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A GNSS Satellite Selection Method Based on SNR Fluctuation in Multipath Environments

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Abstract

Multipath is one of the main error sources that influence GNSS precise relative positioning. To mitigate multipath error, this paper starts from study of variation characteristics of signal-to-noise ratio (SNR) measurements, and then proposes a satellite selection method based on SNR fluctuation for static relative positioning. Test results indicate that positioning accuracy can be significantly improved by the proposed method.

Key words: *multipath, SNR, satellite selection, relative positioning*

1. Introduction

In GNSS precise relative positioning, multipath effect, one of the main error sources, usually causes unfixed integer ambiguity for carrier phase measurements and large positioning errors. Besides corresponding mitigation measures in receiver antennas and tracking loops, multipath errors can be suppressed through proper satellite selection methods, which both guarantee the ratio of fixed integer ambiguity and improve positioning accuracy. Common satellite selection methods include those based on elevation angle or signal-to-noise ratio (SNR), etc [1-4]. Among them, the satellite selection method based on elevation angle excludes satellite observation data with elevation angle lower than the cut-off angle (10 or 15 degrees) and those measurements are omitted from positioning algorithm [5]. Since satellites with lower elevation angles are more vulnerable to multipath effects, the method works in mitigating multipath errors. The satellite selection method based on SNR assigns lower weight to measurements with lower SNR during the positioning process [6, 7]. In view that satellite with lower elevation angle usually has lower SNR value; the method benefits the multipath mitigation.

However, in actual scenarios, multipath signals do not merely stem from satellites with low elevation angles, especially in urban area with lots of huge high rises. Even the satellites with high elevation angles cannot keep themselves immune to multipath effects. This paper studies characteristics of SNR measurements in typical urban multipath areas with use of satellite navigation signal simulator and field test data. We explore that when multipath exists, SNR fluctuates periodically and exceeds normal values in some cases. According to the phenomenon, a satellite selection method based on SNR fluctuation is proposed. Then characteristics of SNR data will be shown, followed by the proposed satellite selection method and verification of its effectiveness.

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2. Characteristics of SNR Measurements in Multipath Environment

2.1. Multipath Signal Model

When multipath effects occur, what receiver acquires is a composite signal of direct wave and reflected wave. The reflection will cause deformation of receiver correlation function, thus affecting the correctness of receiver measurements. The reflectors can be ground surface, slope and surrounding constructions of the antenna. Taking ground reflection for instance, a simple model is shown in Figure 1.

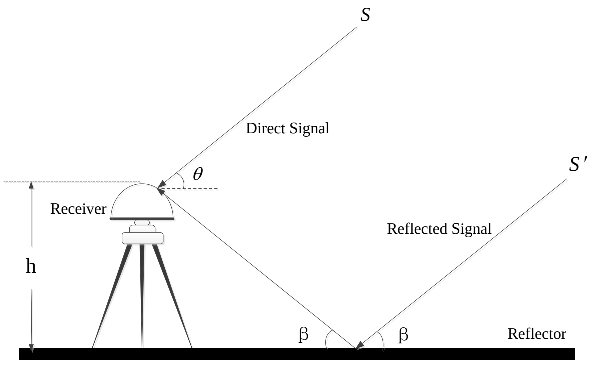

Figure 1. Schematic Diagram of Multipath Phenomenon

Assuming there is only one reflected signal, thus the composite signal can be denoted as [8]:

$$s(t) = Ap(t)\cos(\omega_0 t) + \alpha Ap(t-\tau)\cos(\omega_0 t - \omega_0 \tau + \varphi) \quad (1)$$

where A is direct signal amplitude, p(t) is pseudo-code, ω_0 is angular frequency after taking Doppler effect into consideration, α is attenuation coefficient of reflected wave, τ is transmission delay of direct wave compared with indirect wave, and φ is phase delay of reflected wave.

Without multipath effects, correlation function of the receiver is a typical triangle [9]. When multipath signals exist, there will be a secondary peak in correlation function. Analysis from phase relationship, when reflected signal is in-phase with the direct, the composite signal intensity will increase because of constructive interference; whereas, when the signals are in reversed phase, the composite signal intensity will decrease (Figure 2).

