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*Full Length Research Paper*

# An investigation on multipath errors in real time kinematic GPS method

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**Today real time kinematic GPS (RTK GPS) is the newest and the most common method utilized in tasks requiring real time positions with especially, centimeter accuracies. However, as with all good things in life, this contemporary method of positioning is not flawless, that is, not free from errors. As in static GPS, RTK GPS is also susceptible to multipath errors. This study aims to investigate this source of error and attempts to answers some questions such as how much multipath error causes real time positioning error, in what kind of environment this error is the most effective and how large the positional errors this multipath produces. For these reasons, the fundamental background on multipath error was first covered and the surrounding causing this effect was widely researched, hence a test environment was designed. Various analyses were conducted in light of the findings obtained from the tests carried out and conclusions and suggestions were made in detailed fashion so that they could lead the way to future researches.**

**Key words:** Real time kinematic GPS, multipath error, multipath geometries.

## INTRODUCTION

GPS Techniques come across almost every segment of our lives and are widely used in most engineering projects in need of accurate and fast positions. One of these techniques stands out for its very fast and quite accurate positions: Real Time Kinematic (RTK) GPS; which has very ample areas of use such as hydrographic (Kim and Langley, 2001), resonances, deformations and displacements of engineering structures (Roberts et al., 2003), automatic vehicle navigation (Ai-gong et al., 2003; Abbot and Powell, 1999), deformation analysis (Avallone et al., 2004, Ince and Sahin, 2000), cadastral and GIS surveys (Mekik and Aslanoglu, 2009), ultra-high precision navigation (Kim and Langley, 2002). For all the GPS techniques, RTK GPS is also affected by the errors inherited in GPS. Since RTK GPS is mostly utilized in engineering surveys and urban canyons for its efficiency and positional accuracy, these kinds of surroundings usually give rise to a source of error known as "multipath error". A multipath error occurs when receiving GPS signals reflected from surfaces of ground or other objects in the vicinity of a receiver, and leads to a positional error resulting from the computation of the range between the satellite and receiver. No matter how carefully one tries to avoid this type of error, as the source of this error is the reflection of the GPS signals, increase in the buildings in urban areas and industrial survey settings will still contribute to this because of the nature of the surrounding (Xia, 2004).

A direct GPS signal propagated along the line of sight to a receiver is usually registered at the receiver. However, the receiver can also pick any satellite signal bouncing off any objects around it, causing the multipath error, as the entire receiver antennas are omnidirectional and does not differentiate the signal for which way it propagates (Tiryakioğlu et al., 2006). Hannah (2001) states that if the reflecting surface is approximately 160 m away from the receiver, the probability of a multipath error to occur is very slim since the signal is decorrelated depending upon the correlator type of receiver. As far as the total positional error is concerned, it is reported that the multipath error is not usually larger than 5 cm (Braasch and Van Graas, 1991). Nevertheless the multipath still contributes towards the total error sources encountered in GPS tasks.

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**Figure 1.** Combined application of ground plane and choke-ring antenna.

Anyone utilizing RTK GPS in engineering projects would like to know how much a mean positional error will occur using a standard receiver for their RTK GPS tasks in a surrounding susceptible to give rise to multipath errors. This study generates a controlled test environment to answer the questions regarding the multipath error arisen from the usage of RTK GPS such as how large a positional error can be attained from this error and what type of environment mostly triggers the multipath error. In an attempt to satisfy these inquiries, the multipath geometries given in detail are mimicked in a test environment, and the findings from the tests are presented and examined. Prior to detailing the tests conducted, the authors find it useful to give insight for the theory of multipath error and the most possible multipath geometries found in literature based on its formation.

## THE THEORY OF MULTIPATH ERROR

The multipath can be briefly described as the effect of GPS signals following different paths than the direct path entering a GPS receiver. The multipath error demonstrating distinctive effects depending on the surroundings in which the GPS observations are made can be divided into two different categories as electrical and geometrical (Minami et al., 1999).

Electrically studied, it was found that the electromagnetic signals reflected from objects or ground possess different refractivity indexes. An electromagnetic signal during multipathing should be considered for its two discrete properties. The first property stems from its wave shape propagation and the formation of different energy areas also known as Fresnel Zones. The second property results from its linear nature and conforms to Brewster angle representing the least angle value required for reflection to occur (Lau and Cross, 2007). High refraction index and low Brewster angle is usually the case for especially metal alloy materials in a multipath medium. This is why metal alloy spectacular surfaces are highly prone to cause multipath errors.

A right-hand circular polarized (RHCP) electromagnetic signal, as in GPS signals, changes its property after being reflected from a surface and turns into a left-hand circular polarization with a phase shift of 180° or left-hand elliptic polarization depending upon the incident angle (Bétaille et al., 2003). The basic purpose of signal processing and multipath filtering methods (receiver based techniques) is to separate the right-hand and left-hand polarized (true and reflected) signal.

Many methods and components have been hitherto developed in order to mitigate the effect of multipath error on GPS observations. They can principally be grouped as antenna based and receiver based techniques. In antenna based implementations, the basic idea is to protect the antenna from the reflected signals and to realize this metal ground planes obstructing the signals reflected from ground, and choke-ring antennas for side reflecting signals are developed as seen in Figure 1, depicting ground plane and choke-ring together (Sciré-Scappuzzo and Makarov, 2009; Ray, 1999; Falkenberg et al., 1988; Tranquilla and Carr, 1991). There is a dearth of research regarding multipath error formation using antennas with and without multipath protection (Kamarudin and Amin, 2004; Braasch, 1994)

Some of the receiver based technologies can be given as Narrow Correlator™ spacing (Dierendonck et al., 1992), Multipath Elimination Technique (MET™) (Townsend and Fenton, 1994), the Multipath Estimating Delay Lock Loop (MEDLL™) (Van Nee et al., 1994), Edge Correlator™ Technique (Garin et al., 1996), Strobe Correlator™, Enhanced Strobe Correlator™ (Garin and Rousseau, 1997) and Carrier-Phase Multipath Observable (Serrano et al., 2005).

Although these receiver based techniques attain some success in mitigating the multipath effect, it has been reported that all of these techniques fail when the distance between the reflecting surface and the receiver is less than 30 m (Weill, 1997). In other words, it has not been possible to thwart the multipath error in applications that the reflecting surface is in 30 m or closer vicinity to the receiver.

The geometrical aspects of the multipath effect formation need further understanding. Therefore, a detailed explanation of the multipath geometries is given in the following section.

## MULTIPATH GEOMETRIES

It will be appropriate to better understand the multipath error emerging incidentally and depending on many variables that divulge its formation patterns and limitations. Three multipath geometries play crucial roles in developing into multipath error, which are tested and their results are given in this study.

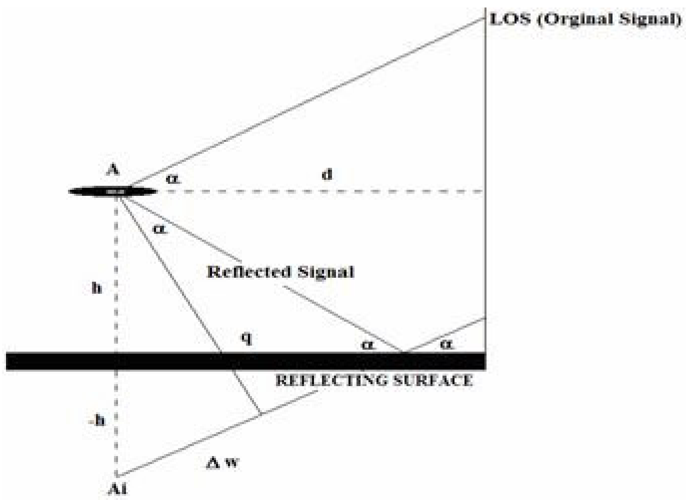


**Figure 2.** Forward scattering geometry

Multipath can be formed in many ways and patterns, however, the most common and effective three linear multipath geometries include; Forward Scatter (F-mode), Backscatter Geometry A (BA-mode) and Backscatter Geometry B (BB-mode). These geometries are also named as F-mode, BA-mode and BB-mode, respectively (Hannah, 2001).

