Multipath and Tracking Performance of Galileo Ranging Signals Transmitted by GIOVE-A

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BIOGRAPHIES

Dr. Andrew Simsky holds a Ph.D. in Physics from the University of Moscow, Russia. He is working as a senior GNSS scientist at Septentrio in Leuven, Belgium. His research interests include differential and standalone navigation algorithms and performance analysis of GNSS receivers. He previously worked on carrier-phase DGPS algorithms for airborne gravimetry at Sander Geophysics Ltd in Ottawa, Canada.

David Mertens holds a M.Sc. in Physics from the University of Louvain and a M.Sc. in Electronics Engineering from the University of Liege, Belgium. He is currently involved with Septentrio's GIOVE-A signal experimentation activity as a data analyst.

Dr. Jean-Marie Sleewaegen is currently responsible for the GNSS signal processing, data analysis and technology development at Septentrio Satellite Navigation. Previously he was associated with the Royal Observatory of Belgium where he was responsible for the data quality monitoring and the reference network management. He received his M.Sc. in Electrical Engineering in 1995 and his Ph.D. in 1999 from the University of Brussels. He received the ION Burka award in 1999.

Dr. Tom Willems obtained a Master's degree in Computer Science from Ghent University, Belgium, in 1999. In 2006 he received a Ph.D. degree from Ghent University, Belgium, for his research on regional GNSS augmentation systems. Since March 2006 he has been employed as a GNSS Signal Processing Engineer at Septentrio Satellite Navigation, Leuven, Belgium.

Dr. Martin Hollreiser works for the ESA Galileo Project Office as Head of the User and Ground Receiver Section. Previously he held the position of Head of the Microelectronics Section in the Technical Directorate of the European Space Research and Technology Centre. Between 1983 and 1990 he was working for Siemens AG R&D and Rohde & Schwarz in Munich on analog and digital VLSI design. Since graduation in 1983 his R&D activities have been focusing on integrated CDMA transceiver design, on GPS/GLONASS and Galileo receiver design and on VLSI payload signal processing with emphasis on fixed, mobile and multi-media satellite communications systems. Martin holds a Master's and Ph.D. degree in electrical engineering. He was a visiting scientist at Carnegie Mellon University in Pittsburg, PA. Martin is a Senior Member of the IEEE and a member of the ION.

Dr Massimo Crisci is currently working as Radio Navigation Engineer for the TEC-ETN section at ESA/ESTEC supporting the Galileo project office in the field of performance, in particular the Signal and Integrity aspects of the Galileo system and of the GIOVE mission. He received his M.Sc. in Electronics Engineering in 1999 from the University of Ferrara and his Ph.D in Automatics and Operations Research in 2003 from the University of Bologna with a thesis on DGPS Baro-Inertial Augmentation and Robust filtering.

ABSTRACT

Analysis of GIOVE-A signals is an important part of the IOV phase of the Galileo program with a particular goal to test the tracking of all the code modulations, evaluate multipath performance of the Galileo signals, verify the design and operation of both signal transmitters and receivers.

In this paper we summarize the results of the performance analysis of the GIOVE-A measurements, collected with the use of Septentrio's GETR receiver during more than a year since the first reception of GIOVE-A signals in the beginning of 2006. GIOVE-A is transmitting the ranging signals using all the code modulations currently foreseen for the future Galileo. Multipath performance of GIOVE-A signals provides a foretaste of the performance of future Galileo signals in real-life applications. Due to the use of advanced code modulations, the ranging signals of

Galileo provide significant improvement of the tracking and multipath performance as compared to current GPS.

A year ago we presented at this conference first results of the performance analysis for GIOVE-A signals: signal power, tracking noise and multipath performance. In this paper the results of the next stage of this research are reported. Based on the same methodology of data analysis, we processed a lot more data sets including the data from different antenna sites, different geographic locations and different antenna types.

The main conclusions of our first paper are now verified on a much wider array of data. Despite significant site-dependent variability of static data the previously stated classification of the signals in terms or multipath performance is confirmed. According to this classification, all the Galileo signals fall into 3 groups: (i) the group of 3 best signals E5AltBOC, L1A, E6A (ii) intermediate group which includes E5a, E5b, E6BC and (iii) L1BC which shows the lowest values of performance indicators.

