stability increase in DF compared to PPP is due to the influence of the PPP frequency stability of the BRUX-CEBR link.

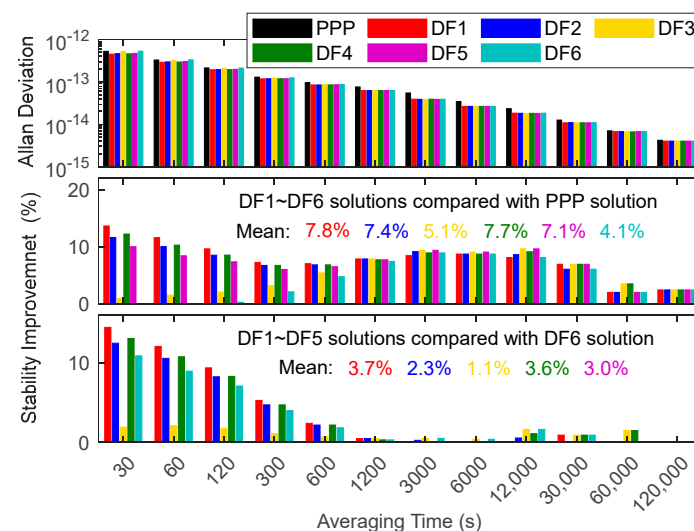


Figure 8. Average frequency instability for DF SD solution and the improvement rate of frequency stability for DF SD solution.

4.3. Performance Analysis of TF SD Time Transfer

Figure 9 shows that the variation trends of the nine SD TF situations were roughly the same. The bias STDs between TF2, TF3, TF4, TF5, TF6, TF7, TF8, TF9 and TF1 solutions are 7.7 ps, 14.2 ps, 6.0 ps, 5.7 ps, 9.7 ps, 6.7 ps, 6.1 ps and 11.0 ps, on average. These values indicate that the bias was stable and met the prerequisite for the time link calibration for each TF SD model. By combining Figures 5 and 7, it can be observed that the clock offset trends of the SD TF and DF are consistent, confirming the correctness of the SD TF time transfer model.

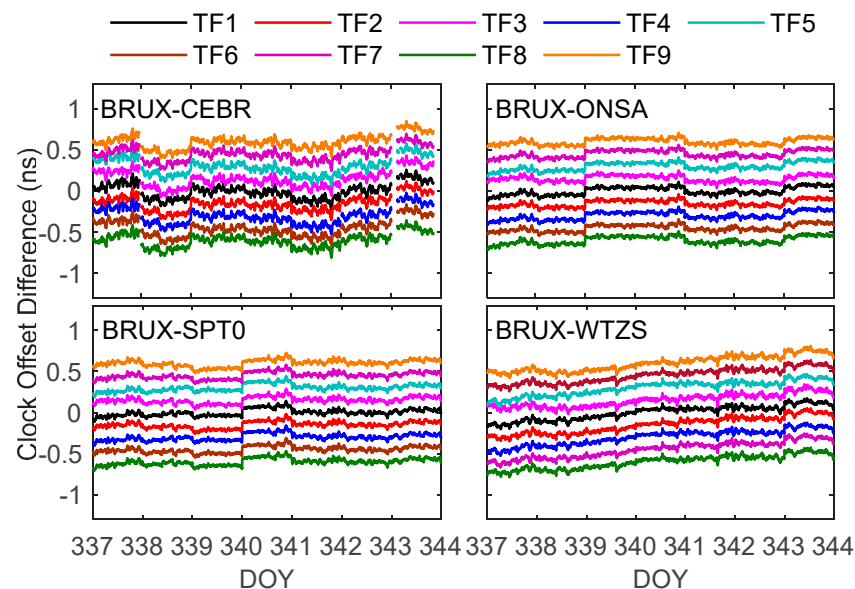


Figure 9. Clock offset differences between the triple-frequency (TF) SD time transfer results of the BRUX-CEBR, -ONSA, -SPT0 and -WTZ links formed in the experiment and IGS reference value.

As shown in Table 5, the STD of each TF model is basically the same. Compared with the DF6, the STD of each TF model is also decreased, with maximum, minimum and average decreases of 16.5%, 3.4% and 9.1%, respectively. Specifically, the mean decrease rate of TF1 was the largest (9.9%), while that of TF9 (7.6%) was the lowest. To better reflect the advantages of multi-frequency, we also compared the results of multi-frequency SD and DF PPP in the following study. Compared with the DF PPP, the mean STD's TF reduction rate (38.1%) is higher than that of DF (36.5%), proving the advantage of the TF observations.

