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Multipath Mitigation Technique under Strong Multipath Environment Using Multiple Antennas *

Nobuaki Kubo[**1], Kaito Kobayashi[1], Li-Ta Hsu[2] and Osamu Amai[3]

[1]*Tokyo University of Marine Science and Technology, Japan*
[2]*The Hong Kong Polytechnic University, Hong Kong*
[3]*National Institute of Maritime, Port and Aviation Technology, Japan*

ABSTRACT

Multipath is a major source of error in high precision Global Navigation Satellite System (GNSS) static and kinematic differential positioning in urban environments. This paper describes a unique approach to mitigate strong multipath error: a new multipath mitigation technique ensuring that antenna motion for a rover-moving platform is maintained in the case that the platform is moving slowly or is stopped. It is known that standard GNSS receivers are vulnerable to multipath interference when the rover antenna is static. This is because stable and strong multipath signals can be easily received when the antenna is not moving, as the carrier phase relationship between the direct signal and the reflected signal changes slowly. Conversely, when a vehicle is moving, the received carrier phase relationship between the direct signal and the reflected signal changes rapidly, meaning that the strong reflected signal will be averaged or disappear. We attempt to use this characteristic to mitigate strong multipath errors. Three experiments were conducted to evaluate the proposed technique. The first test results illustrate the case of receiving strong specular reflection in a static condition. The proposed technique of maintaining antenna motion can reduce multipath errors from over 15 m to 1-2 m. In the second test, results represent the case of multipath mitigation in a car by comparing two closely set antennas: one is where the antenna is fixed on the roof of the car; the other is where the antenna is intentionally shaken manually while the car is stopping. The latter case can reduce significant multipath errors that occur while a vehicle is stopping at an intersection traffic signal. Finally, we set 5 patch antennas on top of a car and connect these antennas to rover receiver through the antenna switching devise developed for this purpose. The equipment can switch the antenna according to the set of switching period. This enables the antenna looks moving while the car is stopped or moving very slowly. The equipment itself is very easy to produce and low-cost. The data was obtained near the building in the static condition. Looking at the horizontal position errors, the results using our proposed method were clearly better than the results of normal single antenna. The maximum horizontal errors were reduced about 70 %.

Keywords: Multipath, Antenna, GNSS

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** To whom correspondence should be addressed, E-mail: nkubo@kaiyodai.ac.jp

I. INTRODUCTION

There are numerous applications that can benefit from improved urban positioning including location-based services, intelligent transport systems, vehicle lane control, advanced rail signaling, and navigation for the blind. High-sensitivity receivers and multiple satellite constellations have vastly improved GNSS signal availability in dense urban areas. However, accuracy remains a problem for applications that require real-time positioning. Even receivers with centimeter-level resolution struggle to retain high accuracy in urban areas. The urban environment presents major challenges to GNSS signal reception. Buildings and other obstacles such as buses block the direct line-of-sight (LOS) to many of the satellites, effectively reducing the number in view. Because the majority of the cross-street signals are blocked by buildings, leaving only along-street signals, the positional solution geometry is inadequate, leading to significantly reduced accuracy in the cross-street direction. The reception of these reflected signals results in significant positioning errors owing to Non-line-of-sight (NLOS) reception and multipath interference. These are often grouped together as “multipath errors” [1].

This paper describes the mitigation of multipath errors using an approach that is different from the conventional methods of antenna design [2], correlator-based techniques [3-7], carrier-to-noise-ratio-based detection [8-9], and 3-dimensional (3D) city models and cameras [10-11]. It is known that standard GNSS receivers are vulnerable to multipath interference when a rover antenna is static. When the speed of a car approaches zero, it is likely that considerable differential GPS (DGPS) errors will occur. This is because stable and strong multipath signals can be easily received when an antenna is not moving, as the carrier phase relationship between the direct signal and the reflected signal changes slowly. Such errors can frequently be seen in dense urban areas, even with the latest high-sensitivity GNSS receivers. Conversely, when a vehicle is moving, the received carrier phase relationship between the direct signal and the reflected signal changes rapidly, meaning that the strong reflected signal will be averaged or disappear [12].

We attempt to use this characteristic to mitigate strong multipath errors. Specifically, we set the rover antenna on a small moving base on the top of a car. This enables the rover antenna to remain in motion while the car is stopped or moving slowly.

