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MULTIPATH AND MULTIPATH REDUCTION IN THE OBSTRUCTED AREAS BY USING ENHANCED STROBE CORRELATOR (ESC) TECHNIQUE

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Preliminary notes

Despite advances in GPS equipment installed at permanent sites, multipath still remains a significant error source. Strobe Correlator technology greatly reduces GPS multipath signals, which can occur when the GPS signals are reflected off tall buildings or other obstructions before captured by the receiver and, thus, increase the distance a signal travels and reduce the accuracy. A GPS receiver using Strobe Correlator performs a series of complex calculations to restore positioning accuracy. I present a technique for evaluating and correcting the multipath at GPS antenna by utilizing the Enhanced Strobe Correlator (ESC) especially in RTK GPS applications. The advanced technique of Enhanced Strobe Correlation is discussed here. In addition, the performance of the technique is presented with the experiments from real multipath environments comparing RTK GPS results with terrestrial ones.

Keywords: *accuracy; ESC performance; GPS; multipath*

Višestaznost i višestazna redukcija u ometanim područjima pomoću ESC tehnike

Prethodno priopćenje

Unatoč poboljšanja GPS opreme postavljene na trajnim mjestima, višestaznost i dalje ostaje značajan izvor grešaka. Tehnologija Strob Korelatora značajno smanjuje GPS višestazne signale koji se mogu pojaviti kad se GPS signali reflektiraju od visokih zgrada ili drugih zapreka prije nego ih prijemnik uhvati, i na taj način povećavaju udaljenost koju signal prelazi te smanjuju točnost. GPS prijemnik sa Strob Korelatorom obavlja niz složenih proračuna kako bi odredio točnost položaja. Ovdje prezentiram metodu za procjenjivanje i ispravljanje višestaznosti kod GPS antenna primjenom Poboljšanog Strob Korelatora (ESC) naročito u RTK GPS aplikacijama. Ovdje se raspravlja o unaprijeđenoj tehnici i performansama ESC, uz eksperimente u stvarnom višestaznom opruženju i usporedbu RTK GPS rezultata i onih na zemlji.

Ključne riječi: *ESC performase; GPS; točnost; višestaznost*

1 Introduction

Multipath is exactly what it sounds like – a signal that travels more than one path. When GPS radio waves propagate from the GPS satellite toward the receiving antenna, it is possible for the incoming radio signal to travel more than one path via reflection, diffraction, or scattering. Reflection occurs when an electromagnetic wave hits an object (such as the surface of the earth, a building, a car, etc.) whose dimensions are larger than the incoming signal's wavelength. Diffraction occurs when the incoming signal bends upon interaction with an obstacle in its path. Scattering occurs when the incoming signal travels through a medium filled with objects which are small (such as leaves on a tree) compared with the signal wavelength. All of these phenomena contribute to multipath because each results in signals which travel along paths other than the line-of-sight path GPS signals. The analysis of the multipath can be performed by examining the associated S/N ratio as a function of elevation angle and time for each satellite. Therefore, there is a big difference in the value of S/N between the reference station at the multipath-free environment and the rover station at multipath environment. GPS satellites have an orbital period of about 23 hours 56 minutes. Multipath is receiver-satellite geometry dependent, hence the effect of the multipath error on positioning will generally be identical on a daily basis for the same baseline. Furthermore, the value of delta pseudo range and the rate of delta pseudo range can be changed by the effect of multipath error on the pseudo range. If the delay of the multipath is less than two PRN code chip lengths, the internally generated receiver signal will partially correlate with it. If the delay is greater than 2 chips the correlation power will be negligible. The multipath is a serious error source for both the static and the kinematic GPS positioning measurements. In case of the real-time kinematic positioning, it is difficult to specify multipath because it comes from any direction and reaches an antenna via more than one path. The goal of this paper is to present and investigate the latest advances in Ashtech multipath rejection technology, the Enhanced Strobe Correlator (ESC). For this purpose, real-time kinematic GPS results of Ashtech Z Max GPS observations were analyzed in the multipath environment on two successive days [2, 3, 4, 7, 14].

2 Multipath

When the signal has multipath the correlation peak in the receiver is deformed. With a deformed peak, the receiver will be tricked into thinking that it received the signal at a different instance of time than it actually did and the pseudo range it calculates will have an error. The positioning accuracy will be degraded due to multipath signal. Pseudo range and carrier phase multipath errors are the last dominant errors in differential positioning and assume significance in high precision positioning applications. The multipath errors can range from a few meters to a few tens of meters in pseudo range and up to a few centimetres in carrier phase measurements. Receiver manufacturers have invented various multipath mitigation schemes with varying degree of successes. In general, more research work has been done to mitigate pseudo range multipath errors than those associated with the carrier phase. In comparison with pseudo range multipath, only a limited number of carrier phase multipath mitigation techniques are available today. Unlike pseudo range multipath effects, the carrier phase multipath does not have a strong signature in the GPS signal observables and, therefore, are difficult to mitigate. Furthermore, the maximum carrier phase multipath error does not exceed one-quarter of a carrier cycle or 4,75 cm for the L1 carrier. The fundamental way to reduce both code and carrier multipath effects is to increase the chipping rate. For example, if the C/A code chipping rate can be increased to the level of P code chipping rate, then the multipath error will be reduced by almost an order of magnitude [2, 3, 4, 7, 14].

2.1 Multipath MP1 and MP2

The two terms (MP1 and MP2) show daily RMS values of L1 and L2 pseudo range multipath for P-code observations, respectively. The RMS values are computed by forming a linear combination of the GPS carrier and phase data. For both MP1 and MP2 the final daily multipath RMS value is the average of the RMS values for all satellites. Although the term multipath is used to describe these derived values, other factors are also influencing the results as well as multipath. They include things such as receiver noise and residual ionospheric delay that has not been completely removed from the formed linear combination [2, 3, 5, 7].

3 Multipath mitigation and detection techniques

The techniques for rejecting the reflected signals are known as multipath mitigation. Significant work has been done to reduce the multipath effects using various methods up to now. For last decade, signal processing techniques have been invented to reduce multipath error. One of the well-known techniques is the narrow correlator and the other is the strobe correlator. In this chapter the theory behind different multipath mitigation like strobe correlator and enhanced strobe correlator techniques is explained. From a practical point of view, these correlators can significantly reduce multipath error. However, the short-delay multipath error is not efficiently mitigated [1, 3, 4, 5, 6].

3.1 Strobe correlator

The strobe correlator was developed by Ashtech in 1996 and involves a linear combination of two narrow correlator discriminator functions. Another type of correlator that makes use of the additional two arms is the strobe correlator, which employs a double delta discriminator. In this correlator, there are two pairs of early and late correlator arms, with each pair spaced at typically 0,1 and 0,2 of a C/A-code chip. Typically in a receiver the early-minus-late correlation value is used as an input for the code tracking loop. The result is a discriminator function which is very narrow and thus is significantly less susceptible to medium and long delay multipath. Strobe correlator technology greatly reduces GPS multipath signals, which can occur when, reflected off tall buildings or other obstructions before reaching the receiver, increasing the distance a signal travels and reduces accuracy. A GPS receiver using strobe correlator performs a series of complex calculations to restore positioning accuracy [1, 8, 9, 10, 11, 12, 13, 14].