This classification, which agrees with theoretical predictions and computer simulations, can be accepted as a general rule, although in some tests E6BC and E5a show performance similar to L1BC, and E6A in the others shows performance more typical to the medium group. Peculiarities of real-life multipath, especially site-dependent variations of typical delays of reflected signals, present a great variety of multipath conditions, which lead to significant site-dependent variablity of multipath statistics. One conclusion is very clear: in all the hitherto performed tests E5AltBOC showed by far the best multipath performance, with the magnitude of multipath errors about 4-5 times lower than for GPS-CA.

It is quite remarkable that GLONASS-L2P signals have the same code modulations as Galileo E6BC. The multipath analysis of GLONASS-L2P sheds additional light on the future performance of the Commercial Service of Galileo which is based on E6BC. It is demonstrated that both GLONASS-L2P and E6BC have similar performance gain with respect to GPS-CA.

Due to significant attention to the car navigation as a potential application field for new Galileo signals, a few car tests have been done. It is shown that in the car tests the differences between the multipath errors for different modulations are much smaller than for the static tests. These results are discussed in the context of the ongoing debate about the possible replacement of BOC(1,1) with MBOC. It is expected by many that MBOC shall perform better in automotive applications, this being one of the most popular arguments in support of MBOC. In fact, the analysis of GIOVE-A data shows that in car tests all the different signals, both of Galileo and GPS show comparable multipath performance, generally much better than in the static environment. Therefore in our opinion, replacement of BOC(1,1) with MBOC cannot become a real differentiator for car navigation applications.

INTRODUCTION

The first Galileo signals were transmitted on January 12, 2006, by the GIOVE-A satellite. The first results for the tracking noise, signal power and code multipath performance of the live GIOVE-A signal obtained with the use of the GETR receiver have been presented in October 2006 [1]. The overview of the on-going GIOVE-A signal experimentation activity including results obtained at ESA, Septentrio NV, and Alcatel Alenia Space can be found in [2]. Results of GIOVE-A signal testing have also been reported in [3, 4]. The purpose of the current paper is to summarize the GIOVE-A signal analysis performed at Septentrio since the beginning of the GIOVE-A mission up to the time of this publication that is during the first 1½ year of the satellite operation.

The ranging signals of Galileo are based on advanced code modulation schemes, which are expected to provide significant improvement of the tracking and multipath performance as compared to the current GPS. With the advent of GIOVE-A these expectations have been verified. The first analysis [1] has clearly shown the advantages of the Galileo signals in comparison to current civilian signals of GPS (C/A and L2C). Further experience based on a wider array of data has confirmed these results. In this paper we summarize the results from a number of data sets obtained at few antenna sites at different geographic locations, as well as the results of kinematic tests in different environments.

The GIOVE-A transmits ranging signals using all the currently foreseen Galileo modulations: L1BC, L1A, E5a, E5b, E5 (or E5AltBOC), E6BC, and E6A [1,5]. The GETR receiver has been custom-built by Septentrio for the reception of GIOVE signals. The GETR is capable of tracking all the transmitted modulations. The output of GETR includes raw measurements, navigation bits and, optionally, correlation function and the samples of the RF signal at the intermediate frequency. The signal acquisition in GETR is implemented with the use of a custom-tailored fast acquisition unit [6].

This paper is based on the analysis of GETR measurements (pseudoranges, phases, Dopplers, C/N0). The emphasis is on the evaluation of the code multipath performance, which is statistically characterized by the dependence of the averaged multipath noise upon elevation. Our approach is to compare empirical data for different sites and different signals and classify the signals in accordance with their average multipath performance. It has already been shown in [10] that the multipath performance of Galileo signals shows significant variability depending upon multipath conditions on individual sites.

In our data analysis we computed code multipath using a well-known formula:

$$M_i = P_i - \Phi_i + 2\lambda_i^2 \frac{\Phi_j - \Phi_i}{\lambda_j^2 - \lambda_i^2} \qquad \textbf{(1)}$$

where M_i is the estimate of the code multipath error on a pseudorange P_i, while Φ_i and Φ_j are the carrier phase observables (in units of length) for wavelengths λ_i and λ_j for the same satellite. j represents any band which is different than i. With multi-frequency Galileo signals, several values of j are possible, but the particular selection of j does not significantly affect the results. Formula (1) estimates a combination of multipath and tracking noise, but the contribution of the tracking noise can be neglected in most practical cases. For those signals which have pilot and data components, we used the pilot component; the multipath is exactly the same for both components but the tracking noise is independent.

