A Portfolio Approach to NLOS and Multipath Mitigation in Dense Urban Areas

Paul D Groves, Ziyi Jiang, Morten Rudi and Philip Strode
University College London, United Kingdom

BIOGRAPHY

Dr Paul Groves is a Lecturer (academic faculty member) at University College London (UCL), where he leads a program of research into robust positioning and navigation and is a member of the Engineering Faculty's Space Geodesy and Navigation Laboratory (SGNL). He joined in 2009, after 12 years of navigation systems research at DERA and QinetiQ. He is interested in all aspects of navigation and positioning, including multi-sensor integrated navigation, improving GNSS performance under challenging reception conditions, and novel positioning techniques. He is an author of more than 50 technical publications, including the book Principles of GNSS, Inertial and Multi-Sensor Integrated Navigation Systems, now in its second edition. He is a Fellow of the Royal Institute of Navigation and holds a bachelor's degree and doctorate in physics from the University of Oxford. (p.groves@ucl.ac.uk)

Dr Ziyi Jiang is a research fellow at UCL. His recent research within SGNL specialised in GNSS multipath and NLOS mitigation and a study on modelling the inter-constellation time scale differences. He completed his PhD at UCL on digital-route-model-aided integrated satellite navigation and low-cost inertial sensors for high-performance positioning on the railways, and holds a BEng in measuring and control technology from Harbin Engineering University, China. In 2012, he also received an ION best presentation award.

Morten Rudi has finished an MSc in Hydrographic Surveying at UCL, including a research project studying multipath and NLOS detection using multiple-frequency GNSS. He holds a BSc in Geomatics from Gjøvik University College, Norway and currently works as a seismic navigator.

Philip Strode recently completed an MSc in Hydrographic Surveying at UCL. He holds a BA in Archaeology from the University of Nottingham and now works as an Offshore Surveyor with Fugro.

ABSTRACT

Non-line-of-sight (NLOS) reception and multipath interference are major causes of poor GNSS positioning accuracy in urban environments. This paper describes three pieces of work to mitigate their effects: a new multipath detection technique using multi-frequency carrier-power-to-noise-density ratio (C/N_0) measurements; the first multi-constellation test of the dual-polarization NLOS detection technique; and a proposal for a portfolio approach to multipath and NLOS mitigation.

Constructive multipath interference results in an increase in C/N_0, whereas destructive interference results in a decrease. As the phase of a reflected signal with respect to its directly received counterpart depends on the wavelength, the multipath interference may be constructive on one frequency and destructive on another. Thus, by comparing the difference in measured C/N_0 between two frequencies with what is normally expected for that signal at that elevation angle, strong multipath interference may be detected. A new multipath detection technique based on this principle is demonstrated using data collected in an urban environment.

The dual-polarization NLOS detection technique separately correlates the right hand circularly polarized (RHCP) and left hand circularly polarized (LHCP) outputs of a dual-polarization antenna and differences the C/N_0 measurements. The result is positive for directly received signals and negative for most NLOS signals. Here, this technique is demonstrated on GLONASS signals for the first time and the effect of removing an NLOS signal from the position solution is assessed.

Finally, a qualitative assessment and comparison of 18 different classes of technique for mitigating and detecting NLOS reception and multipath interference is presented, considering ease of implementation and performance. It is concluded that, for most applications, no one technique is completely effective. A portfolio approach is therefore proposed in which multiple techniques are combined. Suitable portfolios are then proposed for professional-grade and for consumer-grade user equipment.

Institute of Navigation GNSS+ 2013, 16-20 September 2013, Nashville, TN, USA

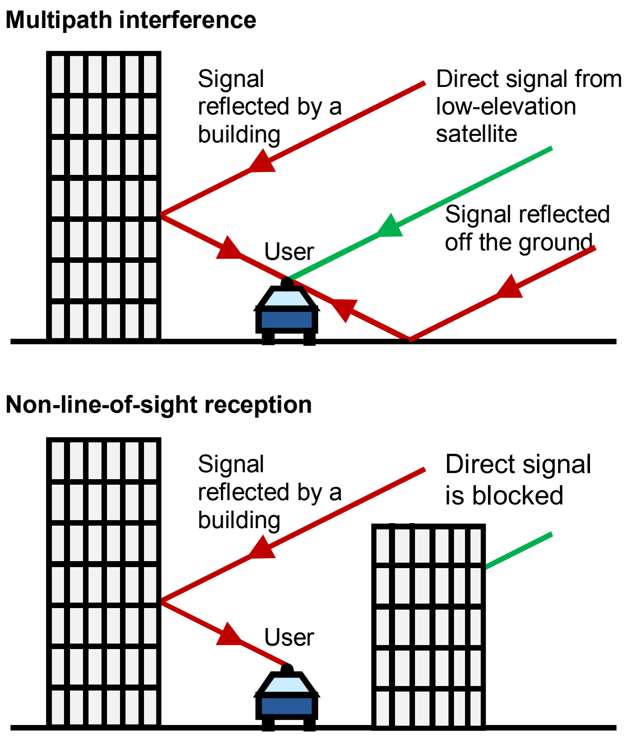

Figure 1: Multipath interference and NLOS reception

1. INTRODUCTION

There are many applications that could benefit from improved urban positioning. These include location-based services (LBS), intelligent transport systems (ITS), augmented reality, vehicle lane control, advanced rail signalling and navigation for the blind. High sensitivity receivers and multiple satellite constellations have vastly improved GNSS signal availability in dense urban areas. However, accuracy remains a problem for applications requiring real-time positioning.

The urban environment presents two major challenges to GNSS signal reception. Firstly, the buildings and other obstacles, such as buses, block the direct line-of-sight (LOS) to many of the satellites, effectively reducing the number in view. Because most signals from across the street are blocked by buildings, leaving the along-street signals, the position solution geometry is poor leading to a much lower accuracy in the cross-street direction [1][2].

The geometry can be improved to a certain extent using height aiding, whereby a terrain height database is used to generate virtual ranging measurements in the vertical direction. This improves the horizontal accuracy by about 35% [3]. Furthermore, a metres-level positioning accuracy in the cross-street direction can often be achieved using shadow matching [4][5][6]. Instead of the ranging method used by conventional GNSS positioning, shadow matching uses pattern matching to determine position by comparing the measured signal availability with that predicted using a 3D city model.

The second major challenge of urban positioning is that these environments contain many flat surfaces that reflect the GNSS signals. Modern glass and metal buildings are particularly strong reflectors, while water enhances the reflectivity of most surfaces. Reception of these reflected signals results in significant positioning errors due to NLOS reception and multipath interference. These are often grouped together as “multipath”. However, they are actually separate phenomena that produce very different ranging errors as Figure 1 illustrates.

NLOS reception occurs where the direct line-of-sight signal is blocked and the signal is received only via reflections. This results in a pseudo-range measurement error equal to the path delay, which is the difference between length of the path taken by the reflected signal and the (blocked) direct path between satellite and receiver. This error is always positive and, although typically tens of metres, is potentially unlimited. Signals received via distant tall buildings can exhibit errors of more than a kilometre. The corresponding carrier-based ranging error is within half a wavelength of the pseudo-range error (noting that phase changes occur on reflection). The strength of NLOS signals varies greatly. They can be very weak, but can also be nearly as strong as the directly received signals. As high-sensitivity receivers can acquire much weaker signals, their use can significantly increase the number of NLOS signals received.

Multipath interference occurs where the signal is received through multiple paths between the satellite and user antenna. Both direct-line-of-sight and NLOS signals may be subject to multipath interference. In the latter case, the signal is received via multiple reflected paths but not directly.

Where multipath interference to directly received signals occurs, the reflected signals distort the code correlation peak within the receiver such that the code phase of the direct LOS signal cannot be accurately determined by equalising the power in the early and late correlation channels. The resulting code tracking error depends on the receiver design as well as the direct and reflected signal strengths, path delay and phase difference, and can be up to half a code chip [7][8]. Code tracking errors are largest where the path delay is about half a code chip (150m for GPS C/A code). Carrier-phase tracking errors are limited to a quarter of a wavelength (assuming the direct LOS signal is stronger than the reflections) and are largest where the path delay is short.

Where a signal is partially blocked by an obstacle, diffraction can occur, bending the path of the signal and attenuating it. The attenuation increases with the diffraction angle with useable GNSS signals receivable at deflections of up to 5° [1][9]. Diffracted signals are also delayed, but typically only by decimeters. They are thus useful for nonprecision positioning and navigation applications. A diffracted signal is normally received instead of the direct signal, but may occasionally be received in addition.

To get the best performance out of GNSS in urban areas, it is necessary to minimise the impact of NLOS reception and multipath interference on the position solution. This is important even where shadow matching is used as conventional ranging-based positioning is still needed for the along-street component of the position solution [2]. For precision applications, it is also important to minimise the impact of diffraction.

University College London (UCL) has investigated the performance of a number of multipath and/or NLOS mitigation techniques in dense urban areas, including solution weighting based on carrier-power-to-noise-density ratio (C/N_0) [10], advanced consistency checking [11], dual-polarization NLOS detection [12] and vector tracking [13][14]. In this paper, we present a new multipath detection technique based on comparing the measured C/N_0 on multiple frequencies and also new dual-polarization results. Meanwhile, other researchers have demonstrated NLOS detection using a panoramic camera [15][16] or 3D city model [17][18] and detection of NLOS and multipath using an antenna array [19]. All of these techniques bring some improvement in positioning performance in urban environments, but none of them eliminate the effects of both NLOS reception and multipath interference completely. As the different techniques are largely complementary, best performance is obtained by using several of them in combination, a portfolio approach.

Detection of NLOS reception and multipath interference is as important as mitigating it directly. Direct, NLOS and multipath-contaminated signals should be treated differently within the positioning algorithm. Where it is unknown which signals are which, there is essentially an ambiguity problem. Making different assumptions about each signal within the positioning algorithm results in different position solutions. Thus, the position solution itself is ambiguous.

