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Effect of different construction materials on propagation of GPS monitoring signals

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ABSTRACT

The GPS carrier phase observations are widely used for the high precision static and kinematic positioning applications. However, GPS signals are seriously distorted when passing through walls and other obstructions. This paper focuses on this issue and outlines the research carried out to investigate the effects of some commonly used construction materials on the GPS signals. For the purpose of generating the multipath in a controlled manner, an experimental set-up is designed to test the effect of typical building surface materials (toughened glass, wood board, PVC board and ceramic tile) on positioning accuracy. The effects of signal attenuation on the accuracy of the positioning solution are explored by an improved particle filtering algorithm and some statistical methods, and reasons for these effects are further analyzed. The findings of the experimental results may be used to enhance the performance of GPS technology.

1. Introduction

The last decade has seen an increase in the use of Global Positioning System (GPS) technology [1]. The geodetic surveying first made use of static positioning method as they were the most reliable [2,3]. The kinematic GPS positioning technique soon followed, and offered higher production rates when compared to static positioning technique. The kinematic positioning became a routine surveying technique as methods of ambiguity resolution have become less cumbersome [4,5]. However, GPS has a number of drawbacks, it is major limiting factor being the requirement of Line-Of-Sight (LOS) between the receiver antenna and satellites. This means the GPS signals are easily distorted by reflection, diffraction, scattering and attenuation that give rise to signal fades and other signal propagation loss. A double-differencing technique is commonly used for constructing the functional model as it can eliminate or reduce many of the troublesome GPS biases (i.e. the atmospheric biases, the receiver and satellite clock biases, and the orbital bias). Yet, some unmodelled biases still remain in the GPS observations, even after such data differencing. The multipath is a major residual error source in the double-differenced GPS observables, and it can have a significant impact on the positioning results.

The multipath refers to the signals reflected from objects in the vicinity of a receiver antenna that causes degradation in the accuracy of LOS signal that comes straight from the GPS satellites. The two main characteristics of a multipath signal are: it is always weaker than the direct signal due to the loss of energy in the reflection (but it can still be strong if the reflecting object is large or if there is no partial obstruction of the signal); and, it is always delayed with respect to the direct signal [6]. There are several ways of dealing with the multipath. The first, i.e. easiest one, is to avoid it by means of an appropriate site selection. Others are more related to antenna design and receiver hardware multipath approaches. Other ways of dealing with the multipath make use of modeling. However, the multipath still cannot be removed completely and the residual may still be too significant to

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ignore in some cases, for example, in dense urban areas, and the improvements of position accuracy may be limited because the obstruction of signals by high building results in bad geometries and multipath effects. There are also some applications, such as volcano and opencut mine slope monitoring, for which it is often impossible to identify the antenna sites which are not vulnerable to the multipath. In the case of the volcano monitoring, all the GPS receivers have to be placed on the slope or at the foot of the mountain. The only antenna site which may be free of multipath is the one on the summit, where there is often a great reluctance to install a receiver [7]. In these cases, the issue of how the reflecting environments affect the GPS signal should be considered in-depth. From the practical point of view, understanding the characteristics of multipath effects on GPS signals is also an essential part of minimizing the multipath effects. A number of experimental studies on the multipath effects generated by reflecting environment have been carried out by many groups worldwide. Satirapod et al. [8] suggested a multipath mitigation technique based on the wavelet decomposition. In order to verify the effectiveness of the method, he used a receiver close to the concrete wall to collect the multipath signals. Fan and Ding [9] presented a method based on the electromagnetic modeling technique for modeling GPS carrier phase multipath signals. To examine the performance of the procedure, an urban environment digital model, which was generated by the CAD and the Wireless In-site software, was used for modeling the multipath environment. Lau and Paul [10] introduced a ray-tracing method to eliminate the multipath effect based on the precise knowledge of the satellite–reflector-antenna geometry and of the reflector material and antenna characteristics. The results showed that it is valid when reflected by steel plate and brick walls, while it is unsatisfactory when reflected by water. For the purpose of characterization and removal of multipath errors encountered in urban zones, Kijewski-Correa and Michael [11] used a 0.9 m square thin aluminum plate as the reflective surface to induce a multipath signature into the GPS position data, experimental results showed that the GPS was a viable technology for documenting background and resonant response, attention might be paid to the multipath issue for successful deployments in urban zones. Lee et al. [12] presented a spatial statistics-based simulation system for mitigating the multipath and improving the accuracy and obtained the attenuation of reflected signals by taking the typical building materials as reflections. In addition, Suh and Shibasaki [13] identified the multipath satellites using the building objects created from 3-D vector maps. Taylor et al. [14] and Li et al. [15] predicted the satellite visibility and multipath effects using 1-m resolution Light Detection and Ranging (LiDAR) data as a digital surface model. Despite there are lots of attempts as mentioned above to investigate the errors of some commonly used construction materials on the GPS signals, generally these have led to improvements in the accuracy of phase measurements only in a certain extent. This is because each antenna installment environment is different when using the GPS positioning; the different environment will cause different multipath errors. Therefore, to systematically conclude the effects of different construction materials on the GPS signals has important meanings on correcting the GPS positioning results.

This paper is concerned with the effects of some commonly used construction materials on the GPS signals, and is especially relevant to applications that require very high accuracy positioning over short and medium distances. In these cases, the multipath is generally considered to be the most significant site-dependent errors. The paper is organized as follows: The first section provides a brief review. Subsequently, four different kinds of construction materials are selected and tested to get the dielectric constant which is the main factor related to the multipath effect. A specific set of generating and monitoring system for the GPS multipath signals is established and verified in the third section. Following that, a series of controlled experiment is carried out to test the effects of the selected construction materials on the GPS positioning accuracy, and the discussion of the test results with previous work is given in Section 4. The last section summarizes the findings of the article, and offers a perspective on future work.

2. Dielectric constant experiment

It is well known that the multipath is influenced by four factors: the reflection coefficient, the distance of the reflector to the antenna phase center, the satellite signal incidence angle and the carrier wavelength. In these factors, the reflection coefficient is directly related to the property of the material itself. When there are metal materials around the GPS antenna, it may cause the total reflection to the GPS signal; while for the non-metallic materials, the multipath effect is directly related to the dielectric constant. The dielectric constant is also called the permittivity, which is an important parameter of material characteristics, and it indicates the strength of the polarization of dielectric mediums. It may change with the environmental conditions (such as temperature and humidity), and even for the same material, different internal structures may also cause the difference of the dielectric constant. Thereby, it is essential to test the dielectric constant of each material before using in the experiment. The test methods are various; herein the DP-5 dielectric spectrometer is used. By the comparison and separation on the signal orthogonal components (the real and imaginary components) of parallel-plate capacitor, in the middle of which the testing materials are put, the dielectric constant can be obtained. Here, four different kinds of construction materials are chosen (toughened glass, wood board, PVC board and ceramic tile) to test the dielectric constants, as these are the most commonly used construction materials for walls and partitions within a building.

