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Exclusion of Multipath-Affected Satellites Using Early Late Phase

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Abstract

This paper presents experimental results of detecting multipath using a recently proposed parameter, early late phase (ELP). The paper shows that positioning error caused by multipath can be reduced by excluding the satellites detected as experiencing multipath from the navigation solution, except where the exclusion causes a significant increase in dilution of precision. Performance of this ELP-based satellite exclusion was compared with standard wide correlators, along with narrow and double delta correlators. It was found that narrow and double delta correlators may in fact increase error when a reflected signal is stronger than the LOS (a scenario possible where the LOS is attenuated) or when multiple reflections are received from the same satellite. In these cases, ELP can still detect multipath and satellite exclusion can mitigate multipath-induced error. Even in more usual cases, satellite exclusion was shown to outperform narrow correlators and performed as well as double delta correlators. However, the exception to this is when there is another satellite affected by multipath not detected using ELP and hence not removed from the solution. In this case, the error may in fact increase by removing one multipath-affected satellite because the multipath biases may be partially cancelling each other.

Keywords: ELP, multipath, narrow correlator, HRC

1. Introduction

With an increasing number of global satellite navigation systems (GNSS) becoming available and new signals being proposed, once such systems are fully operational there may be up to 55 satellites signals that are trackable at a given location by a multi-GNSS receiver (Dempster and Hewitson, 2007). Since the number of satellites required for a navigation solution is significantly lower than this, future GNSS users can afford to disregard satellite signals suspected of inducing error instead of using computational resources on mitigation of that error source. One source of positioning error is the presence of multipath in received signal(s) from one or more satellites. Thus, a multipath detection algorithm can be used to identify and remove affected satellites from the navigation solution. Recently, a parameter known as “early late phase” (ELP) was proposed for multipath detection (Mubarak and Dempster, 2007) and statistically shown to be an effective parameter (Mubarak and Dempster, 2009). This paper presents results for detecting multipath using ELP, together with an analysis of position accuracy by excluding satellites found to be affected by multipath. A similar approach was proposed for mitigating the effect of continuous wave (CW) interference by excluding the affected satellite (Tabatabaei and Motella, 2007).

Various methods have been presented to reduce the adverse effects of multipath. The most popular among them are the use of narrow correlators (Dierendonck et al., 1992), double delta correlators (Irsigler and Eissfeller, 2003), and the multipath estimating delay locked loop (MEDLL) (Townsend et al., 2000). These algorithms, and many others, are based on the code phase difference between the line of sight (LOS) and a reflected signal. They do not take into account the difference in the carrier phase of the two signals. This carrier phase difference leads to a shift of energy from the I channel to the Q channel because of the presence of the same signal on multiple carrier phases. Ratio metrics have been proposed for multipath detection which uses the change in energy in the I channel (Fantino et al., 2009) or multiple correlators (Irsigler and Hein, 2005, Mitelman et al., 2000) on each side of the correlation triangle. ELP exploits this energy shift by using the phase of the standard early and late correlator outputs, i.e. incorporating both I and Q channel outputs.

Since multiple signals are received with different carrier phases in the presence of multipath and the prompt correlator is pushed by the carrier tracking loop to have zero phase, in general, early and late correlators have nonzero phase in the presence of multipath (Mubarak, 2008). ELP is thus computed as a phase difference between early and late correlators. If this ELP increases in magnitude beyond a certain threshold, it indicates the presence of multipath (Mubarak and Dempster, 2009). Mathematically, ELP is defined as:

$$ELP(t) = \tan^{-1}\left(\frac{Q_L(t)}{I_L(t)} - \frac{Q_E(t)}{I_E(t)}\right) \quad (1)$$

where I and Q correspond to the I and Q receiver channels, while subscripts E and L correspond to early and late correlator outputs, respectively.

Another difference between ELP and the above-cited algorithms is that ELP was proposed to used for detecting multipath instead of mitigating its effect (while keeping the satellite in the positioning calculation). Detecting an affected satellite and removing it from the solution is a reasonable approach keeping in mind the upcoming modernized navigation satellite systems and signals, as mentioned earlier. There are also other methods whose objective is to detect multipath, e.g., post processing of pseudo-ranges data or the use of antenna arrays. The former was shown to be effective in detecting the presence of multipath only in a single satellite signal and requires extensive computations (MacDonald et al., 2008). The latter requires complex/multiple receiving antennas (Brenneman et al., 2008). However, ELP computation does not require additional antennas or any other hardware, and because it is independently computed on each channel it can detect multipath in multiple satellite signals at the same time. This claim is corroborated in this paper by using ELP for multipath detection and analysing the resulting performance results. Apart from the comparison with a standard receiver with wide correlators, all navigation results presented here have also been compared with narrow correlator and high resolution correlator (HRC) receivers. Narrow correlators have been selected for comparison because they are the most widely cited multipath mitigation technique, and because of the ease in implementation. HRC is a type of double delta correlator, which means it has two correlators on each side of the correlation triangle. It has been chosen because it has the best theoretical performance in mitigating multipath among all the double delta correlators (Irsigler & Eissfeller, 2003).

2. Experimental Setup

A Spirent GSS6560 12-channel GPS/SBAS simulator was used to generate L1 GPS signals. This simulator is controlled by the PC-based software SimGEN and can generate GPS signals for a given time and location. The main reason for using this simulator instead of a real signal is that it can generate multipath in any satellite signal with a given relative attenuation and delay for the reflected signal with respect to the LOS. The RF output of the simulator was then input to a NordNav rxx2 front-end, with bandwidth of 2 MHz, intermediate frequency (IF) of 16.3676 MHz and sampling frequency of 4.1304 MHz. It was used to collect and store IF samples to computer memory for later processing. An open source software receiver (Borre et al. 2006) was then used to generate the navigation solution (using an elevation mask angle of 10°). Correlator outputs were generated using coherent integration of 1 msec. Spacing between early, prompt and late was set to 0.5 chips and the delay lock loop (DLL) bandwidth was 2 Hz for wide correlators. They were set to 0.05 chips and 4 Hz respectively for narrow and high resolution correlators. Normally a wide band front-end is required for narrow and high-resolution correlators, otherwise the tracking loop may lose lock (Dierendonck et al., 1992). In this case the same 2 MHz front-end has been used. For this bandwidth, the narrow and high-resolution correlators loop did not maintain lock, so an increased DLL bandwidth was used. This ensured that the tracking loop remained locked, although the loop response to jitter and noise is changed. However, this change in loop behaviour does not affect the navigation solution of a static receiver considered in this paper. The receiver code was modified to exclude satellite signals detected by ELP as being multipath affected. A block diagram of this setup is shown in Fig. 1.