This paper comprises three parts. Section 2 presents a feasibility study on a new multipath detection technique using multi-frequency C/N_0 measurements. Section 3 presents the results of the first multi-constellation test of the dual-polarization NLOS detection technique pioneered at UCL. The rest of the paper addresses the portfolio approach to NLOS and multipath mitigation. Section 4 assesses each technique qualitatively for its ease of implementation and its efficiency at detecting or directly mitigating both NLOS reception and multipath mitigation. Section 5 then discusses the compatibility of the different techniques, explaining which techniques may be combined without conflict and which may not. It then proposes suitable NLOS and multipath mitigation portfolios for professional-grade and for consumer-grade user equipment, outlining the future work needed to deliver them. Finally, Section 6 summarises the conclusions.

Note that this paper focuses on applications where an instant fix is required or the user is moving. For static applications with extended observation periods, there are a number of additional multipath and NLOS mitigation techniques based on time-series analysis. However, these are outside the scope of this particular paper. Use of a multi-constellation GNSS receiver is assumed throughout.

2. MULTI-FREQUENCY C/N$_0$-BASED MULTIPATH DETECTION

The effect of multipath interference on measurements of C/N_0 or signal-to-noise ratio (SNR) depends on the phase of the reflected signal with respect to the direct signal which, in turn, depends on the path delay and the phase shift on reflection. Where the phase of the direct and reflected signals differs by less than ±90°, their amplitudes add, resulting in increased prompt correlator outputs within the receiver and hence an increase in the measured C/N_0. This is constructive multipath interference. Conversely, where the phase difference between direct and reflected signals is around 180°, destructive multipath interference occurs which results in a decrease in both the prompt correlator outputs and measured C/N_0. Figure 2 illustrates this. The effect is greatest for phase differences of 0 and 180°.

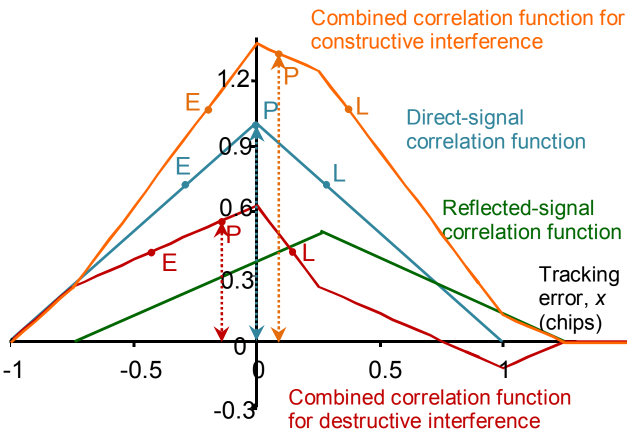

Figure 2: Effect of constructive and destructive multipath interference on size of prompt (P) correlator output (path delay = 0.25 chips; relative amplitude of reflected signal = 0.5; adapted from [7])

For static applications, an oscillatory variation in the measured C/N_0 can be observed over the course of a few minutes as the path delay varies due to satellite motion. The presence of multipath interference may be deduced from this. However, for many applications, much faster detection is needed. As the phase of a reflected signal with respect to its directly received counterpart depends on the wavelength, the multipath interference may be constructive on one frequency and destructive on another. Figure 3 illustrates this.

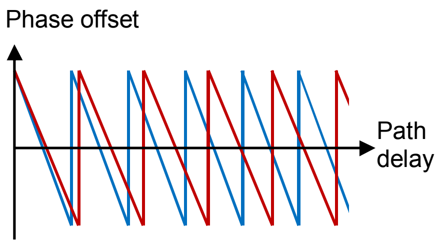

Figure 3: Phase offset of the reflected signal with respect to the direct signal on two different frequencies as a function of the path delay

Thus, by comparing the difference in measured C/N_0 between two frequencies with what would normally be expected for that signal at that elevation angle, strong multipath interference may be detected. However, the converse is not true because, depending on the path delay, the phase of the multipath interference may also be consistent across the two frequencies. Consistency across three frequencies in the presence of multipath interference is much less likely than consistency across two. Therefore, by comparing C/N_0 measured across three (or more) frequencies, the chance of detecting multipath interference should be improved substantially.

Note that the shorter the path delay divided by the chipping rate, the closer the correlation peaks of the reflected and direct signals will be and thus the greater the impact on the measured C/N_0 will be for a given reflected signal amplitude. Therefore, this detection technique will be more sensitive to the short-delay multipath interference that is most disruptive to carrier-phase positioning than to the medium-delay multipath interference that has the greatest impact on code tracking. Furthermore, for a given path delay, there should be a greater impact on the measured C/N_0 of low chipping-rate signals, such as GPS C/A and L2C and GLONASS L1OF and L2OF than on high chipping-rate signals, such as GPS P(Y) and L5. These factors will have the most impact where the reflected signal is very strong (or the direct signal attenuated).

Diffraction also results in variations in C/N_0 that depend on the carrier frequency, so diffracted signals will also result in the difference in measured C/N_0 between two frequencies diverging from its normal value. This can be either a benefit or drawback of the technique depending on whether or not it is desirable to eliminate or downweight diffracted signals in the navigation solution for the application in question.

Here, experimental results are first presented that test the potential of this new multipath detection method. A three-frequency multipath detection parameter is then proposed and tested.

For the initial feasibility study, conducted in summer 2012, both GPS and GLONASS data were collected in both low- and high-multipath environments using a Leica Viva GS15 survey-grade multi-constellation GNSS receiver. The low-multipath data was collected on Parliament Hill in North London, while the high-multipath data in and around UCL in Central London. Full details of the initial feasibility study may be found in [20]. Some example results are presented here.

In the low-multipath environment, the difference in C/N_0 (in dB) between the L1 and L2 frequencies for both GPS and GLONASS signals varied by about ±2 dB at a given elevation angle for elevations above 40° with the variation increasing as the elevation dropped below this. Differences between the ascending and descending data from the same satellite were observed, so much of this variation can be attributed to variations in the antenna gain with elevation. Thus, C/N_0-based multipath detection will be more sensitive at higher elevations than lower elevations.

For GPS, the mean L1–L2 C/N_0 difference was independent of elevation up to 40°, then gradually reduced by about 3dB as the elevation increased to 90°. However, for GLONASS, no variation in mean L1–L2 C/N_0 difference with elevation was observed. At most elevations, the GPS L2C signal was observed to be stronger than the GPS L2 P(Y)-code signal, which is consistent with the design of the GPS system. For GLONASS, the mean L1–L2 C/N_0 difference varied by up to 10 dB from satellite to satellite, despite all of the GLONASS satellites being nominally of the same GLONASS-M design. One possibility is that this is a consequence of GLONASS using frequency division multiple access (FDMA) with the antenna and receiver gain varying with the GLONASS channel number. Thus, in determining the assumed low-multipath L1–L2 C/N_0 difference that current values should be compared with, the satellite type must be accounted for as well as the elevation angle.

GPS L5 signals were only observed from satellite PRN25 as only two satellites were broadcasting L5 at the time of the tests and the other was only receivable at night in London. For this satellite, the L1 and L5 C/N_0 values were more stable than the L2 value.

Figures 4 and 5, respectively, show the L1–L2 and L1–L5 C/N_0 differences for GPS satellite PRN25 for both low-multipath and high-multipath environments as a function of elevation. It can be seen that there is much greater fluctuation in both C/N_0 differences in the high-multipath environment compared to the low-multipath environment.

Figure 6 shows the MP1 parameter for the high-multipath data from GPS satellite PRN 25. It is given by

$$MP1_a^s = \tilde{\rho}_{a,S}^{s,1} - \left(\frac{\left(f_{ca}^1\right)^2 + \left(f_{ca}^2\right)^2}{\left(f_{ca}^1\right)^2 - \left(f_{ca}^2\right)^2} \right) \tilde{\Phi}_{a,R}^{s,1} + \frac{2\left(f_{ca}^2\right)^2}{\left(f_{ca}^1\right)^2 - \left(f_{ca}^2\right)^2} \tilde{\Phi}_{a,R}^{s,2},$$

where $\tilde{\rho}_{a,S}^{s,1}$ is the L1 pseudo-range measurement from satellite s to user antenna a, $\tilde{\Phi}_{a,R}^{s,1}$ is the corresponding L1 accumulated delta range (ADR), derived from carrier phase, $\widetilde{\Phi}_{a,R}^{s,2}$ is the corresponding L2 ADR, f_{ca}^{1} is the L1 carrier frequency and f_{ca}^{2} the L2 carrier frequency. The change over time in the true pseudo-range, troposphere and ionosphere propagation delays largely cancel out, leaving a parameter dominated by the L1 code multipath error and tracking noise. Note that all pseudo-range measurements output by Leica receivers are carrier-smoothed, so the MP1 parameter is commensurately reduced.