Table 5. STD values of the BDS-3/BDS-2 combined triple-frequency (TF) SD solutions when differenced with the IGS final receiver clock offset product (ps).

Link	TF1	TF2	TF3	TF4	TF5	TF6	TF7	TF8	TF9
BRUX-CEBR	34.42	34.52	35.71	35.57	35.87	34.39	35.21	35.69	35.72
BRUX-ONSA	16.71	16.86	17.57	16.73	16.67	16.91	16.47	16.34	16.60
BRUX-SPT0	18.31	18.52	19.38	18.71	19.00	18.86	18.86	18.84	19.39
BRUX-WTZS	22.00	22.06	22.60	22.04	22.11	22.33	22.15	22.18	22.91
Mean	22.86	22.99	23.82	23.26	23.41	23.12	23.17	23.26	23.66

As shown in Figure 10, the significant difference in noise among various TF models (with a maximum value of 0.8) resulted in a slight difference in the short-term frequency stability. In particular, the short-term frequency stability of TF1 is the best, and that of TF3 is the worst, which is related to the minimum noise coefficient of TF1 and the maximum noise coefficient of TF3. However, with the increase in the averaging time, the influence of noise gradually decreases. Furthermore, limited by the accuracy of phase observations, the long-term frequency stability levels of each TF model are similar. In addition, there is no significant difference in the frequency stability of each TF model in the BRUX-WTZS link, which is related to the poor clock performance of the WTZS.

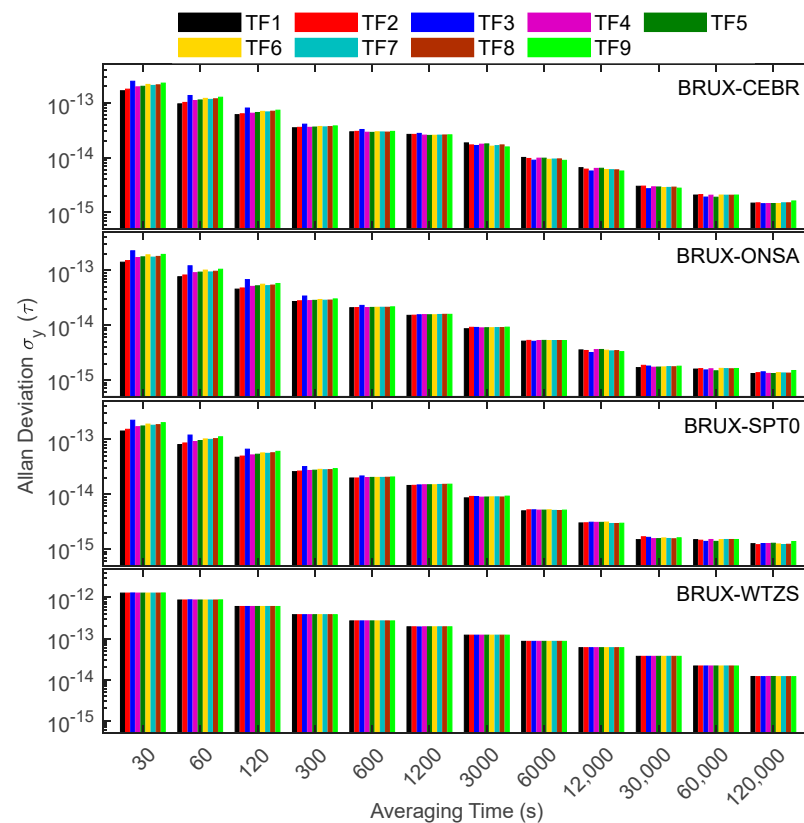


Figure 10. Frequency instabilities of the four links formed in the experiment for TF SD solutions.

Figure 11 shows small differences (less than 1×10^{-13}) in short-term frequency stability (especially before averaging time 300 s) between each of the TF models. However, the long-term frequency stability is the same (especially after an averaging time of 12,000 s). TF1 and TF2 have smaller noise amplification factors, making their corresponding short-term frequency stability better than those of the other TF models. Overall, TF1 has the best frequency stability, while TF3 has the worst. Compared with the DF PPP, TF's frequency stability improvement (7.6%) is higher than that of DF (6.5%), on average. The TF1 (which has the best frequency stability in the TF model) has a 1% increase in stability compared to DF1 (which has the best frequency stability in the DF model), proving the TF signal's small advantage in timing over the DF signal.

