

Research Article

Adaptive Fast Independent Component Analysis Methods for Mitigating Multipath Effects in GNSS Deformation Monitoring

Rong Yuan,¹ Shengli Xie^{ID},² Zhenni Li,³ and Zhaoshui He⁴

¹*School of Automation, Guangdong University of Technology and Guangdong Key Laboratory of IoT Information Technology, Guangzhou 510006, China*

²*Key Laboratory of Intelligent Information Processing and System Integration of IoT (GDUT) and Key Laboratory of Intelligent Detection and The Internet of Things in Manufacturing (GDUT), Ministry of Education, Guangzhou 510006, China*

³*School of Automation, Guangdong University of Technology and 111 Center for Intelligent Batch Manufacturing Based on IoT Technology (GDUT), Guangzhou 510006, China*

⁴*School of Automation, Guangdong, Guangdong University of Technology and Guangdong-HongKong-Macao Joint Laboratory for Smart Discrete Manufacturing (GDUT), Guangzhou 510006, China*

Correspondence should be addressed to Shengli Xie; shlxie@gdut.edu.cn

Received 1 September 2022; Revised 29 September 2022; Accepted 3 October 2022; Published 9 November 2022

Academic Editor: Sweta Bhattacharya

Copyright © 2022 Rong Yuan et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Carrier-phase multipath is the main problem of GNSS deformation monitoring. Traditional methods usually adopt sidereal day filtering to mitigate the multipath. However, the necessity of presetting the session duration of the static baseline solution reduces the timeliness of the methods in real engineering. Moreover, these methods are not suitable for the systems that contain different types of GNSS satellites (e.g., BDS). To address the problems, this paper proposes an Adaptive Fast Independent Component Analysis (AF-ICA) method for mitigating multipath effects in GNSS deformation monitoring, which can effectively process the multi-GNSS data and separate several multipath signals. In the experimental study, compared with Sidereal Filtering in Observation Domain (SF-OD) method, AF-ICA method can improve both the positioning accuracy and peak-to-peak value. In GNSS deformation monitoring positioning accuracy, AF-ICA method can achieve the root-mean-square (RMS) of 1 mm horizon-tally and 2 mm vertically. Compared with the MSF method, the positioning accuracy of the AF-ICA method in the direction of ENU is improved by 44%, 14%, and 31%, respectively, and the corresponding peak-to-peak values increased by 36%, 17%, and 29%, respectively. Our proposed method can automatically get the monitoring information without estimating the orbit period in advance to realize automatic deformation monitoring. Through the automatic monitoring solution, the AF-ICA method in this paper can be applied to the natural disaster monitoring in the Internet of Things and provides real-time data monitoring information for disaster early warning.

1. Introduction

GNSS has been one of the leading high-precision positioning technologies and is widely used in dynamic deformation monitoring of engineering constructions [1, 2], such as dams, bridges, high-rise buildings, and railway roadbeds [3–7]. In short-baseline GNSS measurements for deformation monitoring, differential GNSS techniques can largely eliminate common-mode errors between the reference and the rover GNSS stations resulting from ionospheric and tropospheric refraction and delays, satellite and receiver

clock biases, and orbital errors. However, carrier-phase multipath effects cannot be removed with this approach and still have significant effects on GNSS position estimates [8]. Due to the reflection or diffraction caused by nearby obstacles, GNSS multipath phenomenon occurs when signals travel from a satellite to a receiver via several paths. Multipath is mainly decided by the satellite constellation, receiver environment, and reflector positions. In deformation monitoring, the operation of the satellites directly affects the multipath since the receiver and reflector positions are relatively stable. Thus, multipath features can be extracted and used to reduce

positioning errors by analyzing the operation of the satellites. For example, as the satellite operating cycles are usually stable, the corresponding multipath also has a similar periodic variation. By using the previous observation measurements to model different satellites separately, Sidereal Filtering (SF) was employed to mitigate the multipath [9–12]. But it is necessary to preset the session duration of the static baseline solution in classic deformation monitoring, which reduces the timeliness of the method. Dong et al. [13] constructed a single-difference observation equation based on a single receiver with multiple antennas and proposed to establish a multipath hemispherical map (MHM) with satellite altitude and azimuth as independent variables. However, when these methods are used to mitigate the multi-GNSS multipath, the multipath model will have a very large matrix, which makes it impossible to achieve lightweight calculation. Moreover, an increase in the number of satellite and signal frequency types [14] by using multi-GNSS observation could make the multipath more complicated [15].

In order to mitigate the multi-GNSS multipath result from different types of GNSS satellites, a novel filtering method called AF-ICA is proposed to mitigate multipath in this paper, which can improve the timeliness of dynamic deformation monitoring by combining signal processing technologies and the principle of SF. In the AF-ICA method, the multi-GNSS single epoch solution is input as a signal with multipath to be processed, and the desired output signal is used as the multipath model. First, mean smoothing filter (MSF) method is used to denoise by calculating the mean value of a window. Then, the Fast Independent Component Analysis (FastICA) is adopted to separate the multipath signal generated by different types of satellites from the source signals by combining prior engineering information. Next, to improve the timeliness of the method, first-order Fourier fitting formula is used to get the signal period. We can recover the complete multipath signal by the linear fitting formula according to the period of the separated signal. Finally, we can obtain the final deformation monitoring results by removing the multipath signal. Contributions of this paper can be summarized as follows:

Considering the complicated multipath signal generated by different types of satellites in the GNSS deformation monitoring, we propose to use FastICA to separate the multipath signal from the source signals. In order to improve the timeliness, we design the AF-ICA method: obtain the prior period range of the separated signal (i.e., multipath signal) according to the actual engineering experience, and then use the prior period information as the basis to judge whether FastICA can separate the signal, so as to determine the smallest MSF window. Our method mitigates the multipath in the coordinate domain and can automatically get the session duration of mean filtering by extracting multiple multipath signal periods corresponding to the BDS orbit through the ICA algorithm without estimating the orbit period in advance like classical SF-OD method.