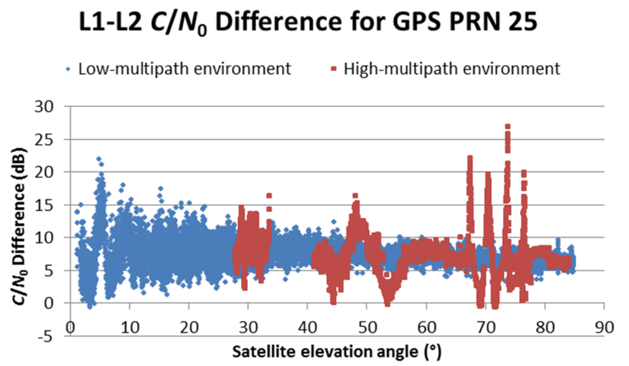

Figure 4: Comparison of low-multipath and high-multipath L1–L2 C/N_0 differences for GPS PRN 25

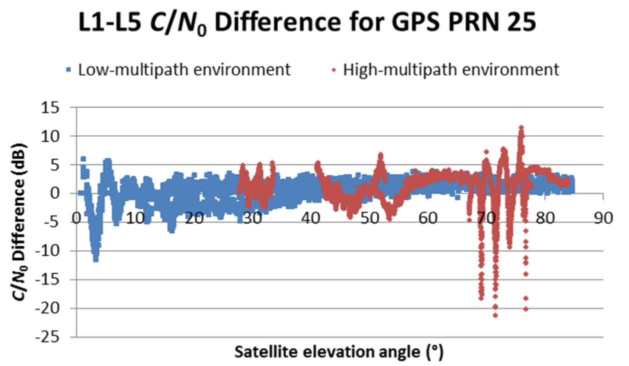

Figure 5: Comparison of low-multipath and high-multipath L1–L5 C/N_0 differences for GPS PRN 25

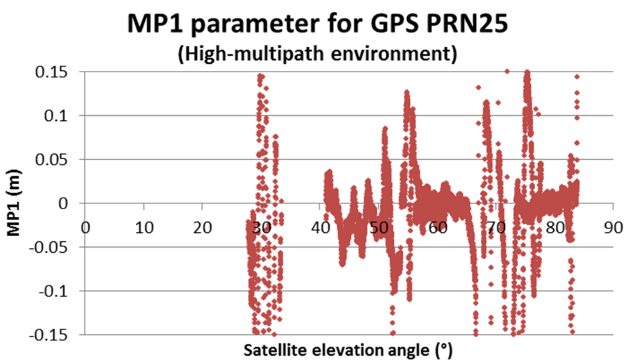

Figure 6: MP1 parameter for GPS PRN 25 in a high-multipath environment

Comparing the MP1 parameter with the C/N_0 differences, it can be seen that both show oscillation at the same time, but that there is no clear correspondence in the size of the oscillation. This is to be expected as pseudo-range multipath errors peak at medium path delays, typically around half a code chip, whereas the C/N_0 measurements are most impacted by short-delay multipath.

Figure 7 shows the L1–L2 C/N_0 difference for GLONASS satellite R12 for both low-multipath and high-multipath environments as a function of elevation while Figure 8 shows the MP1 parameter for the high-multipath data. The GLONASS results are similar to the GPS results.

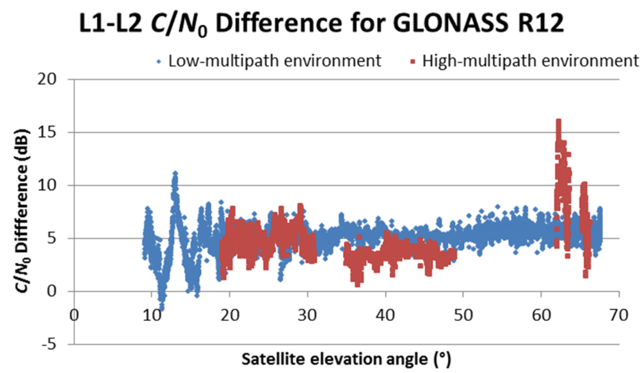

Figure 7: Comparison of low-multipath and high-multipath L1–L2 C/N_0 differences for GLONASS R12

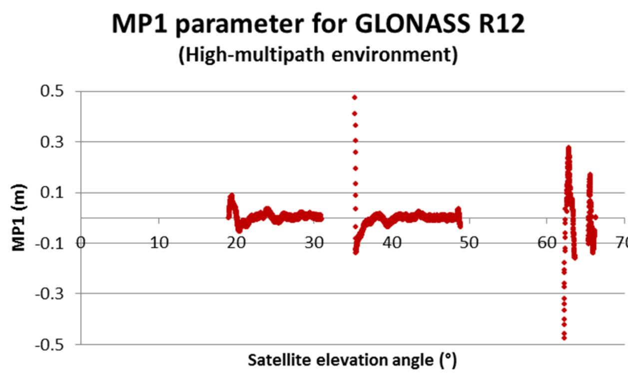

Figure 8: MP1 parameter for GLONASS R12 in a high-multipath environment

To use the differences between C/N_0 measurements on three frequencies for detecting multipath, the following test statistic based on comparisons of both the L1–L2 and L1-L5 C/N_0 differences with their predicted values is proposed:

$$S_a^s = \sqrt{\begin{aligned}&\left[\left(\widetilde{C}/\widetilde{N}_0\right)_a^{s,L1} - \left(\widetilde{C}/\widetilde{N}_0\right)_a^{s,L2} - \Delta C^{12}\left(\theta_{nu}^{as}\right)\right]^2 \\ &+ \left[\left(\widetilde{C}/\widetilde{N}_0\right)_a^{s,L1} - \left(\widetilde{C}/\widetilde{N}_0\right)_a^{s,L5} - \Delta C^{15}\left(\theta_{nu}^{as}\right)\right]^2\end{aligned}},$$

where $\left(\widetilde{C}/\widetilde{N}_0\right)_a^{s,l}$ is the measured C/N_0 (in dB-Hz) by receiver a of signal l from satellite s; ΔC^{12} and ΔC^{15} are, respectively, the predicted L1–L2 and L1–L5 C/N_0 differences; and θ_{nu}^{as} is the elevation angle of satellite s from user antenna a.

The predicted C/N_0 differences were obtained by fitting a polynomial function to C/N_0 data collected in a low-multipath environment. The following functions were used for the results presented here [21]:

$$\begin{aligned} \Delta C^{12}(\theta) &= 2 + 0.098\theta - 0.0011\theta^2 + 2.8\times10^{-6}\theta^3 \text{ dB} \\ \Delta C^{15}(\theta) &= -2.9 + 0.160\theta - 0.0016\theta^2 + 4.7\times10^{-6}\theta^3 \text{ dB} \end{aligned},$$

where the elevation here is expressed in degrees (not radians).

The threshold against which the test statistic is compared was computed as a function of elevation from the standard deviation of the C/N_0 measurements collected in a low-multipath environment and scaled empirically. The threshold used for the results presented here was [21]:

$$T(\theta) = 1.9611 - 0.082\theta + 0.0012\theta^2 - 5.9\times10^{-6}\theta^3 \text{ dB},$$

where the elevation is in degrees (not radians).

To test the new three-frequency detection technique, GNSS data was collected in a variety of urban environments during summer 2013 using a Leica Viva GS15 GNSS receiver and the measurements from the GPS Block IIF satellites, which provide open signals on three frequencies, analysed. Full results are presented in [21]. Here, an example from an urban site near Birkbeck College in Central London is presented. Figure 9 shows the test statistic and threshold for 8000s of data from GPS PRN 25, while Figure 10 presents the corresponding MP1 observable.

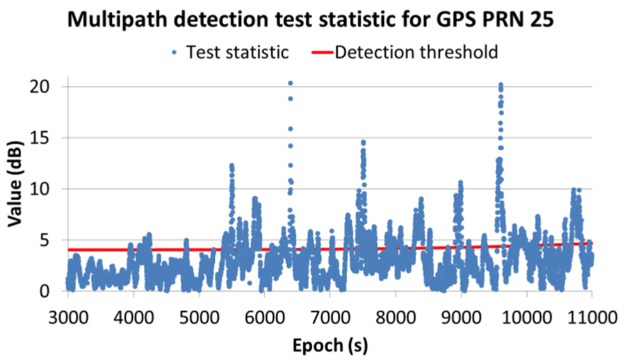

Figure 9: Three-frequency multipath detection test statistic and detection threshold for GPS PRN 25 at the urban test site near Birkbeck College, London

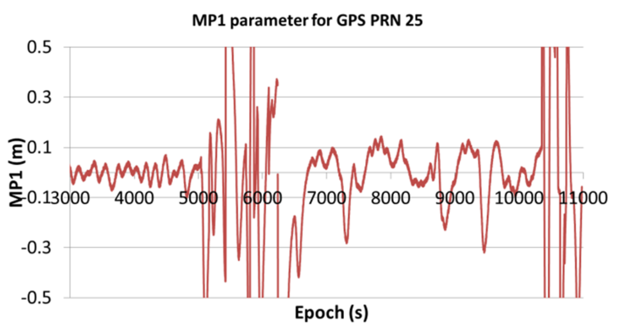

Figure 10: MP1 parameter for GPS PRN 25 at the urban test site near Birkbeck College, London

Comparing the two figures, it can be seen that the three-frequency C/N_0-based test statistic is generally above the detection threshold when the MP1 parameter is large and/or changing rapidly. A closer correspondence is not expected as MP1 is more sensitive to medium-delay multipath whereas the new C/N_0-based test statistic is more sensitive to short-delay multipath. The large spike around 6400s immediately precedes a loss of carrier-phase lock on L1; hence, there is a discontinuity in the MP1 data at this point. The other spikes in the C/N_0-based test statistic coincide with rapid changes in the MP1 parameter.

For dynamic applications, the path delay varies as the user antenna moves, often resulting in the multipath interference oscillating between constructive and destructive faster than the bandwidth of the C/N_0 measurement algorithm. Consequently, multi-frequency C/N_0-based multipath detection is unlikely to work for applications where the user is moving faster than a walking pace.

3. NLOS DETECTION USING DUAL-POLARIZATION ANTENNA

All GNSS signals are transmitted with right-handed circular polarization (RHCP). For angles of incidence less than Brewster's angle, this changes to left-handed polarization (LHCP) on specular reflection. A signal reflected specularly from a complex surface may have a mixture of LHCP and RHCP due to interference between components of the signal reflected with different path delays within the Fresnel zone (i.e. the footprint of the signal) [7].

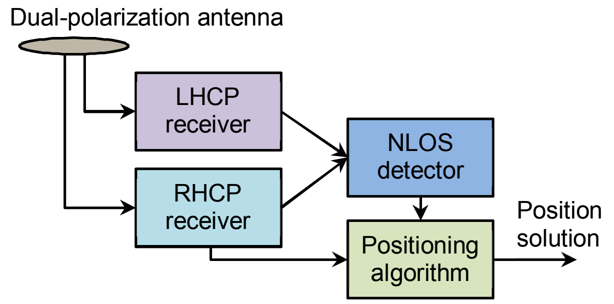

Figure 11: Dual-polarization NLOS detection method

A dual-polarization antenna is a single antenna whose internal elements are combined in two different ways to produce RHCP-sensitive and LHCP-sensitive outputs. A pair of antennas, one sensitive to each polarization, could also be used. NLOS signals may be identified simply by correlating the RHCP and LHCP antenna signals separately within the receiver and determining a separate signal-to-noise ratio (SNR) or carrier-power-to-noise-density ratio (C/N_0) for each polarization. If the LHCP SNR or C/N_0 is the larger of the two, the signal is assumed to be NLOS; otherwise, it is assumed to be direct-LOS [22]. Figure 11 illustrates this. Note that the technique works better for higher elevation signals than lower elevation signals because the antenna's sensitivity to polarization varies with the angle of incidence.