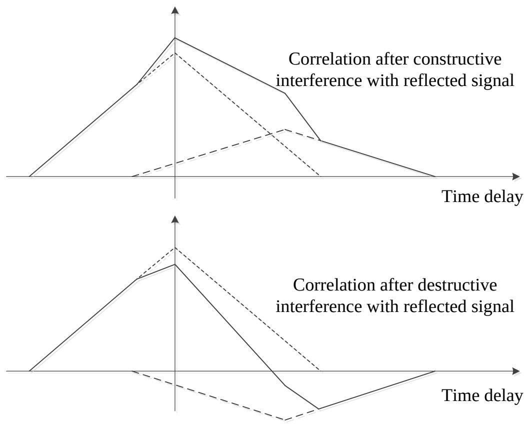

Figure 2. Receiver Correlation Peak with Multipath Effects

As satellites move, the path of multipath signals will change, correspondingly leading to changes of phase relationship, which makes correlation peaks fluctuate at times.

2.2. Research Based on Satellite Navigation Signal Simulator

The simulation is implemented by connecting IFEN satellite navigation signal simulator to NovAtel PP6 receiver. The method includes two times of simulations and data collections. (1) First, collect a whole day observation data that simulator generates without multipath effects, and extract SNR measurements from the data; (2) Second, repeat the first procedure except adding multipath effects. Multipath scenarios are set as following: one reflected path only, 10m vertical distance between antenna and reflecting surface, and 6dB power loss of direct signal to multipath signal. If sample interval is 1s, the SNR data is shown as Figure 3 (the red line represents SNR without multipath, while the blue one represents SNR with multipath).

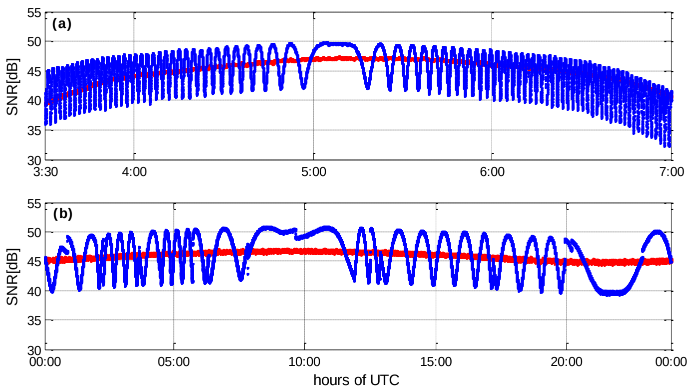

Figure 3. Test Results of Simulator. (A) SNR Of GPS Satellite (MEO), (B) SNR of BDS Satellite (GEO)

It can be seen from Figure 3 that SNR measurements are smoother without existence of multipath and its value is related to satellite elevation angle and antenna gain. When multipath effect happens, SNR fluctuates periodically similar to sine wave, whose periodicity is relevant to types of satellites and elevation angles. For MEO satellites, the fluctuation period is roughly 1.5~20min. For GEO satellites, the fluctuation period augments obviously to 30~130min.

To illustrate the relationship between SNR fluctuation brought by multipath and satellites elevation angles more clearly, the first and second simulated SNR measurements are subtracted (that is, subtracting red line from blue line). The results are shown in Figure 4 and Figure 5.

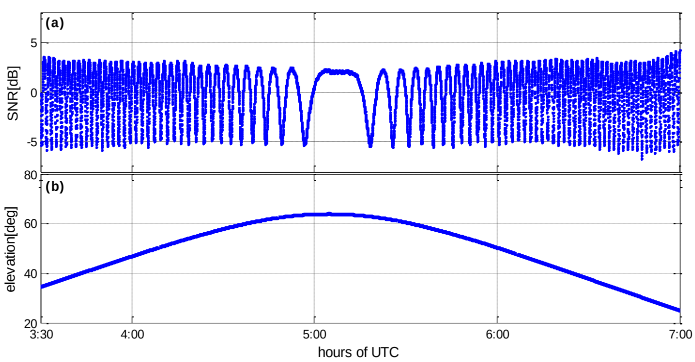

Figure 4. (A) Fluctuation of GPS SNR Measurements Resulting from Multipath, (B) Corresponding Satellite Elevation Angles