3.2 Enhanced Strobe Correlator (ESC)

For most practical purposes the Enhanced Strobe Correlator exhibits true P-code-like multipath characteristics. Specifically, it is virtually insensitive to multipath with delays longer than 50 meters. The Enhanced Strobe Correlator (ESC) is the latest of the Ashtech Multipath Rejection Technologies. The method implements a C/A code and C/A carrier phase multipath error rejection. The Ashtech Z Max GPS receiver implements the latest advances in Ashtech Multipath Rejection Technology: the Enhanced Strobe Correlator. This correlator significantly improves multipath mitigation over the traditional correlator schemes such as standard (1-chip) or narrow (1/10 chip) correlator spacing. The Enhanced Strobe Correlator works properly in any kind of multipath environment regardless of the number of multipath signals present and low SNR environment. In real applications, multipath is usually a combination of many reflections, all with different delays and power. Real-life multipath is often described either close-in multipath or far multipath. Close-in multipath occurs when the reflecting surface is close to the antennas direct line and the delay is small. Reflections come from a surface near the antenna, for example, an antenna attached to a tripod would pick up close-in multipath from reflections from the ground. Very close-in multipath causes only a small change in the ideal correlation function, so it is almost impossible for the correlator-base multipath integration to completely compensate for this error. In order to completely compensate close-in multipath, choke-ring antennas should be used with the Enhanced Strobe Correlation technique. Far multipath can cause very large errors if a good multipath mitigation technique is not used. Far multipath occurs when there is a reflecting surface at some distance from the antenna, such as building, a mast, a mountain, etc. Metal surfaces cause the strongest reflections. Far multipath signals can be mostly eliminated by good correlator-based multipath mitigation techniques. In the following section, we will focus on the tremendous improvements from which the RTCM differential users and RTK users will benefit [1, 8, 9, 10, 11, 12, 13, 14].

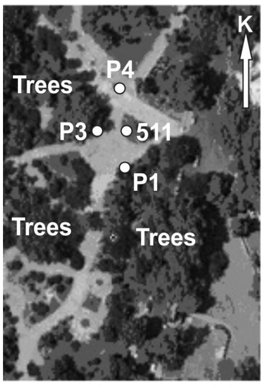

Figure 1 Project area and GPS network in the project area

4 Data capture

4.1 GPS observations and site condition

The experiment was carried out to investigate the accuracy analysis of the Ashtech Z Max GPS receivers

(RTK GPS technique with ESC and without ESC) in the severe multipath environment (near the trees, Fig. 1). For this purpose, four points (511, P1, P3 and P4) were located in the project area (Yildiz region of Istanbul, see Fig. 1, Tab. 1).

Table 1 Coordinates and the standard deviations of the reference point

	X_{ITRF} (m)	Std (mm)	Y_{ITRF} (m)	Std (mm)	Z_{ITRF} (m)	Std (mm)
ISTA	4208830,275		2334850,326		4171267,254	
511	4212735,954	10	2336037,223	10	4166617,765	15

The reference point (511) was mounted on the clear part of the obstruction region (no trees) (Figs. 1 and 2a). However, the rover point (P1) was mounted under the indeciduous tree, which could cause multipath effects (Figs. 1 and 2a). P3 has been obstructed by a deciduous tree (Figs. 1 and 2b). P4 was mounted on with no obstruction region very close to 511 (Figs. 1 and 2a).

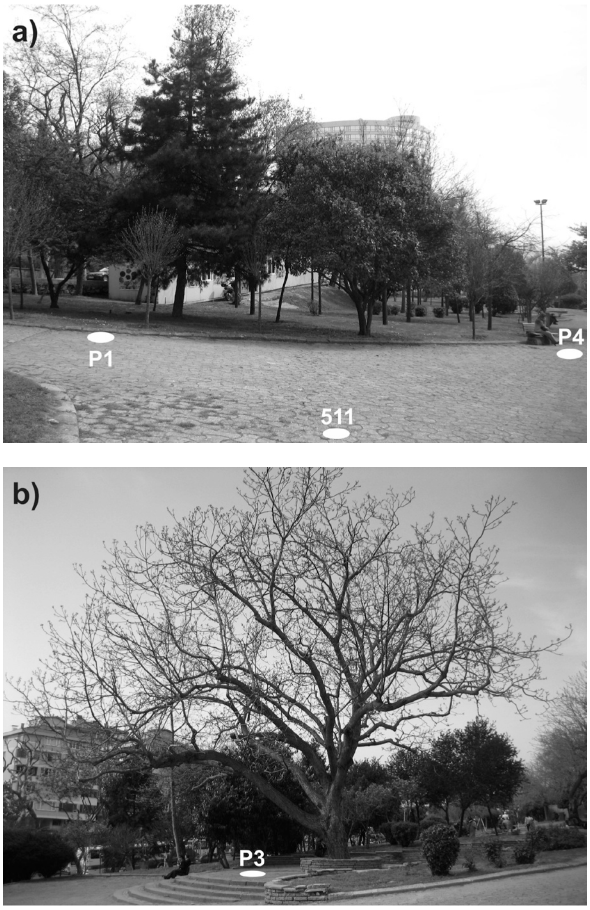

Figure 2 All of the four points in the project area

5 Data processing and analysis

5.1 Evaluating the effect of the multipath mitigation (enhanced strobe correlator technique)

Ashtech Z Max GPS receiver tests were carried out with ESC and without ESC. The data was analysed by TEQC (TEQC is a toolkit for GPS/GLONASS/SBAS data used to solve many pre-processing problems with GPS, GLONASS and SBAS data) software in order to evaluate the GPS data quality on both days. The quality check (QC) portion is for quality checking of kinematic dual-frequency data. In this portion, linear combinations of the pseudo range and carrier phase observations are used to compute (1) L1 pseudo range multipath for C/A or P-code observations, (2) L2 pseudo range multipath for P-code observations, (3) ionospheric phase effects, and (4) the rate of change of the ionospheric delay. Summary report files are created with information about site multipath, receiver signal-to-noise ratios, ionosphere, satellite elevation and azimuth angles, and other useful parameters and statistics. The multipath and signal-to-noise ratio report files are especially important for the assessment of site-specific (environmental and instrumental) errors that have implications on the accuracy of site position results. Data from any GPS receiver can be checked out if they are in RINEX (Receiver Independent Exchange) format or any of a variety of native binary formats. The information which particular satellites are causing the multipath oscillations is an important task for the understanding of their geometry at the GPS site. In addition, TEQCSPEC was used for extracting information from the results of TEQC that is written in MATLAB in order to view high frequency multipath in short-span data. The term multipath metrics is used to denote multipath time series data that are derived from RINEX observation and navigation files using the TEQC software. A sky view of multipath over a particular GPS site is the desired final output. Such information gives the multipath orientation with respect to the geometry of the satellites, and can be used to study site selections or monument design, especially where high-rate data are important. Further investigation of the most severely affected site, both by examining photographs and analysing multipath variations with respect to elevation angle and azimuth, has helped to a better understanding of the kinds of factors contributing to pseudo range multipath. Our main tool for calculating the variation of the L1 and L2 pseudo range multipath at each site was used by the TEQC software. It computes the MP1 and MP2 linear combinations using both pseudo range and carrier phase data to eliminate the effects of station clocks, satellite clocks, troposphere delay and ionospheric delay. In practice, the constant part of MP1 and MP2 is removed so that TEQC actually reports the root mean square (RMS) variation of MP1 and MP2 for each satellite, as well as a mean RMS for all satellites [5].