The DP-5 dielectric spectrometer is used in the test, in which there are wide sinusoidal frequency range synthesized signal source and the lock-in amplifier composed by the multiplier, synchronous integrator, phase shifter. It has the function of weak signal measurement and network analysis, as shown in Fig. 1. The schematic drawing of dielectric constant test is shown in Fig. 2. The connection of the samples and DP-5 dielectric spectrometer are shown in Fig. 3.

Fig. 1. DP-5 dielectric spectrometer.

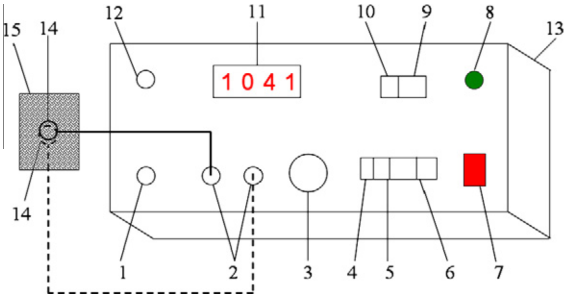


Fig. 2. Schematic drawing of dielectric constant test: (1) output; (2) electrode; (3) phase; (4) datum/sample key; (5) real/imaginary component key; (6) frequency band; (7) power; (8) lock-in; (9) frequency band DIP switch; (10) output selector; (11) digital voltmeter; (12) zero set; (13) potentiometer; (14) plate electrode and (15) testing sample.

The steps of the dielectric constant test for the toughened glass, wood board, PVC board and ceramic tile are:

(i) Put the testing sample between the two plate electrodes, and keep it horizontal to make a good contact with the two electrode plates. In addition, the two plates should be aligned with each other to minimize the influence of the errors;

(ii) Adjust the extent of the signal source. By regulating the potentiometer on the back panel, the real/imaginary component of the reference signal is displayed on the digital voltmeter;

(iii) Choose the appropriate frequency band (×1.0 kHz), and the frequency of the signal source is locked as "45 kHz". Then measure and record the real/imaginary component of the reference signal and corresponding materials' signals.

(iv) By substituting the above parameters to the corresponding formulas, compute the dielectric constants. The corresponding parameters and tested results are shown in Table 1.

From Table 1, it shows that the dielectric constants of these four kinds of nonmetal materials greatly differ from each other.

It is well known that the metal materials have the entire reflection to the electromagnetic wave, of which the electric conductivity of aluminum plate is better, thus the aluminum plate is also taken as the typical reflective medium of metal material here to study the rule of the GPS multipath signals.

3. Testing system set-up

In order to rigorously investigate the effects of different construction materials on the GPS signals, it is necessary to establish a well-defined testing methodology. For that, a specific set of system for the GPS multipath signals generating and monitoring is established on the roof of the 1st laboratory building at Dalian University of Technology, Dalian, China.

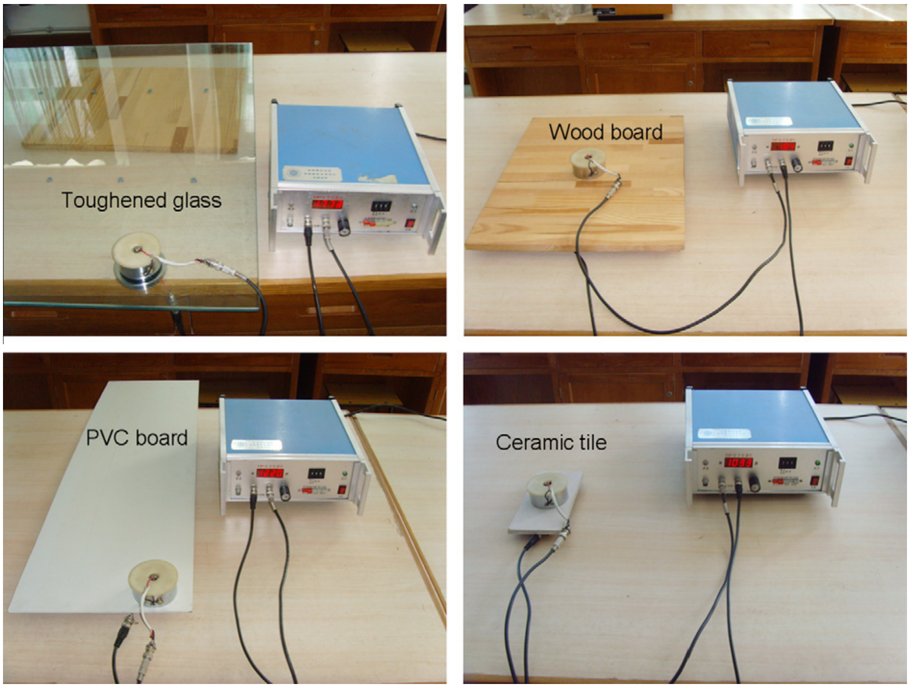


Fig. 3. Dielectric constant test of different construction materials.

Table 1
Test results of dielectric constant.

		Toughened glass	Wood board	PVC board	Ceramic tile
Thickness (Unit: cm)		0.98	1.50	0.27	0.94
Reference signal	Real component	1.520	1.740	1.550	1.775
	Imaginary component	1.510	1.725	1.560	1.780
Materials' signal	Real component	0.021	0.004	0.035	0.017
	Imaginary component	0.028	0.006	0.042	0.031
Dielectric constant	Real component	10.79	2.91	4.52	8.60
	Imaginary component	1.50	0.57	0.43	2.52
Dielectric constant		10.89	2.96	4.54	8.96

3.1. GPS monitoring system

The overall system was configured in three modules comprising the sensors, data transmission and data processing and management systems. In this test, the reference site featured a high-precision Leica GRX1200 Pro GPS receiver and an AX1202 pinwheel antenna, which is susceptible to the multipath signals with low-elevation trajectories, was placed on the concrete pillars which were about 1.50 m in height. The rover site was equipped with a Leica GMX902 GPS receiver and the same pinwheel antenna used in full scale. Fig. 4 illustrates the configuration of the GPS monitoring system.

The data transmission mode used was the network transmission, which is much more stable than the wireless transmission. The reference station, the rover station and the control center (data processing and management system) were composed of a local area network through the network switch. The signals received by the reference station could be transmitted through the network directly, while the signals obtained by the rover station should be transmitted through the RS232 protocol, thus a serial port server was needed to transform the RS232 protocol signals into the TCP/IP protocol network signals.

The data processing and management system (control center) included a computer which was installed with the corresponding control software, the data processing, the analytical software. The control software was the Leica GNSS Spider software, which could control the receivers as well as monitor the whole network. The Leica GNSS QC software was used to check the multipath effect and cycle slips on all the satellites tracked. For the data analysis, the codes were written using the MATLAB environment.

