



HAL
open science

Improving GPS Accuracy for Construction Applications through Phase Multipath Mitigation

Paul Cross, David Bétaille, François Peyret

► **To cite this version:**

Paul Cross, David Bétaille, François Peyret. Improving GPS Accuracy for Construction Applications through Phase Multipath Mitigation. International Symposium on GNSS, Nov 2003, TOKYO, Japan. hal-04505282

HAL Id: hal-04505282

<https://univ-eiffel.hal.science/hal-04505282>

Submitted on 14 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Improving GPS Accuracy for Construction Applications through Phase Multipath Mitigation

Paul Cross¹, David Bétaille^{1,2} and François Peyret²

¹ Department of Geomatic Engineering, University College London (UCL), UK

² Laboratoire Central des Ponts et Chaussées (LCPC), Centre de Nantes, France

paul.cross@ge.ucl.ac.uk, david.betaille@lcpc.fr, francois.peyret@lcpc.fr

BIOGRAPHY

Professor Paul Cross is Leica Professor of Geomatic Engineering at UCL. He obtained his PhD from the University of Nottingham in 1970 and before joining UCL in 1997 he held teaching and research positions at the Universities of Nairobi, East London, Stuttgart and Newcastle. His main research interest is in precise GPS positioning and he currently concentrates on engineering and geophysical applications.

David Bétaille is a junior researcher in the Site Robotics and Positioning team of the LCPC. He has a first degree from the *Ecole Centrale de Nantes*, where he graduated as an engineer in robotics. David Bétaille is currently a full-time student, undertaking a PhD research program at UCL investigating phase multipath in kinematic GPS (a subject closely connected with precise positioning of machines for road construction and maintenance).

François Peyret is a senior researcher and head of the Site Robotics and Positioning team of the LCPC. He obtained a first engineering degree from the *Ecole Nationale Supérieure de Mécanique et d'Aérotechnique*, and a second one from the *Ecole Nationale Supérieure de l'Aéronautique et de l'Espace*. His main topic of research since 1987 has been the application of satellite positioning in the field of computer integrated road construction. He is also a member of the board of directors of the International Association for Automation and Robotics in Construction and leads a number of GNSS technology courses in different engineering schools in France.

ABSTRACT

Despite the enormous improvements in the accuracy of real-time GPS in recent years, there are still problems in reliably delivering the most demanding accuracies required in certain construction applications (e.g. asphalt paving). The limiting error source in such situations is phase multipath, especially that from highly reflective sources close to mobile antennas, such as that from the engineering plant itself.

This paper reviews the role of precise real-time GPS on engineering sites and introduces the relevant parts of the mathematical and physical theory needed to understand fully the phase multipath problem. It also describes a

testing procedure developed at LCPC for assessing multipath (and other) GPS errors in controlled static and kinematic environments.

Details are given of tests with a new multipath mitigation technique invented by Leica Geosystems and based on a window correlator. It is shown that the technique is effective for multipath mitigation when the reflected signal has an additional path length of greater than about 7.5 m. Finally initial results from a proposed strategy to overcome this limitation are given.

1. INTRODUCTION

GPS is becoming an extraordinarily successful means of high precision positioning outdoors in real time, especially on civil engineering and construction sites. In particular, the ability of GPS to deliver single centimetre accuracy in real time (RTK GPS), achieved within the past decade, has opened up the potential for a wide range of new applications. Thanks to these new systems, we can now overcome the weakness currently existing on construction sites, e.g. the huge gap between the design phases, which are highly computerised, and the work site itself where all numerical data coming from the design is, still in most of the cases, reduced to wooden grade stakes.

As far as civil engineering construction equipment is concerned, according to [1], we can divide the machines into three main groups, which differ according to requirements in terms of positioning:

- earth-moving and mining equipment, such as big earthworks machines like shovels, drills, scrapers, dozers, excavators, etc.
- so-called «surfacing equipment», that is to say the machines which move on the surface of the ground, without noticeable changes in height such as compactors, cement spreaders, mixers, etc.
- so-called «profiling equipment», that is to say the machines which modify the profile of the work site by addition or removal of material such as asphalt pavers, autogrades, milling machines, etc.

The paper deals with the positioning issues related to the third group of equipment, which is the most demanding one in terms of accuracy, especially in terms of elevation, which is usually the weakest GNSS coordinate.

Fig. 1 shows a picture of the asphalt paver, or finisher, at work. This machine moves very slowly (some metres per minute), always forward, but has to spread a very smooth and precisely levelled layer of material. This level is directly set by the position of the tool (a « floating screed » attached to the tractor at two articulations called « tow-points » by the intermediate of two « levelling arms »). The high accuracy in terms of level comes from the contractual tolerances in level and cross-slopes currently required for the upper layers of the pavement, typically ± 3 cm and ± 1 cm depending of the type of layer.

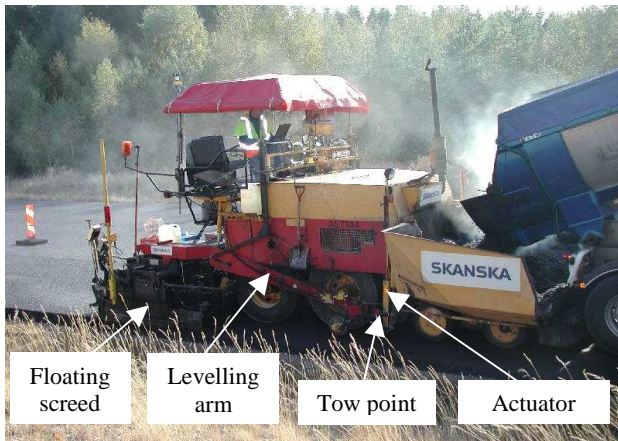


Figure 1 : The asphalt paver

The challenge GPS technology is facing is to be able to provide to the machine this level of accuracy in real-time. Currently, achieved accuracy of state-of-the-art RTK systems are satisfying these requirements in the best conditions of well controlled environments, and very short baselines. However, GPS activities to support construction usually take place in particularly difficult environments. Not only do nearby objects such as buildings, trees or machinery obstruct GPS signals, causing signal loss and diffraction, but also they lead to multipath errors as the direct signals from the satellites are mixed with those reflected from such objects. These multipath errors limit the accuracy of GPS so that, despite the many improvements made in recent years, it still cannot meet the challenge of the highest precision needed by these machines. This paper is directed at methods to improve RTK GPS accuracy, though multipath mitigation, in order to meet such challenges.