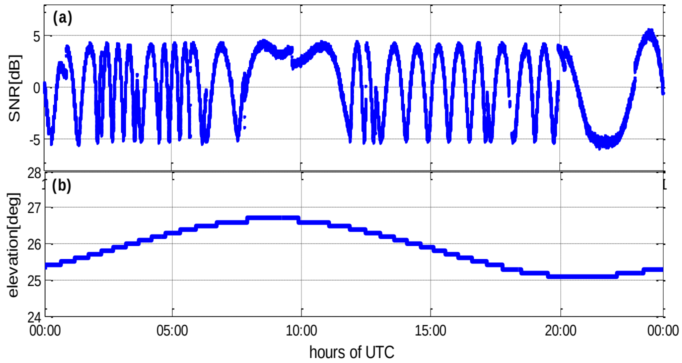

Figure 5. (A) Fluctuation of BDS SNR Measurements Resulting From Multipath, (B) Corresponding Satellite Elevation Angles

It can be drown from Figure 4 and Figure 5 that SNR fluctuations caused by multipath effects feature sine-wave characteristics, whose period varies with satellites elevation angles. The slower elevation angles change, the longer the SNR period is, and in such situation impact of multipath on SNR displays low frequency features. Similarly, the faster elevation angles vary, the shorter the SNR period is, and at the moment multipath effect shows high frequency features. Due to the fact that variation range of GEO satellite elevation angle in a whole day is limited to about 2°, the speed of elevation angle change is not that apparent in Figure 5(b). The SNR measurements in Figure 4 and Figure 5 are endowed with following numerical characteristics (Table 1).

Table 1. Analysis of GPS and BDS SNR Measurements

	GPS(MEO satellite)	BDS(GEO satellite)
Fluctuation Range(dB)	-6.48~3.95	-6.15~6.95
Periodicity(min)	1.50~20.42	25.61~130.85
Average of absolute values(dB)	2.32	2.81
Standard deviation (dB)	2.66	3.20

2.3. Research Based On Real Observation Data

To research impacts of multipath effects on SNR measurements in outdoor environments, our campus is selected as typical scenario to carry on tests. The test environment is shown in Figure 6.

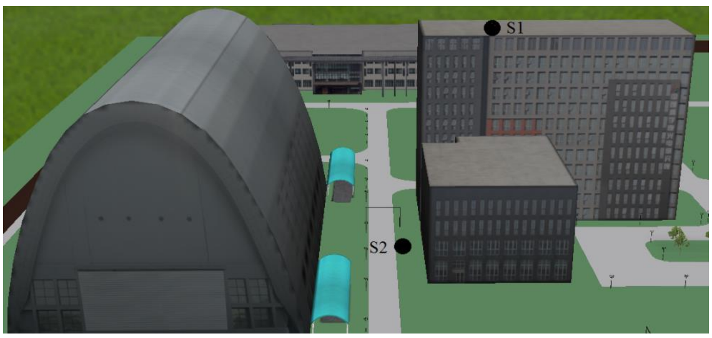

Figure 6. Schematic Diagram of Test Environment

Observation station S1 is located on the roof of a 50m tall building with an obstruction-free horizon, which is treated as no multipath situation. Observation station S2 is located on the ground between two buildings, 18.3m apart from the left mansion (40m tall) and 6m apart from the right mansion (the front part is 30m tall, and the back part is 50m tall). Meanwhile, surface of the left building is an ellipsoid with metal structures forming a spherical reflection, which complicates multipath effects compared with ground reflection. The right one is a vertical wall, inclined to multipath effects. S1 and S2 were observed synchronously using two sets of NovAtel PP6 receivers and NovAtel GPS-703-GGG antennas on 2014/11/23, and the sample interval was 1s. Figure 7 shows the results (the red line is SNR data of S1, and the blue one is SNR data of S2).