5.1.1 Point 1 (P1)

A preliminary study was conducted to evaluate the pseudo range multipath at three rover points. Pseudo range multipath can seriously degrade the accuracy of any application that relies on precise measurements of the pseudo range observable over a short period of time, including differential pseudo range navigation, kinematic and rapid-static surveying. Dual-frequency carrier phase and pseudo range measurements were used to estimate the L1 and L2 pseudo range multipath at each site over the short time period. The main objectives of this study were to identify the most and least affected sites in the project area, to closely investigate problematic sites, and to evaluate the multipath mitigation technique (Enhanced Strobe Correlator).

The picture of P1 in Fig. 2a seems to have a major obstruction nearby (under the indeciduous tree).

Photograph obtained for this point is verified in the presence of the indeciduous tree. Fig. 3a and Fig. 3b show the number and the elevation angles of satellites at the stations of P1 on 3 and 4 April 2008, respectively. The repetition of the same satellite geometry on 3 April 2008 occurred on 4 April 2008 as well. S/N value for L1 and L2 is actually related to signal quality, while elevation is not. So, the elevation cannot indicate errors, because it does not carry any information about obstacles. An easier approach would be to compare directly S/N L1, S/N L2, MP1 and MP2 values on 3 April 2008 (without ESC) to the values on 4 April 2008 (with ESC). The multipath detection and mitigation depend on the S/N L1, S/N L2 and MP1; MP2 values differences between two days (Figs. 4, 5, 6 and 7).

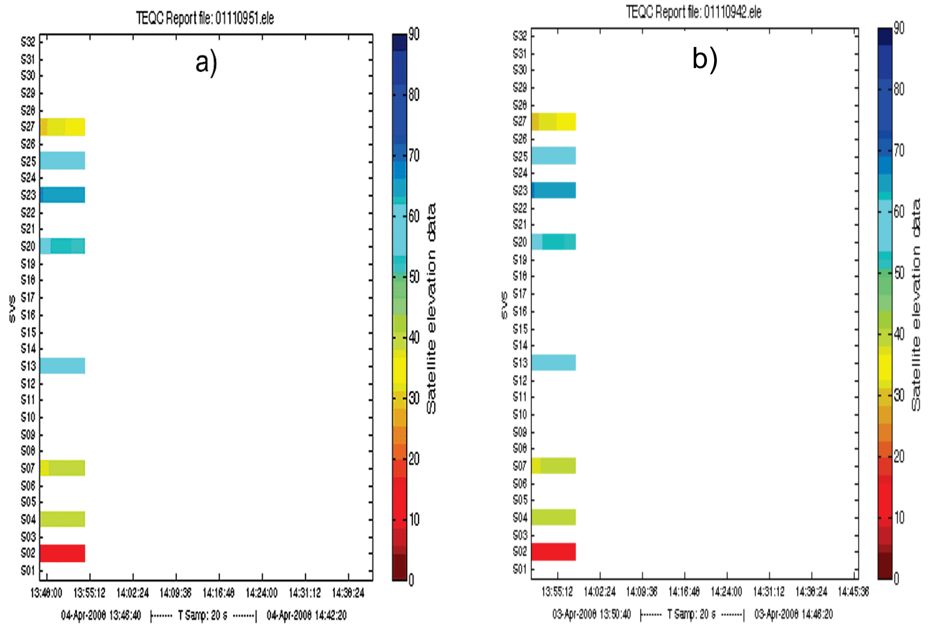

Figure 3 Elevation angles of satellite tracks at rover point (P1) (a) during 13:50:40-14:46:20 UT on 3 April 2008 and (b) during 13:46:40-14:42:20 UT on 4 April 2008

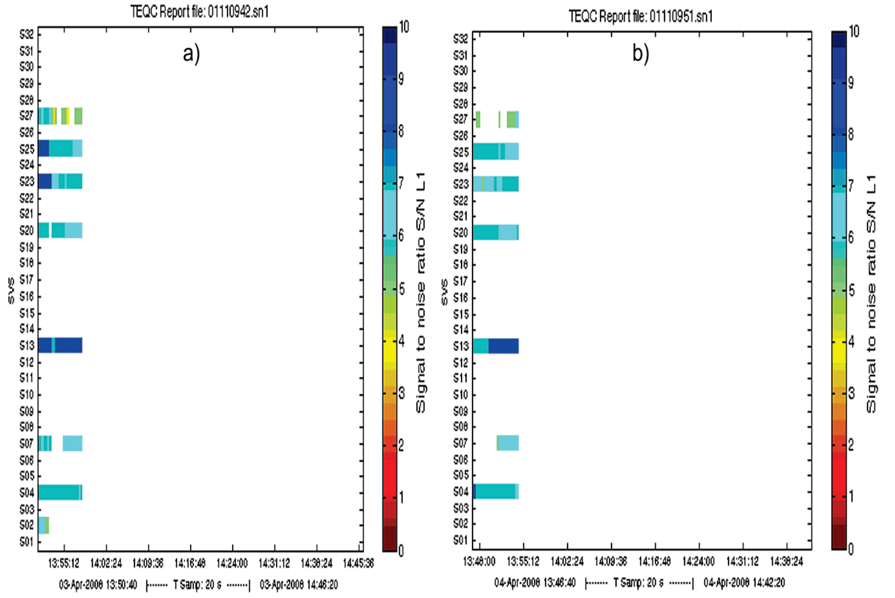

Figure 4 S/N L1 (Signal-to-noise ratio L1) graphics (a) on 3 April 2008 and (b) on 4 April 2008 for P1 point

As explained above, the rover point P1 is under the indeciduous tree which completely attenuated the direct signal from the definite satellites during 13:50:40-14:46:20 on 3 April 2008 and during 13:46:40-14:42:20 on 4 April 2008. The day-to-day repeatability of the multipath effects was taken into account when comparing S/N L1 and S/N L2 values of the same satellites. S/N L1 and S/N L2 values for both days should be equal in principle. The impact of the tree on the signal quality during this period is clearly seen from Figs. 4a, 4b and 5a, 5b. The S/N L1 and S/N L2 values change significantly at rover point (P1) and vary independently from the elevation angle because of the indeciduous tree. In this study, the low S/N L1 and L2 values were observed at P1 on 3 April 2008 (Multipath rejection OFF) against the values on 4 April 2008 (Multipath Rejection ON) because of the effect of ESC.