2. THE THEORY OF MULTIPATH

Reflections take place when waves hit obstacles, such as the surface of water or building structures, and, as a consequence, propagate indirectly from the emission point to the reception point. GPS signals are prone to multipath from the local environment of the antennas, particularly when these are set-up on the roof of machines like pavers or bulldozers.

Certain surfaces, plane and conductive, are particularly likely to create multipath in the environment of a GPS antenna. These surfaces, contrary to others whose geometrical and electrical characteristics are unspecified,

reflect the signal by preserving its waveform. In this case, the signal reflection is denoted “specular”, as opposed to “diffuse”.

The roughness and the size of the surface where a reflection may take place will determine whether it is specular or diffuse. A criterion, known as the Raleigh criterion, describes how rough a surface is, with respect to the wavelength. Note that on engineering sites, and in the tests described in this paper, most surfaces in the local environment of the antenna are smooth enough to be considered as specular reflectors.

If it is required to model the phenomenon of multipath by geometrical methods then another criterion, additional of that of Raleigh, must also be considered. This concerns the size of the reflectors with respect to the wavelength of the carrier. In the case of GPS signal propagation, it is generally considered that the wavelengths (L1: 19 cm and L2: 24 cm) are small in comparison with the dimensions of the obstacles in the environment.

We note that ray-tracing techniques are based on the same assumption, and these techniques provide models and tools classically accepted as valid for GPS multipath.

Assuming these criteria to be satisfied, the reflection is deterministic, and the law of propagation used in geometric optics can be also used to describe reflection of the GPS signal. In this case, the angle of reflection is the same as the angle of incidence.

The reflection causes modifications of the spectral parameters of the signal, mainly in amplitude and phase (and also frequency if the antenna moves in the environment but this will not be considered here as movements on engineering sites are generally at low speed). Electromagnetic theory provides a comprehensive description of the phenomenon. The general concept to bear in mind is the fact that the coefficient of reflection (that links both amplitude and phase of the incident and reflected waves) depends on the material of which the reflector is made and also on the angle of incidence. Its magnitude and its argument respectively affect the amplitude and the phase of the reflected signal.

The main point is that reflection causes a primary attenuation of the amplitude of the signal, because the magnitude of the coefficient of reflection is always less than 1.

Furthermore, the sign of the polarity (i.e. the rotation of the electric field) is inverted if the grazing angle is above the so-called Brewster angle. Then, the phase of the reflected signal shifts by 180° .

The value of the Brewster angle, in the case of a metallic reflector, is a few degrees. Generally in the experiments carried out and reported in this paper, the grazing angle was above the Brewster angle. So, one can consider that there is always a reflection phase shift of 180° .

In addition to the primary attenuation and the reflection phase shift, the gain and phase patterns of the antenna need to be taken into account (i.e. the amplitude and phase

variations applied to the signal by the antenna itself). These are different for right and left polarisations, and also antenna elevation and azimuth dependent.

The gain pattern (see Fig. 2) causes a secondary attenuation of the amplitude of the signal because most GPS antennas are right hand polarised by construction and if they do not reject, they at least attenuate Left Hand polarised waves.

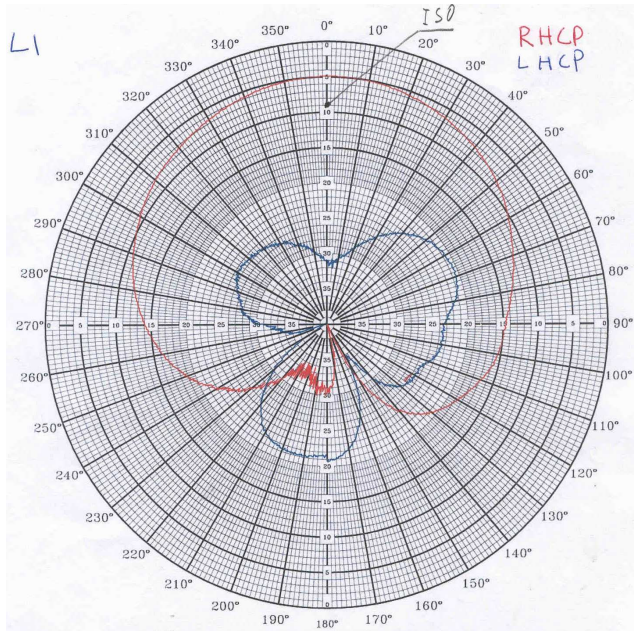


Figure 2 : AT502 L1 phase patterns (AeroAntenna)

Moreover, the phase pattern creates an antenna phase shift that further modifies the phase of the signal, particularly if it is left hand polarised.

In conclusion, we can assume that in the case of reflectors made of metal (such as might be found on an engineering site), the reflection is specular, and the grazing angles are generally above the Brewster angle. Hence, the relative phase between the reflected signal and the direct signal is only dependent on the additional path length, plus the 180° reflection phase shift, plus the antenna phase shift. The attenuation corresponds to that of a left hand polarised signal. Further modelling is based on this assumption.

3. THE PHASE MULTIPATH MITIGATION WINDOW

The Phase Multipath Mitigation Window has been introduced by LEICA through various patents, including, for example, [2]. The phase window correlator is a new sampling technique dedicated to the estimation of multipath errors in phase measurements. Instead of integrating the received signal products with the in-phase and out-of-phase replicas at every clock sample (generally 40 MHz), only the samples immediately preceding and following the code transitions are used (see Fig. 3). It can be shown that this particular sampling technique enables the estimation of the Doppler shift of the received signal to be done theoretically with no bias in the presence of multipath, provided that the reflections are delayed enough for the pair of samples to be taken.