To begin, several test results regarding the relationship between multipath errors and speed are introduced. These test results indicate that a strong multipath occurs frequently when the platform is moving slowly or is stopped. Then, to evaluate the multipath mitigation effect of antenna motion, a comparison test is conducted using two antennas. Two patch antennas are set close to the concrete wall of a building. The first antenna is fixed on the roof of a car. Rotary motion is provided to the second antenna using a record player. The results clearly indicate that the carrier-to-noise-ratio does not fluctuate when receiving a strong reflected signal during periods when the antenna is in motion. Substantial code multipath errors are also significantly mitigated, as with the carrier-to-noise-ratio, when the antenna is in motion. Furthermore, to validate this effect under a kinematic test in dense urban areas, the same test is conducted using a car and similar results are obtained. Manually shaking the antenna intentionally is not contaminated by strong multipath when the platform is moving slowly or is stopped. Finally, we set 5 patch antennas on top of a car and connect these antennas to rover receiver through the antenna switching devise developed for this purpose. The equipment can switch the antenna according to the set of switching period. This enables the antenna looks moving while the car is stopped or moving very slowly. The equipment itself is very easy to produce and low-cost. The data was obtained close to the concrete wall of the building at our university campus. The distance between antennas and the wall was about 10 m. Looking at the horizontal position errors, the results using our proposed method were clearly better than the results of normal single antenna. The maximum horizontal errors were reduced about 70 %. This indicates that our newly proposed method can mitigate the large multipath errors when receiving direct signals as well as strong reflected signals.

II. MULTIPATH ERRORS AND SPEED

It is known that the slow change of the relationship between the direct signal and multipath signal is a significant factor in code tracking contamination by a multipath signal. Multipath errors such as sine curve are a typical example of a slowly changed multipath. Conversely, when a vehicle is moving, the received carrier phase relationship between the direct signal and the reflected signal changes rapidly, meaning that the strong reflected signal will be averaged or disappear. Several real examples are introduced in this section.

Figure 1 indicates the relationship between vehicle speed and DGPS errors. The raw observation data were obtained by a car-based geodetic-quality GPS receiver in semi-urban areas. The reference positions were deduced from the post-processed Real Time Kinematic (RTK) software developed in our laboratory. In the period where the speed of the car approached zero, it is likely that significant DGPS errors occurred. This is because stable and strong multipath signals can be easily received when the antenna is not moving as the carrier phase relationship between the direct signal and the reflected signal changes slowly. Such errors can frequently be seen in urban areas, even with the latest GNSS receivers.

To investigate the relationship between multipath errors and speed in a different manner, a signal-quality monitor receiver was used to obtain the real correlation values in downtown Tokyo. The test course was surrounded by numerous super high-rise buildings with flat walls. The sampling frequency was set at 40 MHz and the bandwidth was 20 MHz. A 0.1 chip standard narrow correlator was used for code tracking. We drove a vehicle equipped with the above receiver and a geodetic-quality antenna in downtown Tokyo.