Our proposed method can automatically get the session duration of mean filtering by extracting multiple multipath signal periods corresponding to the BDS orbit through the ICA algorithm without estimating the orbit period in

advance to realize automatic deformation monitoring and improve engineering efficiency. Through the automated monitoring solution, the AF-ICA method in this paper can be applied to the natural disaster monitoring in the Internet of Things and provides real-time data monitoring information for disaster early warning.

2. Methodology

Considering the complicated multipath signal generated by different types of satellites and the timeliness of traditional SF methods, the AF-ICA method is presented to address the problems in this paper. In our case, the multi-GNSS single epoch solution is input as a signal with multipath to be processed, and the desired output signal is used as the multipath model. First, the multipath signal is weak in the source signals. Thus, the MSF method needs to be first used for denoising to get the multipath signal with enough strength. Then, FastICA is adopted to separate the multipath signal generated by different types of satellites from the source signals by combining prior engineering information. The environmental information includes two aspects: one is that the observation data contains GPS satellites whose orbital period is close to a sidereal day, another is that three multipath signals need to be separated because BDS satellite has three types of orbits. Next, to improve the timeliness of the system, first-order Fourier fitting formula is used to get the signal period. We can recover the complete multipath signal by the linear fitting formula according to the period of the separated signal. Finally, we can obtain the final deformation monitoring results by removing the multipath signal. As shown in Figure 1, AF-ICA method contains two parts: first is the MSF using the single epoch GNSS static positioning solution to wipe off the influence of Gaussian white noise, and second is the FastICA method for extracting multiple multipath signal periods. After removing the high frequency signal with MSF method, the remaining low frequency signal is the multipath signal to be separated.

2.1. MSF for Denoising. Classic GNSS deformation monitoring algorithm uses the static baseline solution method to obtain the positioning accuracy of millimeter level. The static baseline solution needs to set the session duration in advance, and then use the static postprocessing method to solve the baseline. In this paper, the method of single epoch solution combined with MSF is used to obtain millimeter positioning accuracy. The main purpose of MSF is to provide clean multipath signals for subsequent ICA methods. There is no need to preset the session duration, and the duration is automatically controlled by the AF-ICA method. Meanwhile, the final result of MSF algorithm is equivalent to the static postprocessing baseline solution. MSF algorithm using the single epoch solution is described as follows.

Normal equation of fixed solution in the static postprocessing baseline solution can be written as

$$\left(\sum_i^n H_i^T P_i H_i \right) X = \left(\sum_i^n H_i^T P_i Z_i \right), \quad (1)$$

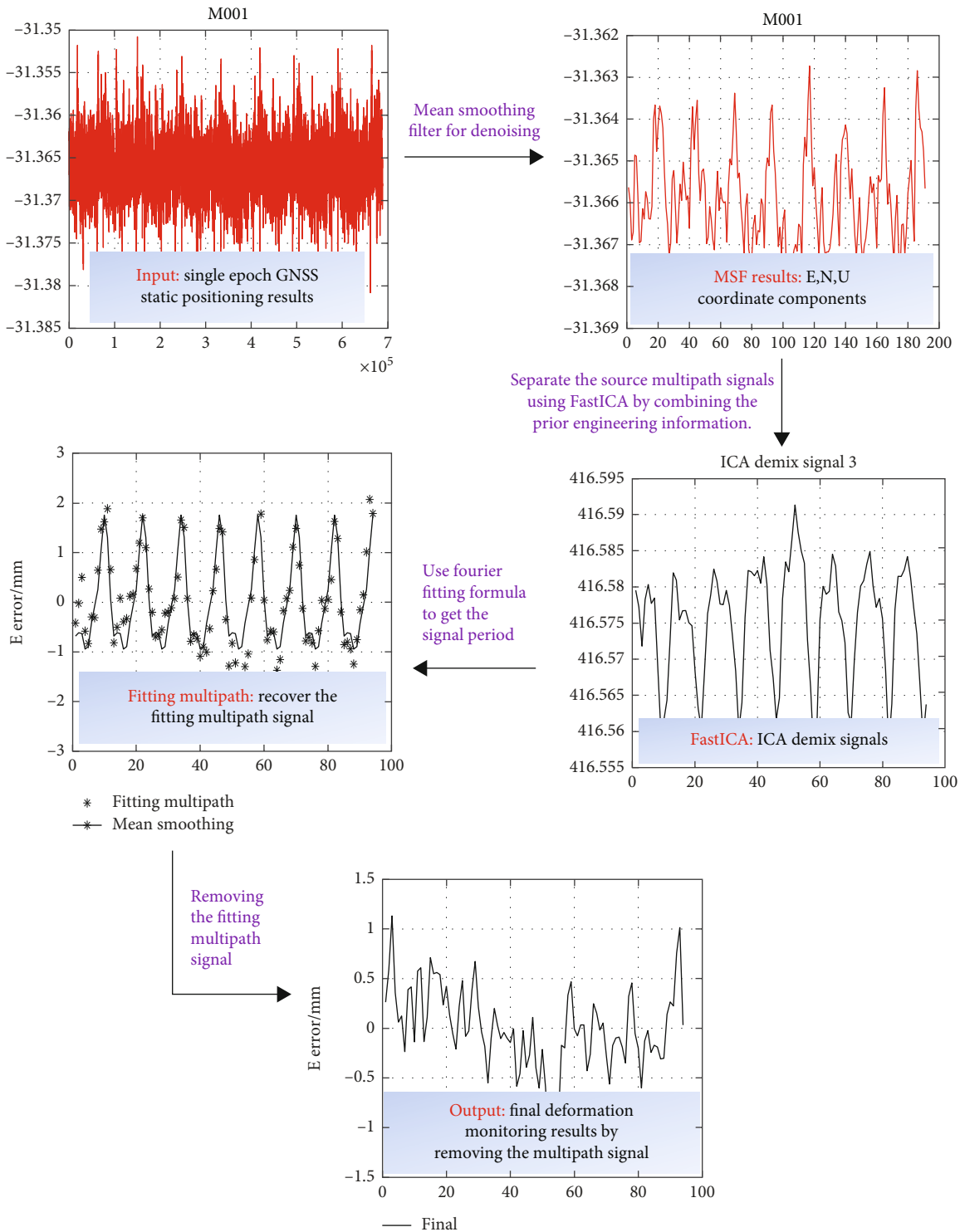


FIGURE 1: Flowchart for the AF-ICA method ((1) input: static single epoch results; (2) MSF: weaken the influence aroused by noise; (3) FastICA: separate the multipath signal; (4) first-order Fourier fitting formula: get multipath signal period; (5) recover the fitting multipath signal; and (6) output: deformation monitoring result by removing the fitting multipath signal).

where $X = [\delta X \ \delta Y \ \delta Z]^T$ is regarded as the baseline component of the fixed solution to be estimated, H_i is the coefficient matrix of the i -th epoch which can be calculated from the satellite position and the receiver position, P_i is the observation

equation weight matrix of the i -th epoch which can be calculated by satellite altitude angle or floating solution residual, and Z_i is the estimated residual of the observation. Each session duration collects n epochs observation data.