The baseline length between the two receivers was about 55 m. These units, when in a differential GPS configuration, could provide the accuracy comparable to the aforementioned full-scale system, with fully real-time capabilities, since the roof of the 1st laboratory building was with excellent satellite visibility and minimal multipath sources, almost all GPS errors but receiver noise was eliminated. Double difference residuals calculated consisted of carrier phase noise and multipath error mainly.

3.2. System performance evaluation

In order to verify the reliability of the system, a real-time monitoring on a two-floor flexible steel frame model was carried out atop the building. Slabs of experimental model were 3 mm thick steel plates, and the beams and columns were made of circular section steel bars whose diameter is 8 mm. The size of model was 500 mm by 500 mm by 1500 mm, as shown in Fig. 5.

In the experiment, the rover station antenna was fixed on the top layer of the model, and the base of the steel frame was fixed on the roof with the construction rubber, as shown in Fig. 6. The top layer of frame was pulled away from it is balance position about 0.3 m at the direction of west–east, then suddenly released to simulate the pulse excitation, and the rover could monitor it is free damped oscillation in three dimensional directions. Five groups were carried on in the experiment, and the receiver's sampling frequency was 20 Hz. In order to obtain the relative motions of the model along the two orthogonal axes, the three-parameter geodetic transformation between the local reference frame and the WGS-84 coordinate system was established. The displacement curves of the model in three dimensional directions are shown in Fig. 7a–c. The displacement spectra of measured data in the N–S and W–E directions were obtained by the power spectral analysis, as shown in Fig. 7d. The results indicate that the designed system can effectively monitor the displacement of the model in three dimensional directions.

3.3. Multipath signal generating system

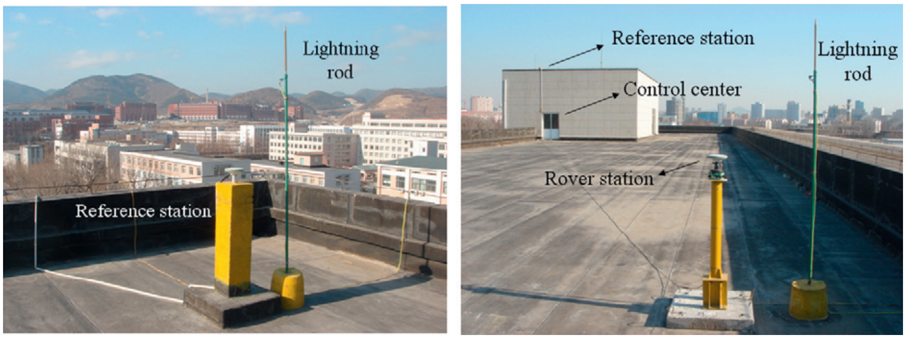
For the purpose of generating the multipath signals by the different construction materials in a controlled manner, an experimental set-up (Utility model patent No. ZL200920013309.9) [16] was designed which included a reflector (a 1.0 m by 1.0 m panel) and a steel frame brace, visible in Fig. 8. The devices could be used to generate the multipath signals with different characteristics depending on the distance that it was placed from the rover station. Also, the height of the panel could be adjusted up or down. After this was established, each construction material was placed at different distances from the rover's antenna.

4. Experimental studies of GPS multipath signals

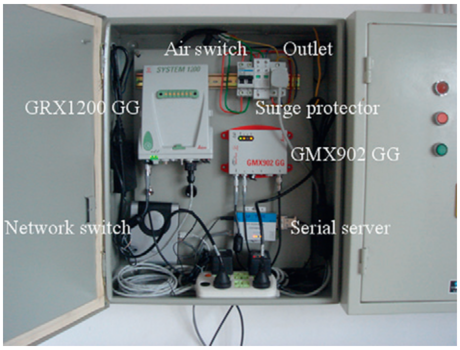
4.1. Data acquisition processing

In the process of the experiment, the satellite elevation angle was 10° and the sampling frequency was 10 Hz. Here, the hypothesis was always made that there was no significant multipath at the rover station. The most important multipath would be actually due to the reflector.

The experiment included three parts:



(a) GPS reference station (b) GPS rover station



(c) GPS control center

Fig. 4. Configuration of GPS monitoring system.

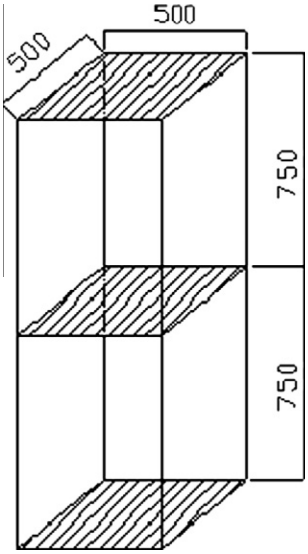


Fig. 5. Size of steel frame model (Unit: mm).

(1) In order to determine the precise 3D coordinates of the rover, one day-long GPS static observation was carried on.

(2) In order to investigate the noise characteristics of the receiver, three-day-long continuous kinematic GPS data were collected with the antenna completely unobstructed to ensure that the receiver was not recording signals from any other source.

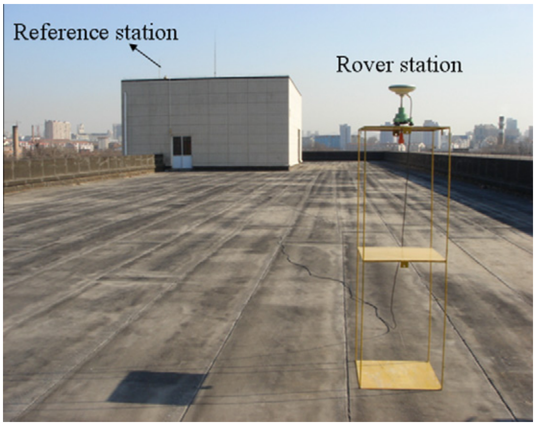
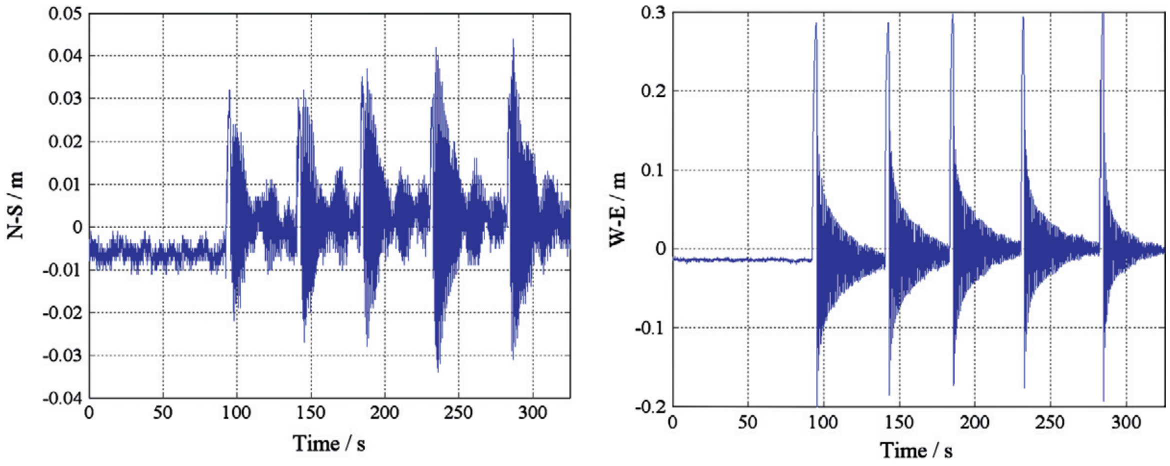