## Forward scatter geometry (F-mode)

It occurs when the reflecting surface is beneath the receiver antenna. Since this is the case for low elevation satellites, it helps reduce the corrupting effect of multipath error on coordinates to select a cut-off angle above 10 degrees.

Forward scatter geometry represents the signals bouncing off the ground and moves forward to the receiver antenna (Smith and Burkholder, 2004) Figure 2 gives a clear demonstration of this geometry. In Figure 2, the GPS antenna is positioned at ‘A’ with ‘d’ horizontal distance farther away from the multipath borderline, ‘h’ the vertical distance up from the reflecting surface (ground) at an ‘α’ angle to line of sight (LOS) and ‘q’ distance perpendicular to the reflecting geometry.

In this geometry, the satellite signal that is reflected from the ground surface should cover an additional distance of Δw to reach A, and this additional distance Δw is given by

$$\Delta w = 2hSin\alpha \quad (1)$$

Also, the propagation distance of LOS signal coming from the right-hand reference borderline is computed by:

$$DA = \frac{d}{Cos\alpha} \text{ Thus, the new signal path} = DA + \Delta w \quad (2)$$

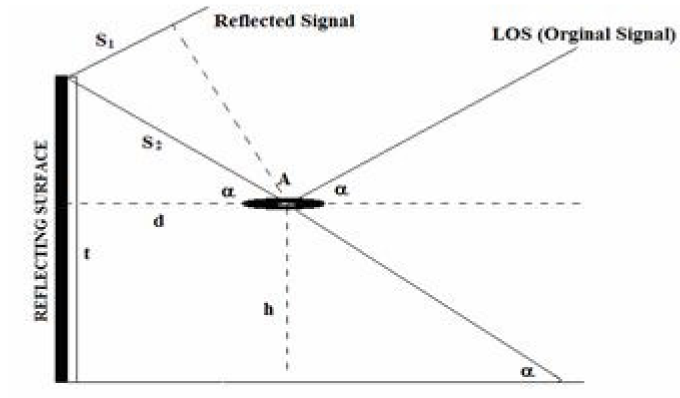


**Figure 3.** Backscattering geometry A (BA-mode).

For a reflecting surface, a vertical multipath borderline ‘h’ and ‘q’ the distance between point ‘A’ and the farthest point of the reflecting surface should be estimated, the following yields the maximum elevation angle ‘α’.

$$\alpha = Arc\tan(\frac{h}{q}) \quad (3)$$

This angle also defines the minimum angle at which the multipath occurs.

## Backscatter geometry A (BA-mode)

In this case, the GPS signals reach the receiver after bouncing off vertical or near vertical reflecting surfaces. In other words, the backscatter geometry A represents the satellite signals passing over the receiver and being reflected by the vertical reflecting surface at the back side of the line of sight direction and entering the receiver. Figure 3 depicts this multipath geometry clearly and here, 'd' is the distance between a vertical reflecting surface positioned within the left-hand borderline and the GPS antenna stationed at an arbitrary point ‘A’, α is the satellite elevation angle and ‘h’ the antenna height. In order for this geometry to occur, the following condition should take place (Hannah, 2001):

$$d > \frac{h}{\tan\alpha} \quad (4)$$

The place at which this mode is realized is referred to as “Zone 1”, and the additional distance covered in this Zone 1 denoted as $\Delta R_a$ is the sum of two distances $S_1$ and $S_2$ which are given by:

$$S_1 = \frac{dCos2\alpha}{Cos\alpha}, \; S_2 = \frac{d}{Cos\alpha} \quad (5)$$

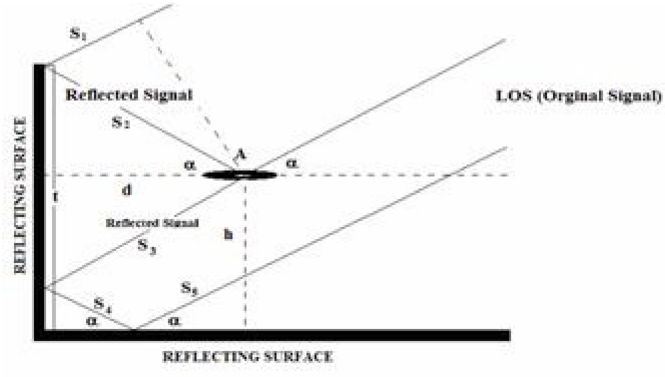


**Figure 4.** Backscattering geometry B (BB-mode).

and

$$\Delta R_a = S_1 + S_2 \tag{6}$$

The maximum satellite elevation can α be obtained is given as follows:

$$\alpha = Arc\tan\left(\frac{(t-h)}{d}\right) \tag{7}$$

Where t is the height of the vertical reflecting surface. Finally, it can be concluded that if the condition given in Equation 4 is not satisfied, then BA geometry is not maintained.

## Backscatter geometry B (BB-mode)

Backscatter geometry B can be considered as the combination of F and BA geometries. In this geometry, as well as Zone 1 where BA-mode occurs, a second region called "Zone 2" is also of interest for a GPS antenna positioned at point 'A' in'd' distance from the reflecting surface at 'h' height with the maximum elevation angle α as depicted in Figure 4. Zone 1 defines the signals coming from the vertical reflecting surface, while Zone 2 is used to describe the signals coming from first the horizontal and then the vertical surface.

The paths $S_1$ and $S_2$ are the same as in Zone 1 and given in Equation (5). On the other hand, for the paths $S_3$, $S_4$ and $S_5$, the signal which goes through in Zone 2 can easily be obtained from the geometry as clearly depicted in Figure 4:

$$S_3 = \frac{d}{Cos\alpha} \tag{8}$$

$$S_5 = 2dCos\alpha - \frac{hCos2\alpha}{Sin\alpha} \tag{9}$$

**Figure 5.** Bird's eye view of the network formed for the experiment (Courtesy of Google Earth™).

$$S_4 = \frac{h}{Sin\alpha} - \frac{d}{Cos\alpha} \tag{10}$$

Hence the additional distance covered both in Zone 1 and 2, respectively $\Delta R_a$ and $\Delta R_b$, are the sums of distances in each zone given as follows:

$$\Delta R_a = S_1 + S_2 \text{ and } \Delta R_b = S_3 + S_3 + S_5 \tag{11}$$

In the assumption that the receiver antenna is protected from the reflected signals below it, the minimum elevation angle, thus, will be predominantly within Zone 1. Then, the maximum elevation angle α is the same as the one given in Equation (7).

## EXPERIMENT AREA AND MATERIALS

The area depicted in Figure 5 in which all the multipath geometry experiments were conducted was chosen just outside a town called Saltukova at a 40 km distance to Zonguldak, located in Western Black Sea Region of Turkey, and is a field of 600 × 700 m that is free from any reflecting or obstructing objects.

First, in the experiment area, a test point was selected to set up the GPS antenna and to carry out all the multipath tests. Since this experiment was conducted to determine the multipath error performance of Real Time Kinematic (RTK) GPS method, a reference station with stable and reliable coordinates is required close to the test point, 185 m away from the test point to be exact. In selecting the reference point, the same criteria for the test point were observed. In order for the reference station and the test point to have high accuracy coordinates (used as the true/static coordinates later in the tests), a network was then established with the help of other two points, one of which is Kozlu and has ITRF96 coordinates and the other is Catalagzi with the first degree triangulation coordinates (Figure 5). These points were observed for 5 h with the reference station using static GPS observations and adjusted in a network design. Figure 6 depicts the experiment area and the positions of the reference point and the test point, or the rover station in RTK GPS jargon.