Least-square method can be used to calculate the fixed solution X in (1)

$$X = \left(\sum_i^n H_i^T P_i H_i \right)^{-1} \left(\sum_i^n H_i^T P_i Z_i \right), \quad (2)$$

where X can be calculated by n epoch iterations. The n -th iteration could be written as

$$\begin{aligned} X^{(n)} &= X, \\ &= \left(\sum_i^n H_i^T P_i H_i \right)^{-1} \left(\sum_i^n H_i^T P_i Z_i \right), \\ &= \mu \cdot (H_1^T P_1 Z_1 + \dots + H_{n-1}^T P_{n-1} Z_{n-1}) + \mu \cdot (H_n^T P_n Z_n), \end{aligned} \quad (3)$$

where $X^{(n)}$ represents the result of the n -th iteration; $X_n = (H_n^T P_n H_n)^{-1} \cdot (H_n^T P_n Z_n)$ represents the least-squares result of the n -th epoch; and $\mu = (H_1^T P_1 H_1 + \dots + H_n^T P_n H_n)^{-1}$ represents the inverse of the coefficient matrix in normal equation.

Iterative formula can be obtained by further decomposing (3):

$$X^{(n)} = \alpha \cdot X^{(n-1)} + \beta \cdot X_n, \quad (4)$$

where α, β is regarded as the smoothing coefficient and can be expressed as

$$\begin{aligned} \alpha &= \left(I + (H_1^T P_1 H_1 + \dots + H_{n-1}^T P_{n-1} H_{n-1})^{-1} \cdot H_n^T P_n H_n \right)^{-1}, \\ \beta &= \left(I + (H_n^T P_n H_n)^{-1} \cdot (H_1^T P_1 H_1 + \dots + H_{n-1}^T P_{n-1} H_{n-1}) \right)^{-1}, \end{aligned} \quad (5)$$

where I is a unit matrix.

2.2. AF-ICA for Mitigating Multipath Effects. In the static baseline solution, the duration of the session needs to be set in advance. While the AF-ICA is proposed in this paper can automatically analyze the session duration by using the single epoch solution. Before introducing the AF-ICA method, let us first introduce the FastICA method.

FastICA is a signal processing method for transforming an observed multidimensional random vector into components that are statistically as independent from each other as possible [16]. The standard ICA model could be written as

$$\begin{aligned} x &= As, \\ &= \sum_{i=1}^n a_i s_i, \end{aligned} \quad (6)$$

where $x = [x_1, x_2, \dots, x_m]^T$ is regarded as the observed mixtures, $s = [s_1, s_2, \dots, s_n]^T$ represents the unknown sources, and $A = [a_1, a_2, \dots, a_m]^T$ is the unknown mixing matrix of size

$m \times n$. With the assumption that $m \geq n$ and that sources s are mutually independent, the ICA could optimally estimate a demixing matrix, say B , to separate the original signals s based on some rules of optimization (such as the least squares). Then the best approximation vector of s can be derived from

$$y = Bx, \quad (7)$$

where $y = [y_1, y_2, \dots, y_n]^T$, which is the best approximation vector of s . Generally, the process of the ICA algorithm can be divided into three steps: first, center x , i.e., subtract its mean vector $m = E\{x\}$ so as to make x a zero-mean variable; second, whiten the observed mixtures to get the whitening signals $z = Vx$, where V is the whitening matrix, and $E\{zz^T\} = I$ (I is a unit matrix); third, get a rotation matrix W , such that $y = Wz$, by the specific independence optimization rule. In the ICA algorithm, the sources s consist of one Gaussian source at most, but the separated components y are uncertain in amplitude and order.

FastICA is based on a fixed-point iteration for finding a maximum of the non-Gaussianity of y . To begin with, we first show the one-unit version of FastICA [17]. Denote the derivative of the nonquadratic functions are

$$\begin{aligned} g_1(u) &= \tanh(a_1 u), \\ g_2(u) &= u \exp(-u^2/2), \end{aligned} \quad (8)$$

where $1 \leq a_1 \leq 2$ is a suitable constant, often taken as $a_1 = 1$.

Object of GNSS deformation monitoring can be expressed by the baseline solution results in three components E, N, and U of the topocentric coordinate system. When using FastICA for multipath signal separation (here we think that the source signal is a multipath signal), we regard the three coordinate components of ENU as mixed signals x , $m = 3$. According to engineering experience and GNSS satellite orbital period [18], we can obtain three kinds of prior information:

- (a) Source signal contains a multipath signal with a period of a sidereal day
- (b) Maximum period of the signal in the source signal would not exceed one sidereal day
- (c) Total number of source signals meets the requirements: $n \leq 3$

3. Results and Discussion

In this section, a comprehensive experimental study has been conducted to inspect the performance of our proposed method. The content consists of three parts: the experimental setup, comparative experiments using the MSF, the SFOD, and the AF-ICA methods, and the discussion.

3.1. Experimental Setup. To test our proposed methods, data from an experiment with a railway roadbed deformation monitoring project were used. This experiment was



FIGURE 2: Distribution of each monitoring station.

TABLE 1: MSF accuracy under different kinds of session duration (Unit: mm).