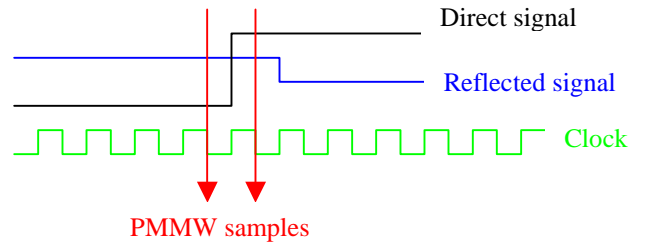


Figure 3 : The phase Multipath Mitigation Window

LEICA included the PMMW implementation in its chipset a few years ago in order to anticipate further improvement of its GPS Measurement Engine (ME). It was recently enhanced with new firmware specifically designed for the phase MMWindow correlator. Various tests were carried in July 2003 to assess the capabilities and limitations of this firmware.

Fig. 4 displays photos of the equipment that was used in the tests. It comprised two pairs of Leica GPS L1/L2 antennas (2 lightweight AT502) and a pair of enhanced Leica SR530 L1/L2 receivers.



Figure 4 : SR530 receiver and AT502 antenna

4. THE TEST FACILITY AND METHODOLOGY

In the frame of its research activity in the domain of site robotics, the *Laboratoire Central des Ponts et Chaussées* has been equipped since 1995 with a test and research facility devoted to real-time and full-scale positioning systems evaluation. The facility is called SESSYL and is situated in Nantes. Fig. 5 shows a picture of SESSYL.

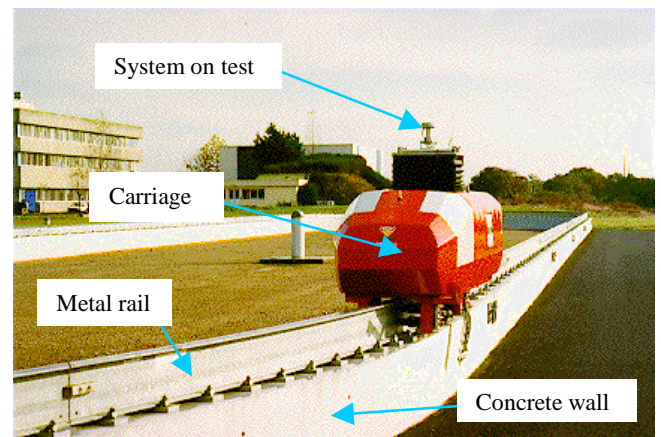


Figure 5 : SESSYL carriage on its track

Its consists of a closed track (overall dimensions 81 m x 16 m), composed of a metal rail fixed upon a concrete wall, with a mobile carriage running on it. The upper part of the

carriage is a platform, which can be varied in height, roll and pitch. Thus, any system to be tested is installed on the platform and can describe a reference trajectory in terms of position and attitude angles, accurately known and perfectly repeatable. Two ranges of speed are available: a range corresponding to the speeds of profiling equipment, from 0 to 1 km/h and a range corresponding to the speeds of earth-moving and surfacing equipment, from 1 to 15 km/h. The deviations between the reference trajectory, obtained from internal measurements and static surveys, and the trajectory delivered by the tested system allows, thanks to a specific post-processing, the determination of the performances of the system, particularly accuracy, but also other interesting features, such as re-initialisation time.

For the purpose of generating multipath in a controlled environment, an experimental set-up additional to SESSYL has been designed that includes a large metallic reflector (a 5 m by 2.5 m steel panel, visible in Fig. 6). This can be used to generate multipath with different characteristics depending on the distance that it is placed from an antenna.

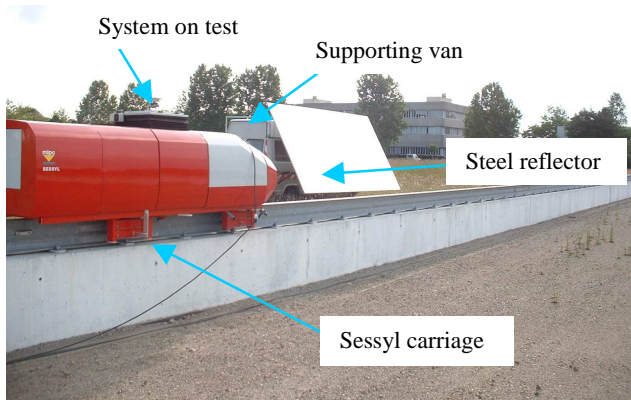


Figure 6 : SESSYL carriage near the multipath panel

The metallic reflector specially constructed to support the tests was fixed to the side of a van parked in the vicinity of the rover station (for static tests) or along the SESSYL track (for kinematic tests). The reflector was always placed north the antenna and was tilted as much as possible from the vertical in order to avoid creation of multipath from low elevation satellites (as actually the signals from these satellites may have already been perturbed by diffraction at the horizon), whilst avoiding the creation of multipath from satellites with an elevation greater than 70° (these are used further as differencing satellites in a double differencing process necessary for the multipath mitigation technique assessment).

The multipath zones are superimposed in sky plots in Fig. 7: one can notice that when the reflector is close to the antenna, it is impossible to eliminate simultaneously low elevation satellites and differencing satellites to enter the panel multipath zone. The priority has been given to the differencing ones.

A total station was used to determine the position of the reflector in the local reference frame with the same

accuracy as the antennas, i.e. 1 mm (1σ). This enabled the theoretical multipath zones to be exactly confirmed (whereas they had been roughly computed when the experiment had been designed). This also enables statistics to be computed for these zones only.

More detailed information about the methodology of the tests can be obtained in [3].