UCL has successfully demonstrated the dual-polarization NLOS detection method in a London urban canyon using GPS measurements only [12]. In these experiments, signals identified as NLOS from the C/N_0 difference were confirmed as so using a map of the surrounding buildings. Furthermore, at one of the test sites, the mean horizontal position error was reduced from 155.9 m to 45.3 m by eliminating from the position solution signals identified as NLOS using the dual-polarization technique. The corrected position solution was relatively poor due to a mixture of poor signal geometry and some of the remaining signals being affected by severe multipath interference.

Figure 12: Antcom 3G1215RL-P-XS-1 dual-polarization antenna, mounting and amplifiers.

Figure 13: Two Novatel Flexpak 6 OEM628 GNSS receivers and logging PCs.

The next step is to test the dual-polarization NLOS detection technique using multi-constellation GNSS receivers. Trials were conducted at five sites in central London on 3 December 2012 using an Antcom 3G1215RL-P-XS-1 dual-polarization antenna and two Novatel Flexpak 6 OEM628 survey-grade multi-constellation GNSS receivers. The antenna assembly is shown in Figure 12, while the GNSS receivers, connected to laptop PCs for data logging, are shown in Figure 13.

At each test site, the RHCP−LHCP C/N_0 difference on both the L1 and L2 frequencies was calculated for every GPS and GLONASS satellite tracked, and a signal identified for which this was predominantly negative. Figures 14 to 18 show the RHCP, LHCP and difference therein for each of these negative RHCP−LHCP C/N_0 difference signals. These signals were then assumed to be NLOS and position solutions were calculated with and without them. Figures 19 to 23 show the position solutions superimposed on an aerial photograph of each site, while Table 1 gives the root mean square (RMS) horizontal errors. In each case, measurements were weighted according to the satellite elevation angle as described in [3]. The apparent discrepancy between the figures and the table is due to the presence of a few extreme outliers that are not included in the figures.

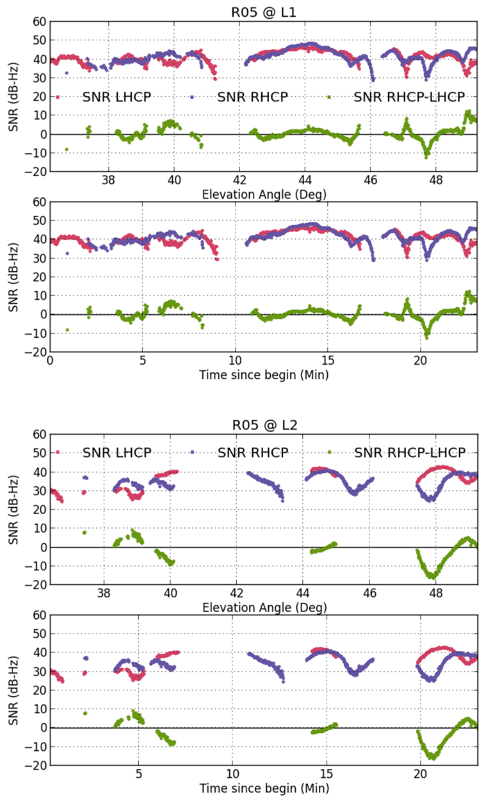

Figure 14: RHCP, LHCP and differenced C/N_0 for GLONASS satellite R05 at Gower Place test site.

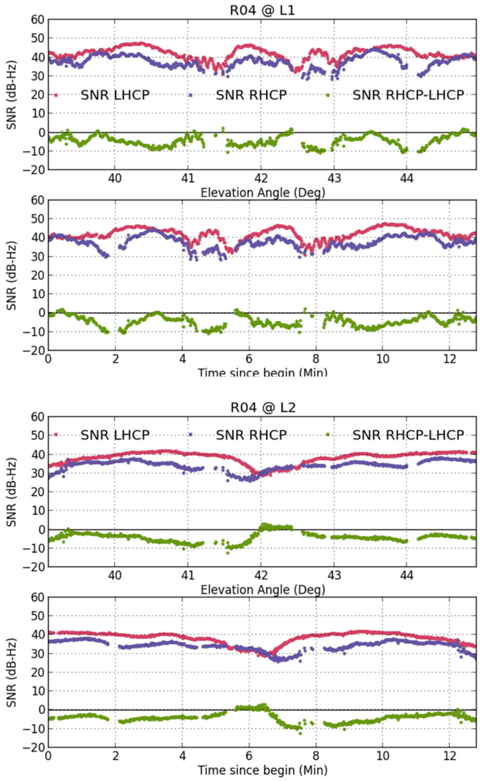

Figure 15: RHCP, LHCP and differenced C/N_0 for GLONASS satellite R04 at Stephenson Way test site.

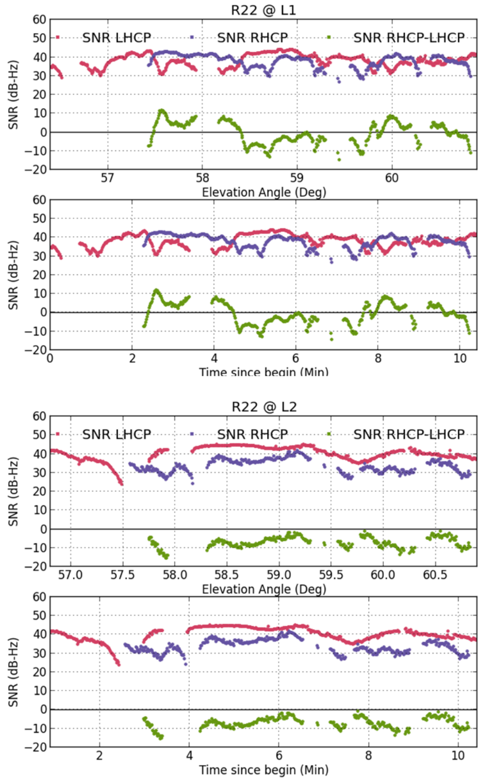

Figure 17: RHCP, LHCP and differenced C/N_0 for GLONASS satellite R22 at Regent Place test site.

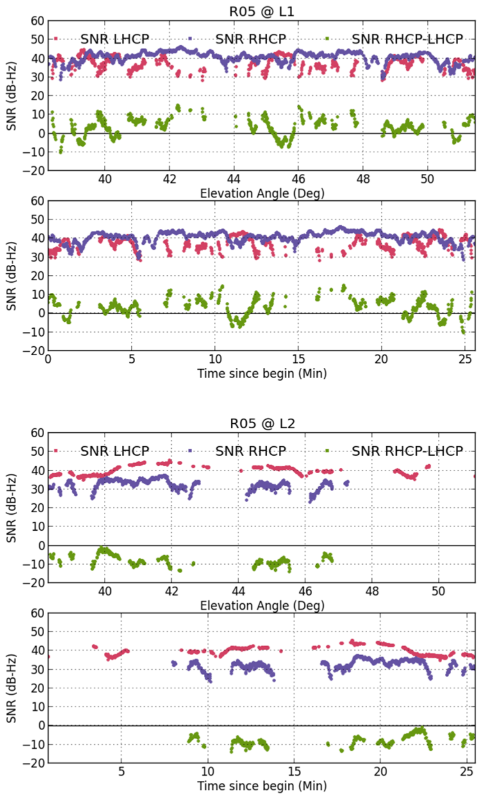

Figure 16: RHCP, LHCP and differenced C/N_0 for GLONASS satellite R05 at Santander, Euston Square site.

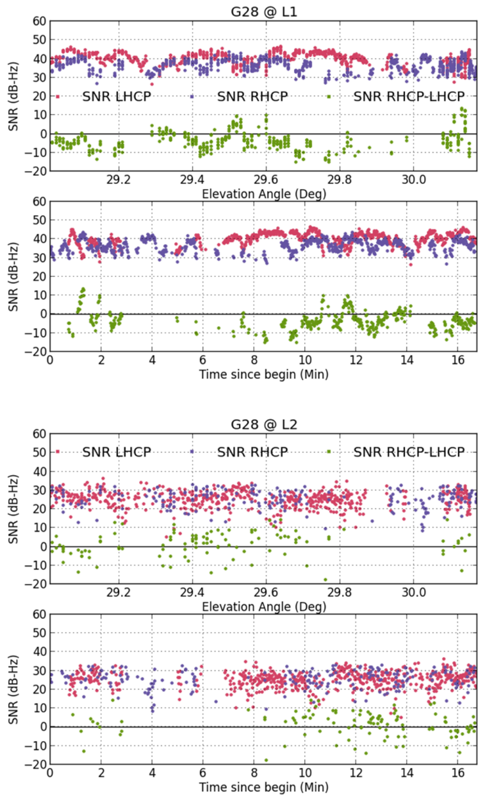

Figure 18: RHCP, LHCP and differenced C/N_0 for GPS satellite G28 at Starbucks, Euston Square test site.