Steel pipes of 700 mm long with a 5 mm diameter were utilized for fixing the points into the ground in the experiments area, and


**Figure 6.** The experiment area and the locations of reference (stationary) and the test (rover) receivers (Courtesy of Google Earth$^{TM}$).

**Figure 7.** Vertical reflecting panel and its supporting bars and wheels.

also for anchoring the tripod feet to the ground.

To imitate the most challenging multipath surrounding, galvanized sheet irons of 2 × 1 m with 2 mm thickness were chosen for this experiment. Because all the three multipath geometries are to be tested, both the vertical and ground (horizontal) reflecting panels were prepared. First, four steel frames, each consisting of 3 × 3 m frames, were connected to make up the final one piece 6 × 6 m panel and then covered by the galvanized sheet irons. We then decided to keep the rover (test) receiver fixed during the tests, so as to evaluate the changes on coordinates reliably. Therefore, this vertical panel would have to move all the time in tests, and this led to add wheels and supporting bars to the panel (Figure 7). However, since it is not easy to move this big apparatus, weighing almost half a ton on a terrain covered with grass and soil, a pair of rail tracks made of steel is utilized to move the vertical panel on the ground easily.

For the reflecting ground (horizontal surface), 28 galvanized sheet irons of 2 × 1 m were placed on the ground wherever the test is to be made (Figure 8), which will be explained in detail in the following sections.

In tests two Z – Max Thales$^{TM}$ RTK GPS receivers (one for the reference and one for the rover station) were used to make all the observations (Figure 9).

The receivers used in the tests make use of a receiver based multipath mitigation technology called Enhanced Strobe Correlator$^{TM}$, which makes it difficult for reflecting signals to be accepted by the receiver beyond 30 m (Garin and Rousseau, 1997).

## Tests

All the tests were carried out in four days. On the first day (stage 1) non-multipath observations were made; on the second day (stage 2), however, the multipath tests commenced with F-mode

**Figure 8.** Horizontal reflecting surface.


**Figure 9.** Z –Max Thales™ receiver and hand-held control.

observations. Third day (stage 3) involves the BA-mode observations while BB-mode measurements were made on the fourth day (stage 4). The following details the tests stages.

### *Stage 1: Non-multipath observations*

The RTK GPS receivers were set up on the reference and rover (both fixed) stations whose coordinates were accurately computed by the network solution carried out before, and collected data for 8 h continuously between 10.00 and 18.00 h with 1 s interval without any reflecting surfaces around. The experiment direction is chosen to be 20° north-east and drawn on the ground in order to obtain the best possible multipath that the satellite-receiver geometry can present (Figure 10). This data set constitutes the control data for all comparison purposes.

### *Stage 2: F-mode multipath observations*

In the forward scattering multipath geometry (F-mode) observations, the horizontal reflecting surface of 52 $m^2$ was placed in a way that the test point constitutes its centre, and the receiver is set to collect RTK GPS data with 1 s interval as seen in Figure 11. After registering the data for 30 m, the reflecting surface was shifted 2 m in the direction determined previously and another data set was measured at this new position (2 m away from the point), repeating this procedure with 2 m distance increments to reach 10 m distance from the test point, in carrying all the sheet irons before each session, a gap of 15 min was allowed. Having collected data at 10 m distance, the distance increment is then changed to 10 m until the point 50 m was reached, that is, the same observations were repeated at 10, 20, 30, 40 and 50 m distances, again allowing a gap of 15 min before each session (Figure 11).