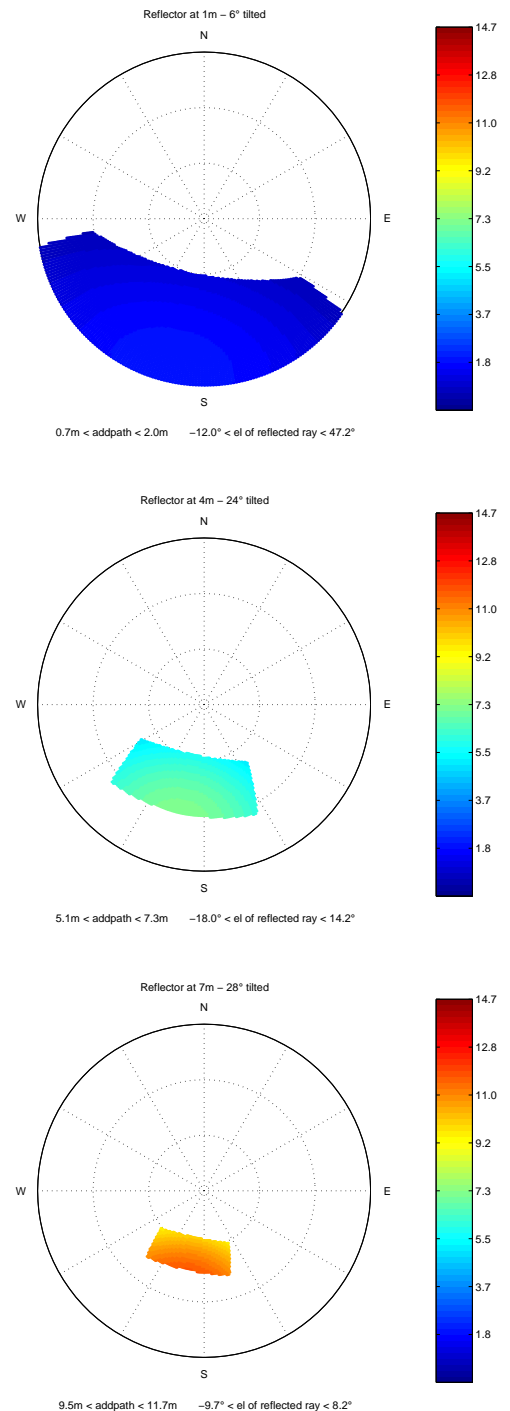


Figure 7 : the skyplot multipath zones when the panel is placed at 1, 4 and 7 m and the additional path length

5. THE TEST RESULTS

A summary of the static and kinematic test programmes is given in table 1, as these were scheduled and carried out. The static tests duration was 23 hours (split into 3 parts for easier computer processing, see, for example, Fig. 9). The kinematic tests duration was 20 minutes, cyclic, with a speed of 0.05 m/s during the first straight line where the panel was set-up. Hence, the time spent in front of the panel was around 100 s at each test. 27 of these tests were carried out each day (but they were stopped at night)

Days	Week 30: kinematic Days 202 to 206	Week 31: static Days 209 to 213
Mon		No reflector
Tues	Reflector at 1 m	Reflector at 1 m
Wed	Reflector at 4 m	Reflector at 4 m
Thr	Reflector at 7 m	Reflector at 7 m
Fri	No reflector	

Table 1 : the tests planning

Note that the kinematic tests with SESSYL started at the same sidereal time each day, in order to keep the same constellation at the antenna locations and so maintain identical geometry between the tests.

In the analysis, we selected every satellite in turn, and checked if its position relative to the reflector and the rover antenna would cause multipath. Time series of Observed-Computed (O-C) Double Differences (DD) of L1 phase measurements are displayed in Fig. 9, as well as the “green” windows delimitating the multipath time zones. The O-C DD rely on the known position of the rover, either it is given by a survey of the tripod (in the case of static tests) or computed from the SESSYL reference coordinates (in the case of kinematic tests). Note that the differencing satellite was always too high to be affected by multipath from the panel.

A geometrical computation, similar to that for multipath, enables the time zones when diffraction occurs (at the edges of the panel) to be defined (see Fig. 8). These correspond to a situation where the satellite is hidden by the panel but still visible in term of signal strength. Diffraction time zones are represented with “red” windows in Fig. 8. Note that the diffraction at the horizon always exist when the elevation is under 15°. Its effect, as well as that of diffraction due to the panel, is visible on the O-C phase DD, which increase unboundedly.

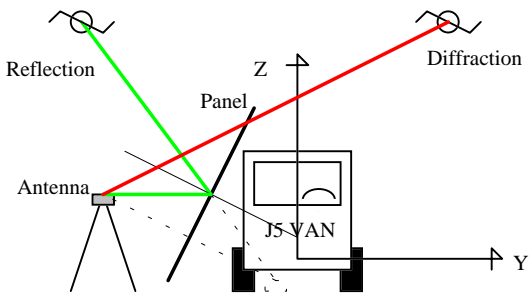


Figure 8 : multipath geometrical computation

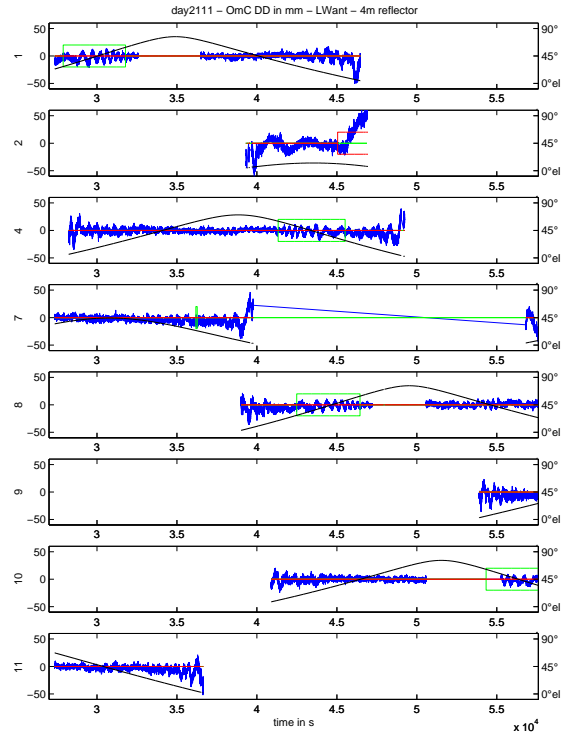


Figure 9 : static test with the reflector at 4 m (8 SVs displayed only)

The analysis was duplicated, with and without applying the corrections of L1 phase measurements provided by the MMW phase correlator. Fig. 10 shows a zoom on SV1 multipath time zone, for both data sets.