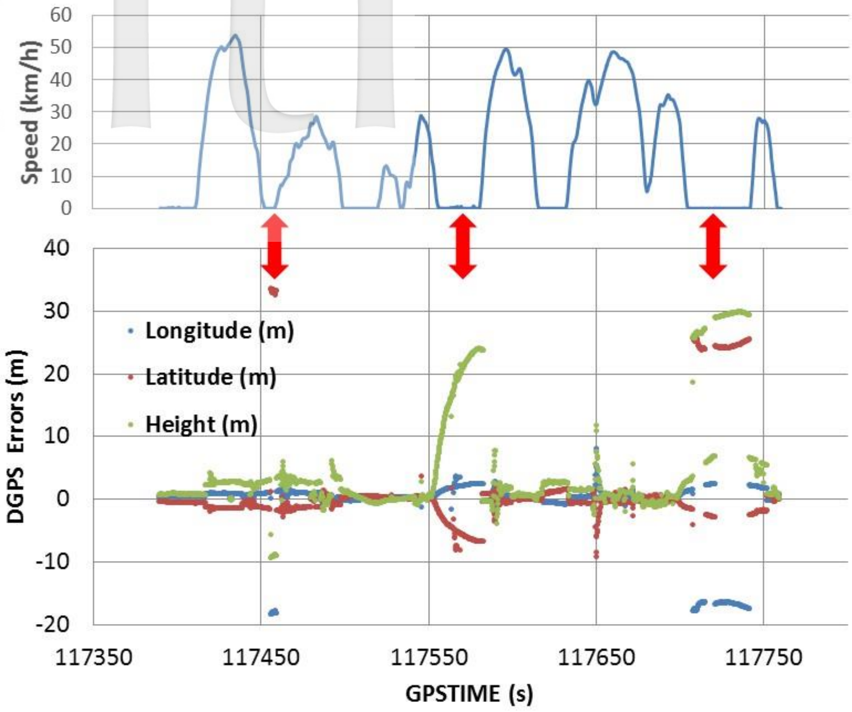

Figure 1 DGPS Errors and Speed

Figure 2 displays the five representative correlation triangles obtained when we stopped at traffic signals. X-axis is relative delay in the tracking loop and y-axis is correlation power of in-phase signal. There is no unit in the correlation power because it is just the result of the sum of the code correlation with regard to sampling frequency. There were numerous similar correlation triangles contaminated by strong multipath signals during a stop or at low speed. Conversely, it was quite difficult to determine clear, strong multipath cases while the car was in motion. Of the five correlation triangles in Figure 2, one is the case where the amplitude of the reflected signal was higher than the amplitude of the direct signal, indicated by the yellow line. Another triangle indicates that the amplitude of the direct signal was approximately equivalent to the amplitude of the reflected signal, indicated by the sky blue line. In these cases, significant multipath errors of over 100 m were frequently generated and therefore, the position of the car was significantly deviated.

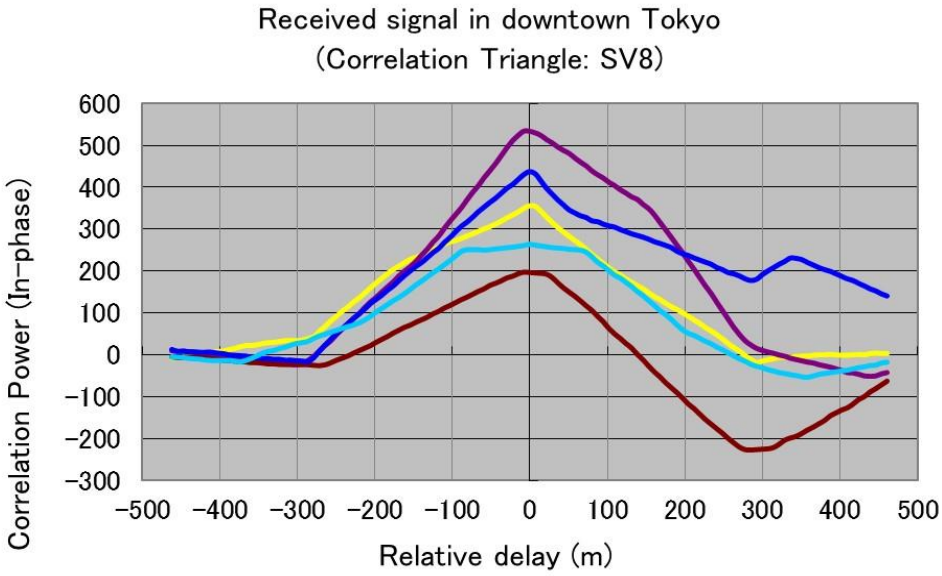

Figure 2 Correlation shots in downtown Tokyo during a stop

As a final experimental test in this section, the raw data and navigation solution of a popular high-sensitivity receiver were obtained by driving a car in downtown Tokyo in the approximate location of the previous experiment. Figure 3 presents the horizontal results of this receiver's navigation solution. To identify the difference of the horizontal errors in terms of speed, we changed the color of the plots. Plots in yellow represent the horizontal positions. Plots in red are the horizontal positions with the exception of the results of slow speed or stopped status. The four sky blue circles indicate the locations where we stopped for more than 2-3 minutes. It clearly illustrates that a significant horizontal deviation of greater than 100 m can be observed frequently in the case of slow speed or stopped status. Substantial deviations can also be seen occasionally in the case of a moving vehicle. The maximum horizontal errors approached 400 m, which indicates receiving a dominant strong reflected signal without sufficient power of the direct signal. There are many high-rise buildings in this extensive business area in the center of Tokyo. Therefore, there is a high probability of receiving a strong reflected signal from the flat surface of a wall, even from distant buildings.