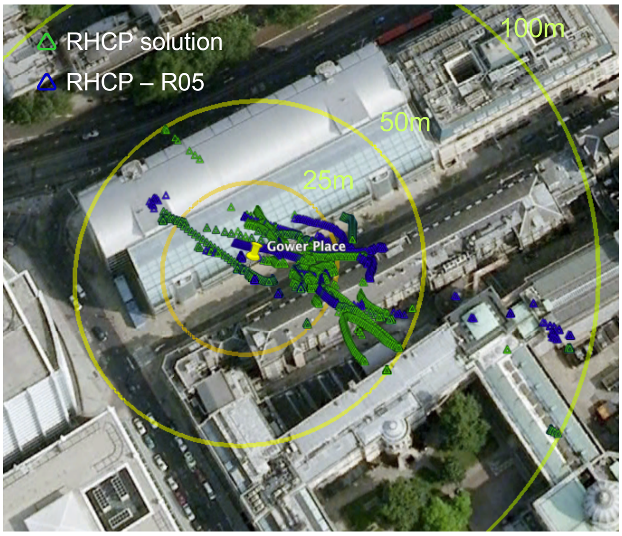

Figure 19: Position solutions with and without GLONASS satellite R05 at Gower Place test site (Background image © 2013 Bluesky).

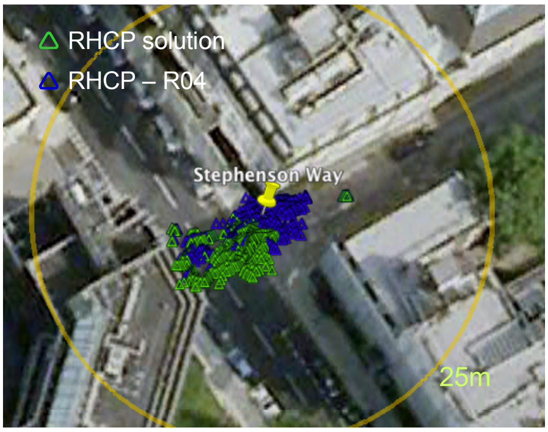

Figure 20: Position solutions with and without GLONASS satellite R04 at Stephenson Way test site (Background image © 2013 Bluesky).

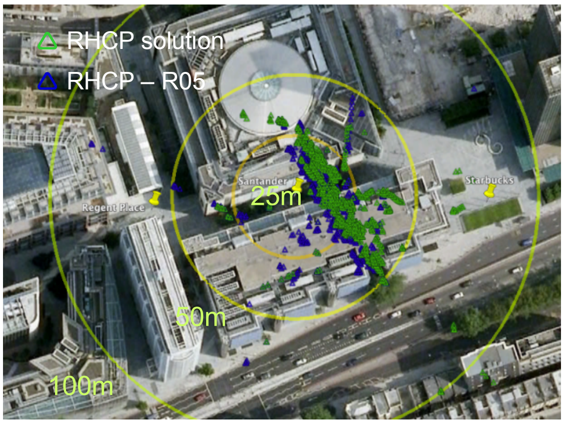

Figure 21: Position solutions with and without GLONASS satellite R05 at Santander, Euston Square test site(Background image © 2013 Bluesky).

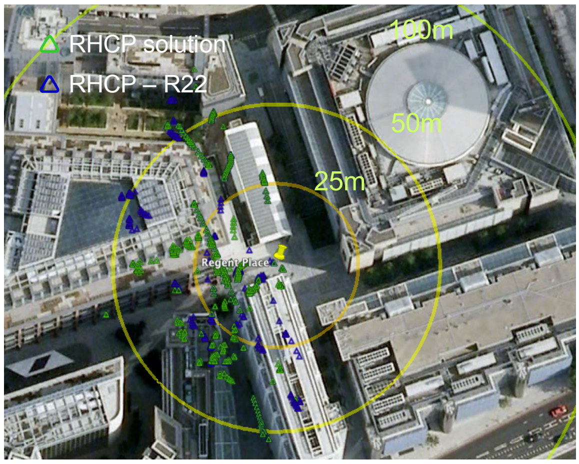

Figure 22: Position solutions with and without GLONASS satellite R22 at Regent Place test site (Background image © 2013 Bluesky).

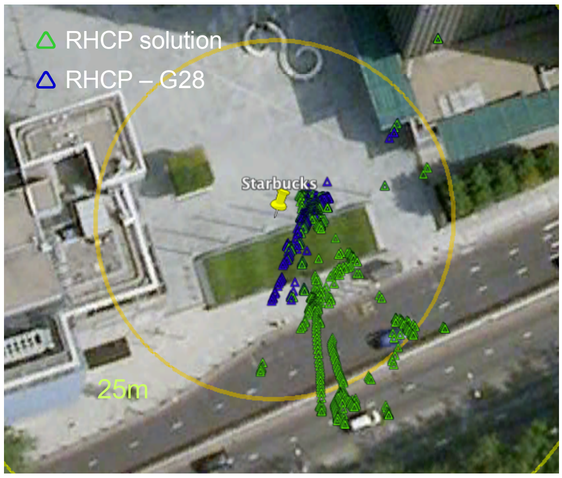

Figure 23: Position solutions with and without GPS satellite G28 at Starbucks, Euston Square test site (Background image © 2013 Bluesky).

Table 1: RMS horizontal errors with and without a suspected NLOS signal removed.

Site	RMS horizontal error All satellites	RMS horizontal error One satellite removed
Gower Place	97.8 m	112.0 m
Stephenson Way	32.9 m	29.4 m
Santander, Euston Square	49.7 m	62.4 m
Regent Place	72.0 m	77.3 m
Starbucks, Euston Square	72.2 m	57.6 m

Examining the results, it can be seen that removing a suspect NLOS signal from the positioning solution improved the positioning performance at the Stephenson Way and Starbucks, Euston Square sites, shown in Figures 20 and 23, respectively, but had a negative impact in the other three cases. There are two factors that can explain these results. Firstly, whether NLOS reception of one of the signals adversely affects the position solution depends on the path delay. A long path delay caused by a distant reflector will introduce a large position error, whereas a short path delay, caused by a near reflector, will have a much smaller effect. The second factor is that the accuracy of the position solution obtained when a signal is removed depends on the quality of the remaining signals, including whether there are additional NLOS signals, whether signals are subject to severe multipath interference and the quality of the signal geometry.

Looking at the C/N_0 measurements of the other signals, it can be seen that for the Stephenson Way and Starbucks sites, there were many good signals with direct line-of-sight reception and little multipath interference. However, at the other three sites, most signals were contaminated by multipath interference, NLOS reception and/or diffraction, noting that it is difficult to distinguish these effects for low-elevation signals. Where the eliminated signal is no worse than those that remain, the overall impact on positioning accuracy can be negative due to the degradation in geometry.

The dual-polarization method will detect most NLOS signals, but not all. A NLOS signal that is reflected twice (or four times) between transmitter and receiver or is reflected with an angle of incidence greater than Brewster's angle will not be LHCP and so will not be detected using polarization. Also, for low-elevation signals, the antenna is less sensitive to polarization, making NLOS reception more difficult to detect. However, these limitations may be mitigated by using the dual-polarization technique as part of a portfolio-based NLOS detection scheme as discussed in Section 5. By eliminating most of the NLOS signals, the dual-polarization technique makes it much easier for other methods to detect the remaining signals. With suitable calibration of the antenna system, the dual-polarization method could also be used to detect severe multipath interference.

4. QUALITATIVE ASSESSMENT OF NLOS AND MULTIPATH MITIGATION AND DETECTION TECHNIQUES

There are many different techniques for mitigating and detecting NLOS reception and multipath interference. Mitigation techniques directly reduce the positioning errors due to these effects, whereas detection techniques just identify the affected signals, enabling them to be eliminated from the position solution or downweighted as appropriate.

This section presents a brief assessment of 18 different techniques, considering ease of implementation and efficiency at mitigating or detection NLOS reception, code multipath interference and carrier multipath interference. Only techniques that operate near instantaneously are considered here. Techniques that require an extended period of signal observation whilst remaining static at one site are outside the scope of this study. Techniques requiring modified or additional hardware are considered first. The section concludes with a comparison table and a discussion on measurement selection for the positioning algorithm.

4.1 Antenna Design

A well-designed GNSS antenna is more sensitive to RHCP signals than LHCP signals by a margin of at least 10 dB at normal incidence [8]. As most reflected signals are LHCP or have mixed polarization, the amplitude of the reflected signals within the receiver is reduced. This reduces the magnitude of both the code- and carrier-tracking errors due to multipath interference. However, NLOS reception is not mitigated unless the signal is attenuated below the receiver's tracking threshold. There is very little polarization discrimination for low-elevation signals.

Polarization-sensitive antennas are standard for professional GNSS user-equipment. The smaller patch antennas used for applications such as road vehicle navigation offer less polarization discrimination, while smartphone antennas are linearly polarized, so are equally sensitive to direct and reflected signals. Cost and size have traditionally limited the scope for polarization discriminating antennas for consumer applications. However, new hexafilar antenna technology enables polarization-discriminating GNSS antennas to be constructed that are only 7.5 mm in diameter and 12 mm in length [23].

4.2 Choke Rings

A choke-ring antenna system uses a series of concentric rings, mounted on a ground plane around the antenna element, to attenuate low- and negative-elevation signals, reflected or direct. This is effective at reducing ground-reflected multipath interference, but provides little protection against higher elevation reflected signals. A choke-ring antenna system is also too large for most dynamic positioning applications; exceptions include ship navigation.

4.3 Controlled Reception Pattern Antenna (CRPA) System

A CRPA system has an adjustable gain pattern and is designed primarily for resisting jamming. Null-steering CRPA systems minimise the gain in the direction of interference sources, while beam-forming systems also maximise the gain in the direction of the direct signal, noting that a separate receiver front-end is then needed for each satellite signal. In principle, a beam-forming CRPA system could also be used for mitigating multipath interference. Tests have shown that it reduces pseudo-range errors by a factor of about two on average, more for high-elevation signals and less for low-elevation signals [24] (see [7] for additional references). CRPA systems are relatively large (at least 200 mm in diameter) and are expensive.