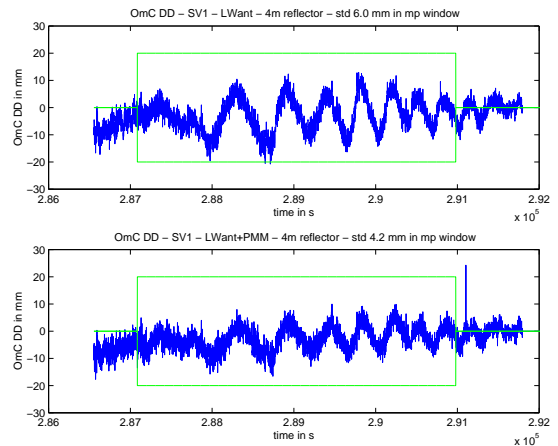


Figure 10 : effect of PMMW on phase DD in static

In Table 2, a gain has been computed as follows:

$$\text{gain (in \%)} = 100 * (\sigma - \sigma_{\text{PMMW}}) / \sigma$$

where:

- σ is the standard deviation of the O-C DDs of phase L1, that means here “standard” L1 phase;
- σ_{PMMW} is the standard deviation of the O-C DDs of PMMW “corrected” L1 phase.

This analysis is generalised to all satellites within the multipath zones and similarly in the equivalent time periods for the test with no reflector (this is displayed in *italic*). The results in static are summarised in table 2.

Static tests	Std σ	Std σ PMMW	Gain
reflector 7 m 9.7 m < addpath < 11.9 m	4.8 mm	2.7 mm	44%
<i>No reflector</i>	<i>2.6 mm</i>	<i>2.5 mm</i>	<i>3%</i>
reflector 4 m 5.2 m < addpath < 7.3 m	5.4 mm	4.3 mm	20%
<i>No reflector</i>	<i>3.1 mm</i>	<i>3.0 mm</i>	<i>4%</i>
reflector 1 m 0.7 m < addpath < 2.0 m	10.9 mm	10.4 mm	4%
<i>No reflector</i>	<i>6.5 mm</i>	<i>6.3 mm</i>	<i>3%</i>

Table 2 : L1 phase DD statistics in static

Table 2 confirms the expected main result: the PMMW efficiency is theoretically and effectively dependent on the additional path length travelled by the reflected signals. The threshold around 7.5 m is confirmed (i.e. 1/40th of a chip length for the 40 MHz clocked implementation in the Leica System 500 receivers).

Note: the statistics when there is no reflector are given as a reference. Two points are especially noticeable as follows.

- There is an improvement of a few % when there is no reflector: this can be explained by the ability of the phase window correlator to mitigate even weak multipath that exists in the general environment;
- The standard deviation is significantly higher within the time periods that correspond to the case of the reflector at 1 m: this is because the satellites are lower in the sky than for the two other positions of the reflector (see Fig. 5).

In the mean time, it is also interesting to notice that the phase window correlator does not address the diffraction mitigation at all (see Fig. 11).

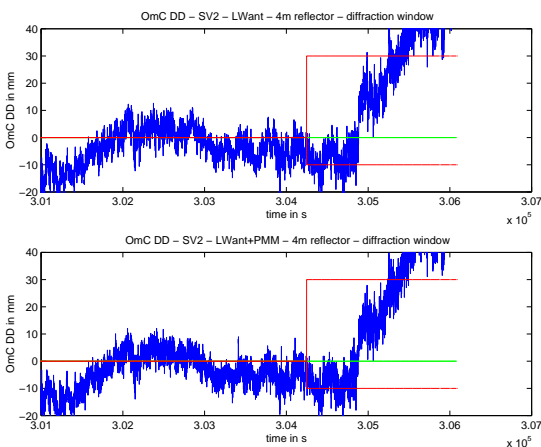


Figure 11 : inability of PMMW to mitigate diffraction

The same analysis can be done for the kinematic data sets.

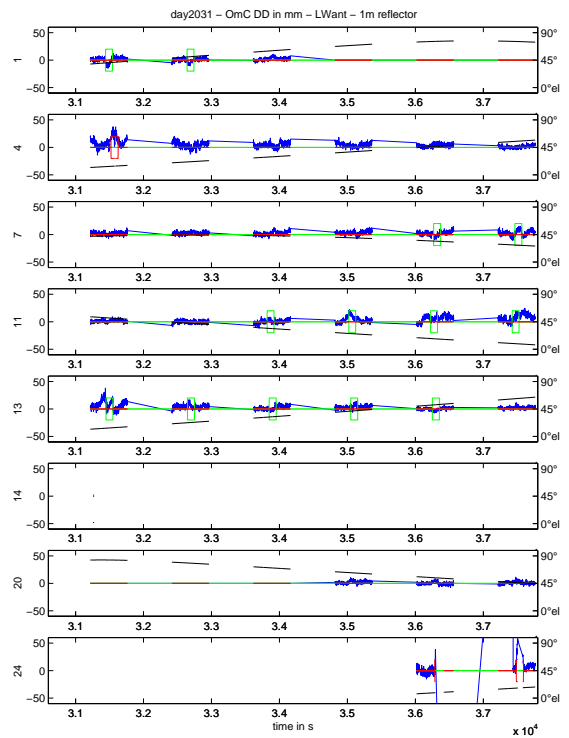


Figure 12 : series of 6 kinematic tests with the reflector at 4 m (8 SVs displayed only)

The results in kinematic are summarised in table 3. They show the same trend as in the static case, although in this case the phase window correlator is slightly less efficient.

Kinematic tests	Std σ	Std σ PMMW	Gain
reflector 7 m 5.1 m < addpath < 11.9 m	4.7 mm	3.3 mm	29%
<i>No reflector</i>	<i>2.4 mm</i>	<i>2.4 mm</i>	<i>4%</i>
reflector 4 m 3.0 m < addpath < 7.6 m	5.9 mm	5.0 mm	14%
<i>No reflector</i>	<i>3.0 mm</i>	<i>2.8 mm</i>	<i>7%</i>
reflector 1 m 0.7 m < addpath < 2.0 m	9.2 mm	8.7 mm	6%
<i>No reflector</i>	<i>5.1 mm</i>	<i>4.9 mm</i>	<i>3%</i>

Table 3 : L1 phase DD statistics in kinematic

It appears that for additional distance of 7.5 m or less, which corresponds to the 40 MHz clock rate of the Leica receivers, the method does not result in such high gains. In other words the test campaign has confirmed the theory that the phase window correlator is unable to mitigate significantly multipath that is due to reflectors very close to the antenna.