Our method of analysis is to compute standard deviation of actual multipath errors given by formula (1) for a few bins of elevations and compare multipath as an empirical function of elevation angle for different signals at the same antenna site. The relative magnitude of thus measured actual multipath errors is expected to correlate with the size of multipath error envelopes shown in Figure 1.

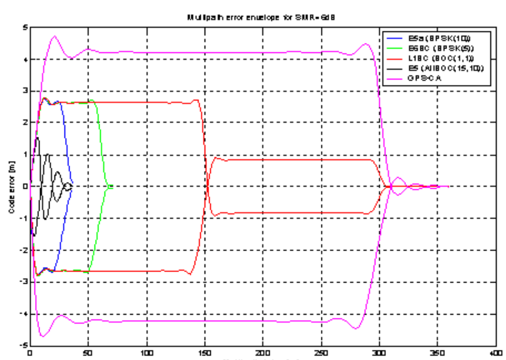

Figure 1. Multipath error envelopes for selected Galileo codes and GPS-C/A.

It can be seen that all the Galileo signals perform better than the GPS C/A code, with L1BC (red curve) being the worst Galileo signal, and E5AltBOC (black curve) being the best. It is easy to notice that the sizes of error envelopes differ mostly in the direction of the X-axis (delays of the reflected signals). This means the real effectiveness of multipath suppression by better modulations depends upon the typical values of delays characteristic for individual antenna sites. For example, for the multipath delays less than 150m, there is no big difference between L1BC and GPS-CA. Only for the delays greater than 150m, the L1BC modulation is expected to show its advantages. As a general tendency, for the sites with predominantly short-range multipath the advantage of better modulations shall be smaller than for the sites with significant contribution of long-range multipath. Because long-range multipath results in higher frequency of multipath variations, one can expect that more advanced signals will show much less high-frequency components in their spectrum [1].

According to Figure 1, E5AltBOC is the only signal with significant suppression of short-range as well as long-range multipath. Our tests have definitely confirmed that the multipath performance of E5AltBOC is always the best as compared to other signals. E5AltBOC is a signal obtained through cooperative tracking of E5a and E5b signals. The exceptional qualities of E5AltBOC are due to its exceptionally high bandwidth. The tracking of E5AltBOC signal is implemented in the GETR in accordance with the algorithm outlined in [7].

STATIC DATA COLLECTED IN LEUVEN AT SEPTENTRIO TEST SITE (LEUVEN-1)

Most of the data presented in this paper have been collected at the rooftop of the Septentrio office building. The wide-band GPS/Galileo antenna provided by Space Engineering is shown in Figure 2. The antenna was mounted on the support structure and was located higher than other objects on the rooftop. However, the adjacent building, which is seen at the photo, was still higher than the antenna and acted as a source of reflected signals. Therefore, the short-range multipath at our site is relatively low, but long-range multipath systematically affects our data especially because we often see GIOVE-A rising or setting in the direction opposite to the adjacent building.

Figure 2. Space Engineering antenna mounted on the rooftop of the Septentrio office (Leuven-1). The site of Leuven-2 was chosen between the ventilation ducts similar to shown in the bottom right corner of this photo in order to get more short-range multipath.

Although GIOVE-A is able of transmitting all the experimental Galileo signals, it can transmit only in two frequency bands at a time. In reality, the satellite is transmitting either a combination of L1+E5a+E5b or a combination of L1+E6. Our assessment of multipath performance for this site is based on the processing of 6 data sets collected from January 15 to October 13 2006. More details about the data sets can be found in [10].

In our analysis we have joined all the processed data for averaged signal power and code multipath errors as functions of elevation into one global array. This data is presented in Figure 3 and Figure 4 for signal power and multipath respectively. The signal power matches the specifications of GSTB-V2, but is not representative of the final Galileo satellites, which shall use different transmitters. The drop of C/N0 at zenith for L1 signals is peculiar to the Space Engineering antenna (see [1] for more details).

Figure 4 contains standard deviations of code multipath for 10-degree bins of the elevation angle. The multipath of GPS-CA, which corresponds to the same antenna and the same location, has clearly higher values than for all the Galileo signals. Galileo L1-BC not only has the highest multipath compared to other Galileo modulations, but is also similar to GPS-CA in a sense of having a steep rise at low elevations. This rise can be attributed to the contribution of long-range multipath at low elevations, which is almost completely suppressed by the best Galileo modulations.