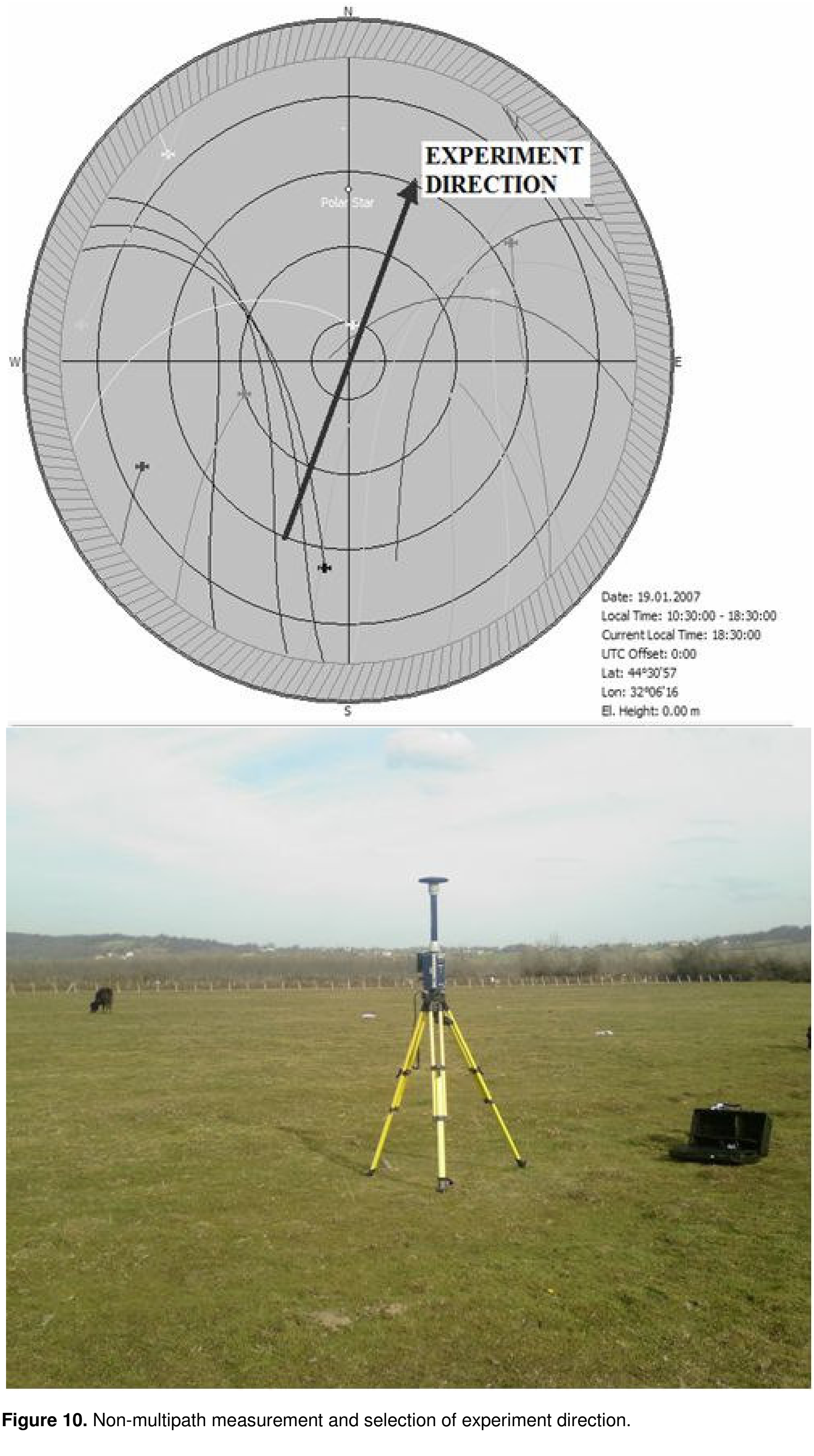


**Figure 10.** Non-multipath measurement and selection of experiment direction.

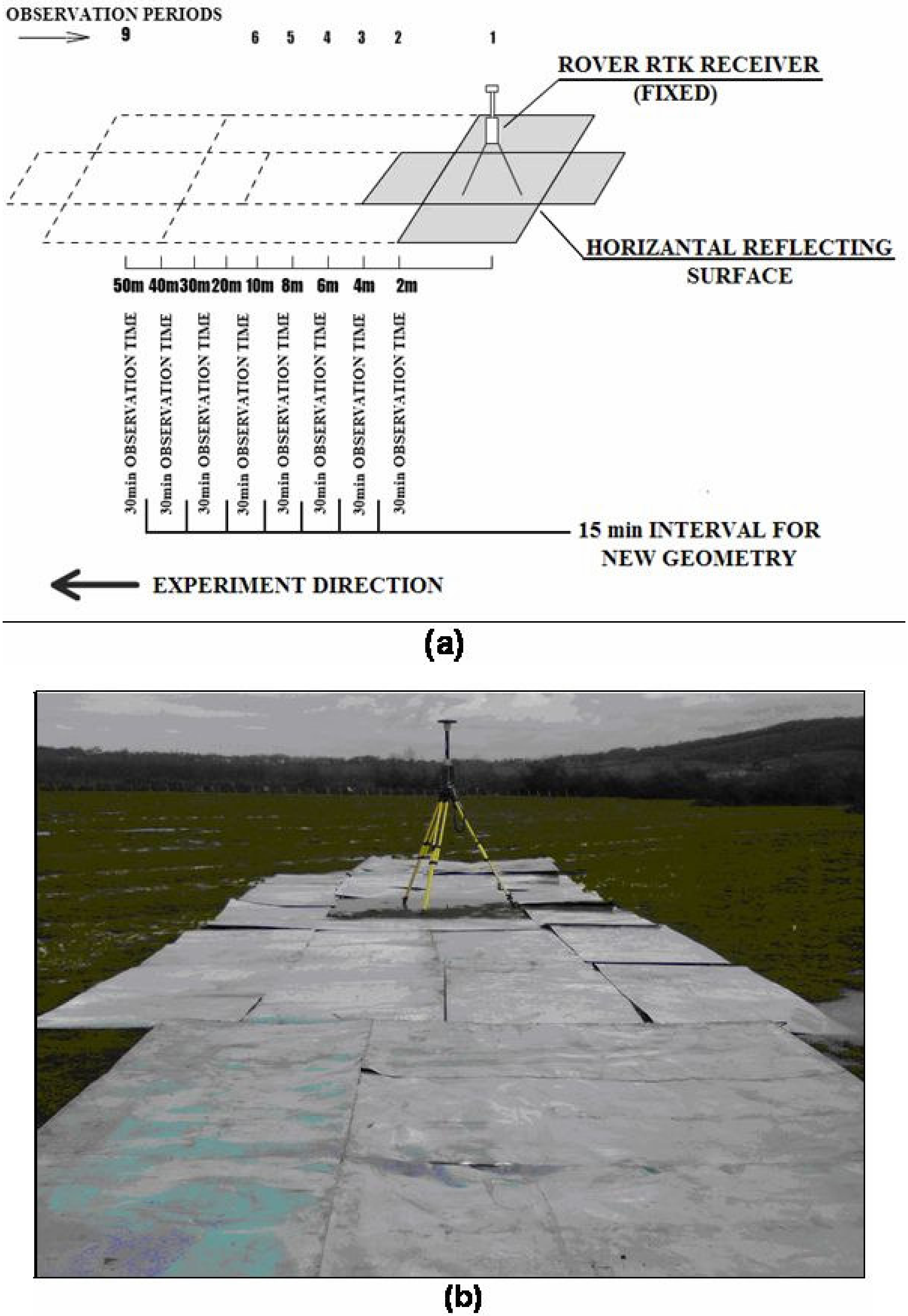


**Figure 11.** (a) Schematic representation of steps followed in F-mode observations. (b) F-mode test layout.

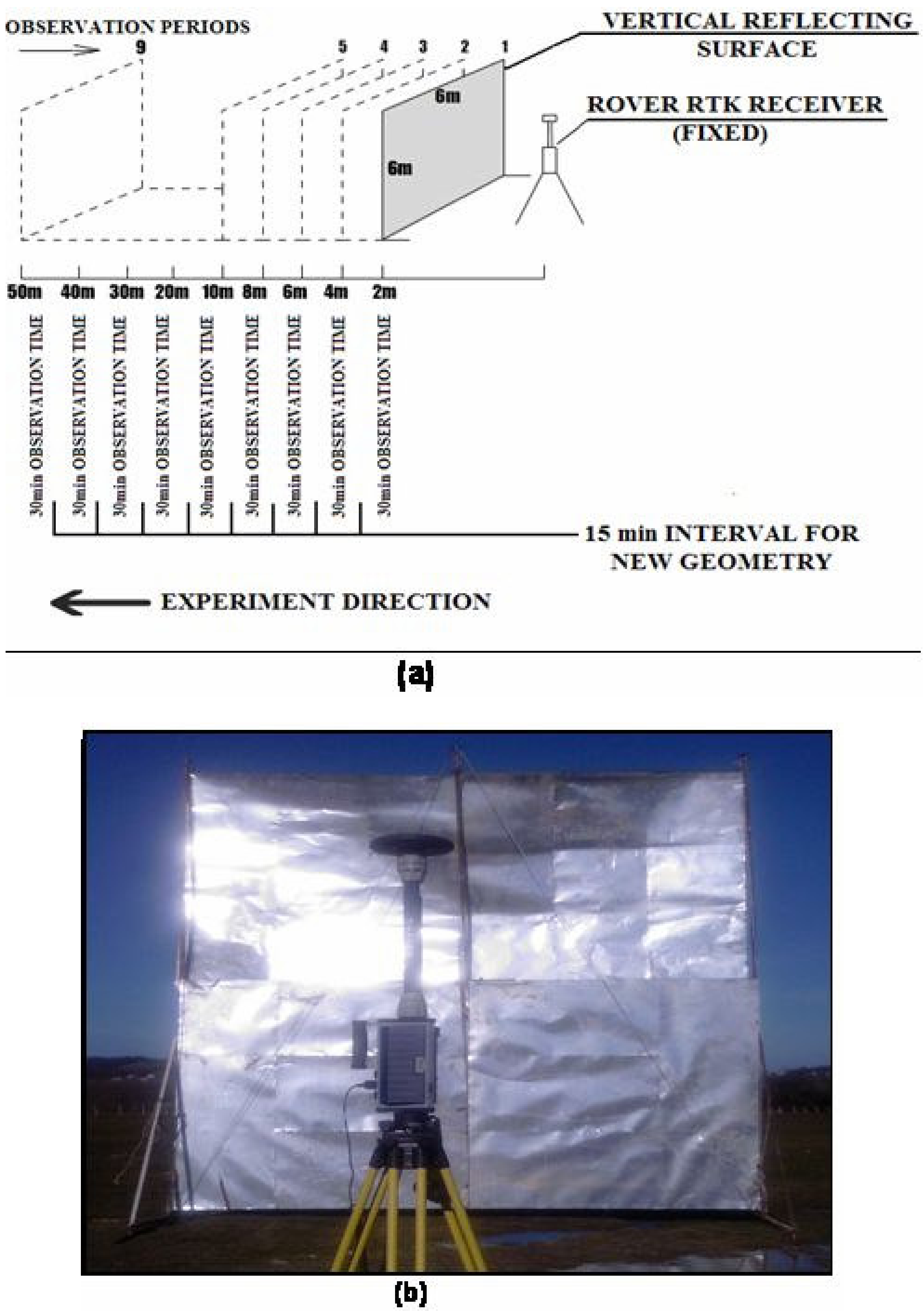


**Figure 12.** (a) Schematic representation of steps followed in BA-mode observations. (b) BA-mode test layout.

***Stage 3: BA-mode multipath observations***

The vertical panel of 36 $m^2$ was placed first at 2 m distance from the test point in the experiment direction for the backscattering multipath observations with 1 s interval and 30 min of data collection. As in stage 1, with the first 2 m distance increment, the observations were repeated until completion of data collection at 10 m distance and then with 10 m increment up to 50 m distance allowing a gap of 15 min before each session (Figure 12).