4.4 Angle of Arrival Measurement

A GNSS antenna array may be used to measure the angle of arrival (AOA) of the signals, essentially inverting the well-known interferometric attitude determination technique [19]. Where the orientation of the antenna is known, NLOS and direct-LOS signals may be distinguished simply by comparing the measured lines of sight with those determined from the satellite ephemeris data. Otherwise, AOA measurements differenced across satellites must be compared with the predictions. If they match, both signals may be assumed to be direct LOS; otherwise, either or both could be NLOS. The technique should also be suitable for detecting strong multipath interference. However, it is expensive as multiple receivers are required as well as multiple antennas.

4.5 Multiple Antennas
For large vehicles, such as ships, trains and large aircraft, multiple GNSS antennas (with associated receivers) may be deployed on different parts of the vehicle. NLOS and multipath-contaminated signals can then be identified through inconsistencies in the measurements made from the different antennas. This is an expensive approach, but is suited to expensive host vehicles.

4.6 Dual-Polarization Antenna
As described in Section 3, the dual-polarization antenna technique is effective at detecting NLOS reception except for the lowest elevation signals and doubly-reflected signals. In principle, the technique could also be used to detect strong multipath interference. However, this would require extensive antenna calibration and/or regularisation of the LHCP antenna gain pattern. In terms of ease of implementation, an additional front-end is required as well as the antenna itself. However, LHCP signals need only be tracked on one frequency and tracking can be initialised from the corresponding RHCP signals, so there is no need for an LHCP acquisition engine.

4.7 Sky-Pointing Camera
A sky-pointing camera with a panoramic lens or an array of cameras can be used to generate an image of the entire field of view above the receiver's masking angle. If the orientation of the camera is known, the blocked and unblocked lines of sight may be determined from the image. By comparing these with the direct lines of sight of the GNSS signals, the NLOS and direct-LOS signals may be distinguished [15][16]. This technique is suited to vehicle applications, such as mobile mapping, where there is space for the camera(s) and the orientation may be determined. However, the need for an accurate attitude and heading solution makes it more difficult to implement on hand-held devices. It does not detect multipath interference.

4.8 Code Discriminator Design
A number of techniques have been developed that mitigate the effects of medium-delay multipath interference on pseudo-range measurements by increasing the resolution of the code discriminator. Some of these techniques also make use of additional correlation channels within the receiver. Examples include narrow correlator spacing, the double-delta discriminator, the gated correlator, the multipath-estimating delay lock look and the vision correlator. References are listed in [7]. These techniques have the greatest impact on low-chipping-rate signals, such as GPS C/A code and can reduce the largest pseudo-range errors caused by multipath interference by a factor of more than 10, provided the precorrelation bandwidth and sampling rate of the receiver is high enough. The impact on high-chipping-rate signals, such as GPS P(Y) code and L5, is much less. There is no impact on carrier-tracking errors or errors due to NLOS reception.

Multipath-resistant code discriminator designs are already a standard feature of professional grade GNSS receivers. However, to implement them on consumer-grade receivers would increase the manufacturing cost and power consumption.

4.9 Doppler Domain Multipath Mitigation
Where the host vehicle is moving with respect to the reflectors, reflected signals will have different range rates from the directly-received signal. Thus, by implementing extended-range tracking in both the code-phase and Doppler shift domains, it is possible to separate out the different signal components by Doppler shift. To achieve the necessary resolution for vehicle applications, the coherent integration interval must be extended to 100 ms, which is easier to do with the new data-free signals [25][26]. This technique enables both the code- and carrier-tracking errors due to multipath interference to essentially be eliminated, but does not mitigate NLOS reception. It requires a much more complex receiver design, increasing the cost and power consumption.

4.10 Early-Late Correlator Comparisons
Where the GNSS receiver provides access to the accumulated correlator outputs, also known as the Is and Qs, these can also be used for detecting multipath interference. Phase differences between the early and late correlation channels are an indicator of multipath for both static and dynamic applications [27]. This relies on the direct and reflected signals being out-of-phase, so works better if two or more frequencies are available. Another approach is to compare the amplitude variation of the early and late correlator outputs [28]. Where multipath interference is present, the late correlator amplitude will fluctuate more as the interference varies between constructive and destructive. This is more effective for dynamic applications where the path delay varies rapidly, making this technique complementary to the multi-frequency C/N_0-based detection technique described in Section 2.

4.11 Carrier Smoothing
For dynamic applications, such as navigation, advantage may be taken of the high spatial variation in multipath errors by implementing carrier smoothing to average out most of the code multipath error. Carrier smoothing may be implemented on a signal-by-signal basis using a Hatch filter inputting carrier-phase or Doppler-shift

measurements [29]. It is also a standard feature of an extended Kalman filter (EKF)-based navigation solution as the EKF inputs carrier-phase or Doppler-shift measurements as well as the pseudo-ranges [7]. All carrier-smoothing methods are straightforward to implement on any GNSS user equipment without significantly increasing the cost, size or power consumption. Carrier smoothing does not mitigate the effects of NLOS reception because the code and carrier are affected in the same way.

4.12 Vector Tracking

Vector tracking combines signal tracking and position determination into a single process [7]. It can reduce the impact of multipath interference in a similar way to carrier smoothing. However, it can also eliminate positioning errors through NLOS reception via distant reflectors by preventing the receiver from locking onto those signals [13].

4.13 Elevation-Based Selection and Weighting

Multipath interference and NLOS reception may be mitigated simply by selecting the highest elevation signals on the basis that the higher the elevation angle, the less likely the signal is to be blocked or reflected by a building. Some multipath and NLOS detection techniques are also less effective for low-elevation signals. However, high-elevation signals can still be NLOS, particularly where a tall building is nearby. Conversely, low elevation signals can be direct-LOS as not all directions are obstructed by buildings in urban areas. Consequently, selecting the highest elevation signals will often result in some of the NLOS signals being accepted and will usually result in many of the direct-LOS signals being rejected. Selecting only high elevation signals also adversely affects the geometry of the solution. Thus, this method can only ever be partially effective and tests in a dense urban environment suggest that elevation-based weighting has little impact on positioning performance [3]. However, the technique has the advantage of being easy to implement as no hardware modifications are required and the processing load is low.

4.14 C/N_0-Based Selection and Weighting

A low C/N_0 or signal-to-noise ratio can be indicative of NLOS reception, destructive multipath interference or diffraction. However it can also occur because of signal attenuation, which can be due to foliage, body masking or a null in the antenna gain pattern. Also, signals reflected from glass, metal, and wet surfaces can be almost as strong as direct signals. Furthermore, most antennas are less sensitive to polarization from low-elevation signals (assuming a level antenna). Mobile phone antennas are linearly polarized, so their gain is the same for LHCP and RHCP signals, but varies with direction. Finally, constructive multipath interference increases C/N_0.

Thus, by rejecting or downweighting low-C/N_0 measurements, the impact of both NLOS reception and multipath interference on the navigation solution may be reduced, but not completely eliminated. Tests in a dense urban environment have shown that C/N_0-based weighting of measurements in the navigation solution provides a more accurate position solution, on average, than elevation-based weighting [3]. This technique also has the advantage of being easy to implement as no hardware modifications are required and the processing load is low.

4.15 Multi-Frequency C/N_0-Based Multipath Detection

As described in Section 2, comparing the difference in measured C/N_0 between frequencies with the value expected for the satellite type and elevation angle can be used as an indicator of multipath interference. Three-frequency comparisons are more reliable than dual-frequency comparisons. The technique is also more reliable for static applications and for reflections from the host vehicle body than for external reflections when the user antenna is moving. It can only be used with a multi-frequency receiver, but is easy to implement with these receivers as no hardware changes are needed and the processing load is low.

4.16 Consistency Checking

Consistency checking operates on the principle that NLOS measurements produce a less consistent navigation solution than direct-LOS measurements. Furthermore, multipath-contaminated direct-LOS measurements produce a less consistent navigation solution than multipath-free direct-LOS measurements. Therefore, if position solutions are computed using combinations of signals from different satellites, those obtained using only the multipath-free direct-LOS signals should be in greater agreement than those that include multipath-contaminated and NLOS measurements. The same principle is used for fault detection in receiver autonomous integrity monitoring (RAIM). However, this task becomes much more difficult in environments where a large proportion of the signals are NLOS or multipath contaminated.

A conventional "top down" sequential testing approach to consistency checking can successfully eliminate NLOS and multipath-contaminated signals in environments where the majority of signals are received by direct line of sight with little multipath contamination. However, in environments with multiple NLOS and multipath-contaminated signals, the sequential testing approach is prone to eliminating the wrong signals. Thus consistency checking using sequential testing actually degrades the average positioning accuracy in dense urban environments [3][10].

UCL has therefore developed a new consistency checking method, based on subset comparison. This identifies the most self-consistent set of signals, retaining the C/N_0-based weighting, and then uses them to calculate the position solution. Subset comparison is thus a "bottom up" approach, in contrast to sequential testing. The subset comparison method performs significantly more reliably in urban areas than the sequential testing approach [11]. However, there are still cases where it selects a suboptimal set of signals, particularly where there are insufficient direct LOS signals uncontaminated by multipath interference. Testing using GPS combined with GLONASS has shown that the current technique is equally likely to improve or degrade positioning in dense urban areas [3]. Further testing is needed to assess performance in more moderate urban environments.

There is a lot of scope to improve the subset comparison consistency checking technique as there is flexibility to vary the criteria for scoring candidate sets of signals. For example, signal geometry could be accounted for as discussed in Section 4.20. Furthermore, once all four GNSS constellations are completed and transmitting inter-constellation time synchronization parameters, there will be more measurements and fewer degrees of freedom in the navigation solution, so consistency checking performance should naturally improve. Map-indicated height can also be used as an additional measurement or constraint to improve the robustness of consistency checking [3][30].

Consistency checking does not require any additional hardware. However, the more sophisticated algorithms needed for dense urban environments may impose a high processing load. Combining consistency checking with other multipath and NLOS detection techniques would reduce the number of signal combinations to consider, reducing both the processing load and the probability of selecting the wrong signal set.

4.17 Innovation Filtering

In a Kalman filter-based estimation algorithm, innovation filtering is used to compare new measurements against predictions of those measurements from the time-propagated navigation solution. Measurements that are inconsistent with their predicted values are rejected [7]. This operates on the same principle as consistency checking, the key difference being that current measurements are compared against previous measurements instead of other current measurements.