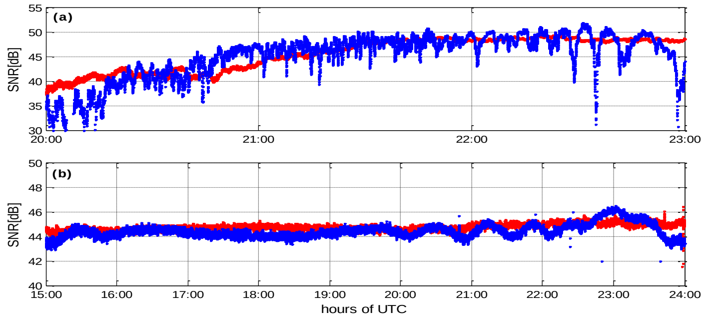

Figure 7. Test Results of Real Observation Environment.(A) SNR of GPS Satellite, PRN3. (B) SNR of BDS Satellite, PRN3.

As can be seen from Figure 7, cyclical fluctuation of SNR measurements will take place in multipath environment, and the fluctuation period of GEO satellites is much larger than that of MEO satellites. Compared with Figure 3, test results of real observation environment share similar features with results of simulator, although the former's periodicity is not so distinct as the latter's.

Results of simulator and real observation data suggest that when multipath effects exist, SNR measurements will oscillate periodically, and even larger than normal values at times. When it doesn't exist, SNR of satellite signals is more stable, barely fluctuating. Therefore, multipath effects can't be accurately determined by merely one SNR value at certain moment, in case that the high SNR value situation also meets multipath effects. So SNR values in a longer period will be better at judging whether the signal includes multipath information or not.

3. Satellite Selection Method Based on SNR Fluctuation

According to the above analysis, a satellite selection method based on SNR fluctuation is proposed. When SNR fluctuation is relatively small, the signal is supposed to be high-quality; contrarily, it is considered to be signal affected by severe multipath effects. Taking advantage of the law as satellite selection rule in precise positioning, we can exclude satellites badly influenced by multipath effects, therefore improving positioning accuracy.

3.1. Carrier Phase Differential Positioning Theory

In precise measurement, differential positioning via setting reference stations and moving stations helps to eliminate or reduce satellite clock error, satellite ephemeris error, receiver clock error, and ionospheric as well as tropospheric delay error, So carrier phase double difference observation data is adopted to implement positioning calculation. The observation equation of carrier phase is as follows [10]:

$$\lambda\Phi_u^j = \rho^j + c\cdot\delta t_u - c\cdot\delta t^j + \lambda N_u^j - I_u^j + T_u^j + \varepsilon_u \tag{2}$$

where j denotes satellites, u denotes user's receivers (moving stations), Φ_u^j is the carrier phase measurements, λ is the GNSS wavelength, ρ^j is the geometric distance from satellites to receivers, c is the light speed, δt_u is the receiver clock error, δt^j is the satellite clock error, N_u^j is the integer ambiguity, I_u^j is the ionospheric delay, T_u^j is the tropospheric delay, and ε_u is the synthetic error due to multipath and random noise. Observing satellite i and j simultaneously at reference station r and moving station u, we get double difference observation equation:

$$\lambda\nabla\Delta\Phi_{ur}^{ij} = \nabla\Delta\rho_{ur}^{ij} + \lambda\nabla\Delta N_{ur}^{ij} + \nabla\Delta\varepsilon_{ur}^{ij} \tag{3}$$

Linearizing double difference observation equation, least square function model is given by [11]:

$$V = AX - L \tag{4}$$

where, V is the residual error of double difference model, L is the carrier phase double difference observations, A is a designed matrix, X is unknown factors (user's position, for example). In the solution, correlation and uncertainty of different measurements can be described by stochastic models. The variance of observations is usually estimated making use of elevation angles of each satellite and further forms variance-covariance matrix. Here, variance of non-difference observations is calculated in the way shown below [12]:

$$\left(\sigma_u^j\right)^2 = a^2 + b^2 \cdot f^2(el)|_u^j \tag{5}$$

In the equation, u and j represent observation stations and observed satellites respectively; a and b are constants, normally a=4mm, b=3mm; $f(el)$ is a function with independent variable of elevation, commonly adopting $f(el) = 1/\sin(el)$.