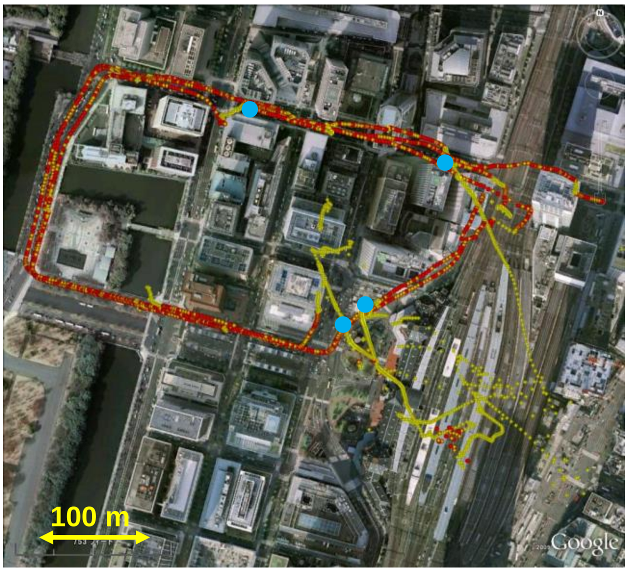

Figure 3 Horizontal results using popular high-sensitivity receiver in downtown Tokyo

III. ANTENNA MOTION TEST IN AUTOMOBILE

In the previous section, we demonstrated the characteristic that standard GNSS receivers are vulnerable to multipath interference when the rover antenna is static. In this section, we attempt to use this characteristic to mitigate strong multipath errors. Two tests were conducted. The first test is the investigation of the effect of antenna motion in a strong multipath environment located near a flat wall. The second test is the investigation of the effect of antenna motion in a strong multipath environment while driving in an urban area.

• *Test 1 and Results*

The raw data were obtained using a popular high-sensitivity receiver and patch antenna near the flat wall of a building. A picture of the test environment is presented in Figure 4. The car was parked near the left sidewalk. Two receivers were set to compare the results between a static antenna and moving antenna. We set the rover antenna on a small moving base, which was actually a record player on the top of a car. Another antenna was set close by the first antenna.

Figure 4 Test environment

Figure 5 illustrates the configuration of the two antennas. The record player rotated at 33 1/3 rpm while we were collecting the data. The diameter of the circle was approximately 30 cm. If we put the antenna on the edge of the circle, the speed is about 1.9 km/h (53 cm/s). In fact, we need to investigate the threshold of this speed to mitigate strong multipath errors. It depends on the cycle of the multipath. To deal with various multipath, we will find out the suitable threshold of the speed for antenna motion in the near future. During this period, the target satellite was QZS (Quasi Zenith Satellite) PRN 193 because specular reflection from the wall was expected in this configuration.

Figure 5 Configuration of two antennas

Figure 6 presents the temporal carrier to noise ratio (C/N_0) of QZS between the static antenna and moving antenna. It clearly indicates that the C/N_0 of the moving antenna was considerably more stable than the antenna in a static condition. It demonstrates that the influence of the strong reflection due to the wall in the case of the moving antenna was highly suppressed by maintaining the motion. Conversely, the static antenna was strongly influenced by the specular reflection.

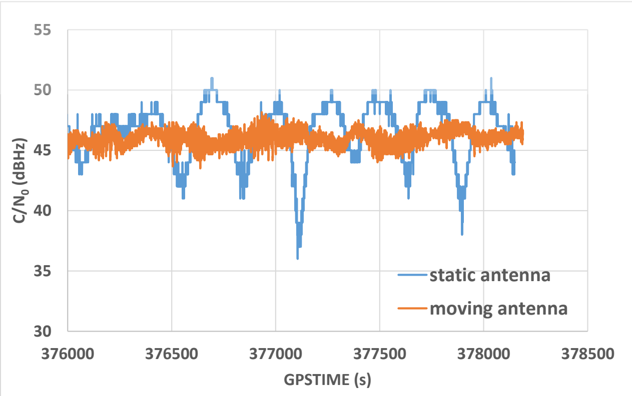

Figure 6 C/N0 comparison between moving antenna and static antenna (QZS)

Figure 7 presents the code multipath error comparison between the static antenna and moving antenna. Code multipath was calculated using the code-minus-carrier technique. Because this result was deduced from only single-frequency observation data, it includes ionospheric errors. However, the magnitude of the ionospheric errors was relatively small in this test. As can be seen from Figure 7, the code multipath error due to the strong reflection was dramatically decreased by maintaining antenna motion. In fact, the standard deviations of code measurement were 4.09 m for the static antenna and 0.67 m for the moving antenna, respectively. This indicates that the positioning performance can be improved by maintaining antenna motion.