Session duration	E	N	U	Session duration	E	N	U
1 s	7.6	7.6	10.6	45 min	3.3	3.2	4.4
15 s	7.1	7.1	9.9	1 hour	3.0	2.9	4.1
30 s	6.9	6.9	9.6	2 hours	2.5	2.3	3.2
60 s	6.7	6.6	9.3	3 hours	2.2	2.0	2.7
3 min	6.0	5.9	8.2	4 hours	1.9	1.8	2.4
5 min	5.6	5.5	7.6	6 hours	1.7	1.6	2.2
15 min	4.5	4.3	5.9	12 hours	0.7	0.7	0.8
30 min	3.7	3.6	5.0	24 hours	0.5	0.6	0.6

conducted on the Guangshan railway. It monitored the impact on the completed roadbed during construction and used GNSS receivers to monitor the deformation. In the monitoring area, we selected a firm position that is not easy to deform at the top of the mountain as the reference point, marked as B001. Four monitoring points noted as M001, M002, M005, and M006 were arranged along the railway in the monitoring area. The distribution of each observation station is shown in Figure 2.

The location was chosen because it was clearly subject to multipath effects from the smooth reflective surfaces of the railway roadbed. ComNav GNSS L1/L2 dual-frequency K506 receivers with Harxon HX-CSX601A survey antennas were used in the base and monitoring stations. The baselines between the base station and monitoring station were about 100-500 m. Due to this short baseline, satellite clock errors, receiver clock errors, satellite orbit error, ionospheric delay, tropospheric delay, and other common errors are removed by double differencing. The test began on March 3, 2020, and lasted for 8 days. The detailed data processing strategy is first analyze the positioning accuracy after MSF denoising, then use the classic SF-OD method to analyze the positioning accuracy after removing the multipath, and finally, use the AF-ICA method to analyze the positioning accuracy after the multipath is removed.

3.2. Experiment with MSF. Position accuracy obtained from the relative positioning of GNSS single epoch (i.e., interval = 1 s) is cm level, which cannot meet the mm level accuracy requirements of deformation monitoring, and MSF processing is required. In order to analyze the relationship between positioning accuracy and session duration in MSF, we designed 16 kinds of session duration: 1 s, 15 s, 30 s, 60 s, 3 min, 5 min, 15 min, 30 min, 45 min, 1 hour, 2 hours, 3 hours, 4 hours, 6 hours, 12 hours, and 24 hours and then used MSF algorithm for processing. The average positioning accuracy of the four monitoring stations' baseline results after MSF was counted in the ENU geographical coordinate system.

In this test, the 3-sigma principle (99.7% confidence probability) is used to count the positioning accuracy. The statistical results are shown in Table 1, and the relationship between positioning accuracy and session duration is shown in Figure 3.

As can be seen from Table 1 and Figure 3:

the longer the session duration, the higher the positioning accuracy. After more than 12 hours, the positioning accuracy is better than 1 mm, and then increasing the duration has little improvement on the positioning accuracy. When the session duration is within 0-1 hour, the effect of increasing duration on the positioning accuracy is very obvious, and it enters a turning point near 1 hour. After the

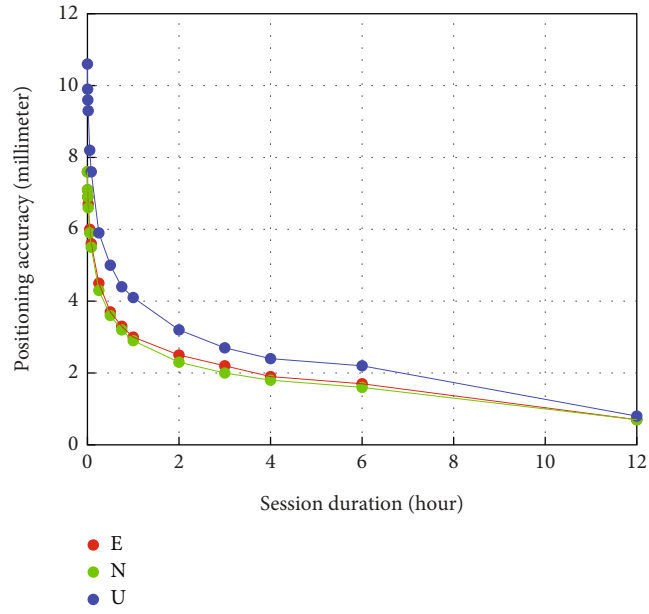


FIGURE 3: Relationship between positioning accuracy and session duration.