5. THE MULTIPATH ERROR RECONSTRUCTION

The objective of the investigations reported in this section is to overcome the key limitation of the PMMW technique. We seek to obtain the same near 50% improvement, irrespective of the distance between the rover antenna and the reflector. In order to do this, we propose an algorithm that is based on multipath error modelling and reconstruction.

The multipath observables are:

- the variation of the signal-to-noise ratio (denoted SNR or C/N0 if it is normalized by the receiver bandwidth), with respect to a satellite elevation template function;
- the code error τ (only for a baseline up to a few kilometres), obtained by computing the variation around the average value of the ionospheric L1 and L2 combination;

$$C1 - (1+2/((f1/f2)^2-1))\Phi1 + (2/((f1/f2)^2-1))\Phi2;$$

- the PMMW correction, which is an estimate of the phase error Φ .

Multipath effects on these observables can be modelled as follows:

$$C/N0_{\text{multipath}} \sim K \sum_i \alpha_i \cos \Theta_i \quad (1)$$

$$\tau \sim \sum_i \alpha_i \cos \Theta_i * d_i \quad (2)$$

$$\Phi \sim \sum_i \alpha_i \sin \Theta_i \quad (3)$$

for a number n of reflected signals (from $i = 1$ to n), where:

$$\alpha_i' = R(d_i + \tau) / R(\tau)$$

R is the code autocorrelation function

d_i is the code delay of the i^{th} reflected signal

Θ_i is the phase delay of the i^{th} reflected signal

α_i is the ratio of amplitude between i^{th} reflected signal and the direct signal

K is a constant, independent of the index i of the direct and reflected signals; K differs between GPS receivers, because the manufacturers do not implement the same formula to output SNR (or C/N0).

This relationship makes the assumption that the reflections follow the law of the geometric optics, which is classically accepted as in [4], [5] or [6].

The SNR-based multipath phase error correction was first introduced by [5]. This method is based on the fact that the signal-to-noise ratio varies harmonically (see Eq. 1) around its nominal value in the presence of multipath.

An identification of the amplitudes (denoted \hat{A}_i) and the arguments (denoted \hat{h}_i) of these components is possible by combining different classical algorithms of signal processing (firstly an ‘‘Adaptive Notch Filter’’ for frequency and amplitude identification, and secondly an

‘‘Adaptive Least Squares’’ for amplitude and argument identification). The outputs (\hat{A}_i and \hat{h}_i) are such that:

$$C/N0_{\text{multipath}} = \sum_i \hat{A}_i \cosh_i \quad (4)$$

This identification provides a way to build a phase correction. Actually, the multipath phase error given in Eq. 3 shows exactly the same amplitude (α_i) and argument (Θ_i) as the multipath variation of the signal-to-noise ratio.

Hence, \hat{A}_i and \hat{h}_i identified before from the variation of the signal-to-noise ratio can be introduced in the Eq. 3 to carry out the phase correction:

$$\Phi \sim 1/K \sum_i \pm \hat{A}_i \sin \hat{h}_i \quad (5)$$

Nevertheless, the identification from the variation of SNR or C/N0 does not give the sign of the argument, since SNR or C/N0 only enables the recovery of the cosine of this argument, and not the sine, therefore the sign remains undetermined. In practice, it can be chosen to best fit the O-C phase DD (or residuals), which entails latency in RT.

An original way [7] to determine the sign of the phase correction is given by the PMMW estimate of the phase error. The basic idea of the algorithm is given in Fig. 13.

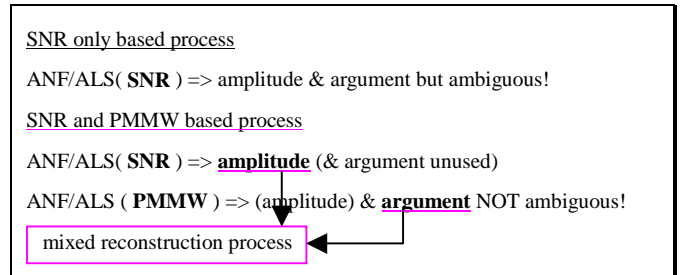


Figure 13 : the SNR and PMMW mixed scenario

This algorithm has been tested on a few data sets (SV1 and SV2) collected in static mode. Fig. 14 displays the standard deviation of the corrected O-C phase DD versus the gain (1/K) applied in the phase error reconstruction processes. It is important to notice that a scenario is relevant if the gain that corresponds to the minimum standard deviation does not depend on the distance to the reflector. The ‘black (+)’, ‘magenta (*)’ and ‘blue (#)’ lines refer to respectively the scenarios with SNR only, with the PMMW estimate + SNR and lastly with the code error + SNR, a scenario that is depicted in the last section.

With the panel at 7 m, the best results are obtained by applying the PMMW correction directly (the corresponding standard deviation is figured by an horizontal black line). However, at 4 m the SNR and PMMW mixed scenario is equivalent as the PMMW direct correction, even slightly better since the effectiveness of the PMMW starts to deteriorate. Moreover, the mixed process gives a more efficient or at least equal correction than the classical SNR based process, except in the case of the very close reflector (1 m) where the PMMW estimation has deteriorated. On the contrary, at 1 m SNR based process remains potentially the most efficient (provided the sign ambiguity is solved).