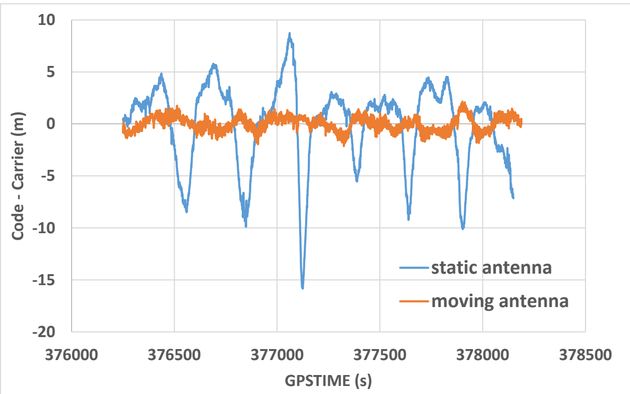

Figure 7 Code-minus-carrier comparison between moving antenna and static antenna (QZS)

- ***Test 2 and Results***

The raw data were obtained using a car in the vicinity of our university. Figure 8 indicates the test route. There were several high-rise buildings around each intersection. The GNSS receiver used in this test was a popular high-sensitivity receiver with standard patch antenna. 5 Hz position results and observation data for the GPS/QZS/BeiDou were obtained. Two similar receivers were prepared. The first antenna was fixed on the roof of a car and the second antenna was set to be able to swing manually. Because the record player was difficult to set properly and safely, to avoid an accident, we did not use it in this kinematic test.

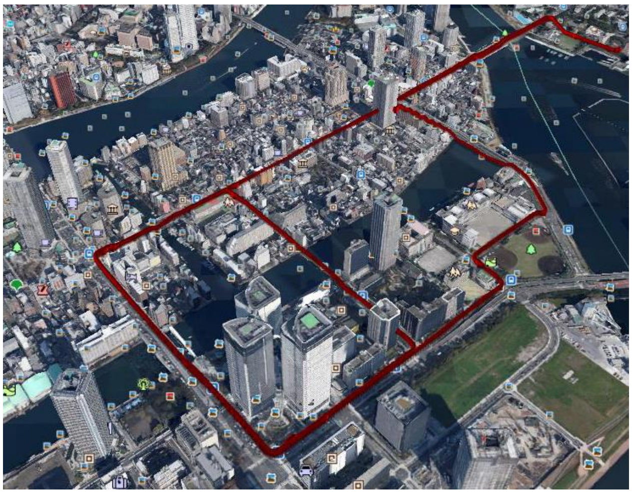

Figure 8 Test route

Figure 9 is a picture of the two antennas. As can be observed in this picture, the second antenna can be shaken by a passenger of the car. This enables the rover antenna to remain in motion while the car is stopped or moving slowly. While I was driving the car, my student shook the second antenna manually when the vehicle speed was less than approximately 5 km/h. The speed of this antenna motion was about 1 m/s. When the vehicle speed was greater than 5 km/h, my student did not move the antenna. Based on the results of this test, there was a distinct difference between the static antenna and moving antenna in terms of position accuracy. We selected two locations that demonstrate the clear improvement of accuracy. Except for the above two locations, errors over 5 m could not be detected in the two antennas.

Figure 9 Rooftop of car in the antenna motion test

Figure 10 compares the horizontal plots of single-point positioning when the car stopped at an intersection surrounded by high-rise buildings. The plots in red indicate the results of the static antenna. The plots in blue are the results of the moving antenna. When we stopped at the traffic signal indicated in the yellow circle twice, the horizontal results of the static antenna suddenly began to deviate, probably owing to the strong multipath error. The maximum deviation based on the stopped position was approximately 6 m. Conversely, the horizontal results of the moving antenna did not deviate at this location. This confirms that maintaining antenna motion can attenuate the effect of a strong multipath signal.