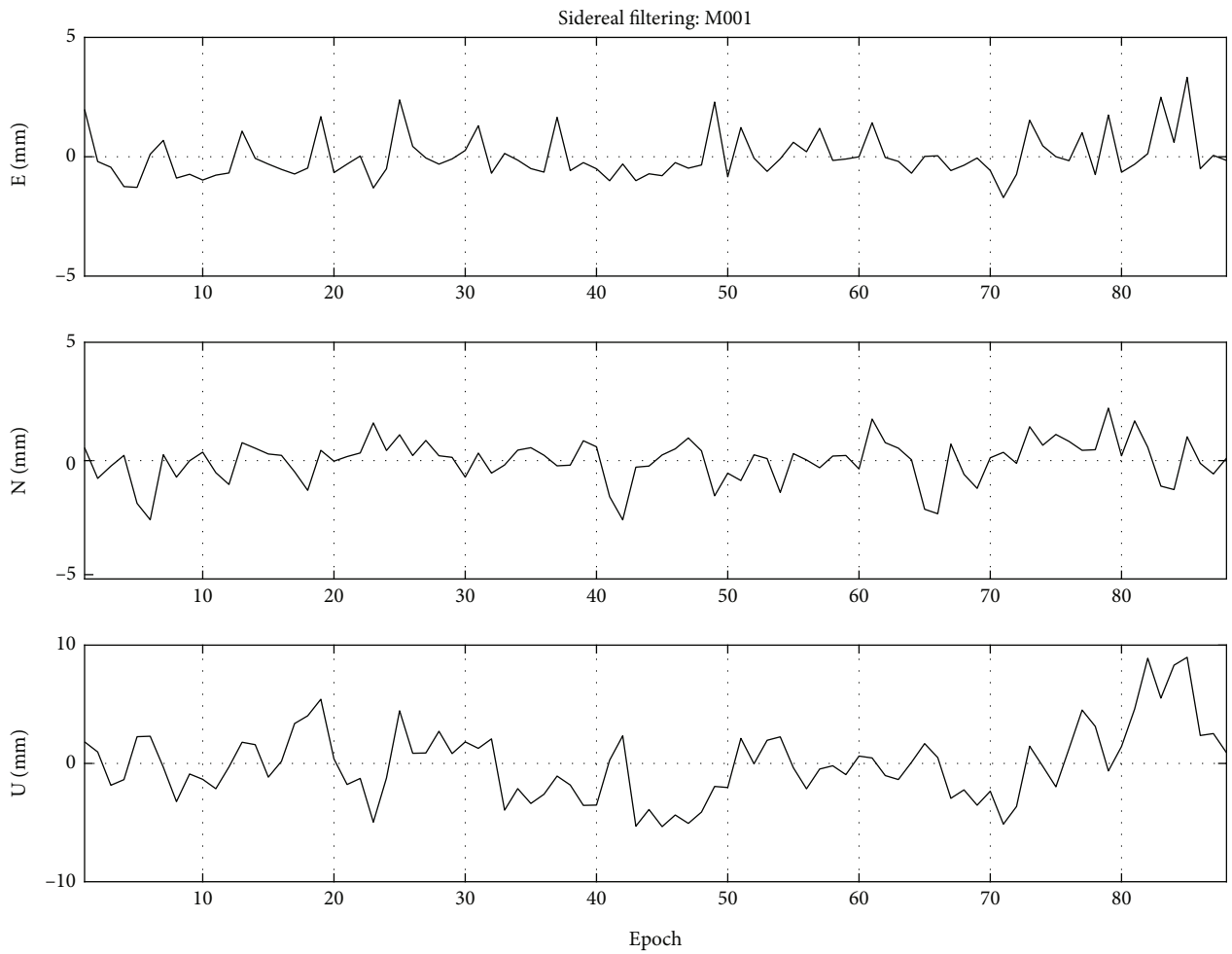


FIGURE 4: ENU error of M001 station after SF-OD.

TABLE 2: Positioning accuracy using 2 hours of MSF and SF-OD methods.

Monitoring station	Positioning accuracy (RMS)/mm						Peak-to-peak value (maximum minus minimum)/mm					
	E		N		U	E		N		U		
	MSF	SF-OD	MSF	SF-OD		MSF	SF-OD	MSF	SF-OD	MSF	SF-OD	
M001	1.0	0.9	0.7	0.9	3.4	3.0	4.2	5.0	3.8	4.7	16.1	14.3
M002	0.5	0.8	0.7	0.5	1.6	2.2	2.4	3.2	3.2	2.7	7.7	12.0
M005	0.8	0.6	0.6	0.6	1.6	1.5	3.5	3.6	2.8	3.3	7.2	10.1
M006	0.8	0.9	0.5	0.7	2.4	1.7	3.4	4.7	2.7	3.9	12.2	9.8

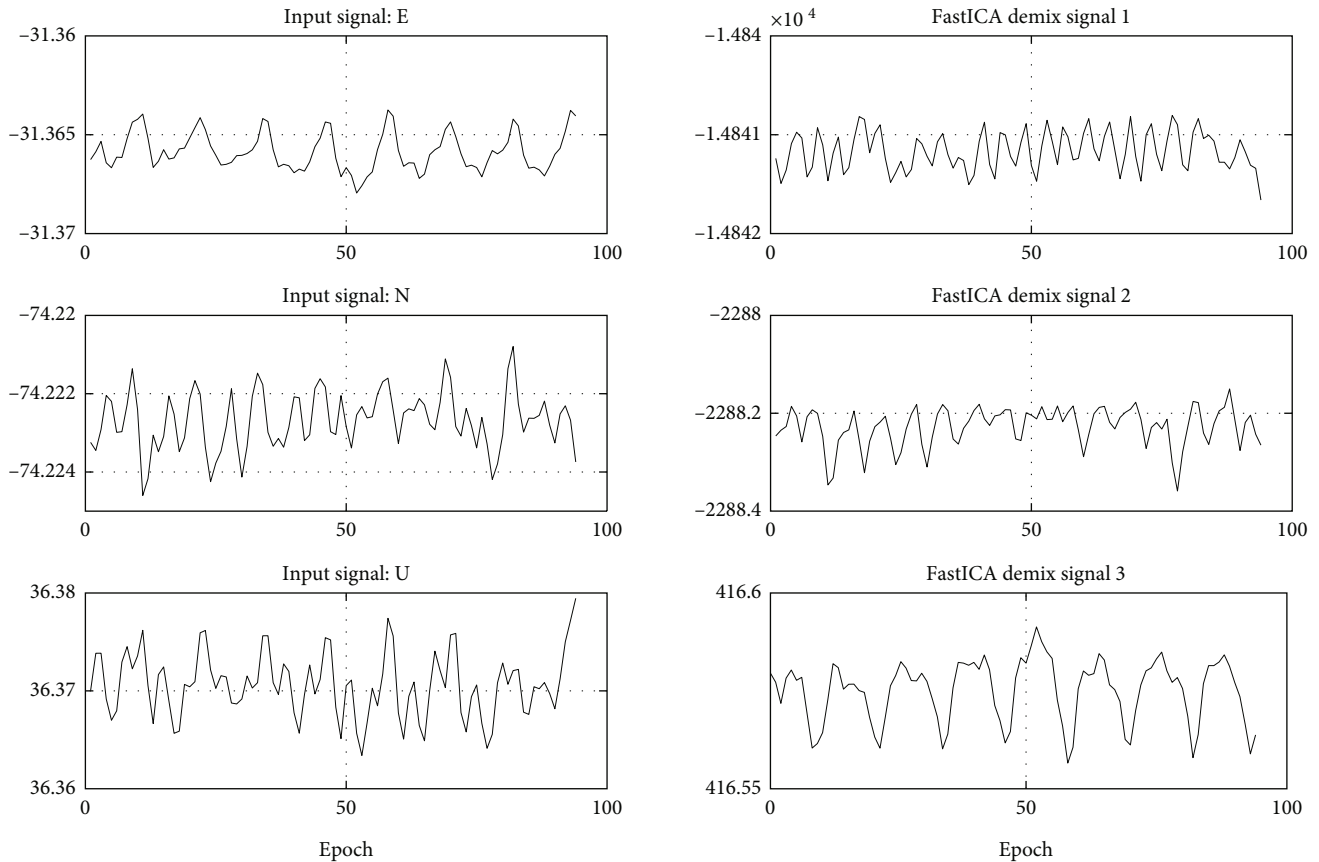


FIGURE 5: Period and graph of multipath signal of M001 by FastICA (three figures on the left are the time series of ENU coordinates, and the three pictures on the right are the multipath signals separated by FastICA).