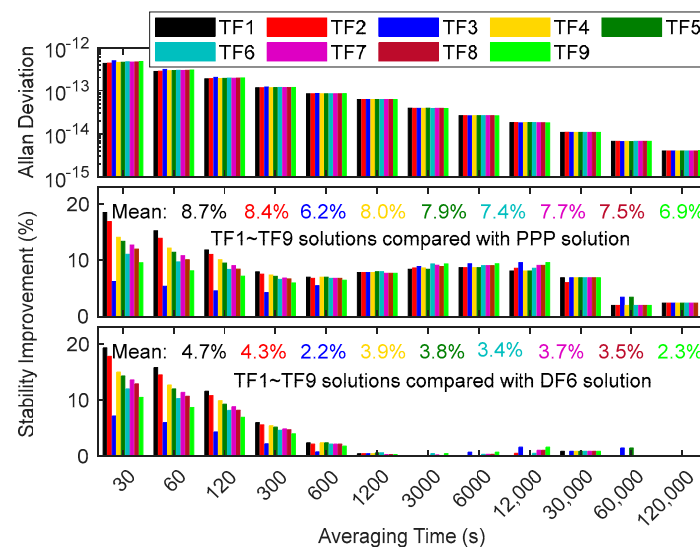


Figure 11. Average frequency instability for TF SD solution and the improvement rate of frequency stability for TF SD solution.

4.4. Performance Analysis of QF SD Time Transfer

Figure 12 shows that the variation trends of the QF1, QF2, QF3, QF4 and QF5 clock offsets are roughly the same. The bias STDs between QF2, QF3, QF4, QF5 and QF1 are 2.8 ps, 6.2 ps, 6.0 ps and 6.2 ps, on average, respectively. The mean STD of the QF (the mean value is 5.3 ps) is smaller than those of the DF (the mean value is 14.5 ps) and TF (the mean value is 8.4 ps), which means that the consistency of the QF models is better than that of the DF and TF models. Compared to Figures 5 and 7, the results of the QF are consistent with those of the DF and TF, indicating there may be no significant improvement in the accuracy of QF compared to DF and TF.

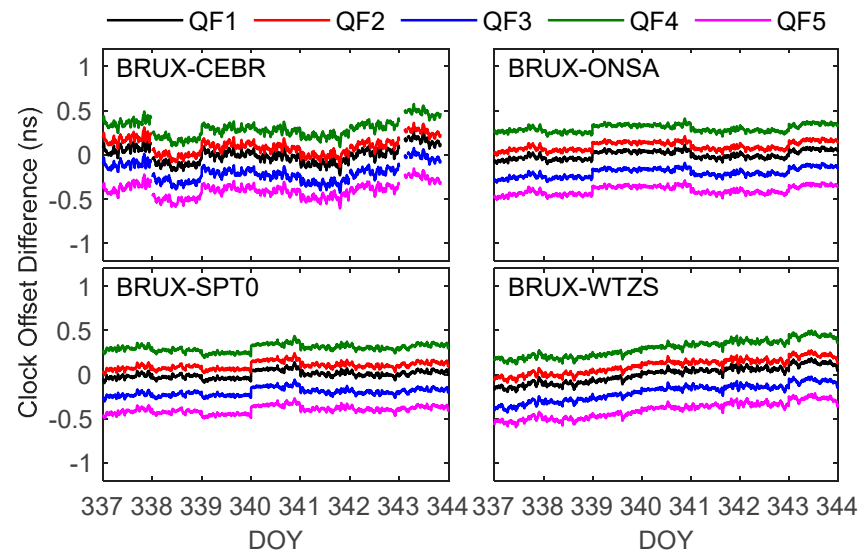


Figure 12. Clock offset differences between the quad-frequency (QF) SD time transfer results of the BRUX-CEBR, -ONSA, -SPT0 and -WTZ links formed in the experiment and IGS reference value.

As shown in Table 6, the STD of each QF model is basically the same (the maximum and minimum difference in the same link are about 1.44 ps and 0.02 ps, respectively). Compared with the DF6, the STD of each QF model is reduced, with maximum, minimum and average decreases of 3.4%, 16.6% and 10.0%, respectively. The mean STD decrease rate of QF1 was the most significant (11.1%), while that of QF3 was the lowest (9.2%). Compared with the DF PPP, the STD values of the five QF models were all decreased, with maximum, minimum and average decreases of 48.8%, 33.6% and 38.8%, respectively. The reduced ratio in the QF STD (38.8%) was higher than that of the DF (36.5%) and TF (38.1%), which proves the advantage of the QF.

Table 6. STD values of the quad-frequency (QF) SD solutions when differenced from the IGS final receiver clock offset product (ps).