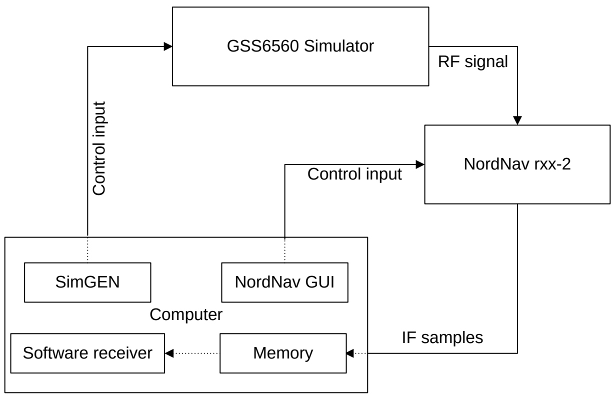

Figure 1: A block diagram of the experimental setup

The paper only considers the conventional L1 signal, since both the simulator and receiver used are only designed for L1. However, the analysis can be extended to multi-GNSS receivers. Moreover, since ELP is based on the detection of multiple receptions of a satellite signal, a scenario where the LOS signal is completely blocked and only reflection is received is not considered here either.

3. Single Reflection Analysis

This section considers the simplest case of multipath, i.e. a single reflection in one of the received satellite signals. Fig. 2 shows results for the first scenario. The location in this case is given by latitude and longitude of -35° and 150° respectively, at UTC time 0708 hrs on 01st May, 2009. At this time and location there were 6 satellites visible: PRNs 4, 12, 16, 18, 19 and 21. Two multipath situations were considered. In the first, multipath was added from PRN 4 with an additional path length of 210 m, while in the second a 215 m additional path length reflection was added to the PRN 19 signal. In both cases multipath attenuation with respect to the LOS (α) is set to 0.5. Navigation errors in the presence of multipath are shown as the red plots in Fig. 2 without using any multipath mitigation (as this is for a wide correlator). It can be seen that in the first case there is less than 10 m easting error, whereas there is around 60 m error in height in the second case. Other than these two, there is around 20 m error in all other cases. Brown plots show results using the narrow correlator receiver, which reduced errors by almost half in all cases, while the HRC receiver results are given by black plots which have effectively been able to remove the error caused by the multipath. ELP is then computed for each channel for all scenarios. In both cases the multipath was successfully detected only for the affected satellite. The navigation solution was then computed using all satellites except those having ELP magnitude higher than the multipath detection threshold. Errors in this case are shown as green plots in Fig. 2. Similar to the HRC receiver, multipath error has been removed in this case as well. Thus, in this case it was shown that ELP-based satellite exclusion is effective in mitigating positioning errors caused by multipath and its performance is indeed better than a narrow correlator and equivalent to a HRC based receiver.

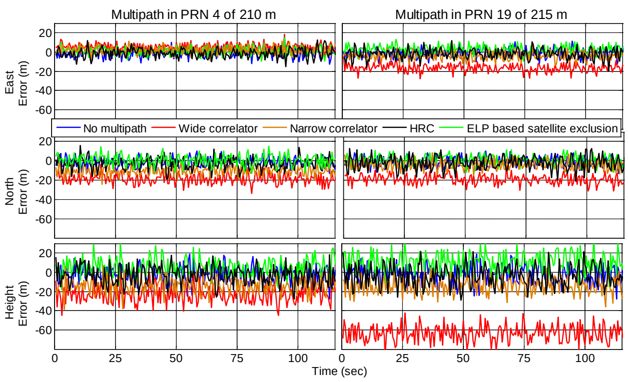

Figure 2: Positioning error due to multipath in a given constellation and effect of using ELP (α = 0.5, latitude = -35°, longitude = 150°, UTC starting time = 0708 hrs on 01st May, 2009)

Exclusion of one or more satellites from the navigation solution increases the dilution of precision (DOP), which can increase positioning error. However, in most cases multipath-induced error is much higher than the error caused by an increase in DOP and thus satellite exclusion gives better overall results - although significant increases in DOP can worsen positioning accuracy. This is further explored using DOP computations presented later in the paper.

A better view of overall positioning accuracy can be obtained using east and north error on each axis. Fig. 3 shows such a plot for the scenarios considered in Fig. 2. It can again be seen that in both cases the error caused by signal multipath was almost entirely removed using HRC and ELP-based satellite exclusion of the multipath-affected satellite. Overall mean error in each case was computed as the distance of the mean of all the points from the origin. It was found that it is 1.94 m in absence of any multipath. This increased to 19.39 m and 25.37 m when multipath was added to PRNs 4 and 19 signals respectively. Using a narrow correlator reduced them to 10.5 m and 6.15 m, while HRC resulted in error of 3.03 m and 2.82 m. However, excluding satellites using ELP reduced them to 1.94 m and 2.91 m. In the second case the higher error was due to the greater increase in the HDOP after exclusion of PRN 19 as compared to excluding PRN 4. It was found that the original HDOP for this constellation was 1.7, which was increased to 1.85 and 2.0 after excluding satellites PRN 4 and PRN 19 respectively. Nevertheless, in both cases positioning accuracy after removing the multipath-affected satellite is close to that obtained in the absence of multipath and using HRC, while it is far better than the narrow correlator-based receiver.