duration exceeds 1 hour, the horizontal positioning accuracy is better than 3 mm and the altitude positioning accuracy is better than 4 mm.

In summary, we suggest that in GNSS deformation monitoring using MSF method, it is more appropriate to select 1-12 hours for the duration, which can not only obtain mm level positioning accuracy but also ensure a fast deformation monitoring result.

3.3. Experiment with SF-OD. We use the SF-OD method to eliminate multipath signals and analyze the positioning accuracy after removing multipath. The data processing strategy of SF-OD is first collect data for one sidereal day, then get the difference between second sidereal day with

the first sidereal day in observation domain, and finally, obtain the deformation of the second sidereal day relative to the first sidereal day. The SF-OD method uses a 2 hours interval for processing. The first day as a reference and calculate the single difference residuals. The positioning solution is carried out after removing the single difference residuals in the same period of the next day. Due to the adoption of the sidereal day period, we only process the GPS dual-frequency data. Figure 4 shows the ENU positioning error of M001 station after removing the multipath signal, Table 2 lists the positioning accuracy statistics using 2 hours of MSF and SF-OD methods.

Compared with MSF, the positioning accuracy of SF-OD increases by -9%, -10%, and 2% in the three directions of

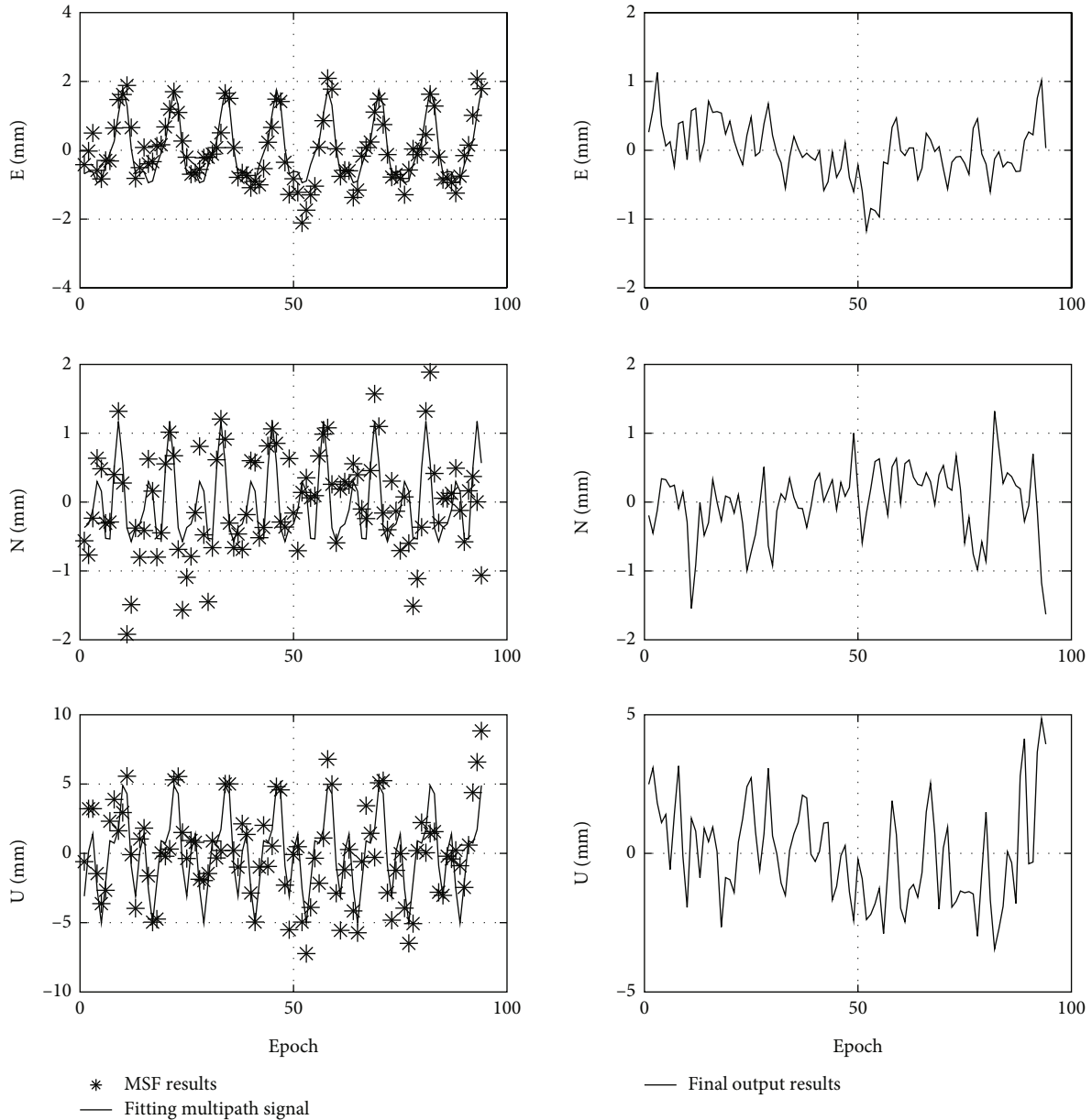


FIGURE 6: ENU error of M001 station after AF-ICA (asterisk points and line on the left figures, respectively, represent the MSF results and fitting multipath signal of ENU coordinates. Line on the right pictures are the ENU positioning results after AF-ICA).

