Multipath Error Correction for Smartphones and Its Impact on Single Point Positioning

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Abstract. With the release of multi-constellation and multi-frequency GNSS chips, the positioning capabilities of smartphones have been improved. However, smartphones are commonly equipped with low-gain microstrip antennas, which make GNSS observations suffer from severe multipath effects. The results of short baseline single difference (SD) show that the multipath error of smartphones is almost 5–10 times higher than that of geodetic receivers, which greatly limits the positioning accuracy of smartphones. The multipath effect is affected by various factors such as equipment, environment, and signal, and it is usually difficult to establish an effective mathematical model for correction in complex urban scenarios. Considering that multipath errors have low-frequency characteristics, this paper proposes a method based on wavelet transform, which can effectively detect and extract multipath errors. First, the short baseline SD residual between the smartphone and the reference station is decomposed into low-frequency error and high-frequency noise. Then, the low-frequency error is compensated to GNSS pseudorange observations after doing wavelet inverse transform reconstruction, thus weakening the influence of multipath errors on the positioning. The experimental results show that different wavelet bases and decomposition layers can effectively improve the positioning accuracy, and the improvement is more obvious when the number of decomposition layers is smaller. When dB1 wavelet base and one layer of decomposition coefficients are selected, the single point positioning (SPP) accuracy of Huawei P40 and Xiaomi 8 in U, N, and E directions reaches 1.07 m, 1.31 m, 0.59 m, and 1.32 m, 0.87 m, 0.47 m respectively after multipath error compensation. Compared with the uncompensated multipath, the positioning accuracy of the two phones is improved by 53.5%, 48.6%, 60.7%, and 25.4%, 32%, 55.2%, respectively.

Keywords: Smartphone · GNSS · Multipath error · Wavelet transform · Single point positioning

1 Introduction

With the improvement of Global Navigation Satellite System (GNSS) technology and the popularity of smartphones, the market scale of GNSS-based high-precision location services (LBS) is growing, and the requirements for smartphone positioning accuracy

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are also growing. At present, the navigation and positioning accuracy of GNSS on smartphones is about 10 m [1], which is far from meeting the demand of users for high-precision positioning.

Since Google opened GNSS raw observations in Android version 7.0 in 2016, many scholars at home and abroad have analyzed and studied the raw observations of smartphones. Zhang et al. found that the smartphone pseudorange residuals varied between −20 and 20 m through short baseline single difference (SD) experiments [2]; the results of Ganga et al. proved that multipath error was the main source of error in smartphone pseudorange measurements, and the multipath error was around ±15 m [3]. Thus, the correction of smartphone pseudorange multipath error is crucial to improve the GNSS positioning performance of smartphones.

Many scholars have conducted many studies on the modeling and elimination of multipath. The most common current multipath processing method is to estimate the multipath error by the linear combination of multi-frequency observations [4]. Comp and Axelrad proposed to extract multipath errors by using the carrier-to-noise ratio [5], JF. Genrich and Y Bock first proposed to use Sideral Filtering based on the Sunday repeatability of multipath errors [6], Song proposed a multipath half-sky sphere model based on the spatial repeatability of multipath. The Multipath Hemispherical Map (MHM) was proposed [7]. In addition, the modeling of multipath by using time–frequency analysis has been gradually paid attention to in recent years. Aram M extracted GNSS multipath error by using wavelet analysis and proved that wavelet analysis screening suitable satellites can improve the accuracy and reliability of positioning when the number of satellites is small [8]; Azarbad modeled multipath error by wavelet analysis. It was proved that wavelet analysis has a good denoising effect [9]; Liu et al. used Empirical Model Decomposition (EMD) to get the coordinate accuracy after weakening the multipath effect, and the results showed that the stability of the coordinate sequence was significantly enhanced after the multipath effect was weakened, and the accuracy of the coordinates was significantly improved [10]; Peng et al. used the variational modal decomposition method to extract pseudorange noise [11]; the results of Li et al. analyzed the effects of different wavelet bases and different decomposition levels on the multipath error extraction effect [12]; Zhu et al. used wavelet analysis and empirical modal decomposition to jointly extract smartphone multipath errors, which proved the effectiveness of multipath extraction in reducing the noise of low precision positioning devices [13].; The research of Liu proved the possibility of wavelet analysis method in real-time GNSS data processing [14]; Wang et al. successfully applied window wavelet in dynamic positioning [15]. Most of the current studies focus on multipath error extraction and modeling, which are also limited to the field of conventional receivers, and lack a systematic analysis of the impact of smartphone multipath error compensation on smartphone positioning performance.