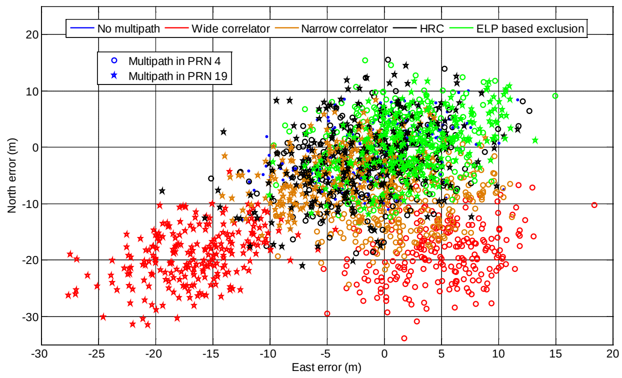

Figure 3: Positioning error on a two-dimensional plot for the scenarios considered in Fig. 2

Next, scenarios of 8 visible satellites were considered and the navigation error was analysed after adding multipath one at a time to each of the satellites. In this case, the simulator settings were set at latitude -10° and longitude 110° for UTC time 1510 hrs on 04th August, 2009. PRNs 4, 7, 9, 13, 14, 20, 21 and 22 were visible.

Fig. 4 shows mean easting and northing error due to multipath for each case. Mean error is used in this paper to compare results in the cases where the standard deviation of error remains almost the same after exclusion of a satellite. In some cases, this standard deviation is increased because of the significant increase in DOP. In those cases, all instantaneous error points will be shown in the plot.

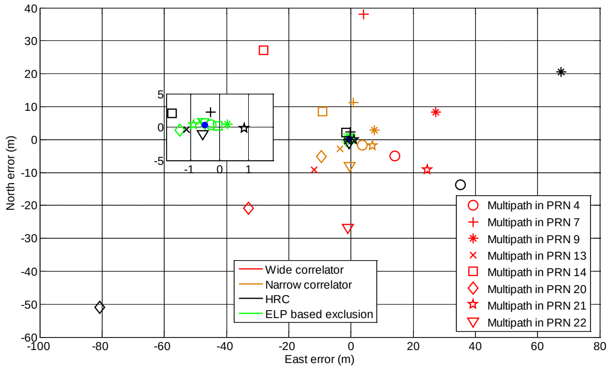

Figure 4: Mean positioning error for multipath in each individual satellite signal (α = 0.5, d = 220 m, latitude = -10°, longitude = 110°, UTC starting time = 1510 hrs on 04th August, 2009) (inset: zoom of results around zero error)

Relative attenuation and additional path length of the reflected signal with respect to the LOS were set to 0.5 and 220 m for all cases. However, due to the different elevations for each satellite, the Doppler offset is different which means that the carrier phase difference between reflected and LOS signals is different in each case. Thus, for each case the positioning error and ELP were different as both are dependent on this phase difference and positioning error is also dependent on geometry. Since carrier phase difference for multipath in the simulator cannot be set or determined, this analysis is helpful to analyse ELP performance for varying phase differences. It can be seen that positioning error from 14 m to 39 m occurs due to this multipath, which is reduced to a range of 4.5 m to 12.5 m using narrow correlators. This was significantly reduced to within 1.45 m in all cases by using ELP-based multipath detection and exclusion of the affected satellite. It should also be noted that in the absence of any multipath, positioning error is 0.65 m, which means that using ELP has almost nullified the adverse effects of multipath. Moreover, the increase in DOP is different for the exclusion of different satellites. The original HDOP in this case was 2.0, which increased to a maximum of 2.7 by the exclusion of each satellite. Thus, in all the cases considered here, DOP is not significantly increased upon removing a satellite.

However, using HRC the positioning error was worse than the wide correlators for PRN 4, 9 and 20, although it reduced error for other cases resulting in a range of 0.88 m to 2.65 m error. The increase in error by using HRC is unusual as it has been used for multipath mitigation. However, it occurred in this case because, although the peak location for the correlation function is not changed, the HRC locks to a sub-peak formed by multipath. This can be explained by considering one of these scenarios. In all the cases considered above, multipath is added at the start of the signal segment recording, which implies that multipath was present since the start of tracking. It was found that if multipath is not present at the start, the HRC does not perform worse than a wide correlator; in fact it is able to remove the error. This is illustrated in Fig. 5 where there is no multipath for the first 35 seconds and then the multipath in PRN 4 has been added with the same parameters as in Fig. 4. It can be seen that using a wide correlator, a similar error as in Fig. 4 is obtained, but the HRC has been able to remove those errors in this case. This implies that in Fig. 4 the HRC locked onto a false peak and stayed there, while in Fig. 5 it starts with the true peak, as multipath was not present at the start, and stayed locked to it. As compared to wide correlators, HRC is more likely to stay locked to a false peak because of a relatively smaller linear region in its discriminator function (Braasch, 2001). It can thus be concluded that the HRC can lock to a correlation peak even if it is a false correlation peak, resulting in worse performance than wide correlators. In practice, as the relative phase of the multipath changes, the HRC will eventually revert back to the true peak. In other words, the event observed in Fig. 4 is relatively short-lived (but long enough to influence this experiment). It is shown later in this paper that similar behavior can also be observed for narrow correlators, along with a distorted correlation function with two peaks.

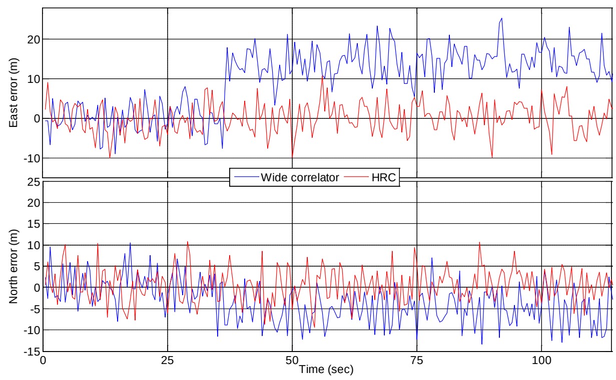

Figure 5: Positioning error for multiple in PRN 4 signal as given in Fig. 4 but with first 35 seconds free of multipath