According to propagation law of errors, the variance-covariance matrix of double difference observations can be given as follows:

$$D = a^2 A + b^2 B_{el} \tag{6}$$

where, $A = \begin{bmatrix} 4 & 2 & \cdots & 2 \\ 2 & 4 & \cdots & 2 \\ \vdots & \vdots & \vdots & \vdots \\ 2 & 2 & \cdots & 4 \end{bmatrix}_{m\times m}$, $B_{el} = \begin{bmatrix} f^2(el)|_{ur}^{1k} & f^2(el)|_{ur}^{k} & \cdots & f^2(el)|_{ur}^{k} \\ f^2(el)|_{ur}^{k} & f^2(el)|_{ur}^{2k} & \cdots & f^2(el)|_{ur}^{k} \\ \vdots & \vdots & \vdots & \vdots \\ f^2(el)|_{ur}^{k} & f^2(el)|_{ur}^{k} & \cdots & f^2(el)|_{ur}^{mk} \end{bmatrix}_{m\times m}$;

$f^2(el)|_{ur}^k = f^2(el)|_u^k + f^2(el)|_r^k$, $f^2(el)|_{ur}^{jk} = f^2(el)|_u^j + f^2(el)|_u^k + f^2(el)|_r^j + f^2(el)|_r^k$, (j=1,2,... ,m). Here, k stands for the reference satellite, m is number of other satellites except the reference satellite k. The weight matrix of double difference observations becomes:

$$P = D^{-1} \tag{7}$$

Based on weighted least square method, the value X can be solved by [13]:

$$X = \left(A^T P A\right)^{-1} A^T P L \tag{8}$$

In process of selecting satellites to develop positioning calculation, cut-off elevation angle is set to exclude satellites, besides determining weights in accordance of elevation angles. In conclusion, the flow chart of conventional satellite selection method is shown as Figure 8.

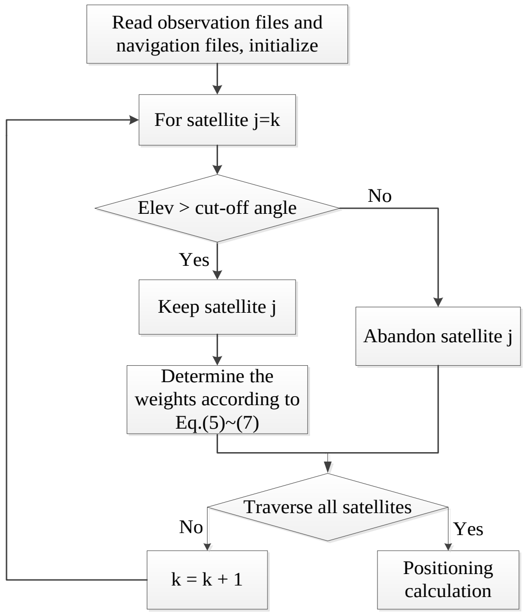

Figure 8. Flow Chart of the Conventional Satellite Selection Method

3.2. Satellite Selection Method Based on SNR Fluctuation

On basis of the conventional satellite selection method in chapter 3.1, a procedure of selecting satellites according to SNR fluctuation is added. The basic principle of satellite selection is as follows(its flow chart is shown in Figure 9):

1) First, primarily select satellites according to the cut-off elevation angle.

2) Choose a length T of time window ahead of current observation time. Then, perform the second selection based on preset SNR fluctuation threshold. SNR fluctuation can be depicted by standard deviation, whose expressions are given by

$$std(SNR)_T = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(SNR_i - \mu)^2} \tag{9}$$

$$std(SNR)_T < Threshold \tag{10}$$

In Eq.(9), SNR_i is SNR observation sequence in duration T, N is the number of SNR observations in duration T, μ is the average value of all the SNR_i.

In Eq.(10), $SNR_{Threshold}$ is the threshold value of SNR fluctuation. If one satellite meets Eq.(10), it is reserved in positioning calculation; for those who do not satisfy Eq.(10), they are rejected directly.

3) For the remaining satellites after two times of selections, determine their weights according to Eq.(5)~(7).

4) Finally, finish the differential positioning calculation.