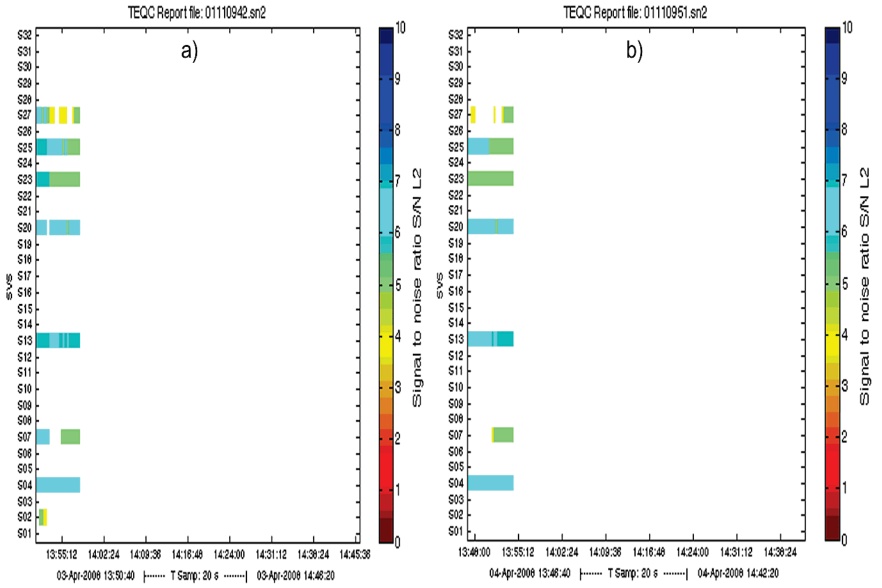

Figure 5 S/N L2 (Signal-to-noise ratio L2) graphics (a) on 3 April 2008 and (b) on 4 April 2008 for P1 point

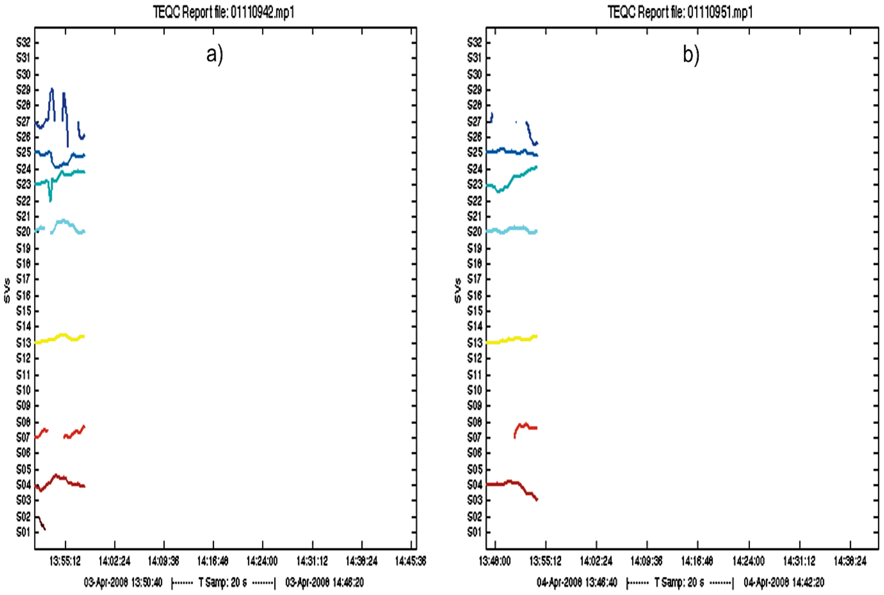

Figure 6 L1 multipath at rover point (P1) (a) on 3 April 2008 and (b) on 4 April 2008

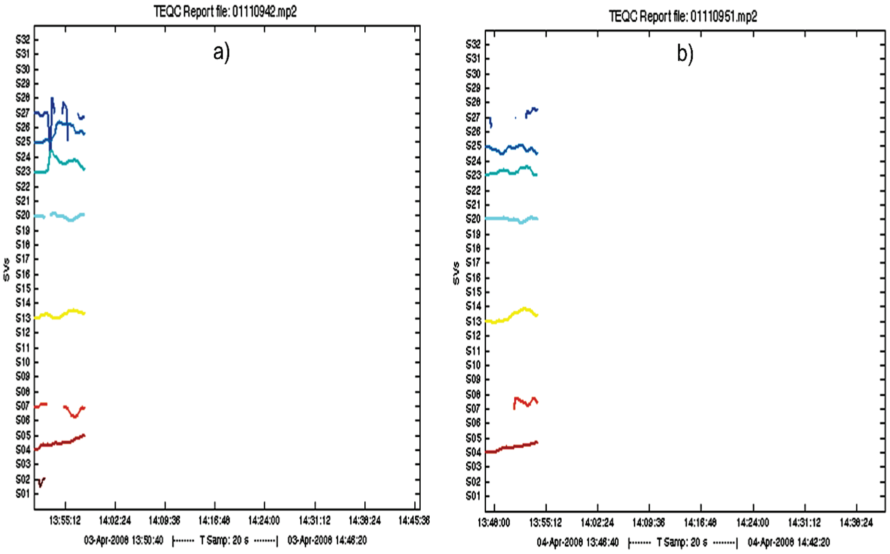

Figure 7 L2 multipath at rover point (P1) (a) on 3 April 2008 and (b) on 4 April 2008

Figs. 6 and 7 are the multipath traces showing the satellite specific pattern on 3 April and 4 April 2008 for P1. The maximum value of the L1 pseudo range multipath on 3 April 2008 is about 2,0 m (satellite number SV27), see Fig. 6a. The maximum value of the L2 pseudo range multipath on 3 April 2008 is about 3 m (satellite number S27), see Fig. 7a. Figs. 3a and 3b are the plots of satellite elevation that correspond to the traces in Figs. 6 and 7. The multipath noise patterns are well correlated with the satellite elevation data (low elevation satellites have noisier multipath signals compared to high elevation angles). The maximum value of the L1 pseudo range multipath on 4 April 2008 is about 1,5 m (satellite number SV27), see Fig. 6b. The maximum value of the L2 pseudo range multipath on 4 April 2008 is about 1 m (satellite number SV27), see Fig. 7b. For a general analysis, the average values were calculated of MP1 and MP2 of P1 on both days and are presented in Table 2. The MP1 and MP2 RMS values on 4 April 2008 are better than the values on 3 April 2008 (Tab. 2). As shown MP1 and MP2 RMS values per satellites in Table 3, the indeciduous tree site tends to be much more affected in MP1 than in MP2 for both days, especially for SV4, SV20, SV23 and SV27.