Fig. 6 shows another scenario but in this case multipath of varying path lengths was added one at a time to the same satellite. Location in this case was set to latitude -20° and longitude -45° at UTC time 1500 hrs on 27th October, 2009. PRNs 1, 2, 8, 11, 12, 17, 23 and 24 were visible at this time above the elevation mask angle. Multipath was added from PRN 11 with α of 0.5 and d was varied from 25 to 250 metres. Tracking error is maximum when the carrier phase difference between the LOS and reflected signal is around an integer multiple of π, but the probability of detection of such multipath using ELP is very low (Mubarak and Dempster, 2009). In the scenario considered here, the Doppler offset in the carrier frequency of PRN 11 is such that the carrier phase difference is close to an integer multiple of π when path delay between them is an integer multiple of 100 metres. Thus, it can be seen that for d equal to 100 and 200 m, although the error due to multipath is maximum, ELP could not detect this multipath and the positioning error remains the same whether ELP is used or not. This is indicated by the overlap of red and green marks on the plot. However, in all other cases ELP was able to detect multipath and since HDOP is only slightly increased by satellite exclusion, positioning error is better than using the narrow correlator approach. Comparing it with HRC, it can be seen that ELP-based satellite exclusion is clearly better than HRC for d equal to 25 and 50 m. This is because HRC is not effective in mitigating short range multipath (Braasch, 2001 & So et al. 2009). Thus, excluding a multipath-affected satellite from the navigation solution is clearly a better solution for short range reflections. Moreover, the shortcoming of ELP, that it is not able to detect multipath when the carrier phase difference is close to an integer multiple of π, can be overcome by using L2C in a multi-frequency receiver (Mubarak and Dempster, 2010).

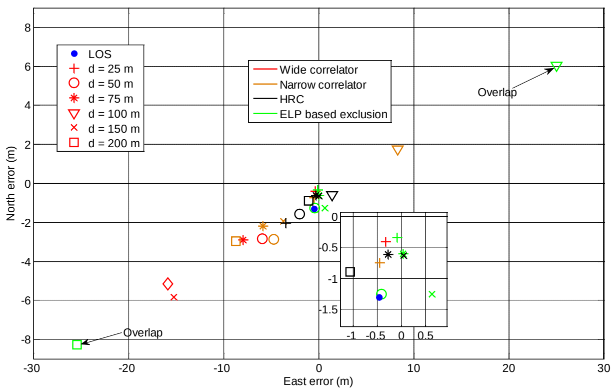

Figure 6: Mean positioning error for multipath in PRN 11 signal (α = 0.5, latitude = -20°, longitude = -45°, UTC starting time = 1500 hrs on 27th October, 2009) Note the worst errors are not corrected using ELP-based satellite exclusion (inset: zoom of results around zero error).

Next, positioning error for varying strengths of the reflected signal was investigated. Fig. 7 shows the mean error plot for the same scenario as considered in Fig. 4 but in this case multipath has only been added to PRN 14 with a delay of 220 m. The relative attenuation of a reflected signal with respect to the LOS is changed from 0.3 to 2. It should be noted that α greater than 1 corresponds to situations where a reflected signal is stronger than the LOS. Such situations can occur in urban environments when the LOS is partially blocked and a reflected signal is received directly after reflection, or where the LOS is attenuated by foliage and the reflected signal is not. It can be seen that, as expected, the error due to multipath increases in a wide correlator receiver as the strength of a reflection increases.

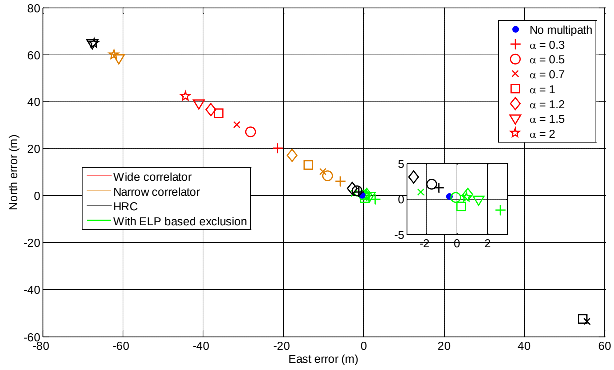

Figure 7: Mean positioning error for multipath in PRN 14 signal (d = 220 m, latitude = -10°, longitude = 110°, UTC starting time = 1510 hrs on 04th August, 2009) (inset: zoom of results around zero error)

It can also be seen that although the narrow correlator and the HRC reduce error for α up to 0.7, as α increases, the error increases in most cases. This is again because of the tracking loop locking to the false peak, as mentioned above. The chances of this happening are higher for stronger reflections as the peak in the correlation function may move as well. This implies that even if the tracking loop is locked to the strongest peak, it still gives a tracking error. Thus, the narrow correlator and HRC are likely to result in reduced accuracy in such a case. This is also true of many other multipath mitigation techniques, including other double delta algorithms such as MET and PAC mentioned earlier. However, the proposed ELP-based satellite exclusion approach was able to remove error caused by multipath in all the cases.

4. Multiple Reflection Analysis

The previous section considered the effect of multipath of only a single reflection. In this section the effects of multiple reflections are investigated. First a case with two reflections received from the same satellite signal is considered. Fig. 8 shows results for two such scenarios for latitude -35° and longitude 150° at UTC time 1020 hrs on 09th September, 2009. At this time, PRNs 1, 8, 10, 15 and 22 were visible. Two multipath scenarios, each having dual reflections, were considered by adding reflections for PRNs 8 and 15. For PRN 8, reflections were added with relative attenuation of 0.5 and 0.7 having additional path delay of 255 and 130 m. However, for PRN 15 relative attenuation of 0.5 and 0.7 were used with shorter path delays of 120 and 65 m. It can be seen that ELP was able to detect multipath in both cases and thus reduce the positioning error by excluding affected satellites. Multipath in PRN 8 and 15 resulted in mean positioning error of 26.12 m and 68.94 m. The narrow correlator and HRC have not been effective in this case. Narrow correlators resulted in 26.5 m and 62.62 m of positioning error, while they are 30.74 m and 55.65 m for HRC. Only ELP-based exclusion was shown to be effective in this case, reducing these errors to 2.68 m and 3.6 m. Most of the research in multipath mitigation assumes a single reflection from the satellite, however multiple reflections can have more complicated distortion in the correlation function. Previously, narrow correlators and MEDLL have been shown to have aberrant behaviour in the presence of multiple reflections (Cox et al., 1999). In the case of MEDLL, which is designed for multiple reflections, this problem arises where there are more reflections than the MEDLL is designed for.