ENU. The corresponding peak-to-peak value increases are -23%, -17%, and -16%. It can be seen that although SF-OD can effectively deal with the influence of sidereal day multipath signals, the positioning accuracy and peak-to-peak value are worse than those of the MSF method. The possible reason is that SF-OD only processes GPS data, while MSF processes GPS+BDS data which contains more satellites.

3.4. Experiment with AF-ICA. According to the data results of the MSF test, the session duration range of MSF is controlled within 1-12 hours. Firstly, four monitoring stations are tested through a priori information in AF-ICA, and it is concluded that the minimum session duration that can separate multipath signals is 2 hours. Subsequent AF-ICA analysis is processed based on the MSF results of 2 hours.

Figure 5 shows the period and graph of separating the multipath signal of M001 station by FastICA method. The input signal is the E, N, and U coordinate components after MSF, and the output signal is the separated three independent multipath signals. Through the first-order Fourier fitting formula, the periods of the three multipath signals are 8 hours, 12 hours, and 24 hours, respectively. It can be seen that compared with the sidereal day period in GPS data, the GPS+BDS data used in this test adds two multipath signals with smaller cycles, which may be mainly due to the use of multiple orbit types of satellites in GNSS relative positioning.

After the multipath signal is separated by the FastICA method, the complete multipath signal is generated by the linear fitting formula. Figure 6 plots the positioning error of M001 station before and after multipath signal removal

TABLE 3: Accuracy after removing multipath signals by AF-ICA compared with MSF.

Monitoring station	Positioning accuracy (RMS)/mm						Peak-to-peak value (maximum minus minimum)/mm					
	E		N		U		E		N		U	
	MSF	AF-ICA	MSF	AF-ICA	MSF	AF-ICA	MSF	AF-ICA	MSF	AF-ICA	MSF	AF-ICA
M001	1.0	0.4	0.7	0.5	3.4	1.8	4.2	2.3	3.8	3.0	16.1	8.3
M002	0.5	0.3	0.7	0.5	1.6	1.4	2.4	1.7	3.2	2.0	7.7	7.4
M005	0.8	0.4	0.6	0.6	1.6	1.0	3.5	1.9	2.8	3.0	7.2	4.5
M006	0.8	0.6	0.5	0.5	2.4	1.8	3.4	2.6	2.7	2.3	12.2	8.8

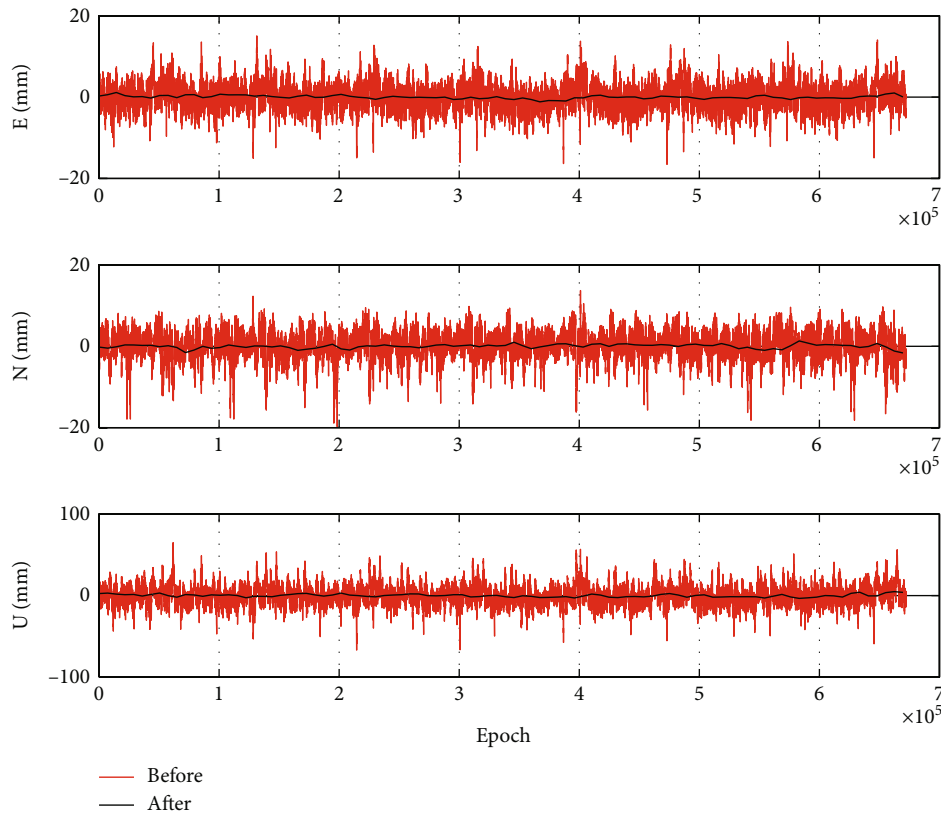


FIGURE 7: ENU error of M001 station before and after multipath signal removal by AF-ICA for 8 days.

by FastICA method. In Figure 6, the results after MSF are represented by asterisk points, fitting multipath represents the complete multipath signal, and finally represents the positioning error after multipath signal removal. Table 3 lists the accuracy statistics after removing multipath signals by AF-ICA compared with MSF. Figure 7 plots the positioning error of M001 station before and after multipath signal removal by AF-ICA.

Compared with MSF, the positioning accuracy of the AF-ICA method is improved by 44%, 14%, and 31% in the three directions of ENU. The corresponding peak-to-peak value increases were 36%, 17%, and 29%. It can be seen that the AF-ICA method can effectively deal with the influence of multipath signals during multi-GNSS fusion positioning, and the positioning accuracy is significantly improved compared with the simple MSF method.