Like consistency checking, innovation filtering only works if there are enough multipath-free direct-LOS signals to generate an accurate navigation solution. However, by using measurements from multiple previous epochs (via the navigation solution), the sensitivity is increased. It also provides a way of incorporating information from dead-reckoning sensors. NLOS reception and multipath can be distinguished by comparing a series of innovations, with the former indicated by a bias and the latter by a larger variance than normal [31].

A key weakness of innovation filtering is that once a contaminated measurement has been accepted into the navigation solution, the probabilities of accepting further contaminated measurements and of rejecting good measurements are both increased. This problem can be mitigated by implementing a bank of parallel filters, each accepting different measurements [7]. However, this imposes a high processing load. As with consistency checking, further research is needed to find the best way of implementing innovation filtering in a dense urban environment.

4.18 NLOS Detection using a 3D City Model

Where the user position is known, it is straightforward to compare the direct-LOS signal paths with a 3D city model to determine which signals are blocked. The NLOS signals are then excluded from the position solution [17][18].

However, the position will often only be known to within a few tens or hundreds of meters. This will be the case if it has been determined using NLOS-contaminated GNSS pseudo-ranges, phone signals or Wi-Fi. In this case, it is necessary to consider signal blockage at multiple locations, which requires two problems to be solved:

1) Calculating the GNSS signal shadowing by the buildings at multiple locations in real time.
2) Determining which signals are NLOS when the exact user position is unknown.

A number of ways of doing this have been proposed in [2].

A 3D city model can also potentially be used for correcting NLOS propagation errors [32] and for detecting multipath interference [33]. However both are highly computationally intensive.

Table 2: Scoring of multipath and NLOS detection and mitigation techniques.

Technique	Code	Carrier	NLOS	EOI	TM
1. Antenna design	8	8	1	8	9
2. Choke rings	7	7	2	4	9
3. CRPA system	3	3	0	3	7
4. AOA measurement	7	7	9	3	7
5. Multiple antennas	7	7	7	3	7
6. Dual-polarization	2	2	7	6	5
7. Sky-pointing camera	1	1	8	4	6
8. Code discriminator	8	0	0	7	9
9. Doppler domain	7	7	1	4	5
10. E-L Correlator	7	7	0	5	5
11. Carrier smoothing	7	0	1	9	9
12. Vector tracking	7	2	3	6	7
13. Elevation weighting	3	3	3	10	9
14. C/N_0 weighting	2	2	5	10	6
15. Multi-freq C/N_0	6	7	0	7	5
16. Consistency	4	4	6	7	5
17. Innovation filtering	5	5	7	7	5
18. 3D City model	0	0	7	6	3

4.19 Comparison of Techniques

Table 2 presents a comparison of the techniques discussed in the preceding subsections. Each technique is scored from 0 to 10, with 10 high, for code multipath mitigation or detection performance, carrier multipath mitigation or detection performance, NLOS mitigation or detection performance, ease of implementation (EOI) and technological maturity (TM). The scores are qualitative and simply represent the personal opinions of the authors.

4.20 Measurement Selection

GNSS signals may be identified as NLOS or subject to severe multipath interference using a number of different techniques. In more open environments, where there are a large number of direct LOS signals with minimal multipath contamination, removing contaminated signals from the navigation solution can be expected to improve the accuracy of the position solution.

However, in dense urban environments, there is often a shortage of uncontaminated direct LOS signals. In these cases, including some of the signals that have been identified as NLOS or multipath-contaminated within the navigation solution can sometimes improve the position accuracy. This can be because the improvement to the signal geometry resulting from adding such a signal can have a greater impact on the position solution accuracy than the ranging error due to multipath interference or NLOS reception. This effect can be seen both in some of the results presented in Section 3 and in in the results presented in [3].

A further issue to consider for NLOS signals is where the signal is reflected. Distant reflectors can produce very large ranging errors. However, if the signal is reflected close to the user antenna, the pseudo-range error due to NLOS reception may not be significantly larger than other sources of error, such as atmospheric propagation delays. Consequently, it is sometimes better to include a pseudo-range measurement from an NLOS signal in the position solution. Thus, when a signal is determined to be NLOS using a technique such as angle of arrival measurement, a dual-polarization antenna, or a sky-pointing camera, the magnitude of the ranging error should be estimated using consistency checking or innovation filtering before determined whether to include or exclude that signal.

In determining whether to include, exclude or downweight a multipath-contaminated or NLOS ranging measurement within the navigation solution, three factors must be considered:

- The predicted accuracy of that ranging measurement;
- The predicted accuracy of the other ranging measurements;
- The impact of the ranging measurement on the solution geometry.

Obviously, the more GNSS constellations tracked by the receiver, the greater the scope to optimise the signal selection. This is a subject on which further research is required.

5. A PORTFOLIO APPROACH TO NLOS AND MULTIPATH MITIGATION

As discussed in Section 4, there are many different techniques for mitigating and detecting NLOS reception and multipath interference. However, none of them are completely reliable. The closest is angle of arrival measurement, which is potentially the most expensive, requires a large antenna array and has a high power consumption. Thus, it is not suited to most applications.

To get the best overall performance, multiple NLOS and multipath mitigation and detection techniques should therefore be combined. This is the portfolio approach that the paper title refers to. This section first considers which of the techniques assessed in Section 4 may be combined and which are incompatible. It then proposes portfolios suitable for professional and consumer applications, outlining the research required to implement them.

5.1 Compatibility Assessment

The majority of techniques described in Section 4 and listed in Table 2 are sufficiently compatible to be used in combination. Therefore, it is quicker to describe those combinations of techniques that are not compatible.

Standard choke rings cannot be used with a CRPA system or AOA measurement because the antenna arrays required are too large. A CRPA system is also difficult to combine with an antenna array used for AOA measurement. Although the antenna elements can potentially be shared, separate receivers are required.

There is little benefit in using both a sky-pointing camera and a 3D city model for NLOS detection as both play a similar role.

Carrier smoothing cannot be used in addition to vector tracking as the former is inherent in the latter.

There is also no point in combining the dual-polarization antenna technique with basic C/N_0-based signal selection and weighting as the former is a more advanced version of the latter.

Apart from these cases, virtually any combination is possible.

5.2 Professional Applications

For applications such as air navigation, setting out for construction, machine control and mobile mapping, rapid mitigation or detection of multipath interference and NLOS reception is required, but high-quality professional equipment may be used. Assuming an antenna array and multiple antennas are too bulky and expensive, the following approach is proposed.

The portfolio should incorporate established multipath mitigation techniques, such as a polarization sensitive antenna and multipath-limiting code discriminator design.

In addition, the dual-polarization technique should be deployed for detecting the majority of NLOS signals. For detecting multipath interference, early-late correlator comparison techniques and multi-frequency C/N_0-based multipath detection should both be deployed as they are suitable for different dynamic conditions. Suspected NLOS and multipath-contaminated signals should be eliminated from the navigation solution. Finally, consistency checking and/or innovation filtering should be deployed to detect and eliminate any remaining NLOS and/or multipath contaminated signals. The residuals of the accepted ranging measurements should then be used to estimate the quality of the position solution. Figure 24 illustrates this process.

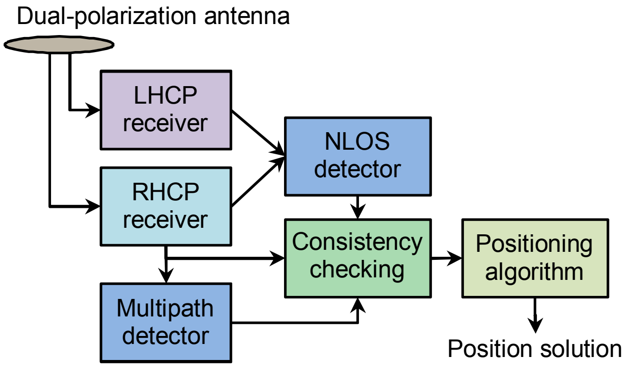

Figure 24: NLOS and multipath mitigation portfolio for professional applications (The multipath detector incorporates both early-late correlator comparison and multi-frequency C/N_0 comparison)

The following research and development is needed to implement this:

- Improve dual-polarization antenna hardware so that the RHCP output offers the same gain and polarization-discrimination as a conventional professional-grade antenna.
- Establish suitable thresholds for detecting NLOS reception from the dual-polarization antenna and multipath interference from early-late correlator comparison and multi-frequency C/N_0 comparison. Note that different thresholds are likely to be required for different applications depending on the balance between the accuracy, integrity, continuity and availability performance requirements.
- Develop more robust consistency checking and innovation filtering techniques.
- Ensure that the different components of the system work well together, testing and tuning them and assessing the overall performance.

5.3 Consumer Applications

For consumer applications, any techniques that significantly increase cost, size and power consumption must be ruled out. Thus antenna design, dual-polarization NLOS detection and multi-frequency C/N_0-based detection cannot be used. Furthermore, the code discriminator design will be a compromise between multipath, sensitivity and power consumption, noting that higher sampling rates require more power.

This leaves early-late correlator comparison, carrier smoothing, elevation and C/N_0 weighting, consistency checking, innovation filtering and NLOS detection using a 3D city model. In practice, different combinations will suit different applications, depending on the environmental and behavioural context [7][34]. For road navigation, a combination of carrier smoothing and innovation filtering works well in most places, particularly when combined with map matching and odometry.

The main challenge lies in providing accurate single-epoch position fixes on a smartphone in a dense urban area. This will need a combination of C/N_0 weighting, consistency checking and NLOS detection using a 3D city model, which will need extensive research to develop. A new class of ranging-based positioning algorithm may also be required that can use NLOS ranging measurements without biasing the position solution [35].Whether this will be able to run in real time on a smartphone or whether a server-based solution will be required remains an open question.

Finally, for best accuracy, the ranging-based position solution may need to be combined with height aiding [3] and shadow matching [4][5][6], a concept known as *intelligent urban positioning* [2].