Table 2 MP1 and MP2 values using 10° elevation mask for P1 on both days

	3 April 2008 (Multipath Rej. OFF)	4 April 2008 (Multipath Rej. ON)
Point Number	P1	P1
Moving Average MP1	0,375 m	0,268 m
Moving Average MP2	0,368 m	0,206 m

Table 3 MP1 and MP2 RMS values per SV for P1 on both days

P1	3 April 2008			4 April 2008		
SV	Elevation (degree)	MP1 rms(m)	MP2 rms (m)	Elevation (degree)	MP1 rms(m)	MP2 rms(m)
4	41,90	0,260	0,252	41,89	0,345	0,223
7	42,42	0,216	0,309	44,54	0,236	0,216
13	61,30	0,130	0,177	61,33	0,123	0,326
20	54,34	0,281	0,134	54,22	0,126	0,089
23	66,05	0,455	0,454	66,06	0,525	0,184
25	59,44	0,322	0,492	59,60	0,088	0,186
27	35,51	1,063	0,899	39,35	0,655	0,247

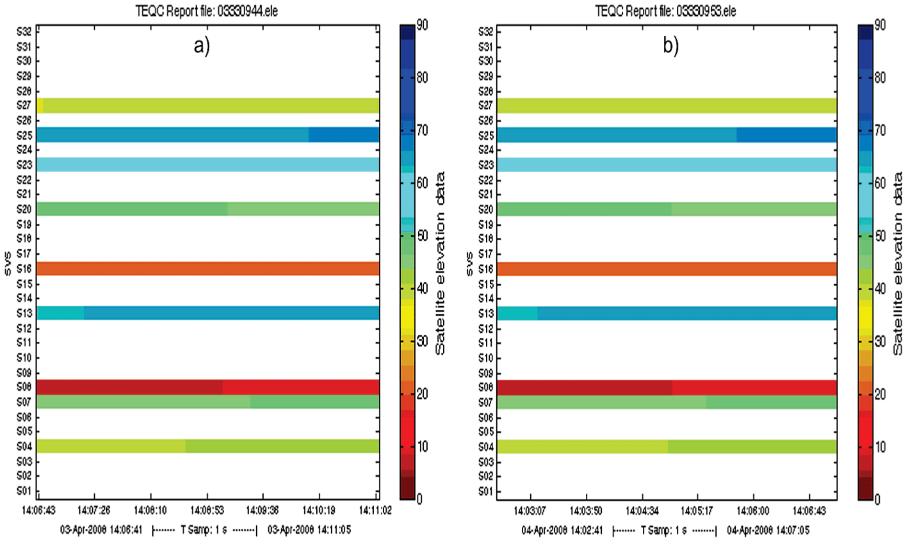

Figure 8 Elevation angles of satellite tracks at rover point (P3) (a) during 14:06:41-14:11:05 UT on 3 April 2008 and (b) during 14:02:41-14:07:05 UT on 4 April 2008

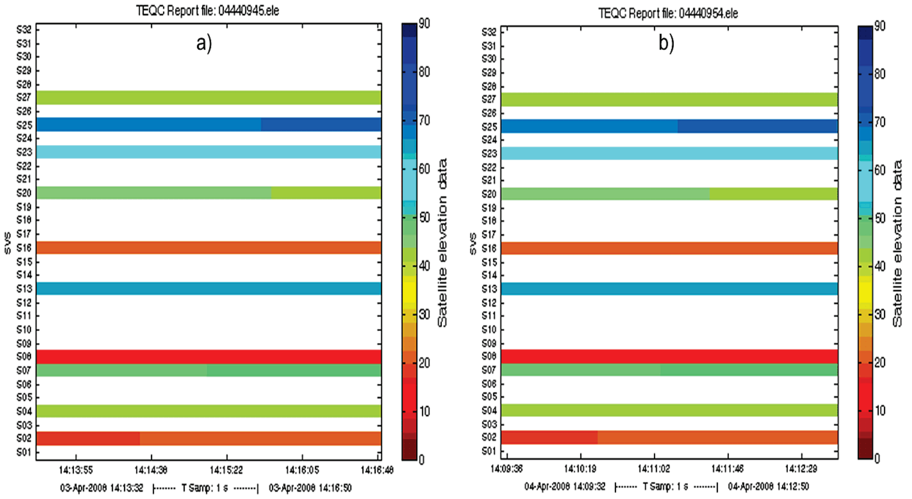

Figure 9 Elevation angles of satellite tracks at rover point (P4) (a) during 14:13:32-14:16:50 UT on 3 April 2008 and (b) during 14:09:32-14:12:50 UT on 4 April 2008

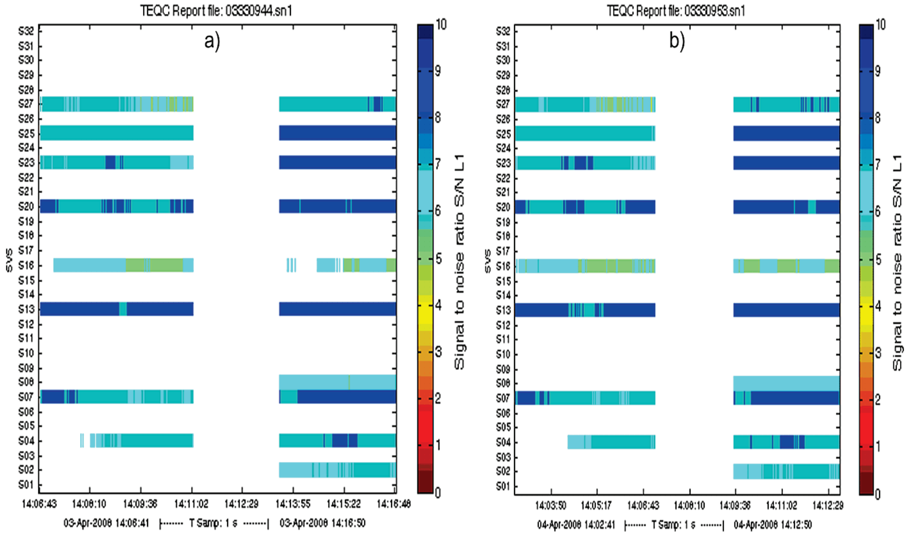

Figure 10 S/N L1 (Signal-to-noise ratio L1) graphics for P3 (left part) and P4 (right part) point (a) on 3 April 2008 and (b) on 4 April 2008