In this paper, we propose a wavelet transform-based approach to effectively extract multipath errors and compensate for pseudorange observations in the observation domain. Firstly, the short baseline SD residuals between the smartphone and the reference station are decomposed into low-frequency error and high-frequency noise, and then the low-frequency error is reconstructed by wavelet inverse transform to obtain the noise-reduced multipath error, which is compensated to the GNSS pseudorange observation, thus weakening the impact of the multipath error on the positioning. In this paper, the analysis is verified by Xiaomi 8 and Huawei P40 smartphones.

2 Proposed Method

2.1 Wavelet Transform Theory

The traditional signal theory is based on Fourier transform. However, as a global transform, Fourier transform does not have the ability of local analysis and cannot analyze non-stationary signals. Although the short-time Fourier transform can give the local information of the signal, it is subject to the fixed window and has no adaptive ability. The wavelet transform solves this problem and provides more possibilities for signal analysis. Wavelet transform is mainly divided into continuous wavelet transform and discrete wavelet transform [16].

The of wavelet transform is to translate and expand the mother wavelet, so as to match the mother wavelet with the signal wave in a certain scale and range. Through continuous translation and expansion, the wavelet transform is created. The continuous wavelet transform (CWT) can be written as:

$$CWT(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\psi(t)*\left(\frac{t-\tau}{a}\right)dt \tag{1}$$

where $f(t)$ is the signal to be transformed,$\psi(t)$ denotes wavelet function, a represents the scale and τ is translation parameter.

Discrete wavelet transform is more suitable for practical data processing than continuous wavelet transform. Making both scale and translation parameters discrete by two integers m and n. Thus, the DWT is defined as: [17]:

$$DWT(m,\mathrm{n}) = \frac{1}{\sqrt{a_0^m}} \sum_k x[k]\psi[a_0^{-m}n - k] \tag{2}$$

2.2 Multi-resolution Analysis

In 1988, S. Mallat put forward the concept of multi-resolution analysis when constructing orthogonal wavelet base, and gave the construction method of orthogonal wavelet and the express algorithm of orthogonal wavelet. Figure 1 gives a schematic diagram of the wavelet multi-resolution decomposition with decomposition layers of 2. In multi-resolution analysis, the signal passes through a low-pass filter and a high-pass filter at each step. The next step is to further decompose the low-frequency part, and so on [18]

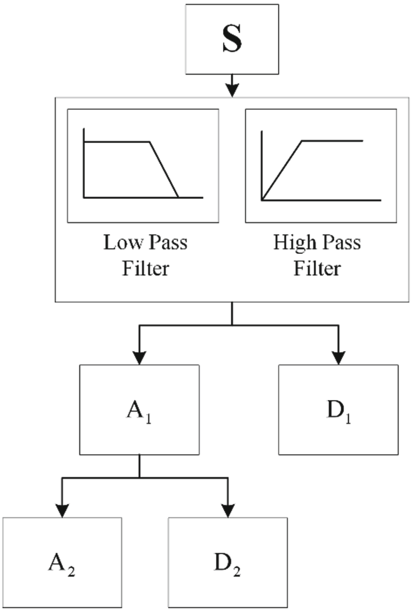

Fig. 1 Wavelet decomposition diagram

2.3 Single Difference Between Stations to Extract Multipath Errors

For the base station b and the rover station r, the pseudorange observations corresponding to a particular satellite frequency f are $P_{b,f}$ and $P_{r,f}$ respectively, and the pseudorange observation equation can be described as:

$$\begin{cases} P_{b,f} = \rho_{\mathrm{b}} + c \cdot (t_b - t^s) + I_{b,f} + T_b + M_b + \varepsilon_b \\ P_{r,f} = \rho_r + c \cdot (t_r - t^s) + I_{r,f} + T_r + M_r + \varepsilon_r \end{cases} \tag{3}$$

where P denotes the pseudorange observation value in m; ρ_{b} denotes the accurate satellite ground distance between the reference station and the satellite with known coordinates; ρ_r denotes the calculated satellite ground distance between the mobile station and the satellite with unknown coordinates; t_b and t_r denotes the receiver clock difference between the reference station and the mobile station, respectively; t^s denotes the satellite clock difference; I and T denote the ionospheric error and tropospheric error error, respectively; M denotes the pseudorange multipath error; and ε denotes the pseudorange observation noise.