6. CONCLUSIONS

A new code and carrier multipath detection technique has been proposed and demonstrated using data collected in an urban environment. The technique works by comparing the difference in measured C/N_0 between frequencies with the value expected for the satellite type and elevation angle.

NLOS detection using a dual-polarization technique has been demonstrated on GLONASS signals for the first time. The impact on accuracy of removing an NLOS signal from the position solution has been assessed in different urban environments.

A qualitative assessment and comparison of 18 different classes of technique for mitigating and detecting multipath interference and NLOS reception has been made, considering ease of implementation and performance. It is concluded that, for most applications, no one technique is completely effective at eliminating the effects of multipath and NLOS reception. A portfolio approach is therefore proposed in which multiple techniques are combined.

For professional applications, a combination of antenna design, code discriminator design, the dual-polarization technique, early-late correlator comparison, multi-frequency C/N_0-based multipath detection and consistency checking is recommended. For consumer applications, a combination of early-late correlator comparison, carrier smoothing, elevation and C/N_0 weighting, consistency checking, innovation filtering and NLOS detection using a 3D city model is proposed.

For both types of application, extensive further research is needed, both to enhance and tune the individual detection and mitigation techniques and to assess how they perform together.

ACKNOWLEDGEMENTS

Dr Ziyi Jiang's work was funded by the Innovative Navigation using new GNSS Signals with Hybridised Technologies (INSIGHT) program. INSIGHT (www.insight-gnss.org) is a collaborative research project funded by the UK's Engineering and Physical Sciences Research Council (EPSRC) to extend the applications and improve the efficiency of positioning through the exploitation of new GNSS signals. It was undertaken by a consortium of twelve UK universities and industrial groups: Imperial College London, University College London, the University of Nottingham, the University of Westminster, EADS Astrium, Nottingham Scientific Ltd, Leica Geosystems, Ordnance Survey of Great Britain, QinetiQ, STMicroelectronics, Thales Research and Technology UK Limited, and the UK Civil Aviation Authority.

For the dual-polarization experiments, the authors would like to thank Novatel for the loan of a pair of multi-constellation GNSS receivers, Dr Yacine Adane of the University of Westminster for designing the amplifiers to work with the antenna, and Mr Lei Wang of UCL for assisting with the data collection.

REFERENCES

[1] Wang, L., P. D. Groves, and M. K. Ziebart, "Multi-Constellation GNSS Performance Evaluation for Urban Canyons Using Large Virtual Reality City Models," *Journal of Navigation*, Vol. 65, No. 3, 2012, pp. 459–476.

[2] Groves, P. D., Z. Jiang, L. Wang, & M. Ziebart, "Intelligent Urban Positioning using Multi-Constellation GNSS with 3D Mapping and NLOS Signal Detection," *Proc. ION GNSS 2012*.

[3] Groves, P. D. and Z. Jiang, "Height Aiding, C/N_0 Weighting and Consistency Checking for GNSS NLOS and Multipath Mitigation in Urban Areas" *Journal of Navigation*, Vol. 66, No. 5, 2013, pp. 653–659.

[4] Groves, P. D., "Shadow Matching: A New GNSS Positioning Technique for Urban Canyons" *Journal of Navigation*, Vol. 64, 2011, pp. 95–105.

[5] Wang, L., P. D. Groves, and M. K. Ziebart, "GNSS Shadow Matching: Improving Urban Positioning Accuracy Using a 3D City Model with Optimized Visibility Prediction Scoring," *Proc. ION GNSS 2012.* Also accepted for publication in *NAVIGATION: Journal of the ION*.

[6] Wang, L., P. D. Groves, and M. K. Ziebart, "Urban Positioning on a Smartphone: Real-time Shadow Matching Using GNSS and 3D City Models," *Proc. ION GNSS+ 2013.*

[7] Groves, P. D., *Principles of GNSS, Inertial and Multisensor Integrated Navigation Systems*, Second Edition, Artech House, 2013.

[8] Braasch, M. S., "Multipath Effects," In Global Positioning System: Theory and Applications Volume I, Parkinson, B. W. and Spilker, J. J., Jr (eds), Washington, DC: AIAA, 1996, pp. 547–568.

[9] Bradbury, J., "Prediction of Urban GNSS Availability and Signal Degradation Using Virtual Reality City Models," *Proc. ION GNSS 2007*, Fort Worth, TX, September 2007, pp. 2696–2706.

[10] Jiang, Z., P. Groves, W. Y. Ochieng, S. Feng, C. D. Milner, and P. G. Mattos, "Multi-Constellation GNSS Multipath Mitigation Using Consistency Checking," *Proc. ION GNSS 2011*.

[11] Jiang, Z., and P. Groves, "GNSS NLOS and Multipath Error Mitigation using Advanced Multi-Constellation Consistency Checking with Height Aiding," *Proc. ION GNSS 2012*.

[12] Jiang, Z., and P. D. Groves, "NLOS GPS Signal Detection Using A Dual-Polarisation Antenna," *GPS Solutions*, 2012, DOI: 10.1007/s10291-012-0305-5.

[13] Hsu, L.-T., P. D. Groves, and S.-S. Jan, "Assessment of the Multipath Mitigation Effect of Vector Tracking in an Urban Environment," *Proc ION Pacific PNT*, 2013.

[14] Hsu, L.-T., "Integration of Vector Tracking Loop and Multipath Mitigation Technique and Its Assessment," *Proc. ION GNSS+ 2013*.

[15] Marais, J., M. Berbineau, and M. Heddebaut, "Land Mobile GNSS Availability and Multipath Evaluation Tool," *IEEE Transactions on Vehicular Technology*, Vol. 54, No. 5, 2005, pp. 1697–1704.

[16] Meguro, J., et al., "GPS Multipath Mitigation for Urban Area Using Omnidirectional Infrared Camera," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 10, No. 1, 2009, pp. 22–30.

[17] Obst, M., S. Bauer, and G. Wanielik, "Urban Multipath Detection and mitigation with Dynamic 3D Maps for Reliable Land Vehicle Localization," *Proc. IEEE/ION PLANS 2012*.

[18] Peyraud, S., et al., "About Non-Line-Of-Sight Satellite Detection and Exclusion in a 3D Map-Aided Localization Algorithm," *Sensors*, Vol. 13, 2013, pp. 829-847.

[19] Keshvadi, M. H., A. Broumandan, and G. Lachapelle, "Analysis of GNSS Beamforming and Angle of Arrival Estimation in Multipath

Environments," *Proc ION ITM*, San Diego, CA, January 2011, pp. 427-435.

[20] Rudi, M., "GNSS Multipath Detection and Mitigation from Multiple-Frequency Measurements," MSc Dissertation, University College London 2012.

[21] Strode, P., "GNSS multipath detection using three-frequency signal-to-noise measurements," MSc Dissertation, University College London 2013.

[22] Groves, P. D., Z. Jiang, B. Skelton, P. A. Cross, L. Lau, Y. Adane and I. Kale, "Novel Multipath Mitigation Methods using a Dual-polarization Antenna," *Proc. ION GNSS 2010.*

[23] Leisten, O. and V. Knobe, "Optimizing Small Antennas for Body-Loading Applications," *GPS World*, September 2012.

[24] Brown, A., and Gerein, N., "Test Results from a Digital P(Y) Code Beamsteering Receiver for Multipath Minimization," *Proc. ION 57th AM*, Albuquerque, NM, June 2001, p. 872–878.

[25] Soloviev, A., and F. van Graas, "Utilizing Multipath Reflections in Deeply Integrated GPS/INS Architecture for Navigation in Urban Environments," *Proc. IEEE/ION PLANS*, Monterey, CA, May 2008, pp. 383–393.

[26] Xie, P., M. G. Petovello, and C. Basnayake, "Multipath Signal Assessment in the High Sensitivity Receivers for Vehicular Applications," *Proc. ION GNSS 2011*, Portland, OR, pp.1764–1776.

[27] Mubarak, O. M., and A. G. Dempster, "Analysis of Early Late Phase in Single- and Dual-Frequency GPS Receivers for Multipath Detection," *GPS Solutions*, Vol. 14, No. 4, 2010, pp. 381–388.

[28] Mattos, P. G., *Multipath indicator to enhance RAIM and FDE in GPS/GNSS Systems*, Patent Application No. 11112819.5, Filed July 2011.

[29] Bahrami, M., and M. Ziebart, "Instantaneous Doppler-Aided RTK Positioning with Single-Frequency Receivers," *Proc. IEEE/ION PLANS 2010*, Indian Wells, CA, May 2010, pp. 70-78.

[30] Iwase, T., N. Suzuki, and Y. Watanabe, "Estimation and exclusion of multipath range error for robust positioning," *GPS Solutions*, 2012, DOI 10.1007s/10291-012-0260-1.

[31] Spangenberg, M., et al., "Detection of Variance Changes and Mean Value Jumps in Measurement Noise for Multipath Mitigation in Urban Navigation," *Navigation: JION*, Vol. 57, No. 1, pp. 35–52.

[32] Bourdeau, A., M. Sahmoudi, and J.-Y. Tourneret, "Tight Integration of GNSS and a 3D City Model for Robust Positioning in Urban Canyons," *Proc. ION GNSS 2012*.

[33] Bradbury, J., M. Ziebart, P. Cross, P. Boulton, and A. Read., "Code Multipath Modelling in the Urban Environment Using Large Virtual Reality City Models: Determining the Local Environment," *Journal of Navigation*, Vol. 60, 2007, pp. 95–105.

[34] Groves, P.D., et al., "Context Detection, Categorization and Connectivity for Advanced Adaptive Integrated Navigation," *Proc. ION GNSS+ 2013*.

[35] Lie, J. P., C.-H. Lim, and C.-M. Samson See, "NLOS Mitigation Methods for Geolocation," In *Handbook of Position Location Theory, Practice, and Advances*, S. A. Zekavat and R. M. Buehrer (eds), IEEE/Wiley, 2012, pp. 557–581.