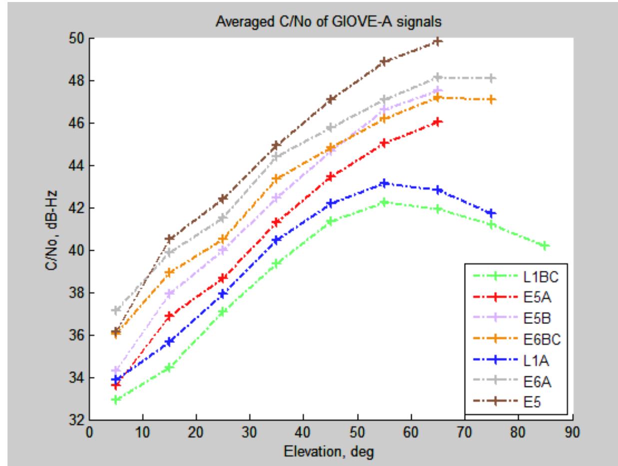

Figure 3. Averaged signal power for all the data collected in Leuven-1

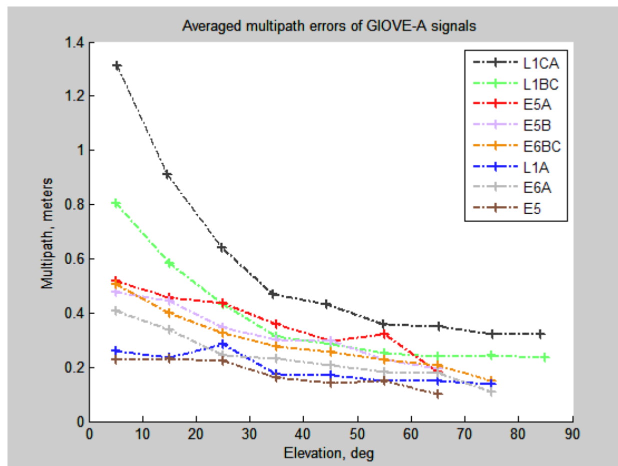

Figure 4. STD of code multipath for Galileo signals in comparison to GPS-CA for the tests in Leuven

According to theory, the Galileo modulations having higher chip rate and advanced modulation structure must be particularly successful in suppressing long-range multipath. The best modulations, such as E5AltBOC, L1A and E6A, show such a complete suppression of long-range multipath that the corresponding curves in Figure 4 are almost flat and show little increase at low elevations.

Comparison of low-elevation and high-elevation multipath is also presented in Table 1. In this table the Galileo modulations are grouped into 3 groups: (i) high-performance group, which included E5AltBOC and the two PRS modulations (L1A and E6A), (ii) medium-performance group, which includes E5a, E5b and E6BC, and (iii) low-performance group, which includes only L1BC and has still better performance compared to CPS-CA. The values of multipath typical for the high-performance group are comparable to the values of tracking noise for GPS-CA code and are for most of the tests nearly equal at low and high elevations. It should be mentioned that practically identical ranking of Galileo signals for multipath performance was obtained by computer simulations in [8].

Signal	Leuven-1 6 days, 2006		Leuven-2 4 days, 2006	
	>10°	<10°	<10°	>10°
GPS-C/A	*0.60*	*0.60*	***	***
L1BC	0.38	0.80	0.40	0.87
E5a	0.38	0.55	0.40	0.85
E5b	0.32	0.50	0.35	0.55
E6BC	0.28	0.42	-----	-----
E6A	0.23	0.40	-----	------
L1A	0.22	0.22	0.25	0.35
E5AltBOC	**0.18**	**0.23**	**0.19**	**0.26**

Table 1. Multipath (STD) in meters from Leuven sites based on all the processed data. Leuven-1 is a general antenna site used most of the time (see Figure 2), while Leuven-2 is a special location on the roof with greater short-range multipath.

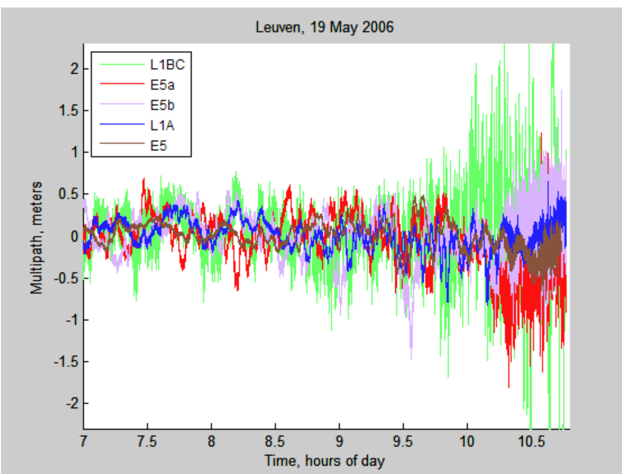

Figure 5. Time series of code multipath for the test of May 19 2006

In Figure 5 the long-range multipath manifests itself in high-frequency variations of multipath error near the right edge of the graph. The same ranking of the Galileo modulations as in the above table can be observed: the multipath errors of L1BC are the highest, while the multipath of E5AltBOC is the lowest and the others fall in-between.