3.5. Discussion. In the above experiments, we use two different methods to mitigate the multipath in deformation monitoring. To compare the MSF method and sidereal day filtering method, we use the SF-OD method to process GPS dual-frequency data. Although SF-OD effectively processes the influence of sidereal day multipath on the positioning accuracy, peak-to-peak values are worse than those of the MSF method. On the other hand, through the analysis of 8-day static test results by the AF-ICA method, according to a priori information of multipath signal, we determined that the minimum session duration meeting the multipath signal separation is 2 h, and successfully separated the multipath signals of four stations. Compared with the simple MSF method, the positioning accuracy of the AF-ICA method is improved by 44%, 14%, and 31% in the three directions of ENU. The corresponding peak-to-peak value increases were

36%, 17%, and 29%. The AF-ICA method can effectively solve the problem of multiperiod multipath signals caused by multiple satellite orbits of GNSS. The AF-ICA can automatically identify the session duration, to realize automatic deformation monitoring.

4. Conclusion

In this study, we proposed a novel method called the AF-ICA method to address the complicated multipath in the deformation monitoring of the GNSS that contains multiple types of satellites and improve the timeliness. The experimental results show that our method can achieve mm level positioning accuracy and meet the requirements of GNSS deformation monitoring. At the same time, by analyzing the value range of session duration, it is found that the session duration of 1-12 hours is more appropriate, which can not only obtain ideal positioning accuracy but also ensure fast deformation monitoring. Compared with the simple MSF method and the SF-OD method, the proposed AF-ICA method is able to improve both the positioning accuracy and peak-to-peak values. In a word, our method is more appropriate for mitigating multipath than the traditional sidereal filtering method, especially in multi-GNSS fusion positioning.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author for academic purposes.

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

The authors acknowledge the National Natural Science Foundation of China under Grant 62273106 and the Key Research and Development Program of Guangdong Province under Grant 2019B010141001.

References

- [1] Y. Yang, J. L. Li, A. B. Wang et al., "Preliminary assessment of the navigation and positioning performance of BeiDou regional navigation satellite system," *Science China Earth Sciences*, vol. 57, no. 1, pp. 144–152, 2014.
- [2] C. Liu, P. Lin, X. Zhao, and J. Gao, "Reducing GPS carrier phase errors in the measurement and position domains for short-distance static relative positioning," *Acta Geodaetica et Geophysica*, vol. 51, no. 1, pp. 81–93, 2015.
- [3] J. W. Lovse, W. F. Teskey, G. Lachapelle, and M. E. Cannon, "Dynamic deformation monitoring of tall structure using GPS technology," *Journal of Surveying Engineering*, vol. 121, no. 1, pp. 35–40, 1995.
- [4] S. Nakamura, "GPS measurement of wind-induced suspension bridge girder displacements," *Journal of Structural Engineering*, vol. 126, no. 12, pp. 1413–1419, 2000.
- [5] X. Meng, G. W. Roberts, A. H. Dodson, E. Cossier, J. Barnes, and C. Rizos, "Impact of GPS satellite and pseudolite geometry on structural deformation monitoring: analytical and empirical studies," *Journal of Geodesy*, vol. 77, no. 12, pp. 809–822, 2004.
- [6] W. S. Chan, Y. L. Xu, X. L. Ding, and W. J. Dai, "An integrated GPS accelerometer data processing technique for structural deformation monitoring," *Journal of Geodesy*, vol. 80, no. 12, pp. 705–719, 2006.
- [7] P. Psimoulis, S. Pytharouli, D. Karambalis, and S. Stiros, "Potential of global positioning system (GPS) to measure frequencies of oscillations of engineering structures," *Journal of Sound and Vibration*, vol. 318, no. 3, pp. 606–623, 2008.
- [8] P. Elósegui, J. L. Davis, R. T. K. Jaldehag, J. M. Johansson, A. E. Niell, and I. I. Shapiro, "Geodesy using the global positioning system: the effects of signal scattering on estimates of site position," *Journal of Geophysical Research*, vol. 100, no. B6, pp. 9921–9934, 1995.
- [9] K. Choi, A. Bilich, K. M. Larson, and P. Axelrad, "Modified sidereal filtering: implications for high-rate GPS positioning," *Geophysical Research Letters*, vol. 31, no. 22, 2004.
- [10] A. E. Ragheb, P. J. Clarke, and S. J. Edwards, "GPS sidereal filtering: coordinate- and carrier-phase-level strategies," *Journal of Geodesy*, vol. 81, no. 5, pp. 325–335, 2006.
- [11] A. E. Ragheb, P. J. Clarke, and S. J. Edwards, "Coordinate-space and observation-space filtering methods for sidereally repeating errors in GPS: performance and filter lifetime," in *Proceedings of the 2007 National Technical Meeting of The Institute of Navigation*, pp. 480–485, San Diego, CA, 2007.
- [12] K. M. Larson, A. Bilich, and P. Axelrad, "Improving the precision of high-rate GPS," *Journal of Geophysical Research*, vol. 112, no. B5, 2007.
- [13] D. Dong, M. Wang, W. Chen et al., "Mitigation of multipath effect in GNSS short baseline positioning by the multipath hemispherical map," *Journal of Geodesy*, vol. 90, no. 3, pp. 255–262, 2016.
- [14] W. Gao, X. Meng, C. Gao, S. Pan, Z. Zhu, and Y. Xia, "Analysis of the carrier-phase multipath in GNSS triple-frequency observation combinations," *Advances in Space Research*, vol. 63, no. 9, pp. 2735–2744, 2019.
- [15] X. Tang, G. W. Roberts, C. M. Hancock, and J. Yu, "GPS/BDS relative positioning assessment by zero baseline observation," *Measurement*, vol. 116, pp. 464–472, 2018.
- [16] W. J. Dai, D. W. Huang, and C. S. Cai, "Multipath mitigation via component analysis methods for GPS dynamic deformation monitoring," *GPS Solutions*, vol. 18, no. 3, pp. 417–428, 2014.
- [17] A. Hyvarinen and E. Oja, "Independent component analysis: algorithms and applications," *Neural Networks*, vol. 13, no. 4-5, pp. 411–430, 2000.
- [18] Q. Zhang, W. Yang, S. Zhang, and X. Liu, "Characteristics of BeiDou navigation satellite system multipath and its mitigation method based on Kalman filter and Rauch-Tung-Striebel smoother," *Sensors*, vol. 18, no. 2, p. 198, 2018.