Link	QF1	QF2	QF3	QF4	QF5
BRUX-CEBR	34.27	34.41	35.32	34.40	35.71
BRUX-ONSA	16.44	16.68	16.80	16.58	16.79
BRUX-SPT0	18.20	18.40	18.68	18.79	18.34
BRUX-WTZS	21.98	22.12	22.06	22.16	22.08
Mean	22.72	22.90	23.22	22.98	23.23

Figures 13 and 14 show some differences (of less than 1×10^{-12}) in short-term frequency stability among the QF1, QF2, QF3, QF4 and QF5 models. However, the long-term frequency stability of those models is basically the same (especially if the averaging time exceeds 6000 s). The short-term frequency stability of QF1 is the best, and that of QF5 is the worst, which is related to the minimum noise factor of QF1 and the maximum noise factor of QF3. With the increase in the averaging time, the influence of noise on time transfer gradually decreases, resulting in the long-term frequency stabilities of each QF model being similar. Overall, QF1 and QF2 have the best frequency stability, while QF5 has the worst. By comparison with DF PPP, the frequency stability of an improved rate of QF (8.3%) is higher than those of DF (6.5%) and TF (7.6%), on average. In addition, by comparison

with DF6, the mean value of the frequency stability improvement rate of QF (4.2%) is higher than those of DF (2.7%) and TF (3.5%), which proves the advantage of QF over DF and TF in timing.

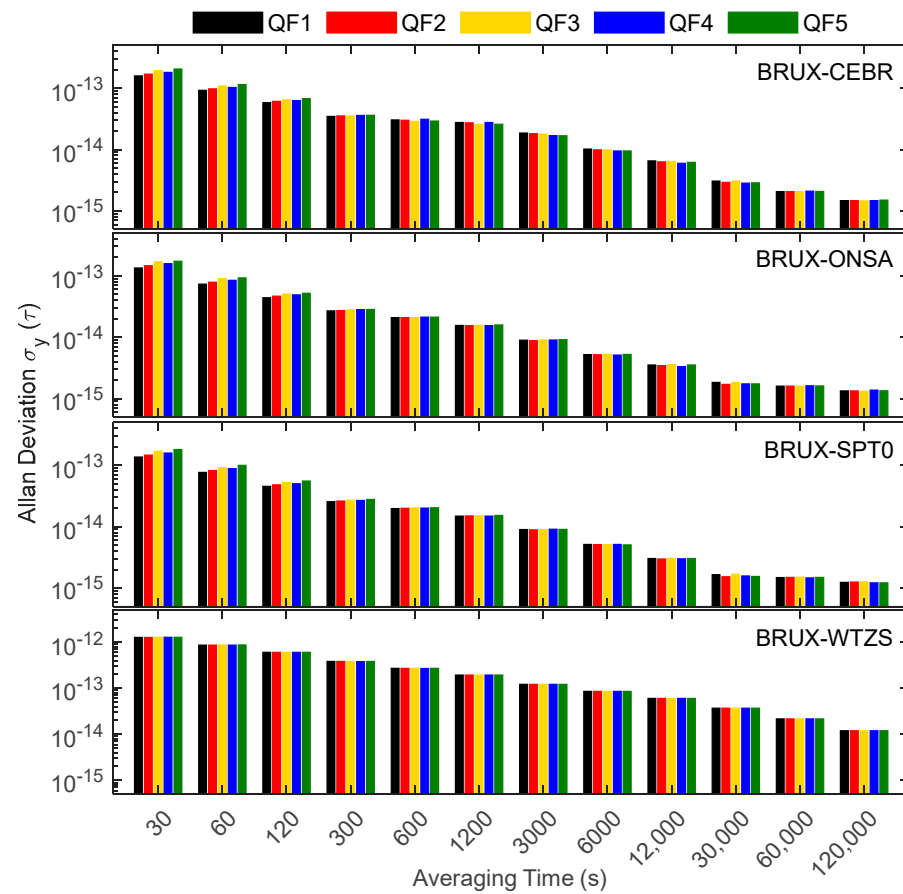


Figure 13. Frequency instabilities of the four links formed in the experiment for QF SD solutions.