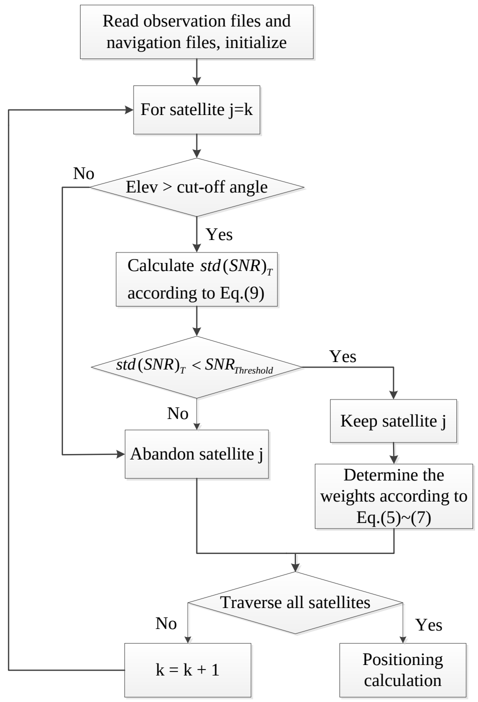

Figure 9. Flow Chart of Satellite Selection Method Based on SNR Fluctuation

4. Verification Results Using Test Data

To verify availability of the proposed satellite selection method for improving differential positioning precision, test data are collected in the multipath environment shown in Figure 6. The station S1 is chosen as base station and S2 as moving station. We observed GPS and BDS satellites using two sets of NovAtel PP6 receivers and NovAtel GPS-703-GGG antennas at the same time on 2014/12/01. Static observation lasted 9h with sample interval of 1s. Positioning calculation utilizes GPS/BDS combined measurements.

Test data are processed respectively by the conventional satellite selection method in Figure 8 and the satellite selection method based on SNR fluctuation in Figure 9. Set the width of time window T in Eq.(10) as 10min and the SNR fluctuation threshold $SNR_{Threshold}$ as 4dB.

Comparing the positioning results of S2 with its actual coordinates, we acquire position errors shown in Figure 10 and Figure 11 (blue dots represent the fixed solution and red dots represent the float solution).

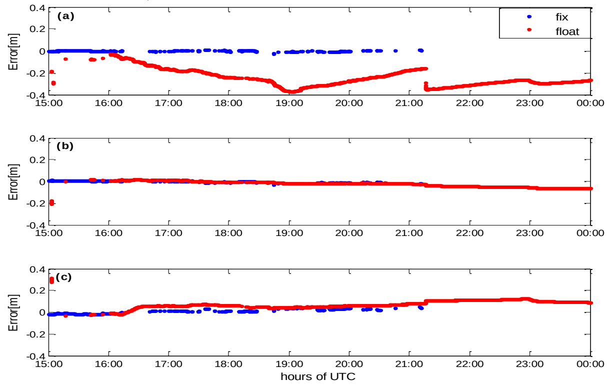

Figure 10. Position Errors of Conventional Satellite Selection Method. (A) E Direction. (B) N Direction. (C) U Direction

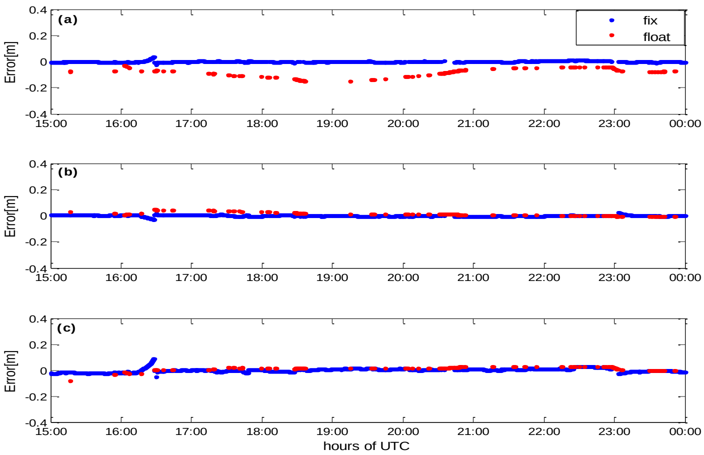

Figure 11. Position Errors of Satellite Selection Method Based on SNR Fluctuation. (A) E Direction. (B) N Direction. (C) U Direction

Seen from Figure 10, merely using conventional satellite selection method, the number of float solutions is significantly larger than fixed solutions, which demonstrates the fact that multipath environments surrounding station S2 make the integer ambiguity unable to be fixed. Therefore, only float solution of poor-precision can be obtained. As for the positioning accuracy, N direction is the best, followed by U direction, and E direction is the worst. The reason is that buildings around the observation station face in direction of north-south, blocking satellite signals from east-west direction, which causes position errors of E direction augment apparently.