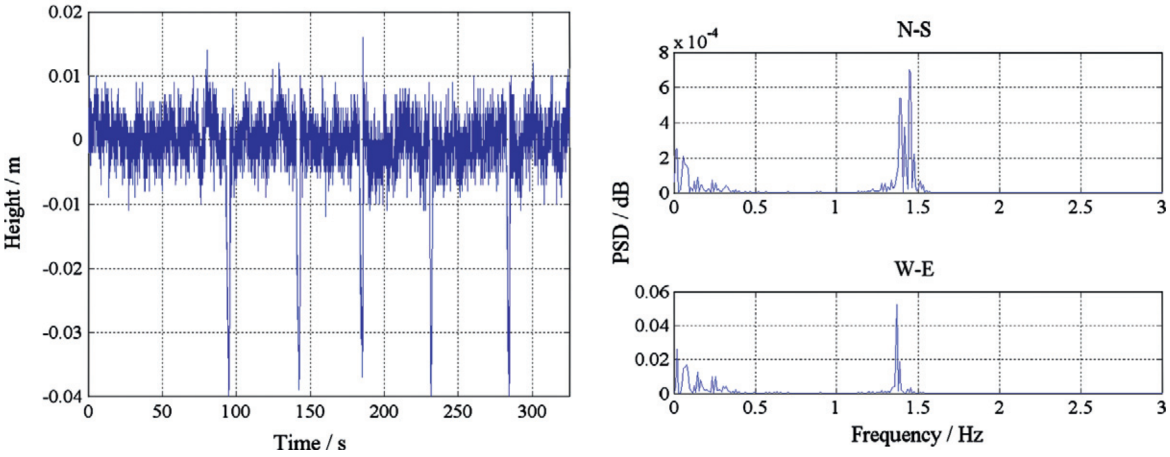
Fig. 6. Experimental model atop the building.

(3) For the purpose of studying the characteristics of the multipath signals caused by the different construction materials at different distances, the reflector was placed during consecutive days at 1, 4, and 7 m from the antenna, on the antenna's west side (so that the reflector was facing east), in kinematic mode, respectively. The heights of the reflector at different distances were determined according to the receiver's satellite elevation angle (10°), as shown in Fig. 9. The twelve-day-long continuous kinematic GPS data gathering was carried on by laying aside the reflector nearby the rover's antenna



(a) Displacement curve in N–S direction

(b) Displacement curve in W–E direction



(c) Displacement curve in vertical direction

(d) Displacement spectra in N–S and W–E directions

Fig. 7. Results of the reliability verification experiment.

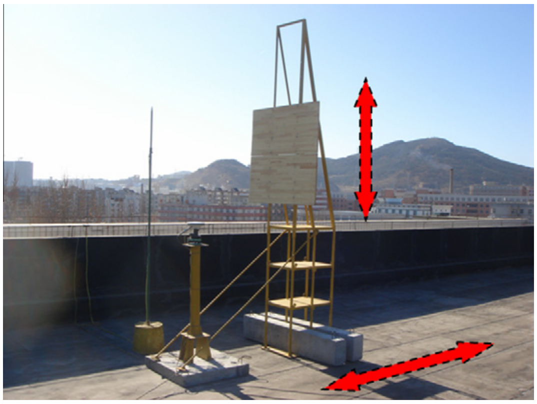


Fig. 8. Set-up of the reflector near the rover antenna.

(three-day-long data were recorded for each material). Additionally, the data was also logged for the transition period between no material and insertion of a material in front of the antenna, so as to determine whether the rover lose lock or not during the test.

4.2. Characteristics of multipath signal attenuation

It is known that the receiver's noise and multipath error are mixed in the receiver. Thus, the noise should be properly and effectively eliminated firstly. In Ref. [17], the author proved that the improved particle filtering algorithm could effectively eliminate the noise mixed in the multipath signal by establishing the system equation and observation equation so long as the noise distribution was known.

4.2.1. Study on the distribution of rover' noise

In process (2) of the experiment, the three-day-long continuous kinematic GPS data were collected with the antenna completely unobstructed within 50 m. Therefore, the double-differenced carrier-phase residuals obtained from

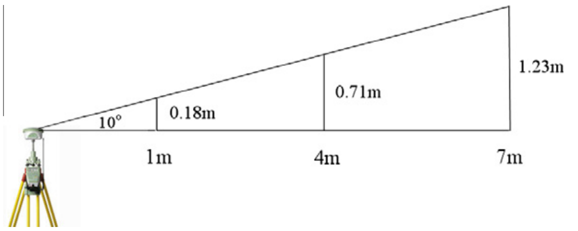


Fig. 9. Heights of the reflector at different distances from the rover's antenna.

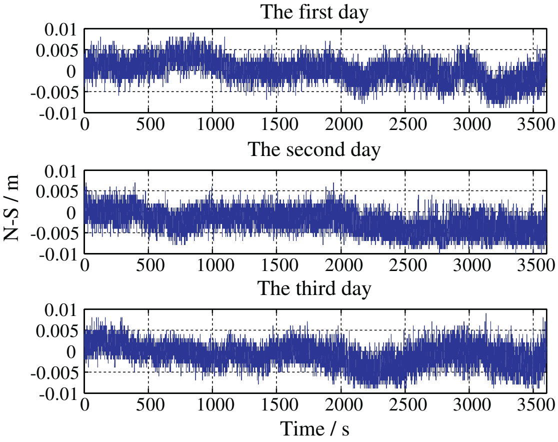
the receiver exhibit only 3D coordinates and observation noise. By subtracting the coordinates got in process (1) from the results of process (2), the receiver's system noises in the north–south, west–east and vertical directions can be obtained. The corresponding 1 h observation noises in three consecutive days are shown in Fig. 10. From Fig. 10, one may see the multipath signatures as the noise changes have some correlations in different days, however, they are small. Table 2 summaries the basic results calculated in three consecutive days as those of the receiver's noise.