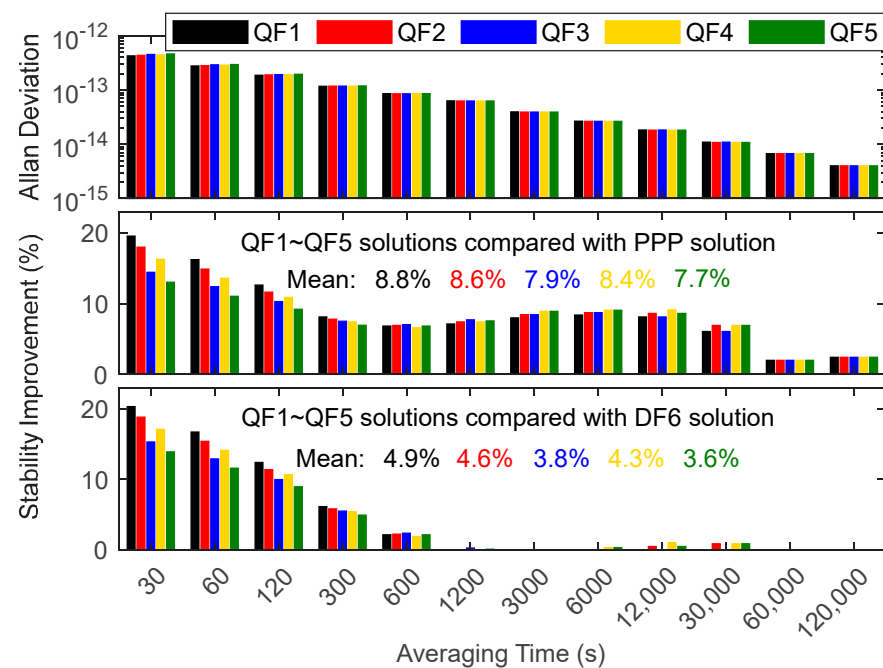


Figure 14. Average frequency instability for QF SD solution and the improvement rate of frequency stability for QF SD solution.

4.5. Performance Analysis of PF SD Time Transfer

As shown in Figure 15, the variation trends of each PF model are roughly the same. The bias STDs between PF1, PF2, PF3 and PF4 are 7.2 ps, 6.7 ps and 6.0 ps, on average, respectively. The average STD of the PF (6.6 ps) is smaller than those of the DF (14.5 ps) and the TF (8.4 ps) but bigger than that of the QF (5.3 ps). This phenomenon may be related to the stability of IFB parameters estimated by PF1, PF2 and PF3 models.

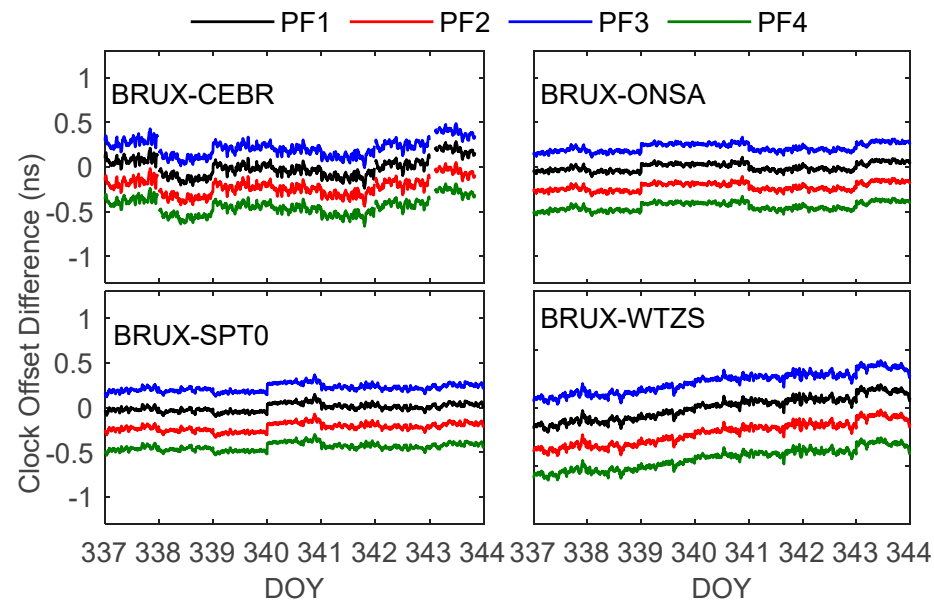


Figure 15. Clock offset differences between the penta-frequency (PF) SD time transfer results of the BRUX-CEBR, -ONSA, -SPT0 and -WTZR links formed in the experiment and IGS reference value.

As shown in Figure 16, the maximum of IFB reaches 10.0 ns, the minimum is only 0.2 ns and IFB is a relatively stable parameter. The STD of PF1 (IF₁₃) is the largest, which may be related to the small number of satellites in BDS-2. The STD of PF1 (22.3 ps) is greater than that of PF2 (14.4 ps), while the STD of PF2 is greater than that of PF3 (7.3 ps). Since IFB is strongly correlated with receiver clock offsets, the stability of IFB will directly affect the performance of timing, which means that the PF3 time transfer performance will be better than those of PF1 and PF2.