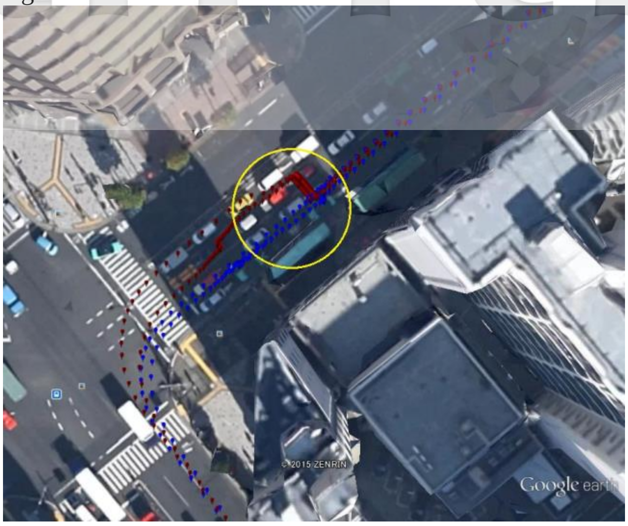

Figure 10 Comparison of horizontal plots between moving antenna and static antenna

Figure 11 compares the horizontal plots of single-point positioning when the car stopped at an intersection surrounded by high-rise buildings and an overpass. The environment of the GNSS radio propagation was certainly not good in this location. The plots in red indicate the results for the static antenna. The plots in blue are the results of the moving antenna. When we stopped at traffic signal indicated in the yellow circle twice, the horizontal results of the static antenna suddenly began to deviate, probably owing to the strong multipath error. The maximum deviation based on the stopped position was approximately 20 m. Conversely, the horizontal results of the moving antenna deviated approximately 5 m at the same location. This confirms that maintaining antenna motion can significantly attenuate the effect of a strong multipath signal.

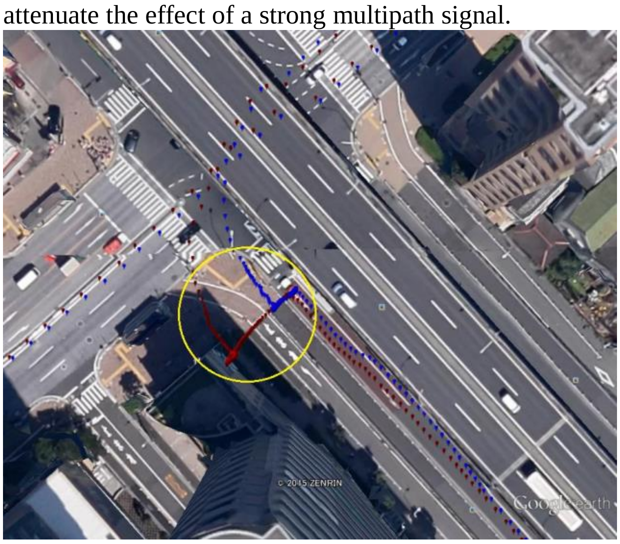

Figure 11 Comparison of horizontal plots between moving antenna and static antenna

The results in Test 1 demonstrate that maintaining antenna motion is effective to mitigate specular multipath errors in the case that the speed is zero. However, we cannot determine what types of multipath errors can be received in the case of Test 2. Although we investigated the raw observation data thoroughly in the selected two locations in Test 2, it is difficult to determine if the type of received multipath was specular reflection or NLOS. However, it is certain that a considerable variation of the C/N_0 can be seen in the case of the static antenna. Compared with Test1 and Tes2, record player is more suitable than hand shaking because record player can be effective for any direction of multipath. On the other hand, in the case of hand shaking, it is impossible to deal with every direction because the direction of the motion is normally fixed.

IV. NEWLY PROPOSED MULTIPATH MITIGATION METHOD USING MULTIPLE ANTENNA

We have demonstrated that the reception of a multipath signal is strongly related to the speed of the moving platform. Although we did propose a unique approach to maintain antenna motion to mitigate strong multipath errors when the speed was slow or zero in the previous section, the implementation of this idea may not be practical. In this section, we propose a new method to mitigate multipath errors using multiple antenna. Specifically, we set 5 patch antennas on top of a car and connect these antennas to rover receiver through the antenna switching devise developed for this purpose. The equipment can switch the antenna according to the set of switching period can be changed from 0.1 s to 2.0 s with 0.1 s resolution. This enables the antenna looks moving while the car is stopped or moving very slowly. The equipment itself is very easy to produce and low-cost.