In order to reduce the influence of the satellite end error and atmospheric error, the short baseline method is used for SD calculation, and the following equation is obtained:

$$\Delta P_{rb,f} = \Delta\rho_{rb} + c \cdot \Delta t_{rb} + \Delta\rho_r + \Delta M_{rb} + \Delta\varepsilon_{rb} \tag{4}$$

where Δt_{rb} is the difference between the receiver clocks of the mobile station and the reference station, and $\Delta\rho_{rb}$ is the difference between the guard earth distance of the mobile station and the reference station, which can be eliminated by parameter estimation; $\Delta M_{rb} + \Delta\varepsilon_{rb}$ denotes the residual of the SD between the short baseline stations. It should be noted that it is difficult to completely eliminate the parameter estimation of $\Delta\rho_{rb}$ and Δt_{rb}, so the residual term $\Delta M_{rb} + \Delta\varepsilon_{rb}$ will contain this part of the error. Considering that the residual error has similar low-frequency characteristics as the multipath error, wavelet analysis is used to separate the multipath combination term ΔM_{rb} from the noise term $\Delta\varepsilon_{rb}$ in the SD residual between stations, so that the multipath combination term can be compensated in the observed value domain to improve the positioning accuracy. On the other hand, this method requires the base station to be located in an open environment, i.e., ΔM_{rb} to reflect the multipath error of the mobile station (smartphone) as much as possible, so as to avoid the impact of the base station error on the positioning performance of the smartphone.

3 Experiments

3.1 Experimental Data Processing

In order to verify the correctness of the multipath error extracted by the wavelet analysis method used in this paper, the observed data of Xiaomi 8 and Huawei P40 cell phones are processed and analyzed. The experimental data were collected at the playground of College Road Campus of Beihang University, with a 1-s interval to RINEX 3.03 over a timespan of 1 h (1:30–2:30 UTC) on March 22, 2022, with the use of Geo++ RINEX Logger ver. 2.1.4. The ultra-short baseline data was composed by using a Storix receiver with a smartphone, and the baseline length is about 20 cm. The experimental scene is shown in Fig. 2.

Fig. 2. Experimental scene

The corresponding data processing flowchart is given in Fig. 3, with the following steps.

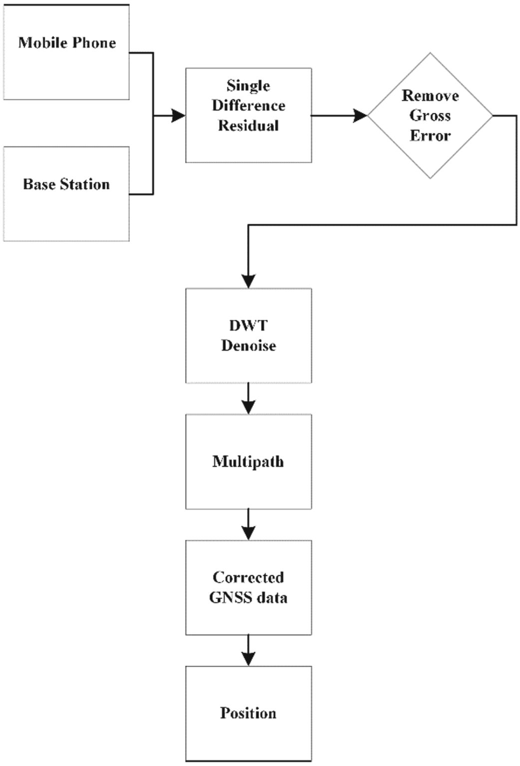

Fig. 3. Data processing block diagram

(1) The smartphone and receiver combine short baseline observation data for SD between stations.
(2) Perform outlier detection, and reject the observations which exceed the threshold.
(3) Perform discrete wavelet transform on the single-difference observation, decompose it into low-frequency multipath error and high-frequency random noise, noise reduction on the high-frequency noise, and then invert it to extract multipath error.
(4) The pseudorange observations are corrected for the multipath error, and the corrected pseudorange observations are positioned and solved.

3.2 Multipath Error Extraction

With sym3 wavelet, a three-layer decomposition is used to extract multipath errors by wavelet noise reduction of the short baseline SD residuals of the smartphone and receiver, where the smartphone position is not fixed. The time series of Mi8 smartphone and receiver before and after wavelet noise reduction of SD residuals are presented in Fig. 4. The RMS values and the percentage boost of the time series before and after the noise reduction of the single-difference residual sequence are given in Table 1, and the percentage boost of the RMS of the single-difference residual sequence at two frequency points for the two smartphones are given in Figs. 5 and 6.