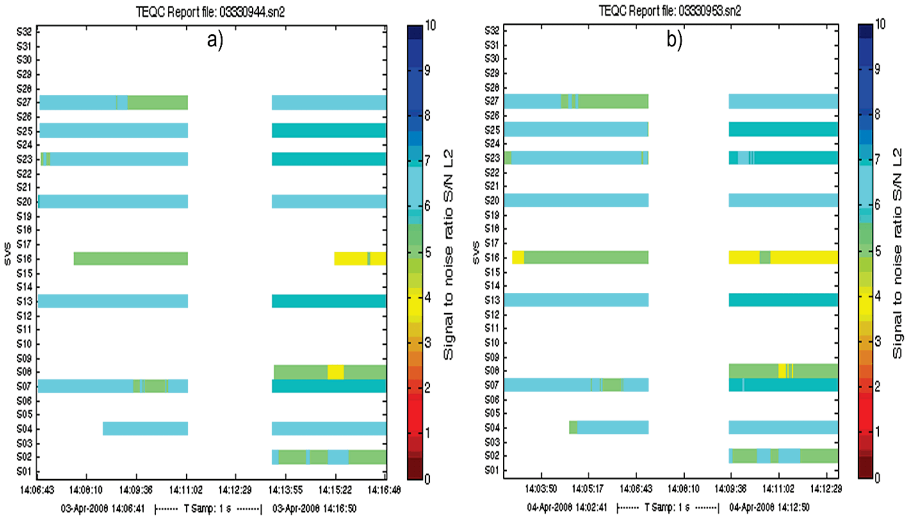

Figure 11 S/N L2 (Signal-to-noise ratio L2) graphics for P3 (left part) and P4 point (right part) (a) on 3 April 2008 and (b) on 4 April 2008

5.1.2 Point 3 (P3) and Point 4 (P4)

The rover point P3 was mounted under the deciduous tree (no leaves), see Fig. 2b. A photograph is obtained for this point in order to verify the presence of the deciduous tree. Fig. 8a and Fig. 8b show the number and the elevation angles of satellites at the stations of P3 on 3 and 4 April 2008, respectively. The same satellite geometry on 3 April 2008 occurred on 4 April 2008 as well. An easier approach would be to compare directly S/N L1, S/N L2, MP1 and MP2 values on 3 April 2008 (without ESC) to the values on 4 April 2008 (with ESC). The multipath detection and mitigation were related with the S/N L1, S/N L2 and MP1, MP2 values differences between two days (Figs. 10, 11, 12 and 13).

The rover point P3 is under the deciduous tree which is completely attenuated by the direct signal from the definite satellites during 13:50:40-14:46:20 on 3 April 2008 and during 13:46:40-14:42:20 on 4 April 2008. The day-to day repeatability of the multipath effects was taken into account when comparing S/N L1 and S/N L2 values of the same satellites. In usual sense, the S/N L1 and S/N L2 values on both days should be identical. The impact of the tree on the signal quality during this period is clearly seen from Figs. 10 and 11. The S/N L1 and S/N L2 values change significantly at rover point (P3) and vary independent from the elevation angle because of the deciduous tree. However, a little low S/N L1 and L2 values were observed at P3 on 3 April 2008 (Multipath rejection OFF) against the values on 4 April 2008 (Multipath Rejection ON) because of the effect of ESC.

Figs. 12 and 13 are the multipath traces for P3 showing the satellite specific pattern on 3 April and 4 April 2008. The maximum value of the L1 pseudo range multipath on 3 April 2008 is about 1,0 m (satellite number SV27). The maximum value of the L2 pseudo range multipath on 3 April 2008 is about 1,0 m (satellite number SV13). Figs. 8a and 8b are the plots of satellite elevation that corresponds to the traces in Figs. 12 and 13. The multipath noise patterns are well correlated with the satellite elevation data (low elevation satellites have noisier multipath signals compared to high elevation angles). The maximum value of the L1 pseudo range multipath on 4 April 2008 is about 1,0 m (satellite number SV4). The maximum value of the L2 pseudo range multipath on 4 April 2008 is about 2,5 m (satellite number SV16). For a general analysis, the average values for the rover point P3 were calculated of MP1 and MP2 on both days and are presented in Tab. 5. The MP1 and MP2 RMS values on 4 April 2008 are approximately equal to the values on 3 April 2008 (Tab. 4). Tab. 5 shows MP1 and MP2 RMS values per satellites.

Table 4 MP1 and MP2 values using 10° elevation mask for P3 on both days

	3 April 2008 (Multipath Rej. OFF)	4 April 2008 (Multipath Rej. ON)
Point Number	P3	P3
Moving Average MP1	0,204 m	0,191 m
Moving Average MP2	0,228 m	0,233 m

Figs. 12 and 13 are the multipath traces for P4 showing the satellite specific pattern on 3 April and 4 April 2008. The maximum value of the L1 pseudo range multipath on 3 April 2008 is about 1,5 m (satellite number SV16). The maximum value of the L2 pseudo range multipath on 3 April 2008 is about 1,5 m (satellite number SV16). Figs. 9a and 9b are the plots of satellite elevation that correspond to the traces in Figs. 11 and 12. The multipath noise patterns are well correlated with the satellite elevation data (low elevation satellites have noisier multipath signals compared to high elevation angles). The maximum value of the L1 pseudo range multipath on 4 April 2008 is about 0,5 m (satellite number SV16). The maximum value of the L2 pseudo range multipath on 4 April 2008 is about 0,5 m (satellite number SV16). For a general analysis, the average values for P4 were calculated of MP1 and MP2 on both days which are represented in Tab. 6. In general, the MP1 and MP2 RMS values per SV for P4 on 4 April 2008 are less than the values on 3 April 2008 (Tab. 7). The low and medium elevation of the satellites generally affected MP1 values much more than MP2 RMS values in the multipath environment (see Tab. 5, Tab. 3, and Tab. 7).

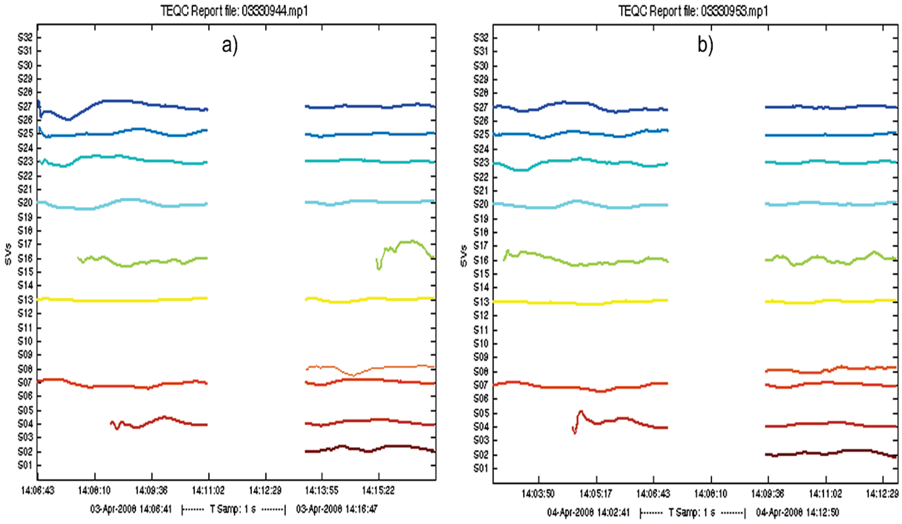

Figure 12 L1 multipath at rover points (P3 (left part) and P4 (right part)) (a) on 3 April 2008 and (b) on 4 April 2008