Figure 12 shows the exterior of the antenna switch equipment. DC INPUT power range is 5 to 30 V. Figure 13 shows the inside of the equipment.

In this paper, the target frequency of the multipath from satellites is GPS L1 and BeiDou B1 frequnecy. The approximate wavelength of these signals is 19 cm. In our proposed method, we need to change the delay of the multipath to the direct path intentionally to mitigate the multipath effect. Therefore, it is better to change the antenna randomly within the rage of approximate 19 cm because the phase of multipath is also varied according to the delay of the multipath. As a result, multipath error is leveled and reduced. From this point of view, we need to allocate the antenna toward not only one direction but also multiple direction. If we set only two antennas, it is not so effective to the multipath signal from the perpendicular direction to the straight line of two antennas. In the section Ⅲ, the antenna was shaking in the perpendicular direction to the direction of the car because most of multipath signals arrive from the direction of the wall in each side of the road.

Figure 12 Exterior of the antenna switch equipment

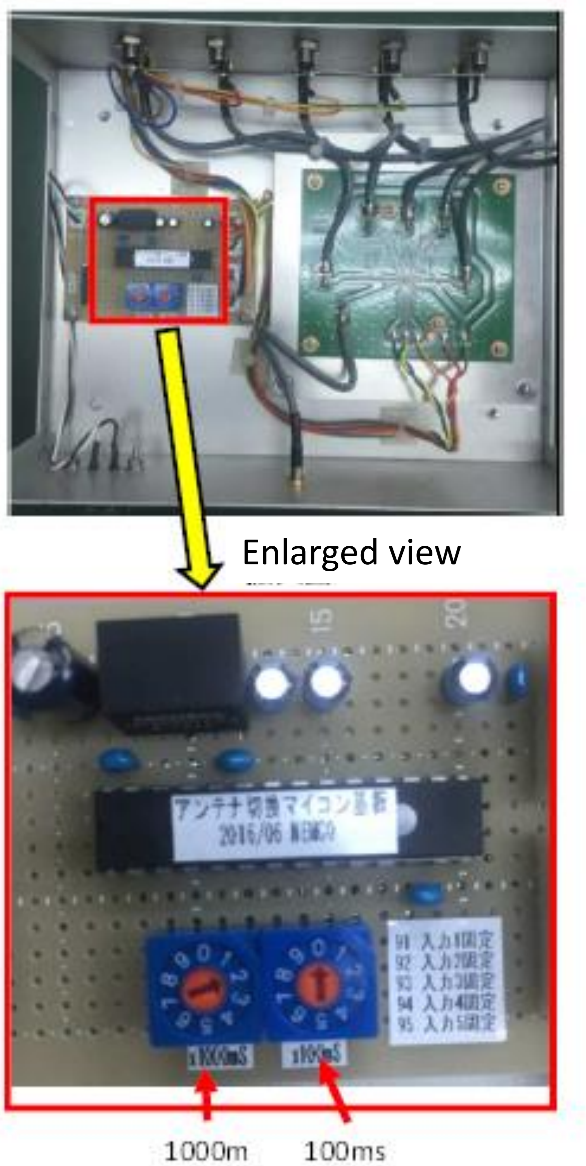

Figure 13 Inside of the antenna switch equipment

To evaluate the multipath mitigation effect using our proposed method, the 5 patch antennas were set close to the concrete wall of the building at our university campus. The timing of the switch for five antennas was set 0.2 s in this test.

The normal single patch antenna was also set to compare two results. We used a popular low-cost high-sensitivity receiver that can outputs raw data as well as NMEA sentences. The distance between antennas and the wall was about 10 m. The elevation angle of the target satellite was 40–50° during the test, and the normal carrier-to-noise-ratio at this elevation angle is approximately 40-50 dB-Hz under open sky conditions. Figure 14 shows the test configuration.