From the Fig. 10 and Table 2, it can be seen that the consecutively three-day-long receiver's noise has no obvious relevance in 3D directions, and the amplitude variation range is within the nominal accuracy of the receiver. To determine the distribution of the receiver's noise, the power spectral density of the receiver's noise are compared with it is corresponding Gaussian distribution in each direction (the mean value and standard deviation of Gaussian distribution are the same as those of noise), and it is found that the distributions of the receiver's noise anastomose well with the Gaussian distribution, as shown in Fig. 11 (only the data of the first day is typically given here). This implies the assumption of the Gaussian distribution is reasonable from the discussions herein. Based on the understanding of receiver's noise as discussed here, there has reason to believe that the multipath signals can be extracted form the measurement data by the particles filtering algorithm [17].

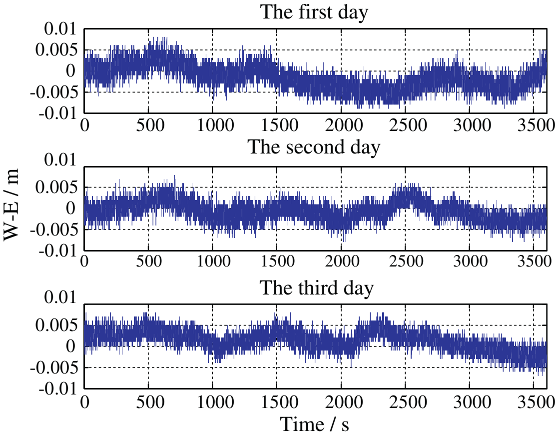
4.2.2. Experimental results for field measurement data

In process (3), the experiment using the five typical construction materials to examine the characteristics of reflection attenuation was conducted, as shown in Fig. 12. For study the reflection propagation, it is assumed that every signal be specularly reflected by a mirror-like surface that reflects a signal from a single incoming direction to a single outgoing direction. A preliminary experiment was first carried out to check for the satellite availability. Seven or more satellites were visible at all times during the twelve days of testing. Also, the positional dilution of precision (PDOP) was below three at all times during the testing. Since the full 24 h sidereal day plot is too long to include here, only an excerpt (1 h) is provided here to demonstrate the results.

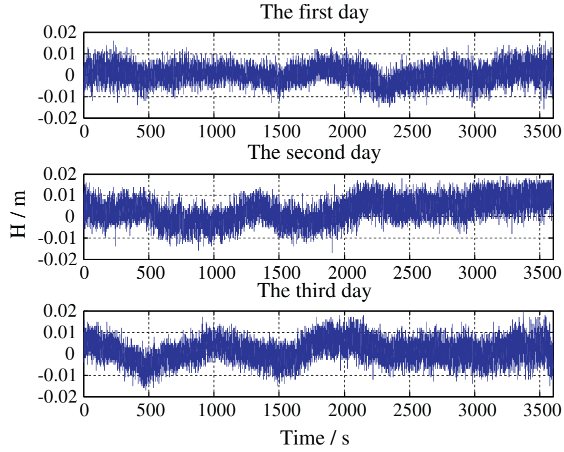
Since the differential GPS positioning was used in the experiment, the common errors could be eliminated between the reference station and rover station. The results recorded in the process (2) when the antenna was unobstructed, was taken as the control. The results of the process (3) were only influenced by the multipath signals and receiver's system noise. Thus, the difference values between the results of process (3) and process (2) were the mixed sequence of multipath signals and receiver's noise.



(a) N-S direction



(b) W-E direction

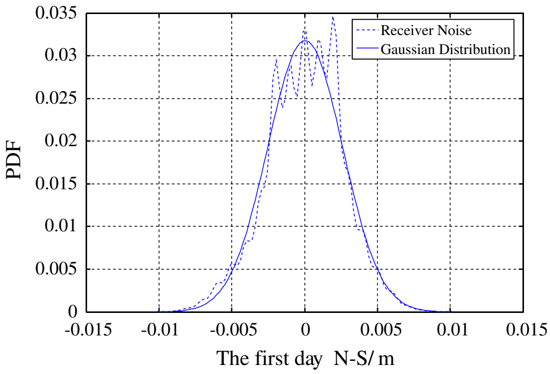


(c) Vertical direction

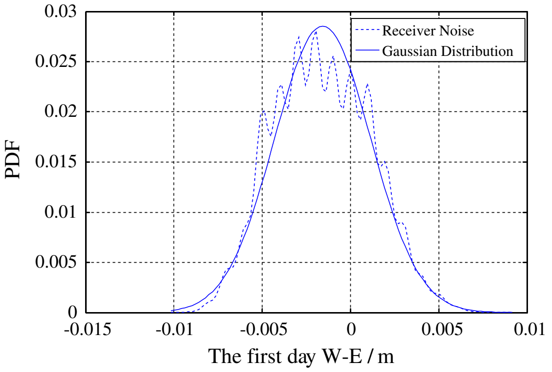
Fig. 10. Receiver's noise series in 3D directions in three consecutive days.

Table 2
Statistics of GPS receiver's noise (Unit: cm).

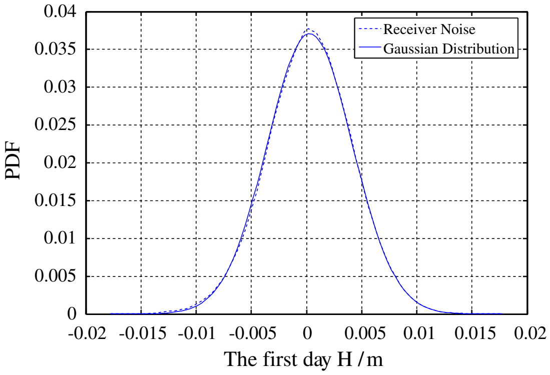
Days	Mean value			Standard deviation		
	N–S	W–E	Height	N–S	W–E	Height
1st day	0.01	−0.16	0.03	0.26	0.27	0.39
2nd day	−0.24	−0.06	0.29	0.25	0.21	0.52
3rd day	−0.10	0.14	0.13	0.25	0.21	0.47



(a) N-S direction



(b) W-E direction



(c) Vertical direction

Fig. 11. PDF of the receiver's noise of the first day in 3D directions.

Based on the characteristics of the GPS receiver's noise obtained in the process (2), the results processed by the improved particle filter algorithm. Since the full 24 h sidereal day plot is too long to include in the paper, only an excerpt (1 h) is provided here to demonstrate the results (The time had been homogenized by the constant 3 min and 56 s to account for the difference between UTC and mean solar day.). Figs. 13–15 provide the monitoring signals when the reflector is at 1 m, 4 m and 7 m after filtering.