In Figure 11, the number of fixed solutions increases sharply because of adopting the proposed satellite selection method, leaving only few float solutions. Compared with Figure 10, position errors obviously decrease, which reveals that satellites severely affected by multipath have been excluded. As a result, carrier phase integer ambiguity can be fixed in positioning calculation and then the precision is improved.

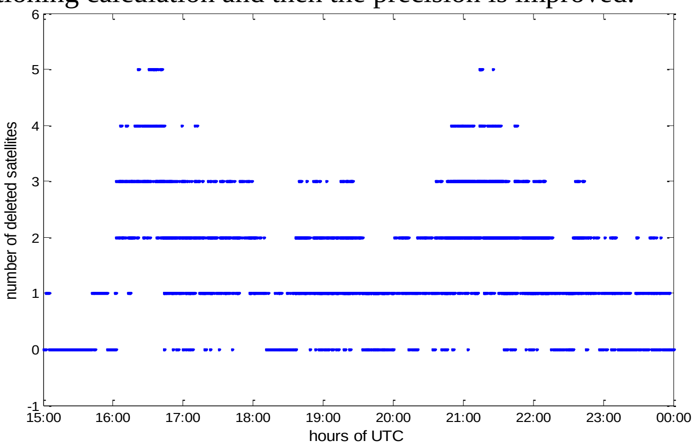

Figure 12. Difference of Number of Excluded Satellites between the Two Methods

Compared with the conventional satellite selection method, the novel one based on SNR fluctuation can efficiently exclude more satellites with poor quality. Figure 12 illustrates the difference of number of the excluded satellites between the two methods. As shown in the figure, most epoches (about 31%) differ in only one satellite. A part of epoches exclude the same number of satellites (about 26%) or two satellites more (about 27%). Quite a few epoches (about 16%) own the number of three and above.

To quantitatively analyze positioning results of the satellite selection method based on SNR fluctuation, root mean square (RMS) values of positioning errors and the number of fixed solution are given in Table 2, with E, N and U representing the East-West, North-South and vertical directions respectively.

Table 2. Comparison of the Positioning Results of Two Methods

	RMS of positioning errors(cm)			Number of fixed epoches	Number of total epoches	Fixed ratio
	E	N	U			
Conventional method	23.56	3.71	7.34	6500	32400	20.06%
Method based on SNR fluctuation	3.13	0.75	1.47	28774	32400	88.81%

Since the proposed method is adopted, the ratio of fixed solutions of differential positioning calculation has increased from 20.06% to 88.81%. Overall, the East-West positioning accuracy is improved from 23.56m to 3.13m, the North-South positioning accuracy is improved from 3.71m to 0.75m, and the vertical positioning accuracy is improved from 7.34m to 1.47m, with RMS errors reduced by 87%, 80% and 80% respectively.

As can be seen from Table 2, the satellite selection method based on SNR fluctuation enables a significant improvement in positioning accuracy.

5. Conclusions

This paper first studies characteristics of SNR measurements by satellite navigation signal simulator and real observation data. The analysis indicates that multipath effects will lead to oscillations in measured SNR data which take on a form of periodic sine wave. Sometimes SNR data even exceed normal values.

A satellite selection method based on SNR fluctuation is proposed in this paper for static relative positioning. The method helps to determine whether a satellite should participate in the positioning calculation according to fluctuation of SNR. After applied to real observation data and compared with conventional method, this satellite selection method is proved to be well-suited to mitigating multipath effects, which is able to improve the performance of ambiguity solution and reduce the positioning error of Global Navigation Satellite System.

In future works, assignment of the time window and the SNR fluctuation threshold can be further researched.

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