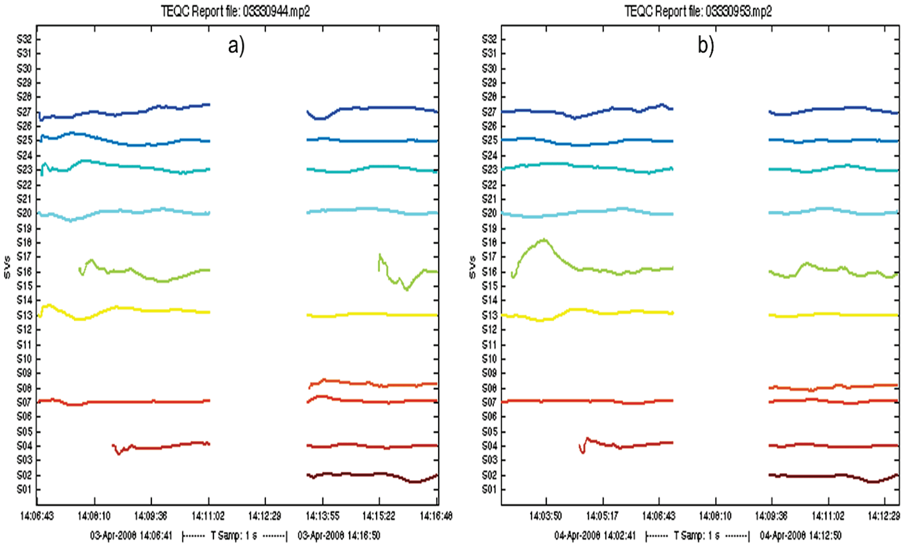

Figure 13 L2 multipath at rover points (P3 (left part) and P4 (right part)) (a) on 3 April 2008 and (b) on 4 April 2008

Polar plots of both the unfiltered multipath time series are shown in Figs. 14 and 15 for the time spans 14:06:40-14:16:49 on 3 April 2008 for the rover point P3 and P4, 14:02:41-14:12:50 on 4 April 2008 for the rover point P3 and P4. It is clear that the signal quality values on 4 April 2008 are better than the values on 3 April 2008.

In this study, the most severely affected site was P1 point. Tabs. 3 and 4 show that P1 station exhibits much larger MP1 and MP2 numbers than any other points. Figs. 6 and 7 clearly show that the severely affected P1 sites seem to be much more affected in MP1 than MP2.

Table 5 MP1 and MP2 RMS values per SV for P3 on both days

P3	3 April 2008			4 April 2008		
SV	Elevation (degree)	MP1 rms (m)	MP2 rms (m)	Elevation (degree)	MP1 rms (m)	MP2 rms (m)
4	41,15	0,220	0,176	41,15	0,307	0,170
7	46,33	0,189	0,078	46,34	0,181	0,058
13	63,76	0,070	0,239	63,77	0,080	0,214
16	22,12	0,184	0,359	22,02	0,290	0,706
20	46,66	0,206	0,202	46,58	0,138	0,169
23	60,14	0,221	0,236	60,16	0,225	0,194
25	65,56	0,167	0,258	65,74	0,142	0,150
27	39,18	0,383	0,284	39,25	0,222	0,200

Table 6 MP1 and MP2 values using 10° elevation mask for P4 on both days

	3 April 2008 (Multipath Rej. OFF)	4 April 2008 (Multipath Rej. ON)
Point Number	P4	P4
Moving Average MP1	0,119 m	0,099 m
Moving Average MP2	0,124 m	0,111 m

Table7 MP1 and MP2 RMS values per SV for P4 on both days

P4	3 April 2008			4 April 2008		
SV	Elevation (degree)	MP1 rms (m)	MP2 rms (m)	Elevation (degree)	MP1 rms (m)	MP2 rms (m)
2	20,20	0,140	0,180	20,22	0,134	0,145
4	41,14	0,132	0,076	41,13	0,109	0,076
7	49,45	0,116	0,074	49,48	0,094	0,066
8	11,30	0,198	0,112	11,35	0,135	0,102
13	65,17	0,092	0,058	65,19	0,065	0,040
16	22,87	0,442	0,439	22,42	0,231	0,250
20	44,07	0,078	0,133	43,99	0,055	0,128
23	58,05	0,066	0,148	58,06	0,062	0,124
25	68,77	0,034	0,047	68,98	0,045	0,041
27	42,14	0,069	0,149	42,23	0,055	0,132

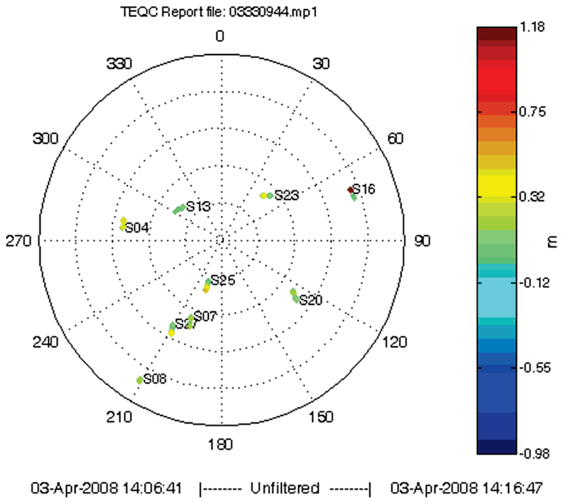

Figure 14 Polar map of unfiltered multipath in the time span 14:06:40-14:16:49 on 3 April 2008 for points P3 and P4. Satellite numbers are indicated at the end of the satellite tracks

In contrast, Figs. 12 and 13 show the MP1 and MP2 graphics for one of the least affected stations in GPS network, P3 and P4. If we compare RMS error of the pseudo ranges for the selected time periods from Tabs. 5 to 7, the very low multipath pattern can be seen in the observations on April 4th. It is also important to notice that the Enhanced Strobe Correlator does not degrade the overall noise performance of the receiver. The Enhanced Strobe Correlator uses the slope of multiple narrow correlators and shows very good long delay multipath mitigation performance. However, in a strong and fast changing multipath environment, they do not completely eliminate the effects. The code tracking (Enhanced Strobe Correlator) can be improved by at least 40 % in the rover point (P1) [8, 9, 10, 11, 12, 13, 14].