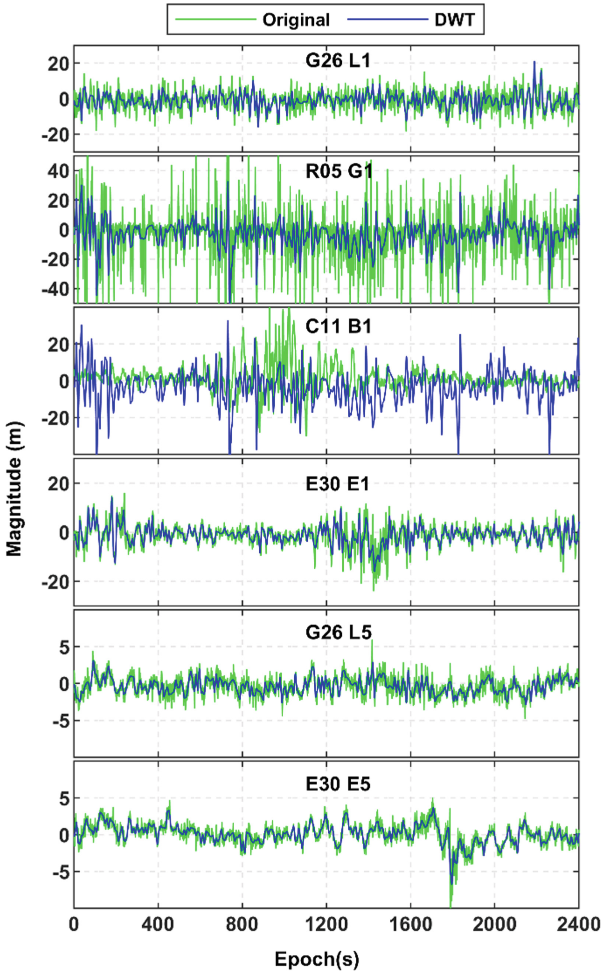

Fig. 4. Original pseudorange SD residual of Mi8 and pseudorange SD residual after DWT

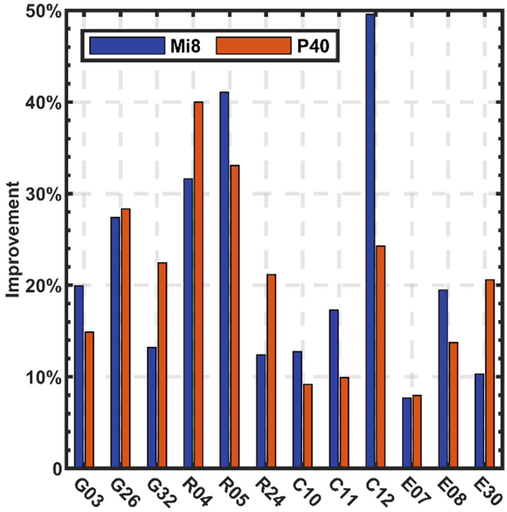

Fig. 5. Improvement percentage of the RMS value of the SD residuals, processing by the DWT method (L1,G1,B1,E1)

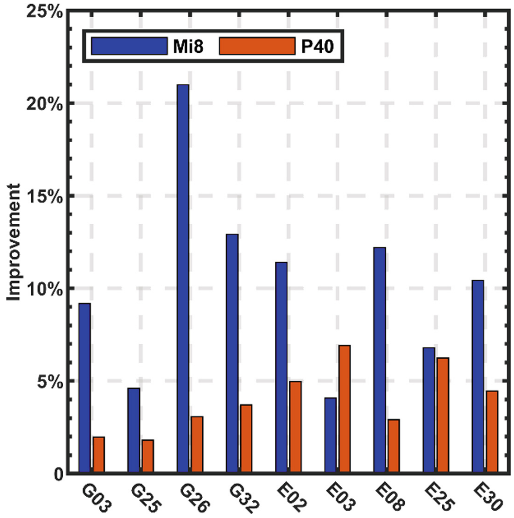

Fig. 6. Improvement percentage of the RMS value of the SD residuals, processing by the DWT method (L5, E5)

Table 1. RMS statistics of the SD residual and RMS improvements in percentage after applying the DWT method