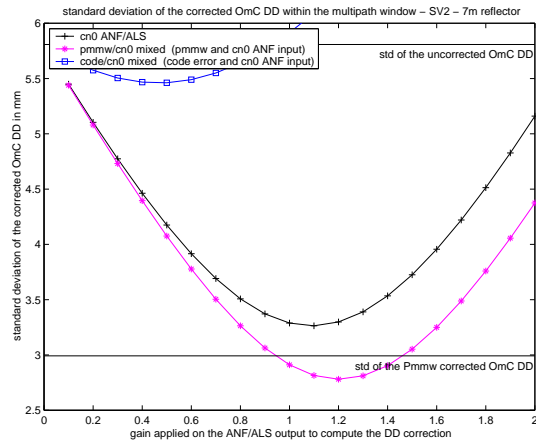
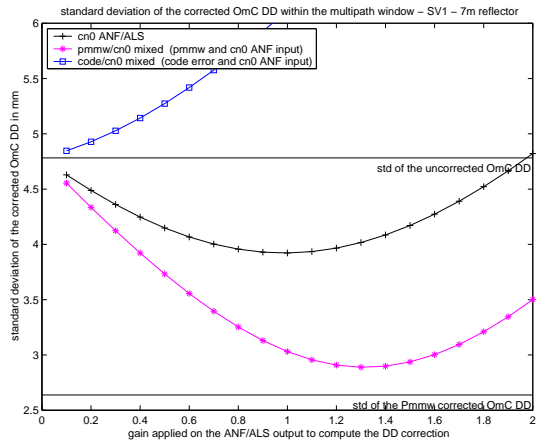


Figure 14a : the investigated SNR and code mixed scenario compared to SNR and PMMW/SNR mixed scenarios in the case of the 7m distant reflector (SV1 and SV2)

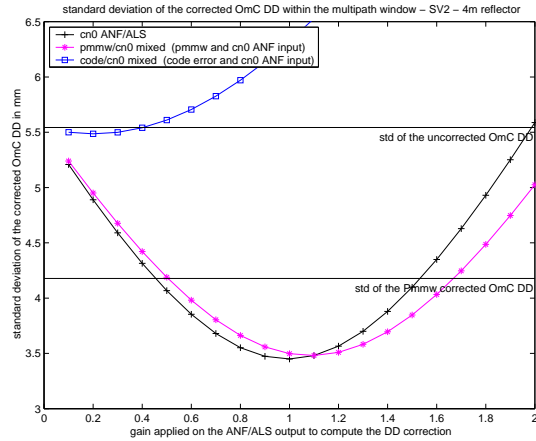
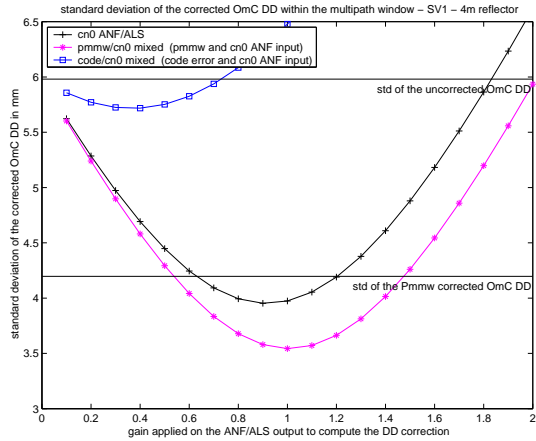


Figure 14b : the investigated SNR and code mixed scenario compared to SNR and PMMW/SNR mixed scenarios in the case of the 4m distant reflector (SV1 and SV2)

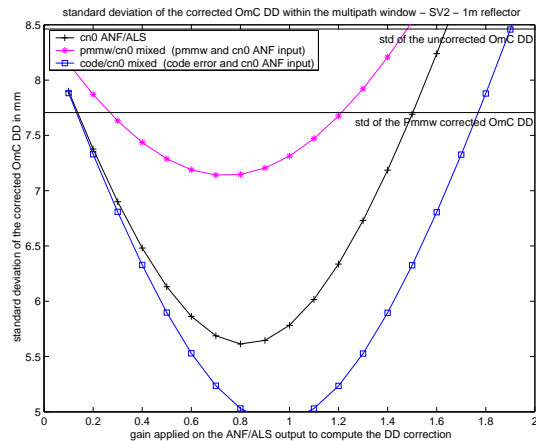
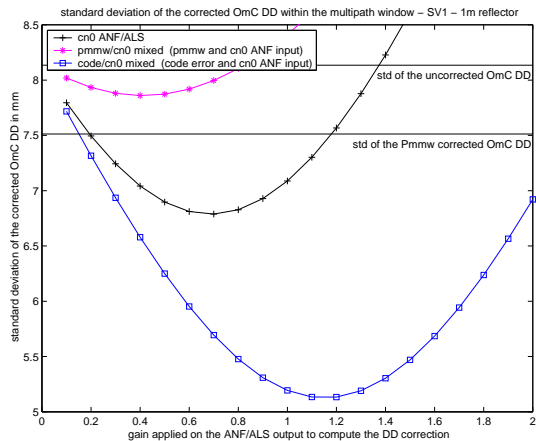


Figure 14c : the investigated SNR and code mixed scenario compared to SNR and PMMW/SNR mixed scenarios in the case of a very close reflector, i.e. 1m distant (SV1 and SV2)

7. USING CODE ERROR FOR CLOSE MULTIPATH

Another mixed reconstruction algorithm is suggested in [7] in order to take into account the specific behaviour of the code error in the case of a very close reflector. It actually appears (contrary to Eq. 2) that the multipath code error shifts in phase at around 1.5 m additional path to become in quadrature with the SNR variation and in phase with the phase error. This is probably due to details of implementation, as well as the fact that the signal is not of infinite bandwidth. An illustration of this observation is given Fig. 15c.