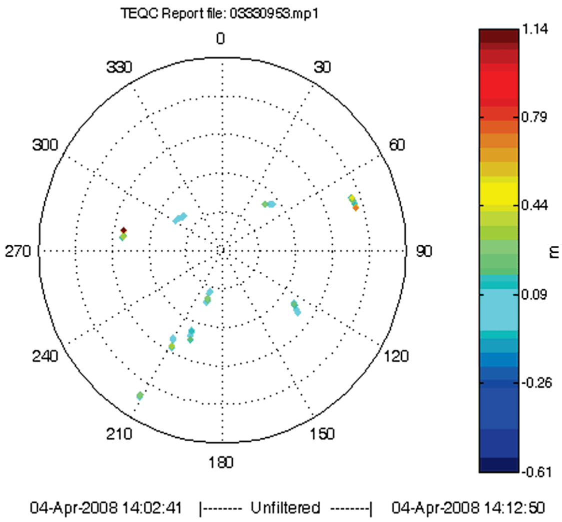

Figure 15 Polar map of unfiltered multipath in the time span 14:02:41-14:12:50 on 4 April 2008 for points P3 and P4. Satellite numbers are indicated at the end of the satellite tracks

6 Evaluating the effect of the multipath for the baselines

The code-carrier phase processing was performed along with the RTCM processing. The data was collected at the base and at the three rovers in real-time by using Ashtech Z Max GPS receivers (3 and 4 April 2008) and Topcon Hiper Pro receivers (GPS+GLONASS), (5 April 2008) in the project area, respectively (Tab. 9). The main goal here was to find out how good the raw code-carrier phase measurements were for the Ashtech Z Max GPS receivers when the code-carrier phase multipath rejection is ON. Furthermore, the high precision terrestrial surveys were used to check the real-time kinematic GPS results especially for the spatial distances and height differences. A Topcon DL-102 digital level surveying instrument and a barcode rod were used to determine the height differences. A Nikon DTM 330 Total Station was used to measure spatial distances between experiment points. Distance and height measurements were done (3 series) and then mean value of all measurements was calculated as shown in Tab. 10. The quality of the real-time kinematic GPS results can be assessed in comparison with the spatial distances and height differences determined by the terrestrial measurements.

Table 8 The RTK GPS results for the three rover points

	X	*Y*	*H*
P1	4546688,675	416730,417	98,904
P1	4546688,662	416730,430	98,864
P1	4546688,659	416730,444	98,724
P3	4546704,078	416716,370	98,781
P3	4546704,074	416716,365	98,796
P3	4546704,071	416716,357	98,800
P4	4546714,050	416727,671	100,528
P4	4546714,048	416727,666	100,526
P4	4546714,043	416727,668	100,531

The height and distance differences for the baseline 511-P3 and 511-P4 indicate that multipath effect is not severe as the one for the line 511-P1. It is evident that the observations were affected from the indeciduous tree environment, i.e. in the presence of multipath. Also the differences for both distances and height differences become worse on the first day (3 April 2008, Multipath Rejection OFF). When the multipath rejection is ON (Enhanced Strobe Correlator) the results are good enough in the presence of multipath compared to the multipath rejection OFF (without Enhanced Strobe Correlator) (Tabs. 9 and 10).

Table 9 The values for the three rover points

	HRMS	VRMS	SATS	DATE	TIME	Equipment
P1	0,018	0,043	7	03.04.2008	04:57:26	Ashtech Z Max
P1	0,019	0,045	7	04.04.2008	04:53:26	Ashtech Z Max
P1	0,015	0,022	7+2	05.04.2008	04:49:26	Topcon Hiper Pro
P3	0,012	0,022	8	03.04.2008	05:10:50	Ashtech Z Max
P3	0,014	0,027	8	04.04.2008	05:06:50	Ashtech Z Max
P3	0,013	0,021	8+2	05.04.2008	05:02:50	Topcon Hiper Pro
P4	0,010	0,016	10	03.04.2008	05:16:46	Ashtech Z Max
P4	0,010	0,016	10	04.04.2008	05:12:46	Ashtech Z Max
P4	0,010	0,015	10+2	05.04.2008	05:08:46	Topcon Hiper Pro

Table 10 Comparison of the RTK GPS results with the results of the terrestrial survey especially for the three baselines

Line	$S_{\text{RTK GPS}}$	$\mathrm{d}H_{\text{RTK GPS}}$	S_{Terres}	$\mathrm{d}H_{\text{Level}}$	ΔS (m)	ΔH (m)	Multipath rejection
511-P1	15,345	−1,096	15,385	−1,260	−0,040	0,164	OFF
	15,358	−1,136	15,385	−1,260	−0,027	0,124	ON
	15,361	−1,276	15,385	−1,260	−0,024	−0,016	
511-P3	14,064	−1,219	14,077	−1,185	−0,013	−0,034	OFF
	14,069	−1,204	14,077	−1,185	−0,008	−0,019	ON
	14,077	−1,200	14,077	−1,185	0,000	−0,015	
511-P4	10,404	0,528	10,388	0,546	0,016	−0,018	OFF
	10,403	0,526	10,388	0,546	0,015	−0,020	ON
	10,398	0,531	10,388	0,546	0,010	−0,015	

7 Conclusion

In this study, we present the effects of the multipath on Ashtech Z Max receiver's performance. Our results show that the point (i.e. P1) closer to the multipath environment is affected by the multipath in both horizontal and vertical components. The comparison was done with the terrestrial survey assuming it as a ground truth. Depending on the terrestrial methods, it can be said that the bias caused by multipath could be reduced by up to ~4 cm for distances and ~16 cm for height differences by the use of Ashtech Z Max receivers in without ESC mode (Tab. 10). This result is significantly improved by using ESC mode as the bias 2 cm for distances and ~5 cm for height differences (Tab. 10). If the multipath is not severe as shown for the lines 511-P3 and 511-P4, the bias level is pretty small (1 ÷ 2 cm) for both distances and height differences. Although, the performance of Ashtech Z Max seems to become worse for 511-P4 line, the effect on results does not appear to be significant and could be related to the fact that Ashtech's Enhanced Strobe Correlator performs well in the presence of not severe multipath. This can be seen in the results concerning the line 511-P4 in that with the use of Z Max (with ESC) and (without ESC), the bias on the spatial distance and on height difference is slightly amplified. Under normal conditions ESC might not always improve the noise level. On the other hand the magnitude of the bias is much smaller (<1 cm) compared to the one occurring in the presence of not severe multipath (e.g. check results concerning the line 511-P4, see Tab. 10.

The enhanced strobe correlator (ESC) represents a significant improvement on the strobe correlator [8]. This technique also provides better carrier tracking. This technology follows some basic principles that are deeply rooted in its implementation. They are: 1) The method does not estimate any of the multipath parameters. 2) It does not depend on any multipath model. 3) Independent correction of every channel at the tracking level. 4) Works well in any kind of multipath environment, specular or diffuse. The Enhanced Strobe correlator is quite simple and promising [1, 8, 9, 10, 11, 12, 13, 14] .

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