Device	Satellite	Frequency	Original RMS(m)	DWT RMS(m)	IMP(%)
Mi8	G26	L1	6.37	4.63	27.38
		L5	1.26	1.00	20.98
	R05	G1	15.86	9.35	41.06
	C11	B1	6.29	5.20	17.28
	E30	E1	3.44	3.09	10.29
		E5	1.71	1.53	10.44
P40	G26	L1	6.02	4.32	28.33
		L5	2.18	2.14	3.07
	R05	G1	6.19	4.14	33.06
	C11	B1	4.13	3.72	9.92
	E30	E1	6.02	4.78	20.58
		E5	1.69	1.62	4.46

The results show that except for the GLONASS R05 satellite, the SD residuals of G1, B1, and E1 of the rest systems of Mi8 smartphone are around 3 m–7 m, and the SD residuals of L5 and E5 are around 1–2 m; after wavelet noise reduction, the RMS is improved in all of them, among which the RMS improvement of L1/G1/B1/E1 is more significant, generally improved by 15%–30%, and the R05 satellite SD The RMS of the residuals is even improved by 41.06%. This indicates that the wavelet analysis method has a good noise reduction effect. The improvement of L5/E5 is relatively low, taking Galileo E30 as an example, the accuracy of E5 observation is only improved by 4.46%, which is mainly due to the better anti-noise performance of the L5/E5 signal.

3.3 Positioning Accuracy Evaluation

3.3.1 Impact of Multipath Error Correction on Positioning Results

The impact of multipath correction pseudorange extracted by wavelet analysis on the single point positioning (SPP) accuracy of smartphones is studied with sym3 wavelet and decomposition layer of 3. The positioning performance is also compared with that of carrier-smoothed pseudorange and Doppler-smoothed pseudorange SPP. Four constellations of GPS, BDS, Galileo, and GLONASS are used for positioning, and the carrier-to-noise ratio random model is used for weighting, with high-precision ephemeris and clock-difference products. The ionospheric error is corrected using the GIM model and the tropospheric error is corrected using the GPT2w model. The 3D positioning errors of Mi8 and P40 smartphones are given in Figs. 7 and 8.

By counting RMS, the experimental results show that the positioning accuracy of Mi8 in U, N, and E directions without compensating multipath is 2.55 m, 2.30 m, and 1.50 m respectively, and the positioning accuracy of P40 is 1.77 m, 1.28 m, and 1.05 m; the positioning accuracy of Mi8 in carrier-smoothed pseudorange single-point positioning is only 2.32 m, 1.93 m and 1.21 m, and the positioning accuracy of P40 is only 1.60 m, 1.03 m and 0.88 m. The positioning accuracy of P40 is only 1.60 m, 1.03 m, and 0.88 m; the positioning accuracy of Mi8 in Doppler smooth pseudorange single-point positioning is 2.31 m, 1.82 m, and 1.22 m, and that of P40 is 1.65 m, 1.06 m, and 0.87 m. And after compensating for multipath errors, the positioning accuracy of Mi8 reached 1.30 m, 1.04 m, and 0.57 m, respectively, which improved the 3D accuracy by 49.0%, 54.8%, and 62.0%, respectively, compared with single-point positioning; the single-point positioning accuracy of P40 reached 1.39 m, 0.91 m, and 0.57 m, respectively, which improved by 21.5%, 28.9%, and 45.7%. It can be seen that the multipath error correction of pseudorange by wavelet analysis can significantly improve the positioning accuracy of SPP, and its positioning performance is better than carrier-smoothed pseudorange and Doppler-smoothed pseudorange SPP.