***Stage 4: BB-mode multipath observations***

Since the backscatter geometry B is the combination of F and BA geometries, both the horizontal (as used in F-mode) and the vertical panel (as used in BA-mode) are utilized in this test. The test was

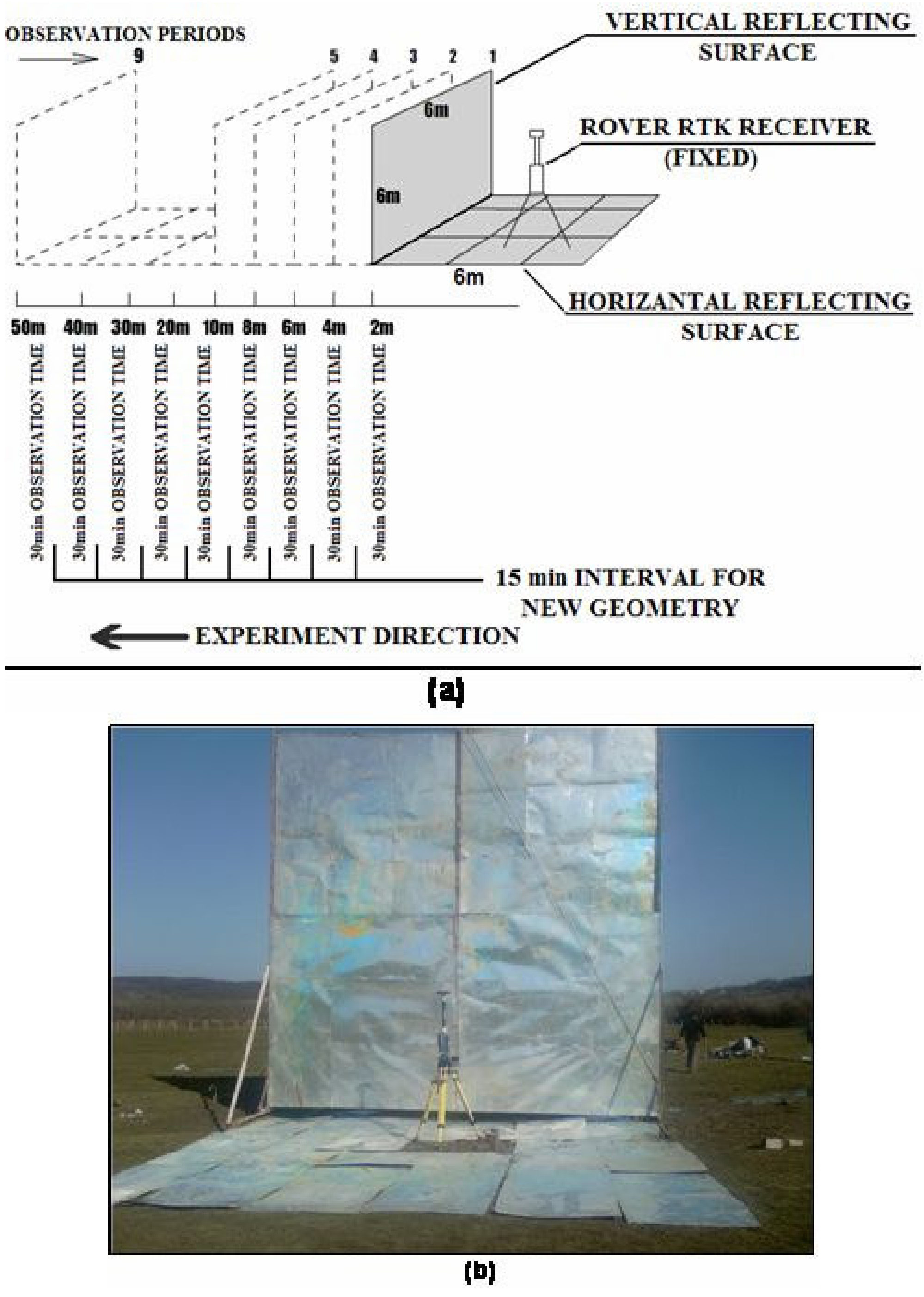


**Figure 13.** (a) Schematic representation of steps followed in BB-mode observations. (b) BB-mode test layout.

carried out in the same fashion as the F and BA modes (Figure 13).

## ANALYSES OF THE OBSERVATIONS

As long as the arrangement of satellite-reflecting surface-receiver is in appropriate position for the multipath effect, it will contribute towards the error budget of the observations due to the nature of this effect. In this experiment, the data were obtained for one non-multipath environment and three different multipath geometries under the same satellite-reflecting surface-receiver position, each completed in one day with nine sessions of observations. Since most of multipath errors is geometry dependent

(Ray and Cannon, 1999), all the GPS measurements on non-multipath and multipath areas were collected under the same number of satellites and the same satellite configuration. This means that every test day commenced four minutes earlier than previous day because all the satellites complete their full rotation around the earth in 11 h and 58 min, twice a day, hence four minutes ahead of the earth rotation in 24 h. In other words, each test day is made to correlate the observations of previous day, and the magnitude of the day-to-day correlation is typically found to be around 85% (Radovanovic, 2000), depending on how static the reflective environment is.

After the dataset collected for four days were superposed to maintain the same satellite configuration, the observations obtained under the multipath geometries were investigated by comparing them with the non-multipath observations (control group) and the positions from the static observations. The double differences were utilized in the analyses, since the atmospheric (ionospheric and tropospheric) effects, satellite-receiver clock offsets and orbit errors were cancelled out for short baselines (here < 1km) GPS observations (Collins and Langley, 1996; Grejner-Brzezinska et al., 1998).

As far as the multipath and non-multipath observations are concerned, since the only difference between them is the presence or absence of reflecting panels (both vertical and horizontal), one can deduct that the difference between these data is assumed to emerge from the multipath error plus random error. As for the multipath errors, the erroneous zones were marked where the geometry is prone to produce multi- path errors after all reflective-receiver-satellite configurations were individually studied using the graphs from the analyses. The rest of the zones were accepted to be only corrupted with random errors. However, when comparing the results from the multipath geometries to the ones from the control data, the difference still significantly represents the multipath errors since the same random errors occur during the control observations and is presumed to cancel out on differencing.

In order to see the differences between the static (true) and multipath coordinates of the test point, the initial changes were charted against three coordinate components, namely X, Y and Z (Figures 14a, b and c).

The results indicate that the changes in X and Y coordinates are greater than those in Z coordinates. Furthermore, the BB geometry seems to produce more multipath errors than the other multipath geometries. Another interesting finding is that almost all of the outstanding multipath errors in all three geometries occur in the first 6 m distance to the reflecting source. As for the control coordinates, that is, the RTK GPS results obtained in a non-multipath surrounding, they are quite in line with the true coordinates as expected.

For comparison purposes, in lieu of drawing three graphs for each coordinate component, the authors decided to compute positional errors using the coordinate differences between the coordinates from each multipath geometry and the true (static) coordinates, and to demonstrate them in one graph. The positional error is given by:

$$m_i = \sqrt{(dX_i)^2 + (dY_i)^2 + (dZ_i)^2}$$

Where $dX_i$, $dY_i$ and $dZ_i$ are the coordinate difference between the true coordinates and the coordinates obtained from multipath geometries, hence the subscript 'i' represent the multipath geometries. The graph given in Figure 15 is drawn with these positional errors of the multipath geometries. Figure 16 is presented in order for the reader to easily observe the behavioral changes of the geometries in a smoothed trend in which Figure 15 is smoothed to the fifth degree polynomial.