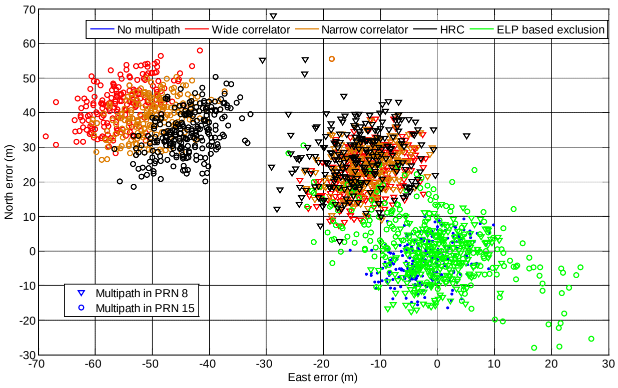

Figure 8: Positioning error due to the presence of dual reflections from the same satellite for latitude = -35°, longitude = 150°, UTC starting time = 1020 hrs on 09th September, 2009 a) PRN 8 (α_1 = 0.5, d_1 = 255 m & α_2 = 0.7, d_2 = 130 m) b) PRN 15 (α_1 = 0.5, d_1 = 120 m & α_2 = 0.7, d_2 = 65 m)

It can also be seen from the plots that exclusion of PRN 15 results in more error compared to the exclusion of PRN 8. The reason for this is that the original HDOP of 1.7 is only increased to 1.85 when PRN 8 is excluded, but it goes up to 3.8 after exclusion of PRN 15. Although in this case positioning error is still lower than that caused by multipath, exclusion of a satellite may need to be avoided in case of significant increase in HDOP. This is discussed later in this section.

It was seen in the previous case that although the narrow correlator approach may not be effective when there are multiple reflections from the same satellite, ELP can still mitigate the multipath effect. It was also seen earlier that ELP cannot detect multipath if the carrier phase difference between the LOS and reflected signal is an integer multiple of π, because in this case there is no energy shift from the I to Q channel which ELP exploits for multipath detection (Mubarak and Dempster, 2007). However, in such a case, multiple reflections can actually improve ELP performance because only one is required to shift energy to the Q channel to increase the ELP magnitude and to result in successful detection. It can be shown by considering missed multipath detections in Fig. 6. Fig. 9 shows the same scenario as in Fig.6, but with multiple reflections added for d equal to 100 m and 200 m. These two have been selected as they were not detected in Fig. 6. Attenuation for these reflections was set to 0.5 and that for secondary reflections was set to 0.3. This means the stronger reflection still has the carrier phase difference with the LOS close to an integer multiple of π. It can be seen that for d_1 = 100 m ELP was able to detect multiple reflections when d_2 is 250 m. However, when d_2 is set to 200 m, multipath is not detected as in this case both reflections have carrier phase difference with the LOS equal to an integer multiple of π. Next, d_1 is set to 200 m and d_2 to 135 m and 275 m. It can be seen that for d_2 275 m ELP was able to detect multipath but for 135 m, it was not able to detect it. This is because when the first reflection is 100 m, it may have had carrier phase difference with the LOS of an odd integer multiple of π resulting in a decrease of energy in the in-phase component of the LOS signal. This implies that the second reflection with attenuation of 0.3 can actually be regarded as relatively more than 0.3 with respect to the combined LOS and first reflection. However, when the first reflection is changed to 200 m, the carrier phase difference is an even integer of π implying an increase in the in-phase component of the LOS signal. This means that effectively the attenuation of the second reflection with respect to the combined LOS and first reflection is less than 0.3, and thus it is less likely to be detected using ELP because the probability of multipath detection using ELP is decreased for relatively lower strength reflections. The experiment is then repeated using α_2 = 0.5. ELP was able to detect multipath in this case. This explanation assumed that the 100 m reflection is an out of phase one and 200 m is in phase. This is confirmed later in this section. In summary, it has been shown that reflections having carrier phase difference closer to an integer multiple of π with the LOS signal can be detected in the presence of multiple reflections, unless other reflections also give this phase difference closer to an integer multiple of π or the combined strength of the LOS and first reflection is significantly higher than other reflections. Intuitively, it can be stated that in the presence of multiple reflections in “real life”, the probability of these two exceptions is low. This implies that the statistical performance of ELP computed for a single reflection (Mubarak and Dempster, 2009) may be improved for multiple reflections. This still has to be proven from a theoretical point of view.

It can also be seen in Fig. 9 that the narrow correlator and HRC give mixed responses. In some cases they reduce error caused by multipath, while in others they increase it as they have locked to a sub-peak formed by multipath and because of the smaller linear region in the discriminator function of narrow correlators and HRC as compared with the wide correlators (Braasch, 2001), they remained locked to a false peak. It was confirmed for HRC in Fig. 5, and this can be analyzed here for the narrow correlator by simulating the same scenario with a multipath-free initial period. Fig. 10 shows east and north errors for reflections with relative path delay of 200 m and 275 m; and relative attenuations of 0.5 and 0.3 respectively but with no multipath in first 40 seconds. Again it can be seen that using a wide correlator, a similar error as in Fig. 9 is obtained, but the narrow correlator has been able to remove those errors in this case. This confirms that in Fig. 9 the narrow correlator locked to a false peak. In order to further explain this, a scenario with reflections having additional path length of 100 m and 200 m with relative attenuation of 0.3 and 0.5 respectively is considered. It can be seen in Fig. 9 that both HRC and narrow correlators perform worse than wide correlators in this case. Fig. 11 shows a correlation function of 1 msec of simulated signal used in the experiment above with the local code. An obvious false peak can be seen here because of reflection with an additional path length of 200 m. It can also be confirmed that the 100 m reflection gave a "dip" in the correlation function implying an out of phase reflection, whereas the 200 m reflection gave a secondary peak implying an in phase reflection.