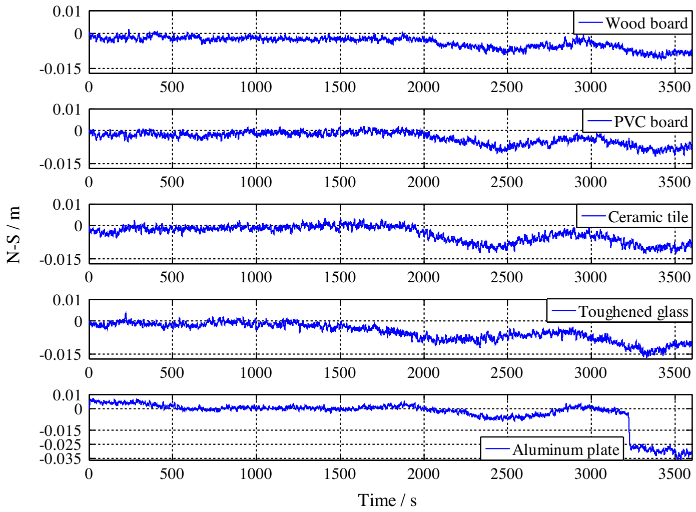
It can be noted from Figs. 13–15 that fairly large errors are found in the kinematic positioning solutions when the

(a) 1m

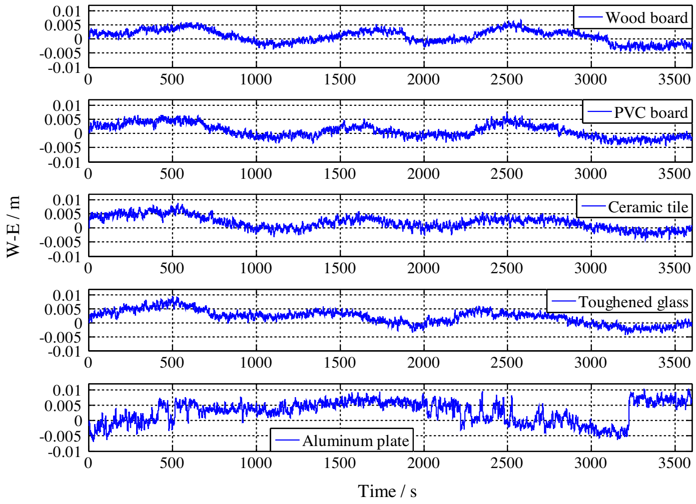
(b) 4m

(c) 7m

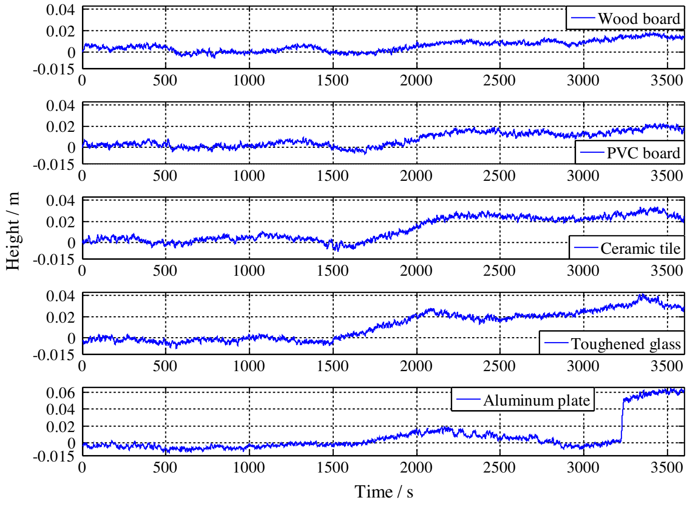
Fig. 12. Set-up of the reflector at different distances of antenna.



(a) N-S direction

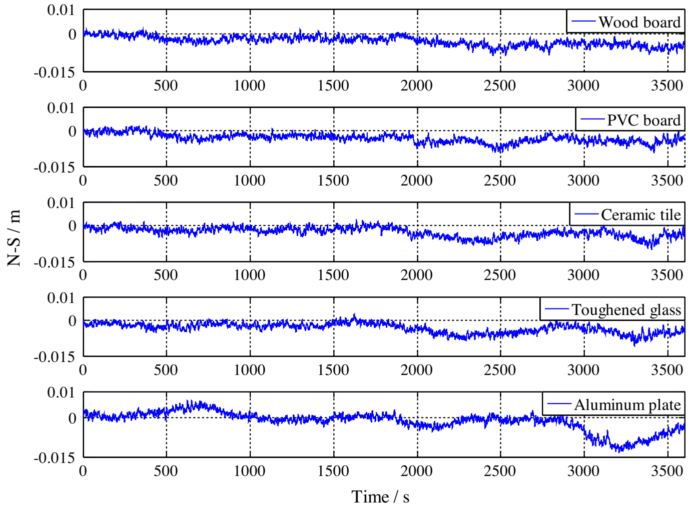


(b) W-E direction

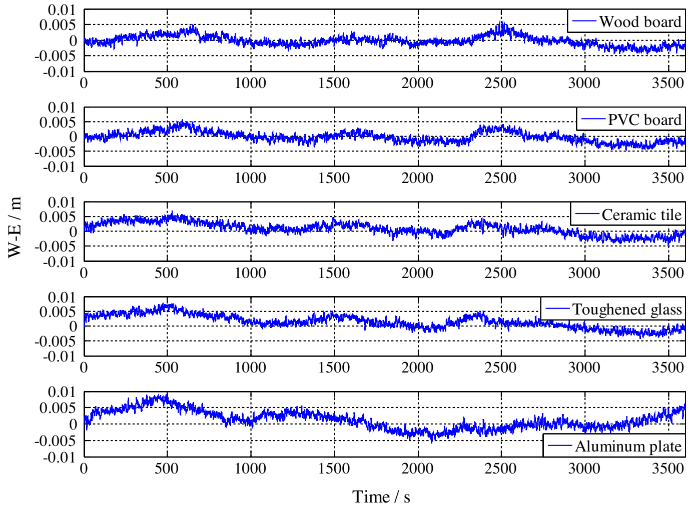


(c) Vertical direction

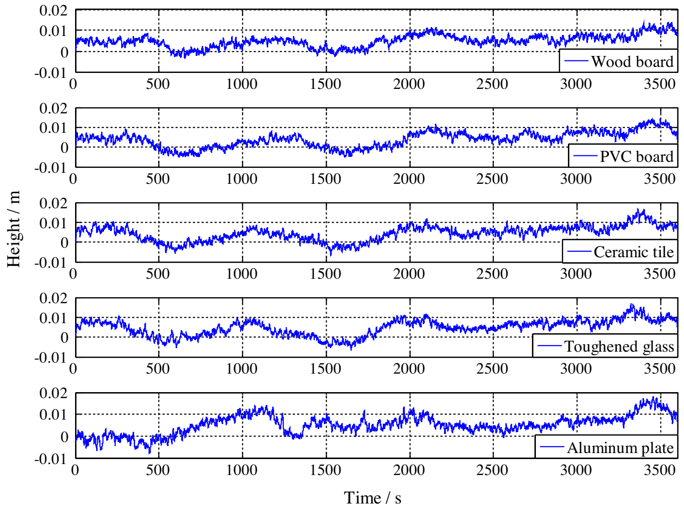
Fig. 13. Monitoring signals when the reflector is at 1 m after filtering.