Having studied all the results, whether they are charted against their coordinate differences or against their positional errors, Backscattering geometry B (BB geometry) stands out to produce more multipath errors than any other geometry. Since the BB geometry at 2 m distance is more prone to this error than the rest, it is beneficial to see the positional errors solely, for this geometry in detail. Therefore, Figure 17 is given to this effect and the positional errors of the reference (control) observations are also included in the graph to see the change clearly.

## CONCLUSİONS AND SUGGESTİONS

It is only fair to admit that the multipath errors encountered in the tests are not the ordinary multipath creating surroundings, especially the geometries and the materials utilized. In other words, the RTK GPS receiver is forced to its limits in terms of multipath mitigation capabilities. Nevertheless, since the material used for reflecting panels is a galvanized sheet iron and has a very high reflecting property, it is possible to say that the engineers making use of RTK GPS observations can only come across similar conditions in particular observation sites such as urban canyons with shiny glass walled buildings, construction sites, container ports and industrial sites.

The results from the tests conducted in three possible multipath geometries indicate that the largest multipath error is approximately 6 cm. However, the average magnitude for multipath error in positions was found to be 1 - 3 cm in an ordinary urban surrounding without any obstruction in sky visibility with an ideal satellite configuration. The Real Time Kinematic GPS method is readily applicable to any engineering and surveying tasks that this positional accuracy is acceptable.

It is expected that the longer the distance to the reflecting surface, the longer the range between satellite and receiver, thus causing increase in total positioning error. However, irregular behavior in multipath error budget is observed in increasing the reflecting surface-receiver distances (Figures 14a, b, c and 15). In other

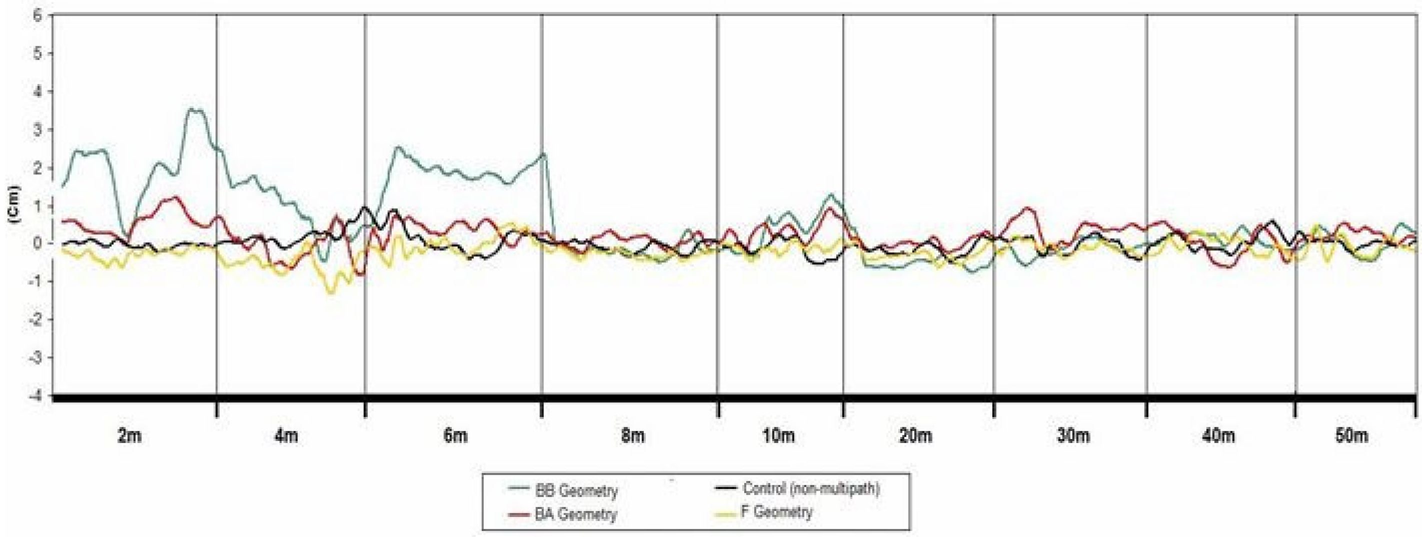


**Figure 14a.** Changes in X coordinates.

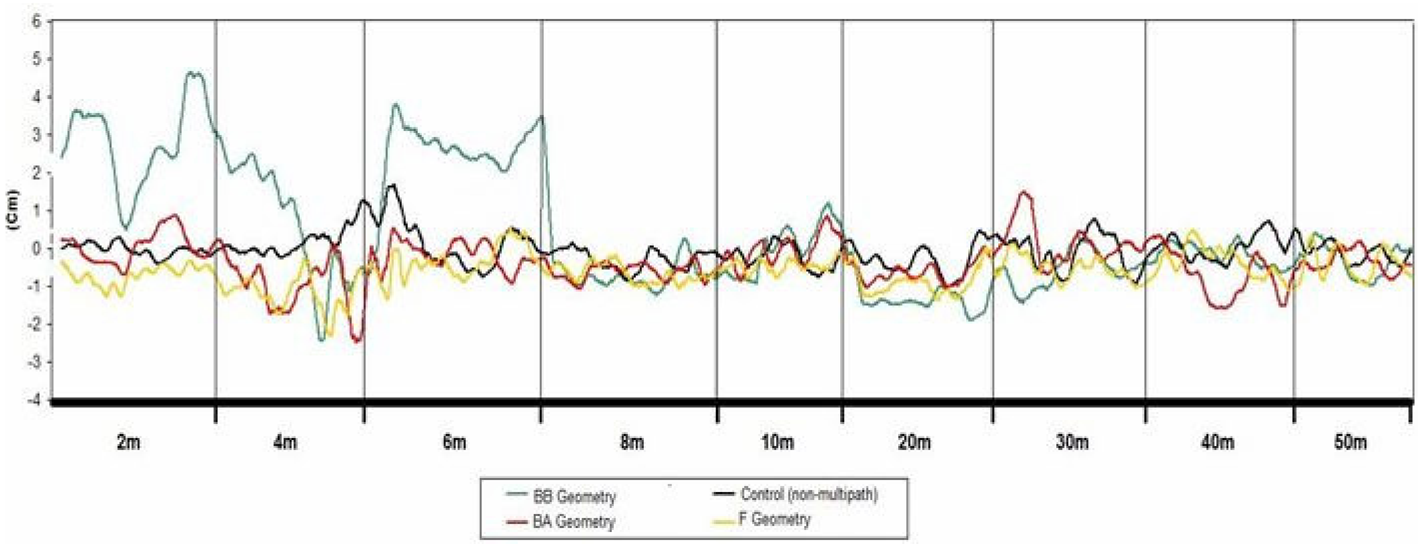


**Figure 14b.** Changes in Y coordinates.

words, the similar positional values to the control measurements were obtained from all the multipath geometries in distances over 30 m. This can be interpreted as a consequence of multipath mitigation techniques adopted by the GPS receivers.

Another finding from the tests is the extraordinary multipath errors encountered in BB geometry especially in first 6 m. An attempt to explain this should include the characteristics of signal propagation. As explained in section 2, a right-handed circular polarized GPS signal is converted to a left-hand circular polarized signal after being reflected from a surface. The satellite signal is however, reflected twice before entering a receiver in BB multipath geometry, therefore, returning to its original form, that is, the right-handed circular polarization. In this case, the receiver finds it hard to notice this multipathed signal and uses it to compute its erroneous position.