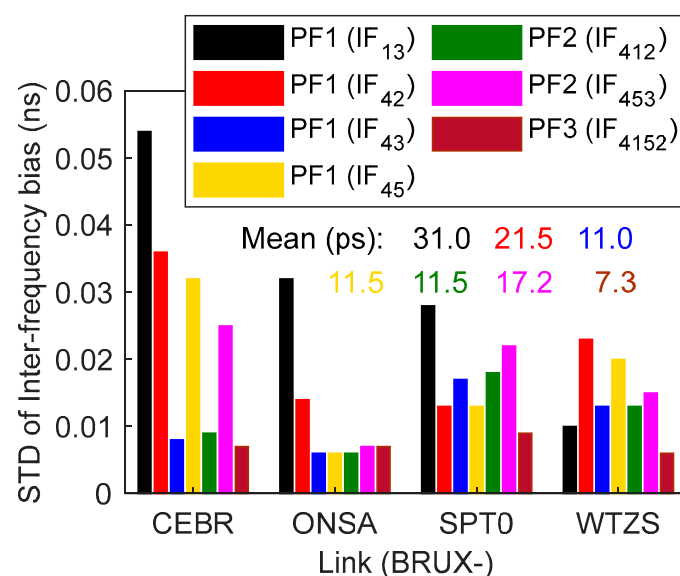


Figure 16. STD values of single-differenced inter-frequency bias (IFB) at BRUX-CEBR, -ONSA, -SPT0 and -WTZR links for PF1, PF2 and PF3 CV SD solutions.

As shown in Table 7, the STDs of PF1, PF2, PF3 and PF4 are 23.4 ps, 23.2 ps, 23.0 ps and 22.6 ps, on average, respectively. The PF4 has the smallest STDs, and with the increase in IFB to be estimated, the STDs gradually increase, which is related to the accuracy of the estimated IFB. Combining Figure 14 and Table 7, it can be seen that PF3's time-transfer STD is better than PF2's, and PF2's time-transfer STD is better than PF1's, which corresponds to the STD of PF1, PF2 and PF3 IFB parameters, and further proves that there is a strong correlation between IFB and receiver clock offset. Compared with the traditional DF6, the STDs of the four PF models are decreased, with maximum, minimum and average decreases of 4.8%, 18.5% and 9.8%, respectively. Specifically, the mean decrease rate of PF4 was the largest (11.4%), while that of PF1 was the lowest (8.5%). Compared with the DF PPP, the STDs of each PF model are decreased, with maximum, minimum and average decreases of 48.9%, 33.0% and 38.7%, respectively. We found that the mean STD reduced ratio of PF4 (39.8%) is slightly higher than those of DF1 (36.5%), TF1 (38.1%) and QF1 (39.5%), which proves the slight advantage of the penta-frequency.

Table 7. STD values of the PF SD solutions when differenced from the IGS final product (ps).

Link	PF1	PF2	PF3	PF4
BRUX-CEBR	35.04	34.90	34.82	34.21
BRUX-ONSA	16.74	16.73	16.68	16.57
BRUX-SPT0	18.89	18.98	18.25	18.21
BRUX-WTZS	22.82	22.20	22.08	21.47
Mean	23.37	23.20	22.96	22.62

Figures 17 and 18 show the frequency instability of the PF1-PF4 models for four-time links. It can be found that the frequency stabilities of the PF1-PF4 models tend to be consistent (the stability difference is less than 1×10^{-13} @30 s). Especially when the averaging time exceeds 3000 s, the frequency stability is the same. The PF4 model's short-term frequency stability is better than those of the PF1, PF2 and PF3 models because it does not need to estimate additional IFB parameters. Overall, PF4 has the best frequency stability, while PF1 has the worst. Although the flexibility of the PF1, PF2 and PF3 models is better than that of the PF4 model, the stability levels of PF1, PF2 and PF3 are slightly worse than that of the PF4 due to the additional estimation of IFB. Considering that the noise amplification factor of the PF4 is less than those of PF1, PF2 and PF3, we recommend the PF4 for PF time transfer and the use of PF2, PF2, or PF3 to supplement the PF4 in cases of PF data loss. Compared with the DF PPP, the mean frequency stability improvement rate of PF (9.2%) is higher than those of DF (6.5%), TF (7.6%) and QF (8.3%). Compared with the DF6, the frequency stability improvement rate of PF4 (the best frequency stability in the PF model) is increased by 1.5%, 0.6% and 0.3% over DF1 (the best frequency stability in the DF model), TF1 (the best frequency stability in the TF model) and QF1 (the best frequency stability in the QF model), on average, which proves the slight advantage of PF in time transfer compared with DF, TF and QF.