(a) N-S direction

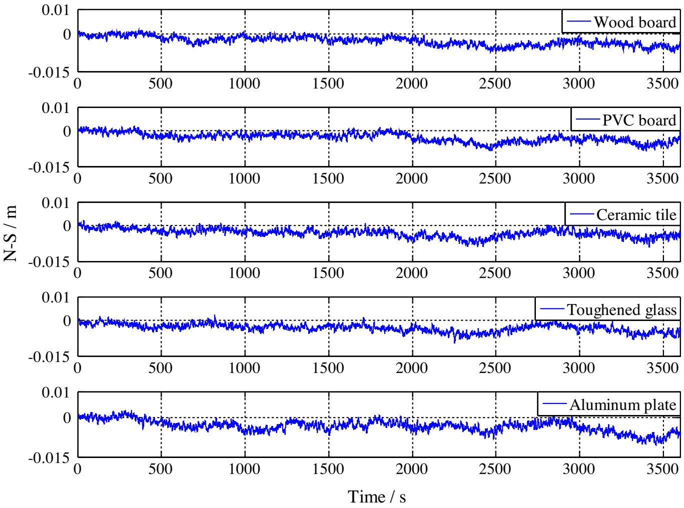


(b) W-E direction

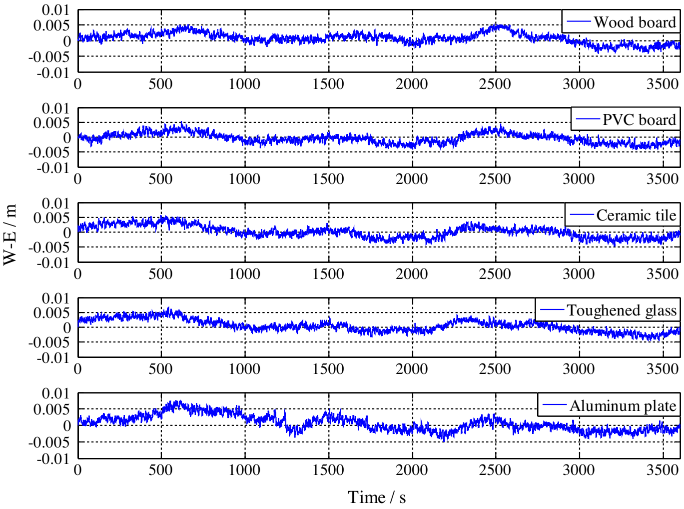


(c) Vertical direction

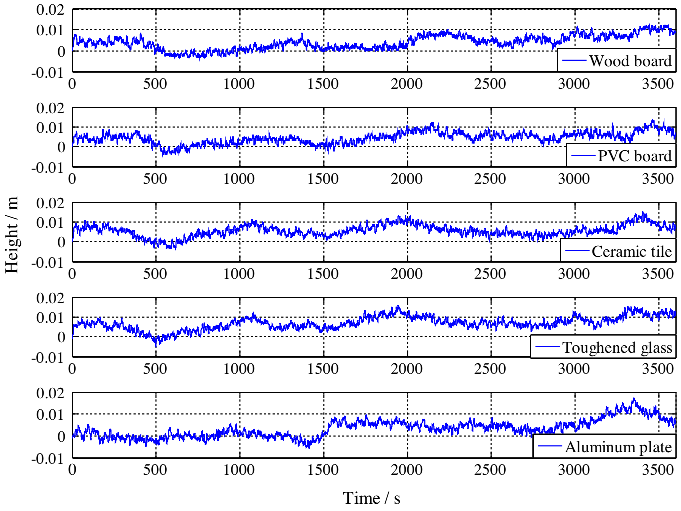
Fig. 14. Monitoring signals when the reflector is at 4 m after filtering.



(a) N-S direction

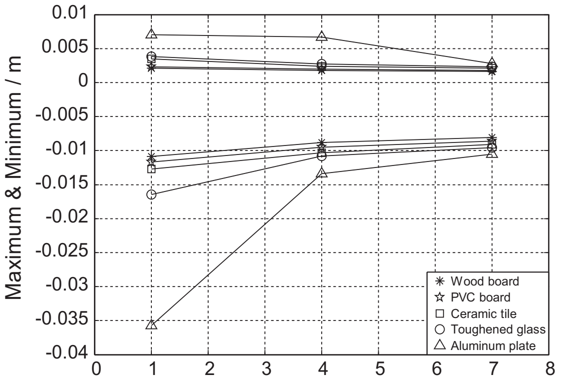


(b) W-E direction

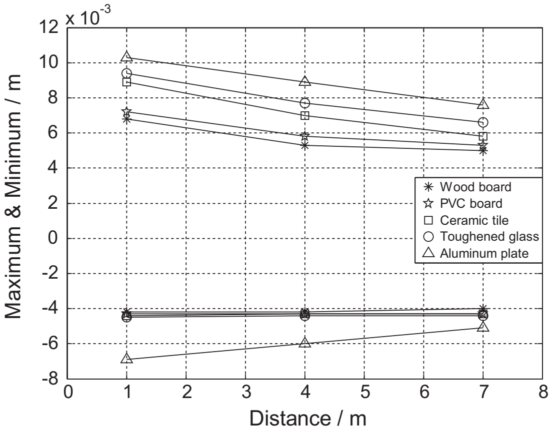


(c) Vertical direction

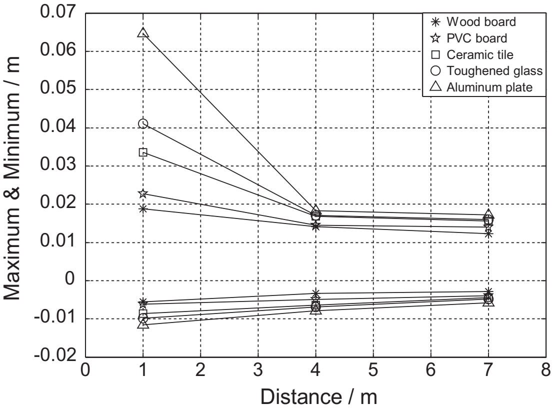
Fig. 15. Monitoring signals when the reflector is at 7 m after filtering.