In addition to the findings mentioned before, the authors find it beneficial to include some information and pointers to mitigate multipath errors as follows:

1. Positional error theoretically stemmed solely from multipath error in RTK GPS positioning is usually not greater than 5 cm.
2. Receiver based multipath mitigation filters may not detect multipath error when the distance between the

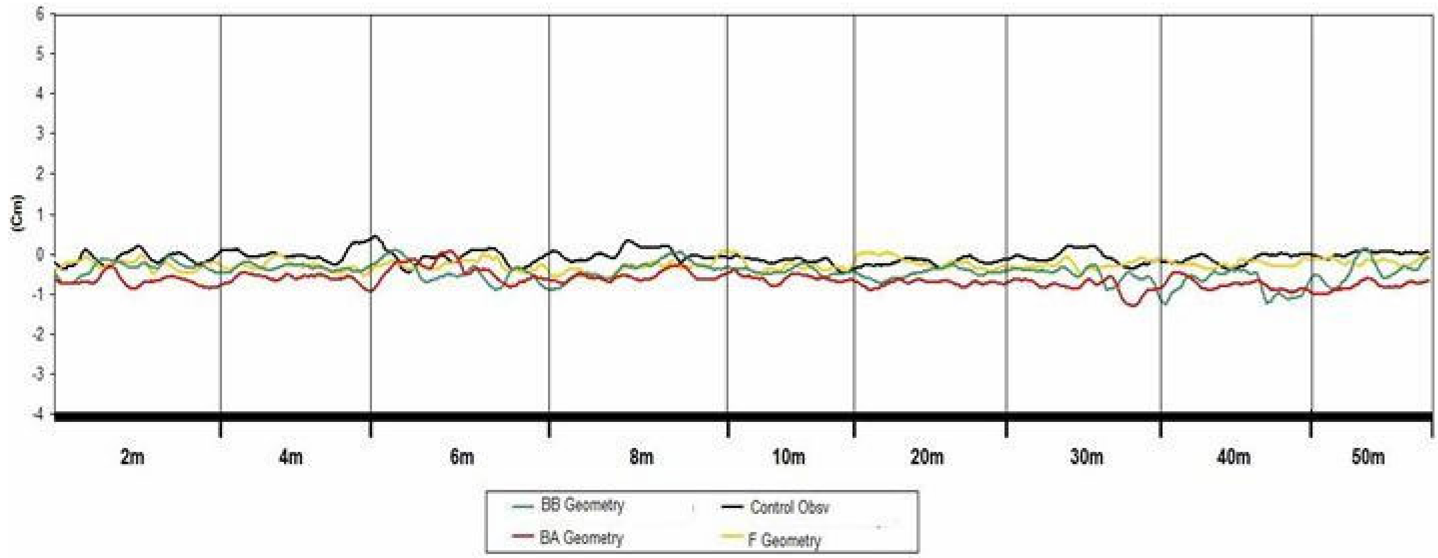


**Figure 14c.** Changes in Z coordinates.

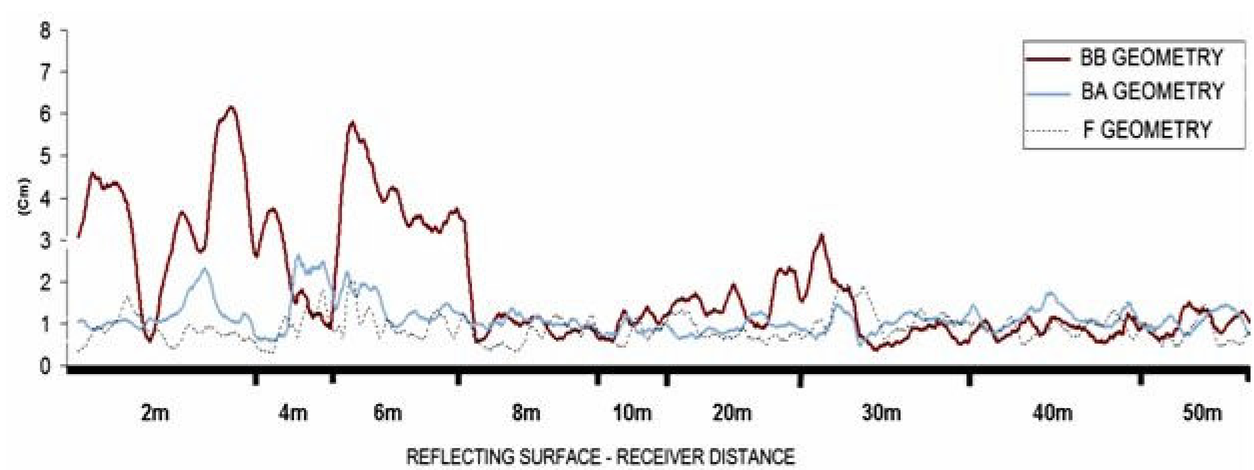


**Figure 15.** Positional errors of multipath geometries.

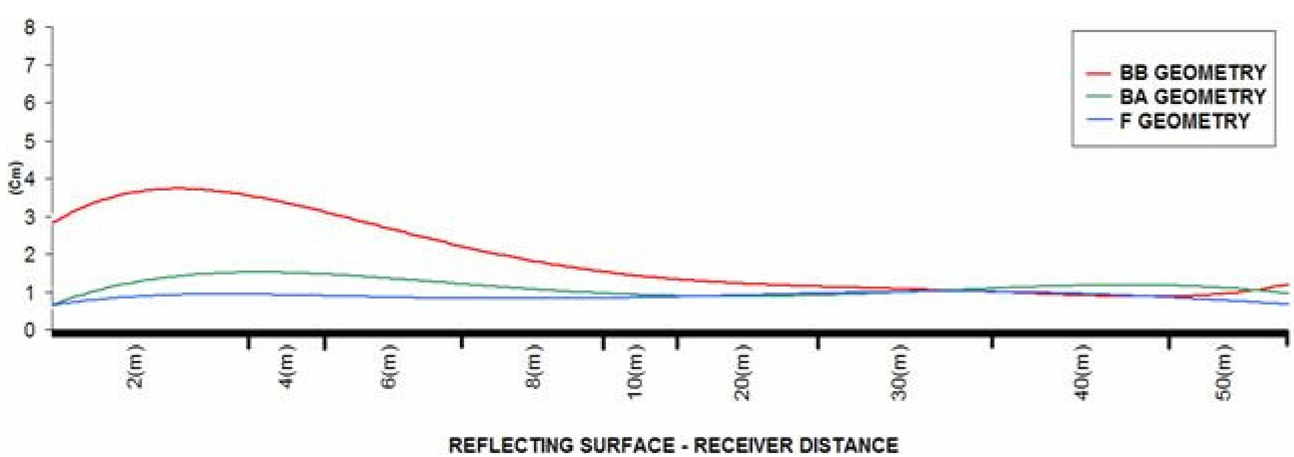


**Figure 16.** Smoothed graph for the positional errors of multipath geometries.

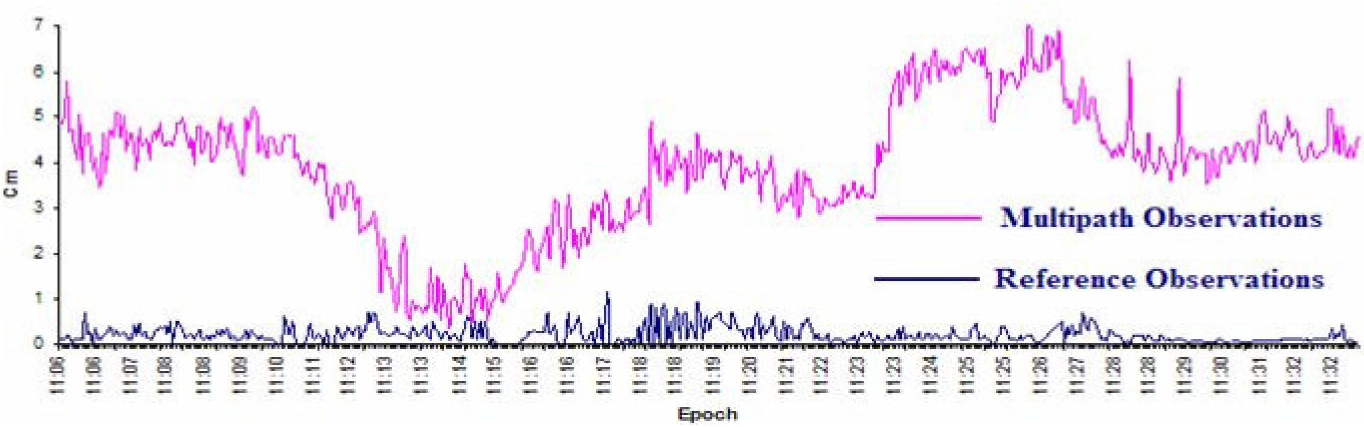


**Figure 17.** Positional errors from BB geometry and reference observations at 2 m distance to the panels.

receiver and reflecting surface is less than 30 m.