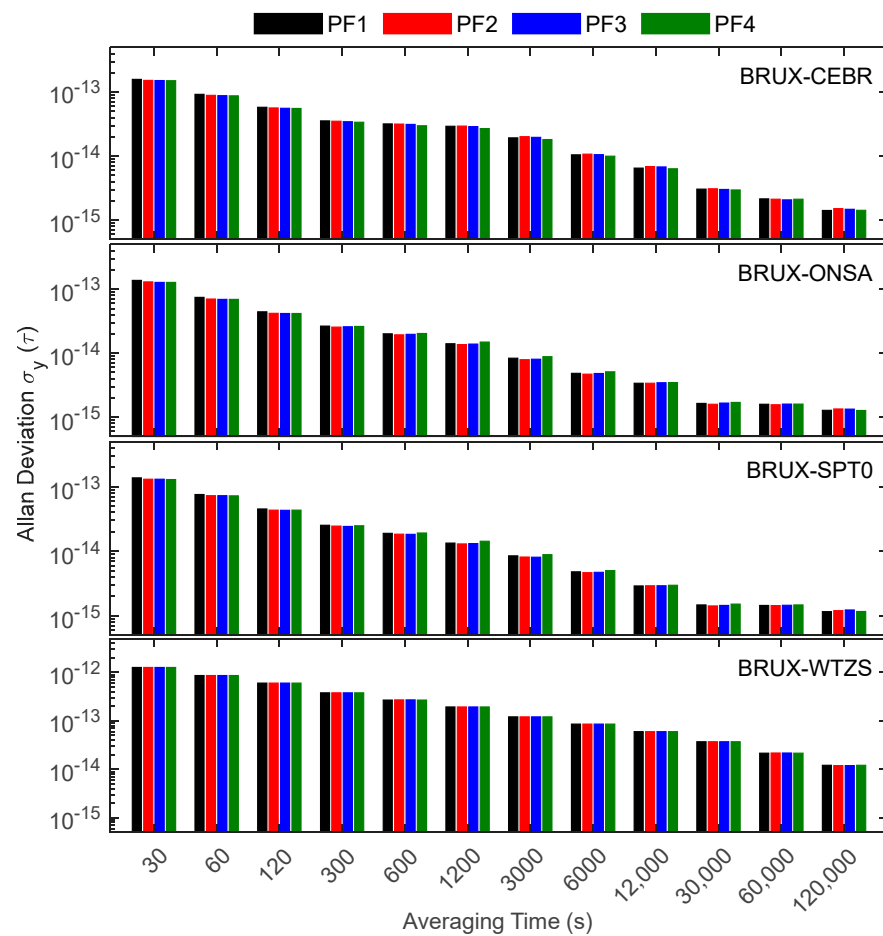


Figure 17. Frequency instabilities of the four links formed in the experiment for PF SD solutions.

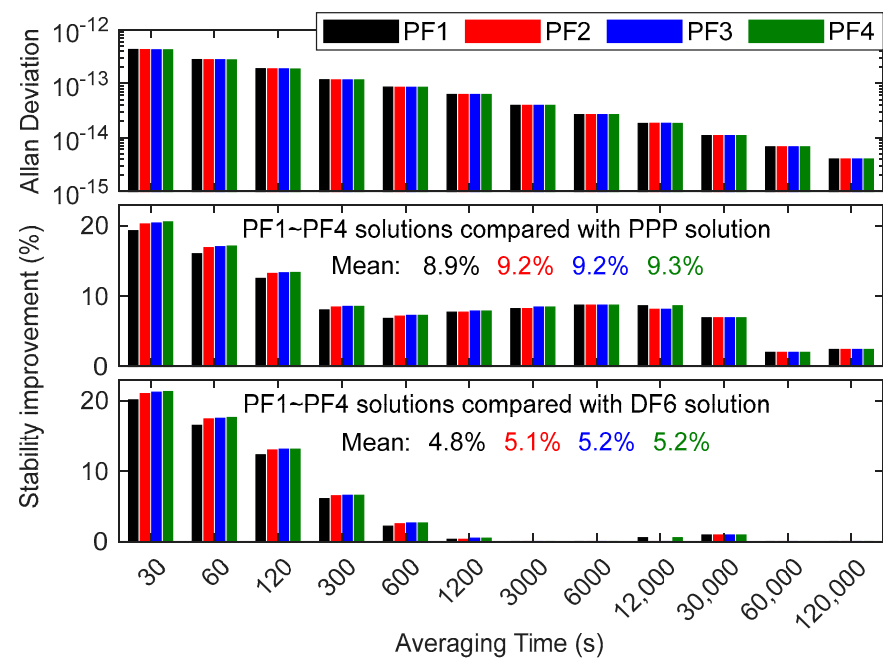


Figure 18. Average frequency instability for PF SD solution and the improvement rate of frequency stability for PF SD solution.