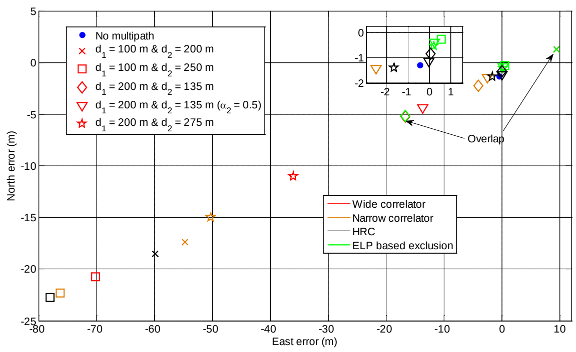

Figure 9: Mean positioning error for multiple reflections in PRN 11 signal (α_1 = 0.5, α_2 (unless stated otherwise) = 0.3, latitude = -20°, longitude = -45°, UTC starting time = 1500 hrs on 27th October, 2009) (inset: zoom of results around zero error)

Next, positioning error in the presence of reflections from two different satellites is analysed. Relative attenuation between the LOS and reflected signals is set to 0.5 for this experiment. In this case, the same location and time is used as for Fig. 2. Two different multipath scenarios are considered. In the first case multipath was added to PRNs 12 and 18 with relative delay of 110 m and 85 m respectively. As shown in Fig. 12, a narrow correlator and HRC were able to reduce error. The mean error was reduced from 25.76 m to 11.02 m for the narrow correlator and to 2.66 m for HRC. However, in this case ELP-based exclusion has drastically increased the error standard deviation. This is because the HDOP increased from 1.7 to 8 due to exclusion of PRNs 12 and 18. Thus, it is confirmed that satellite exclusion can only be usefully performed if there is not a significant increase in DOP. As shown in a later part of the paper, in such scenarios excluding one of the multipath-affected satellites may also increase error.

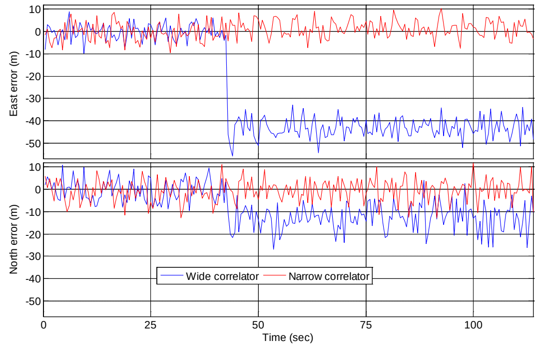

Figure 10: Positioning error for multiple reflections in PRN 11 signal as given in Fig. 9 but with first 40 seconds free of multipath (d_1 = 200 m, α_1 = 0.5, d_2 = 275 m, α_2 = 0.3)

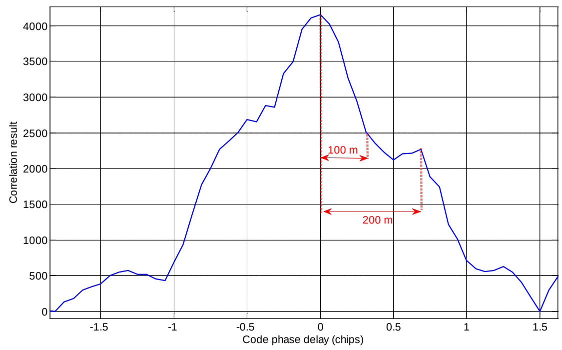

Figure 11: Correlation of a received signal with a local code in the presence of multiple reflections (d_1 = 100 m, α_1 = 0.5, d_2 = 200 m, α_2 = 0.3) as given in Fig. 9

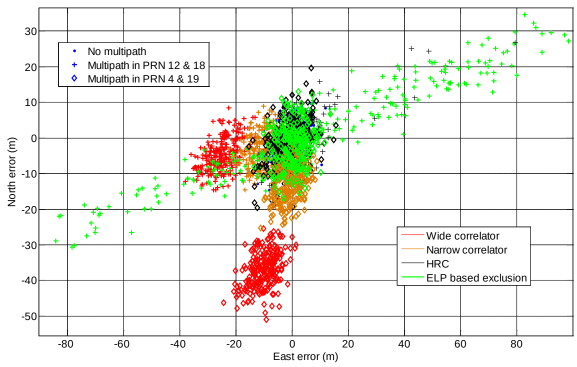

Figure 12: Positioning error due to the presence of dual reflections from two different satellites for latitude = -35°, longitude = 150°, UTC starting time = 0708 hrs on 01st May, 2009 a) PRNs 12 & 18 (α_{12} = 0.5, d_{12} = 110 m & α_{18} = 0.5, d_{18} = 85 m) b) PRNs 4 & 19 (α_4 = 0.5, d_4 = 210 m & α_{19} = 0.5, d_{19} = 215 m)

The second case is a combination for two cases considered in Fig. 3. Earlier PRNs 4 and 19 were individually analysed in the presence of multipath path length of 210 m and 215 m. However, here a scenario is formed where both of those reflections are present at the same time. The results for positioning error are shown in Fig. 12. The error due to multipath in PRNs 4 and 19 can be compared with Fig. 3. In that case, individually both reflections resulted in negative northing error, however PRN 4 and PRN 19 gave positive and negative easting error respectively. Thus, in Fig. 12 when both of these reflections are present, northing error was increased due to constructive combination, and easting error is reduced due to destructive combination. Nevertheless, since both of the reflections are detectable, as seen in Fig. 3, multipath error was removed in this case. The HDOP of the further reduced constellation is 2.08.

So far, only static multipath conditions have been considered, which means the multipath remains the same for the duration of a scenario. Next, results from a 15 minute experiment are presented with changing multipath conditions. In this case, latitude and longitude were set to 0° and -105° respectively starting at UTC time 2315 hrs on 07th October, 2009. At this time, signals from 8 GPS satellites could be received: PRNs 4, 6, 7, 9, 13, 19, 21 and 22. Multipath with relative attenuation of 0.5 was added to all these satellites over a 15 minute period, up to 3 reflections at a time, with varying path delay as shown in Fig. 13. Although the figure shows continuous plots, as path delays are required to be manually entered in the simulator, they are actually changed every 30 seconds.