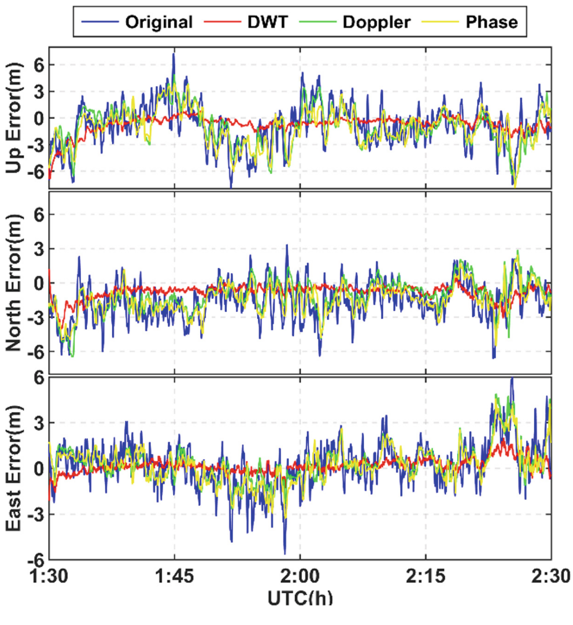

Fig. 7. Positioning error of Mi8

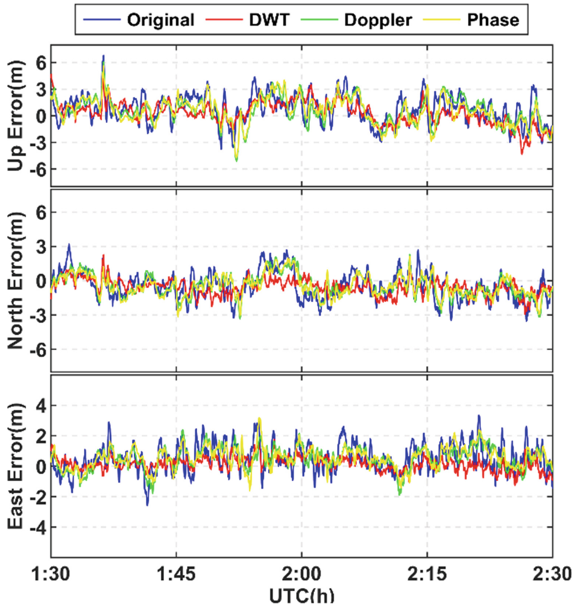

Fig. 8. Positioning error of P40

3.3.2 Impact of Multipath Error Correction on Positioning Results

In this section, we study the influence of wavelet bases and decomposition levels on the positioning results by comparing the positioning results of different wavelet bases and different decomposition levels after multipath error correction.

The results in Table 2 show that as far as the statistical results of positioning accuracy RMS are concerned, the effect of different wavelet bases is not significant; however, as the decomposition level increases, the RMS in the three directions of UNE is gradually increasing, which means that the positioning accuracy is gradually decreasing. For SPP, the wavelet analysis 1-layer decomposition is the best. When dB1-type wavelet basis and one-layer decomposition coefficients are selected, the positioning accuracy of the Mi8 and P40 phones is improved by 53.5%, 48.6%, 60.7% and 25.4%, 32%, 55.2%, respectively, compared with the uncompensated multipath when the multipath is compensated.

Table 2 RMS results of 2 types of wavelet bases at different levels in the NEU direction

Device	Wavelet base	Decomposition level	U(m)	N(m)	E(m)
MI8	Db1	1	1.24	1.00	0.48
		2	1.25	1.02	0.50
		3	1.31	1.07	0.59
		4	1.46	1.20	0.74
	Sym3	1	1.23	1.00	0.47
		2	1.24	1.01	0.50
		3	1.30	1.04	0.57
		4	1.40	1.16	0.73
P40	Db1	1	1.32	0.87	0.47
		2	1.33	0.88	0.49
		3	1.36	0.94	0.56
		4	1.45	1.08	0.71
	Sym3	1	1.31	0.86	0.47
		2	1.34	0.89	0.48
		3	1.39	0.91	0.57
		4	1.42	1.07	0.69

4 Conclusion

In this paper, wavelet analysis is used to extract pseudorange multipath from smartphones and the impact of multipath correction pseudorange extracted by wavelet analysis on the single point positioning (SPP) accuracy of smartphones is studied. It is shown that the noise of the pseudorange residuals can be effectively suppressed by wavelet analysis, and thus the multipath error can be effectively extracted. After the extracted multipath error is corrected for SPP, the results show that the positioning accuracy of Mi8 and P40 in U, N and E directions is improved by 53.5%, 48.6% and 60.7% and 25.4%, 32% and 55.2%, respectively. On the other hand, the results of this paper also show that for smartphone pseudorange SPP, the selection of wavelet bases has no significant effect on the correction effect of multipath error, which can be neglected. However, the number of decomposition layers has a more significant effect on multipath error correction, and the lower the number of decomposition layers, the better the improvement effect on the pseudorange positioning performance.

This paper uses static short baseline data to demonstrate the effectiveness of the wavelet analysis method for single-point positioning performance improvement of smartphones, and it should be noted that the method is also applicable to real-time dynamic processing. When the smartphone is far away from the reference station, high-precision ionospheric delay information needs to be introduced to effectively ensure the applicability of the method. Further research on pseudo-range multi-path suppression and positioning performance improvement of smartphones with medium and long baselines will follow.

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