5. Discussion

This research establishes an SD time transfer model with BDS PF observation and verifies the accuracy and reliability of the proposed DF, TF, QF and PF SD models through experiments. The noise amplification factor of a multi-frequency IF combination is smaller than that of a traditional DF IF combination, and as the number of signals increases, the noise amplification factor shows a gradually decreasing trend. The reduction in the noise amplification factor significantly improved the accuracy and short-term stability of SD time transfer. However, limited by the accuracy of carrier phase observations, the long-term stability of the multi-frequency SD model does not show significant improvement compared to the DF SD model. Therefore, it will still be worth studying how to use BDS multi-frequency signals to improve the long-term stability of SD time transfer in the future. It is worth noting that the weight ratio between multi-frequency observations is also an important factor affecting the accuracy of multi-frequency SD time transfer, and the reasonable weighting of multi-frequency observations is still worth exploring.

Moreover, due to the difficulty of achieving precise separation in receiver clock offset and ambiguity parameters in SD float solutions, and because of the failure to utilize the integer characteristics of ambiguity parameters, the accuracy of SD time transfer may be affected. Considering that there are too many types of IF combinations of multi-frequency signals, the noise of the IF combination is amplified by, at least, about two times, and various types of IF combinations will inevitably create a certain pressure when fixing ambiguity. Therefore, future research will focus on BDS multi-frequency un-combined SD time transfer and fix multi-frequency un-combined SD ambiguity to improve the performance of SD time transfer.

Furthermore, although the PPP time transfer model has a wider range of tasks compared to the SD time transfer model, SD time transfer still has certain advantages, especially in real-time processing, short baselines and network solutions, in which the benefits of that model and its accuracy are more pronounced. Therefore, the research and evaluation of multi-frequency SD time transfer models are necessary and have strong practical significance.

6. Conclusions

In this research, BDS-3/BDS-2 combined PF IF combination CV SD time transfer models with B1I, B3I, B2I, B1C, B2a and B2b signals were established, and the BRUX, CEBR, ONSA, SPT0 and WTZS stations, which are equipped with atomic clocks, were selected to establish four time-links for the experiment. The time transfer accuracy and frequency stability of the BDS DF, TF, QF and PF IF combination SD models were evaluated.

The results demonstrate that the multi-frequency SD time transfer accuracy and frequency stability can reach sub-nm and about 1×10^{-15} @120,000 s, respectively. The time transfer performance of SD is slightly better than that of PPP. The accuracy of multi-frequency SD time transfer is higher than that of traditional dual-frequency (B1I and B3I IF combination), with the STD and stability decreased by 5.9% and 4.0%, on average. This is especially due to the reduction in noise after multi-frequency IF combination, which significantly improves the short-term frequency stability of multi-frequency. However, limited by the accuracy of the observations, the frequency stability improvement of multi-frequency compared to DF is relatively limited. It is interesting that as the number of IF combined signals increases, the performance of the time transfer also steadily and slowly improves, and the performance of PF is slightly higher than those of other multi-frequency models (the stability of PF increased by 2.5%, 5.3% and 8.5% compared to DF, TF and QF, respectively), demonstrating the advantages of multi-frequency signals. Moreover, the DF1 (B1C and B2a DF IF combination), TF1 (B1C, B2a and B2b TF IF combination), QF1 (B1C, B1I, B2a and B2b QF IF combination) and PF4 (B1C, B1I, B2a, B2b and B3I PF IF combination) SD models have better performance in timing, and the PF4 SD model has the best performance. It is worth noting that the time transfer performance of PF1, PF2 and PF3 is slightly worse than that of PF4 due to the stability of the additional estimation of IFB parameters. Considering that the PF4 SD model does not require an estimate of IFB and that its noise factor is minor compared with the PF1, PF2 and PF3 SD models, we recommend the PF4 SD model (with PF signals to form a single IF observation equation) for multi-frequency time transfer and the use of the PF2, PF2 or PF3 SD model to supplement the PF4 SD model in cases of penta-frequency observation loss.

Since the four major global GNSS have supported at least triple-frequency signals and the advantages of the SD model in short baseline, real-time and network solutions, the SD time transfer technology of multi-frequency signals will expand the application of GNSS in the field of time and frequency measurement, which is of great significance for promoting the development of time and frequency measurement technology.

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