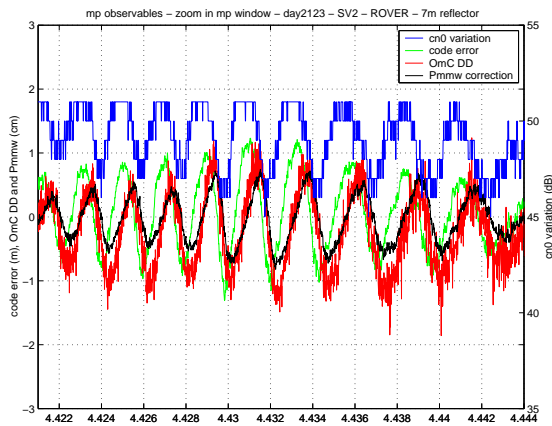


Figure 15a : observables and O-C L1 DD (7 m test)

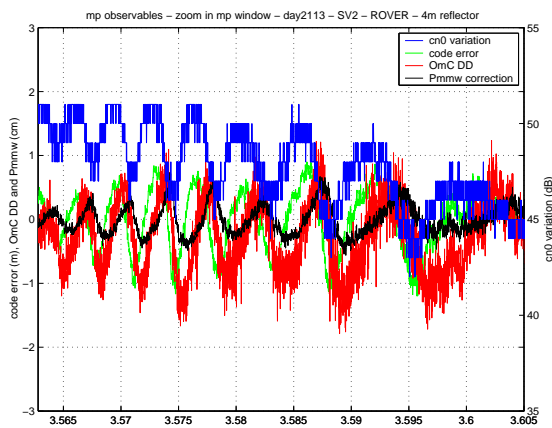


Figure 15b : observables and O-C L1 DD (4 m test)

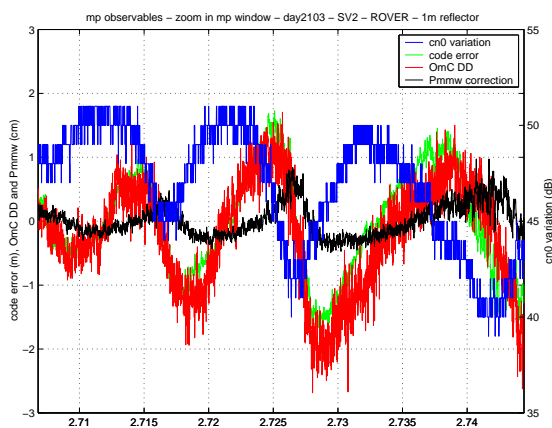


Figure 15c : observables and O-C L1 DD (1 m test)

This scenario mixes SNR and code error (see Fig. 16).

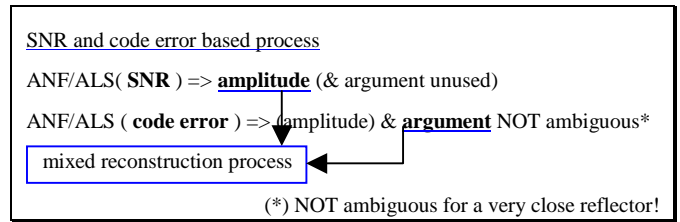


Figure 16 : the SNR and PMMW mixed scenario

The test at 1 m (see Fig. 14c) shows the potential of the code error to estimate a phase correction. But Fig. 14a and Fig. 14b confirm that it is only relevant for very close multipath.

8. CONCLUSIONS

We can assume that on most engineering sites, multipath errors are caused by specular reflection with grazing angles generally above the Brewster angle. Hence, the relative phase between the reflected signal and the direct signal is only dependent on the additional path length, plus the 180° reflection phase shift and an antenna phase shift. The resulting multipath error is also dependent on a number of other factors including the characteristics of the antenna and the reflecting surface.

Methods for the mitigation of such multipath errors can be tested using the dedicated facility at LCPC, which enables strong multipath signals to be generated through specular reflections in highly controlled static and kinematic environments.

As far as the specific testing of the Leica PMMW correlator is concerned, previous conclusions are confirmed, i.e. that the method is up to 50% efficient at reducing multipath from reflectors leading to additional path lengths of greater than 7.5m, but less efficient for closer reflectors.

Initial efforts at combining output from the PMMW correlator with SNR and code data suggest that SNR is always useful to determine the amplitude of the correction. However, the argument of the correction needs to be computed from either the PMMW estimation or the code error, depending on the distance to the reflector. So, it appears that the two strategies are both potentially rather efficient, but for two different situations in terms of distance to the reflector. The next step that is envisaged in this research is the fusion of these reconstruction processes.

Finally it is mentioned that more data (especially that collected in a kinematic mode) should be processed before firm conclusions are drawn regarding the relative efficacy of, and the best way to fuse, the three multipath observables: PMMW output, SNR and code multipath estimates. Early indications are, however, that a combination of the three data types has great potential for the mitigation of phase multipath in both static and kinematic engineering applications.

ACKNOWLEDGEMENTS

The authors thank Leica Geosystems for its support of the research reported in this paper. In particular they thank Hans-Juergen Euler and Jon Maenpa for sharing their extensive GPS knowledge and experience, and for their guidance in determining the directions that the research has taken.

Thanks are also due to Nicolas De Moegen and Emmanuel Roy of Leica France for providing receivers, and Charles Lemaire and Jean-Marie Prual, both of LCPC, for their technical assistance during the SESSYL tests.

REFERENCES

- [1]: Peyret F., The paradigm of computer integrated construction applied to civil engineering, Proceedings of the 16th International Symposium on Automation and Robotics for Construction, pp. 3-10, Madrid, Spain, 1999
- [2]: Stansell, T.A., J.E. Knight, R.G. Keegan, R.R. Hatch, C.R. Cahn, Mitigation of multipath effects in GPS receivers, world patent WO 96/37789, 1996
- [3]: Bétaille, D., A testing methodology for GPS phase multipath mitigation techniques, Proceedings of ION GPS-03, The Institute of Navigation, Portland, Oregon, 2003
- [4]: Georgiadou, Y., A. Kleusberg, On carrier signal multipath effects in relative GPS positioning, Manuscripta Geodaetica, Vol. 13, pp. 172-179, 1988
- [5]: Comp, C.J., P. Axelrad, An adaptive SNR-based carrier phase multipath mitigation technique, Proceedings of ION GPS-96, pp. 683-697, The Institute of Navigation, Kansas City, Missouri, 1996
- [6]: Ray, J.K., M.E. Cannon, P. Fenton, Code range and carrier phase multipath mitigation using SNR, range and phase measurements in a multi-antenna system, Proceedings of ION GPS-99, pp. 713-725, Nashville, Tennessee, 1999
- [7]: Bétaille, D., J. Maenpa, H.J. Euler, P. Cross, Overcoming the limitations of the phase multipath mitigation window, Proceedings of ION GPS-03, The Institute of Navigation, Portland, Oregon, 2003