3. Ground plane and choke-ring antennas are strongly effective for all F geometry multipath errors.

4. When positioning in an environment with high reflecting materials as in industrial surveying, it is better to stay away from any geometries susceptible to BB and BA type multipath errors.

6. It is advisable to make RTK GPS observations at a distance that is longer than the height of the vertical reflecting surface when the observation surrounding conforms to BB geometry.

For all RTK GPS observations carried out in urban canyons, it is crucial to take notice of all the reflecting surfaces around the observation point, the distance to these surfaces and the geometry they form, and if possible, to change the location of the point to where the multipath error is least likely to occur. When positioning with high accuracy expectations (2 cm or less), it is also better to keep it under advisement to study the locations of the reflecting surfaces and satellite configurations so as to carry out a multipath error investigation before conducting GPS observations.

## REFERENCES


Abbot E, Powell D (1999). Land-Vehicle Navigation Using GPS. Proceedings IEEE, 87: 145-162.

Ai-gong X, Keck-voon L, Law CL, Dong-kai Y (2003). In-Vehicle GPS/DR Navigation System Development and Test Results in Singapore. Wuhan Univ. J. Nat. Sci., 8: 544-550.

Avallone A, Briole P, Agatza-Balodimou AM, Billiris H, Charade O, Mitsakaki C, Nercessian A, Papazissi K, Paradissis D and Veis G (2004). Analysis of eleven years of deformation measured by GPS in the Corinth Rift Laboratory area. Comptes Rendus Geosci., 336: 301-311.

Bétaille D, Maenpa J, Euler H-J, Cross PA (2003). New approach to GPS phase multipath mitigation. In: Proceedings of ION national technical meeting, Anaheim, California, USA; pp. 243-253.

Braasch MS (1994). Isolation of GPS Multipath and Receiver Tracking Errors, Navigation: J. Inst. Navig., 41: 415-434.

Braasch MS, Van Graas F (1991). Guidance accuracy considerations for realtime GPS interferometry. ION GPS-91; Proceedings of the 4th International Technical Meeting of the Satellite Division of the Inst. of Navig., Albuquerque, NM; USA; pp. 11-13.

Collins P, Langley R (1996). Limiting Factors in Tropospheric Propagation Delay Error Modelling for GPS Airborne Navigation. Presented at the Inst. of Navig. 52nd Annual Meeting, Cambridge, Massachusetts, USA.

Dierendonck AJ, Fenton P, Ford T (1992). Theory and Performance of Narrow Correlator Spacing in GPS Receiver. Navigation: J. Inst. Navig., 39: 265-293.

Falkenberg W, Kielland P, Lachapelle G (1988). GPS Differential Positioning Technologies for Hydrographic Surveying, Proceedings of IEEE PLANS, Orlando, USA, pp. 310-317.

Garin L, Van Diggelen F, Rousseau J (1996). Strobe and Edge Correlator Multipath Mitigation for Code, Proceedings of ION GPS-96, Kansas City, USA, pp. 657-664.

Garin L, Rousseau J (1997). Enhanced Strobe Correlator Multipath Rejection for Code and Carrier. Proceedings of ION GPS-97, September 16-19, Kansas City, USA, pp. 559-568.

Grejner-Brzezinska DA, Da R, Toth C (1998). GPS error modeling and OTF ambiguity resolution for high-accuracy GPS/INS integrated system. J. Geod., 72: 626-638.

Hannah BM (2001). Modeling and simulation of GPS multipath propagation, Ph D thesis, Queensland University of Technology, Australia.

Ince CD, Sahin M (2000). Real-time deformation monitoring with GPS and Kalman Filter. Earth Planets Space, 52: 837-840.

Kamarudin MN, Amin Z M (2004). Multipath Error Detection Using Different GPS Receiver's Antenna. Proc. of 3rd FIG Regional Conference, Jakarta, Indonesia.

Kim D, Langley RB (2001). Mitigation of GPS Carrier Phase Multipath Effects In Real-Time Kinematic Applications, ION GPS, Salt Lake City, UT, USA, pp. 2144-2152.

Kim D, Langley R (2002). On Ultrahigh-Precision GPS Positioning and Navigation. ION GPS 2002: 15th International Technical Meeting of the Satellite Div. of The Inst. of Navig.; Portland, OR, USA.

Lau L, Cross P (2007). Development and testing of a new ray-tracing approach to GNSS carrier-phase multipath modelling. J. Geod., 81: 713-732.

Mekik C, Arslanoglu M (2009). Investigation on Accuracies of Real Time Kinematic GPS for GIS Applications. Remote Sensing, 1: 22-35.

Minami M, Morikawa H, Aoyama T, Mizumachi M (1999). An adaptive multipath estimation /elimination technique for GPS signals reception. Trans. Inst. Electron. Info. Commun. Eng. BI. 11: 2043-2050.

Radovanovic R (2000). High Accuracy Deformation Monitoring via Multipath Mitigation by Day-To-Day Correlation Analysis. 13th International Technical Meeting of the SAT Division of the ION, Salt Lake City. USA.

Ray JK (1999). Use of Multiple Antennas to Mitigate Carrier Phase

Multipath in Reference Stations. ION GPS ’99, Nashville, TN, USA.
Roberts G, Meng X, Meo M, Dodson A, Cosser E, Iuliano E, Morris A (2003). A Remote Bridge Health Monitoring System Using Computational Simulation and GPS Sensor Data. Proceedings, 11th FIG Symposium on Deformation Measurements, Session I2, Santorini, Greece.
Sciré-Scappuzzo F, Makarov SN (2009). A Low-Multipath Wideband GPS Antenna With Cutoff or Non-Cutoff Corrugated Ground Plane. IEEE Trans. Antennas Propag. 57: 33-46.
Serrano L, Kim D, Langley RB (2005). A New Carrier-Phase Multipath Observable for GPS Real-Time Kinematics Based on Between Receiver Dynamics." Proceedings of the 61st Annual Meeting of the Inst. of Navig., Cambridge, MA, USA; pp. 1105-1115.
Smith JR, Burkholder RJ (2004). Channeling Phenomenon in Electromagnetic Forward Scattering at Low Grazing. IEEE Trans. Geosci. Remote Sens., 42: 1731-1738.
Tiryakioğlu I, Taktak F, Cetintas F (2006). GPS Signal Multipath Error and Elimination Methods (in Turkish). Yapi ve Teknolojileri Elektronik Dergisi, 2: 35-41.
Townsend B, Fenton P (1994). A Practical Approach to the Reduction of Pseudorange Multipath Errors in a L1 GPS Receiver, Proceedings of ION GPS-94, Salt Lake City, USA, pp. 143-148.
Tranquilla J, Carr J (1991). GPS Multipath Field Observations at Land and Water Sites. NAVIGATION, J. Inst. Navig., 37:393-414.
Van Nee R, Fenton P, Townsend BR (1994). The Multipath Estimating Delay Lock Loop Approaching Theoretical Limits”, in IEEE PLANS 94, Las Vegas, USA.
Weill LR (1997). Conquering Multipath: The GPS Accuracy Battle, Innovation, GPS World, 8: 59-66.
Xia L (2004). Multipath in GPS Navigation and Positioning; GPS Solutions, 8: 49-50.