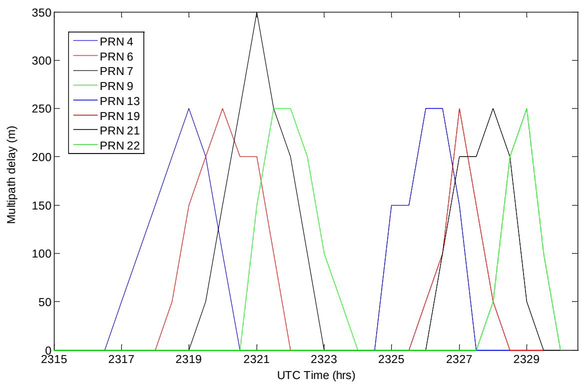

Figure 13: Path delay for multipath added over time for the experimental results of Fig. 14 and Fig. 15

Fig. 14 shows east and north error over time. ELP was able to detect and eliminate multipath in most of the cases, although at some points it could not detect it. Compared to the narrow correlator and HRC receivers, ELP performs almost equally well apart from some instances. Fig. 15 shows the two-dimensional plot of these errors and confirms the overall improvement obtained using ELP over standard wide correlators. In comparison with narrow correlators and HRC, average error in this 15 minute period is computed. It was reduced from 20.5 m to 9.1 m, 5.8 m and 8.5 m using a narrow correlator, HRC and ELP-based satellite exclusion. It may also be noted here that although in this case the performance of ELP-based exclusion is almost the same as the narrow correlator and slightly worse than HRC, the scenarios where the narrow correlator and HRC performs worse were not considered in this case. Such scenarios include reflections stronger than the LOS and multiple reflections from the same satellite. Moreover, similar to rest of the results in this paper, this is obtained using a single-frequency receiver, but better ELP performance in terms of multipath detection can be obtained using a dual-frequency receiver (Mubarak & Dempster, 2010).

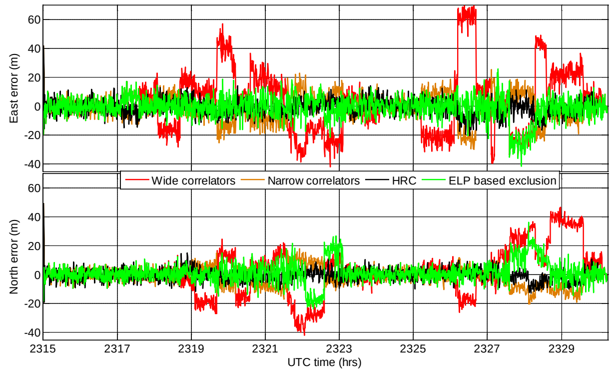

Figure 14: East and north error for multipath pattern given in Fig. 13

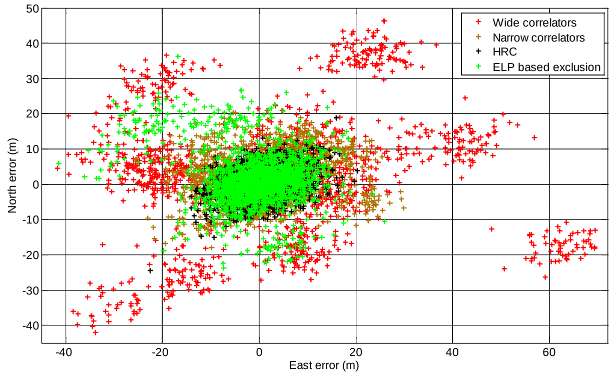

Figure 15: Fig. 14 positioning error shown in two-dimensional space

All the results presented in this paper are obtained for scenarios when there are at least four multipath-free satellite signals, which implies that multipath-affected satellite signals can be excluded from the navigation solution while still keeping a minimum number of satellites required to compute a position, albeit causing an increase in DOP. However, in reality such an assumption may not be valid in urban environments where multipath is common. This provided motivation to analyse ELP-based multipath detection and satellite exclusion in cases where most of the signals received are affected by multipath and four multipath-free signals were not available.

Four different multipath scenarios have been created for a location defined by latitude and longitude 25° and 30° respectively at UTC time 1620 hrs on 15th November, 2009. PRNs 3, 5, 15, 17, 23 and 24 signals were trackable at this time and location. Table-I shows the multipath parameters for each of the satellites for these scenarios. Scenarios A, B and C have multipath in four satellites, while in the last case multipath was added to 5 of them. Since there are not enough multipath-free satellite signals to perform positioning, some of the multipath-affected satellites need to be kept in the navigation solution. Two approaches were considered in this paper. In the first approach satellites with the highest magnitude ELP were excluded. However, since tracking error is higher when ELP is lower (Mubarak and Dempster, 2009), in the second approach among the satellites having ELP higher than the threshold those with the lowest ELP magnitudes were excluded. The results of both these approaches are presented in Fig. 16 along with the case when all the satellites are used without using ELP and assuming wide correlators. It can be seen that whichever approach is used to select the satellite to be excluded, it does not improve accuracy; in fact in most cases it actually decreases accuracy. The increase in error is because multipath error in different satellites can be added constructively or destructively, as shown in Fig. 12. Destructive combination is more likely because of the geometry of satellites, and thus error in this case due to the presence of multipath in one satellite may actually be cancelling the error caused by another one. This implies that when some of the multipath-affected satellites are removed, the effect of multipath from some other satellites can become more pronounced and positioning error may in fact be increased. Thus, it can be concluded that in the case where there are not enough multipath-free satellite signals for positioning, the best option is to keep using all of the satellite measurements in the navigation solution.

On the basis of the above analysis, Fig. 17 shows a flowchart to determine whether to exclude multipath-affected satellites or not. When multipath is detected on any channel in the receiver, firstly a check is made to see if there are at least four multipath-free channels. Secondly, the increase in HDOP by the exclusion of the affected satellites is computed. From the results in this paper, it is proposed that an increase in HDOP of less than 1.5 is acceptable, as multipath is likely to be a dominant error and satellite exclusion improves accuracy. Thus, only if there are fewer than four multipath-free satellites or in the case of a significant increase in DOP multipath-affected satellites are not removed from the navigation solution. Moreover, although ELP has been used to detect multipath in this paper, this flowchart can also be used for satellite exclusion using any other multipath detection algorithm where multipath is independently detected on each channel.