(a) N-S direction

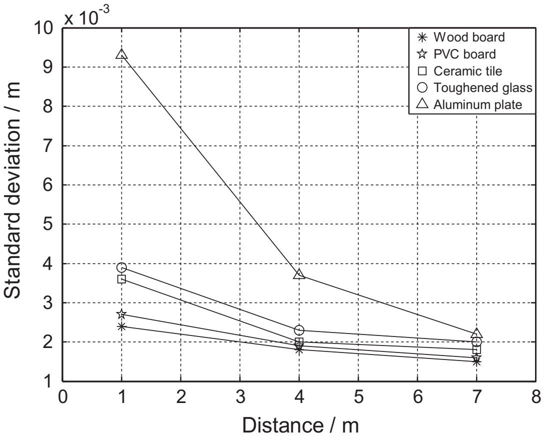


(b) W-E direction

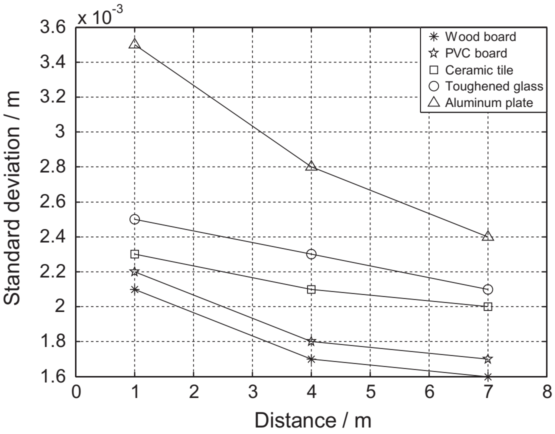


(c) Vertical direction

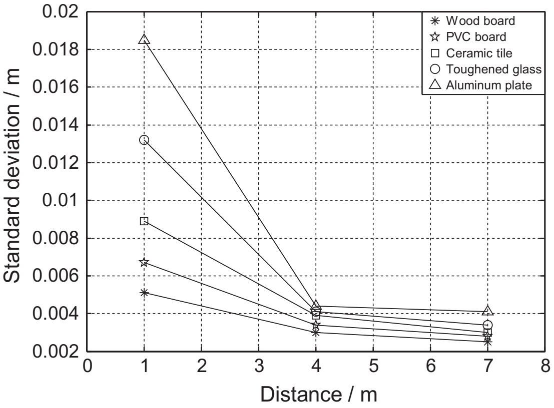
Fig. 16. Maximum and minimum of multipath observables corresponding to different distances of reflector.



(a) N-S direction



(b) W-E direction



(c) Vertical direction

Fig. 17. Standard deviation of multipath observables corresponding to different distances of reflector.

signal is obstructed with the different tested construction materials. The positioning solutions obtained here show a wide dispersion from the 'true' position. As the geometry between the GPS satellites and a specific receiver–reflector location repeats every sidereal day, the multipath tends to exhibit the same pattern for the non-mental materials. Although the patterns appear to be similar, they are not of the same magnitude when looking at the peaks since the relative permittivity of the tested materials is different that might cause different reflections of GPS signals. This error can only be attributed to the presence of the reflector obstructing the transmitting antenna of the rover, because all other variables were kept constant. The daily repeatability is analyzed by the correlation among those data series, the results show that although there are certain correlations between the multipath signals along with the distance increase, the correlations gradually become smaller. In addition, the correlation of the multipath signals caused by non-metal materials in three directions as the same distance is larger than that of metal materials. As is clear from Fig. 13, the tests involving aluminum plate show the largest error in position. It appears that for the group of solutions at 1 m, the rover had lost lock during the observation period.

The computed maximum and minimum errors for each tested material are shown in Fig. 16. These errors in the positioning solutions from 0.16 cm for the wood board to as high as 6.47 cm for the aluminum plate. The aluminum plate completely blocked out the signal when the reflector was at 1 m, and hence it showed the largest error in the recorded results. As explained in Section 2, the amplitude of the multipath error arising from such reflections is highly dependent on the relative permittivity of the medium; this could be verified from Fig. 16. It is also noted from the figure that the amplitude of multipath signals in three directions decrease with the increase of distances, and the decreased rate gets smaller. The changed rate of multipath signals in the vertical direction is about 2 times bigger than that in the horizon, and the multipath signals tend to be gentle along with the increase of distances in three directions. As expected, the differences between tested materials tend to fall near the zero no matter in horizontal direction or vertical direction.

The standard deviation of multipath signals caused by the tested materials as shown in Fig. 17 obtained by the results of 1 m, 4 m and 7 m after filtering. It is found that the standard deviation of the multipath signals caused by different materials in three directions increase along with the dielectric constant of the materials; the same feature is noted from the magnitude of the multipath signals. The standard deviation of the multipath signals caused by the metal materials is bigger than those caused by the non-metal materials, especially in N–S direction.

5. Conclusions

A GPS receiver tracks a signal composed of a direct and reflected components. The receiver cannot distinguish them and then tracks the composite signal. The multipath provokes errors in both pseudorange and carrier phase measurements, depending mostly on the reflecting environment. This paper provides background, explanation and initial results for the effect of different construction materials on the propagation of GPS monitoring signals. What needs to be pointed out is that the experiments in the paper only provide the results of multipath from very low elevation angles (i.e. less than 10°), and the following conclusions are obtained as:

(i) A specific set of system for the GPS multipath signals generating and monitoring was devised and fully calibrated for both static and kinematic tests. This equipment could also be used in the future to assess the efficiency of any new multipath mitigation strategy.

(ii) The distribution of GPS receiver's noise was studied and the five different construction materials on the propagation of GPS monitoring signals were investigated for the first time. Of the materials the tested wood board caused the smallest error to the positioning solutions, followed by the PVC board, ceramic tile, toughened glass, and aluminum plate. The amplitude of multipath signals arising from such reflections is highly dependent on the relative permittivity of the medium, so do the standard deviation of the multipath signals. The correlation of the multipath signals caused by the non-metal materials in three directions as the same distance is larger than that of metal materials. It is also noted that the amplitude of multipath signals in three directions decrease with the increase of distances, and the decreased rate gets smaller. The changed rate of multipath signals in the vertical direction is about 2 times bigger than that in the horizon, and the multipath signals tend to be gentle along with the increase of distances in three directions. In future application of GPS technology in certain environment, these computed results may be applied as corrections to improve the accuracy of positioning. Note that the GPS signals are used here as examples of the GNSS signals throughout but the conclusions are fully applicable to the modernized GPS, GLONASS and Galileo.

(iii) The improved particle filtering algorithm has the advantage of being able to adapt to the close reflector situation, while remaining quite efficient when the reflector gets further away (1, 4 and 7 m during the present tests). The day-to-day repeatability of the multipath can be exploited to improve positioning accuracies. Given known coordinates of a point, the multipath signal at every epoch can be extracted by the improved particle filtering algorithm from the collected phase data. Once obtained, this signature can then be applied at any time in the future to remove distortions due to the multipath effects and changing satellite orientations, provided that the multipath sources, i.e., surrounding obstructions, remain unchanged. The method will have important practical applications for correcting for the multipath in the well-constrained environments, and it can be used to simulate the realistic multipath errors for various performance analyses in high-precision positioning.

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