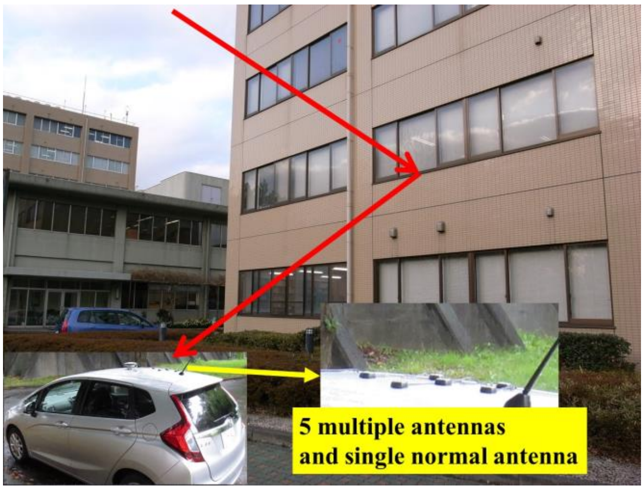

Figure 14 Test configuration

The stand-alone positioning results clearly showed that the carrier-to-noise-ratio did not fluctuate when receiving the strong reflected signal during the periods when the antenna was switching.

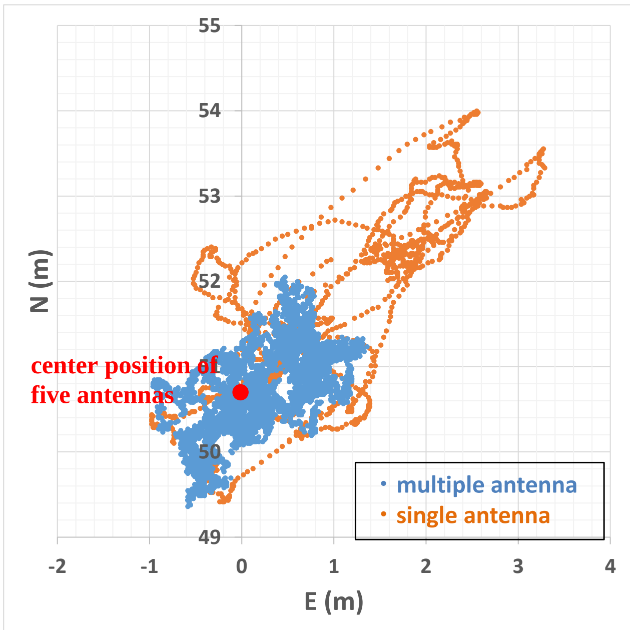

Figure 15 Comparison of horizontal position between the single antenna and the switched multiple antenna

Figure 15 shows the comparison of the horizontal position between the single antenna and the switched multiple antenna. The figures in each direction mean the offset from base station on the roof top of the next building. The true center position of five antennas is approximately coordinates (0, 51). Blue plots show the horizontal position in the case of multiple antenna. Orange plots show the horizontal position in the case of single antenna. Looking at the horizontal position errors, the results using our proposed method was clearly better than the results of normal single antenna. The maximum horizontal errors were reduced about 70 %. This indicates that our proposed method can mitigate the large multipath errors when receiving direct signals as well as strong reflected signals.

Furthermore, to validate our proposed method, several tests in the different places were conducted in the same manner. It also showed that the horizontal errors were reduced compared with the normal antenna especially when the strong reflected signal was received.

V. CONCLUSIONS

A unique approach to mitigate strong multipath error was introduced in this paper. To ensure that the underlying concept for this approach was appropriate, several tests were conducted. These test results demonstrated that GNSS receivers were vulnerable to multipath interference when the rover antenna was static. There was a significant probability of substantial GNSS error when the speed of the car was slow or zero. Further, we verified the proposed method for maintaining antenna motion for the rover-moving platform in the case when the speed was slow or zero. Substantial specular multipath errors were mitigated from over 15 m to 1-2 m based on the above idea in a static condition. Furthermore, deviations due to strong multipath were also reduced significantly in the kinematic test using a car. Finally, we proposed a new approach to mitigate strong multipath errors in a practical way using multiple antennas with the antenna switching devise. The equipment can switch the antenna according to the set of switching period. The equipment itself is very easy to produce and low-cost. The data was obtained close to the concrete wall of the building at our university campus. Looking at the horizontal position errors, the results using our proposed method was clearly better than the results of normal single antenna. The maximum horizontal errors was reduced about 70 %. This indicates that our newly proposed method can mitigate the large multipath errors when receiving direct signals as well as strong reflected signals.

In this paper, it was demonstrated that the specular type of multipath reflection could be mitigated using the proposed technique. However, it remains to be confirmed if this method can be effective for NLOS reception. We will investigate the relationship between an NLOS signal and the speed of a moving platform in a future study. Also, the suitable speed of the antenna motion was not investigated. We will check the threshold of the speed of the antenna motion to mitigate various multipath.

ACKNOWLEDGMENT

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