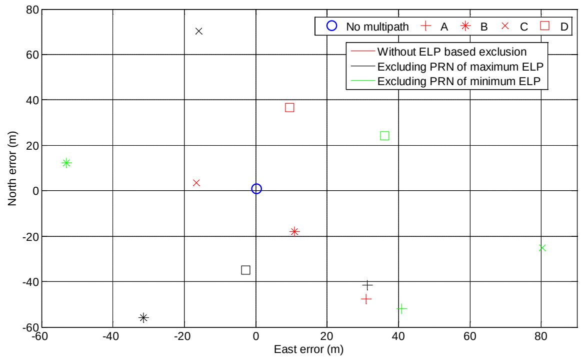

Figure 16: Positioning error for scenarios given in Table-I, when there are less than four multipath-free satellite signals available (latitude = 25°, longitude = 30°, UTC starting time = 1620 hrs on 15th November, 2009)

Table 1: Multipath parameters for scenarios studied

		PRN 3	**PRN 5**	**PRN 15**	**PRN 17**	**PRN 23**	**PRN 24**
A	***α***	0.6	-	-	0.3	0.8	0.5
	***d* (m)**	130	-	-	205	160	180
B	***α***	0.6	-	-	0.5	0.4	0.5
	***d* (m)**	75	-	-	155	195	120
C	***α***	0.6	-	0.5	0.7	0.4	0.8
	***d* (m)**	140	-	150	110	120	205
D	***α***	-	0.3	0.6	0.4	0.5	0.5
	***d* (m)**	-	115	160	205	230	85

5. Conclusion

This paper presents experimental results for detecting multipath using ELP under various scenarios. It showed that positioning error caused by multipath can be mitigated by excluding satellites detected as being affected by multipath using ELP. The performance of this ELP-based exclusion has also been compared with the narrow correlator and HRC approaches, and it was found that although a narrow correlator and HRC reduce multipath-induced error in most of cases, they may in fact increase the error if a tracking loop locks to a false peak formed by the multipath. The likelihood of this happening is higher for stronger reflections. Nevertheless, even when they reduce multipath error, the error obtained from an ELP-based satellite exclusion is lower than the one obtained using narrow correlators and almost the same as using HRC, although HRC performance deteriorates for short range reflections. However, it is only true as long as the remaining constellation after satellite exclusion still has a reasonable DOP. In the results presented in this paper, it was found that unless DOP is significantly increased, multipath error is higher than the increase in error due to the increase in DOP and thus satellite exclusion is a reasonable approach.

ELP is not able to detect multipath when the carrier phase difference between the LOS and reflected signals is close to an integer multiple of π. In this case it was found that ELP performance improves in the presence of multiple reflections from the same satellite because any one of them having a non-integer multiple of π carrier phase difference with the LOS signal can lead to multipath detection.

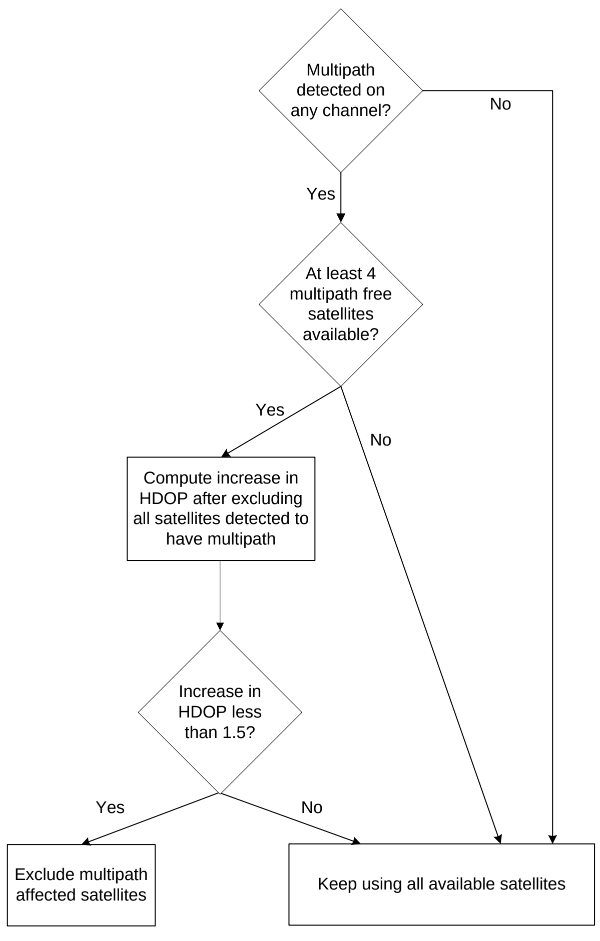

Figure 17: Flowchart for satellite exclusion in the presence of multipath

It has also been found that positioning error can increase when fewer than four multipath-free satellites are available. It was shown that in such a case, excluding satellites with either maximum or minimum ELP magnitude may still increase the error. It is thus recommended that when there are fewer than four multipath-free satellite signals available, all satellites should be used for positioning computations. The possibility of having at least four multipath-free satellites in a multi-GNSS receiver is likely to significantly increase with the introduction of new GNSS systems.

Acknowledgments

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Biography

Omer Mohsin Mubarak recently completed PhD in Surveying and Spatial Information Systems from the University of New South Wales, Australia. He completed a Master of Engineering in Electrical Engineering from the same university in 2006 and a Bachelor of Science in Electronics Engineering from Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan in 2002. His current research is focused on multipath mitigation using modernised GNSS signals.

Andrew Dempster is Director of Research in the School of Surveying and Spatial Information Systems at the University of New South Wales. He was project manager and system engineer on the first GPS receiver to be designed in Australia and has been teaching satellite navigation for over a decade. His current research interests are in signal processing for satellite navigation, new receiver techniques and new location technologies.