The high-amplitude high-frequency variations of multipath shown in Figure 5 and other similar plots correspond in fact to a quasi-period about 20 seconds. The zoomed plot of these variations is shown in Figure 6. This plot clearly demonstrates how complete is the suppression of long-range multipath by the best Galileo modulations.

A similar example, which includes E6A, is shown in Figure 7.

Although most of the data demonstrate similar behaviour for all the 3 modulations of the best group (E5, L1A, E6A), a more careful analysis shows that L1A and E6A on some occasions show greater values of multipath, more similar to the values typical for the "medium-performance" group. An example is presented in Figure 8. The E5AltBOC on the other hand always shows an exceptionally stable performance: its values of multipath errors are always the lowest as compared to the other modulations (see Figure 9, Figure 10, Figure 11).

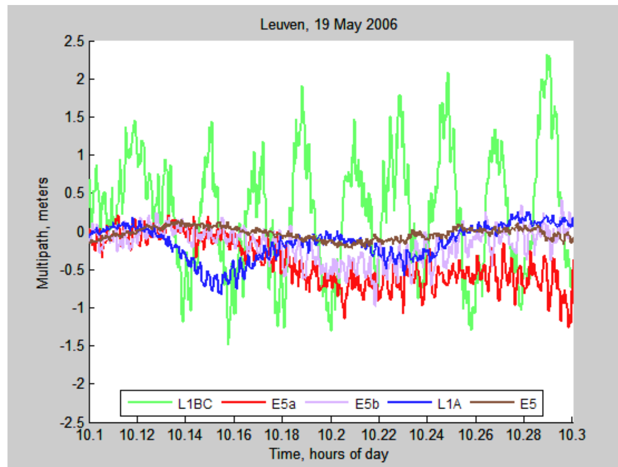

Figure 6. Zoomed view of the high-elevation part of the previous plot.

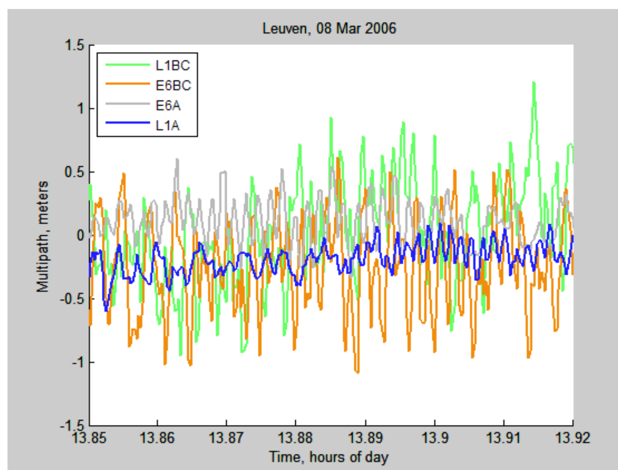

Figure 7. Similar example from another data set which includes E6A

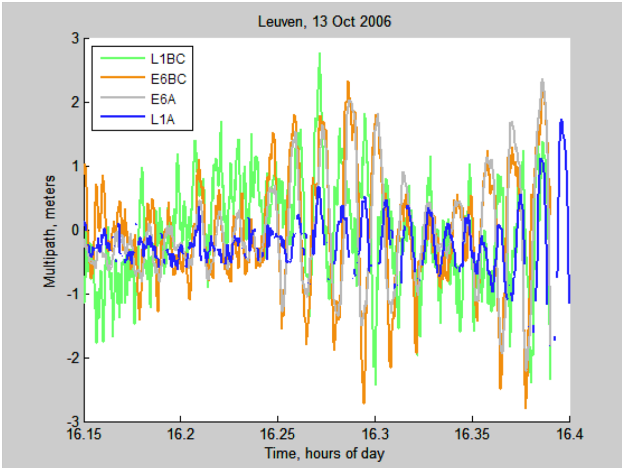

Figure 8. An occasion of relatively high multipath errors by L1A/E6A

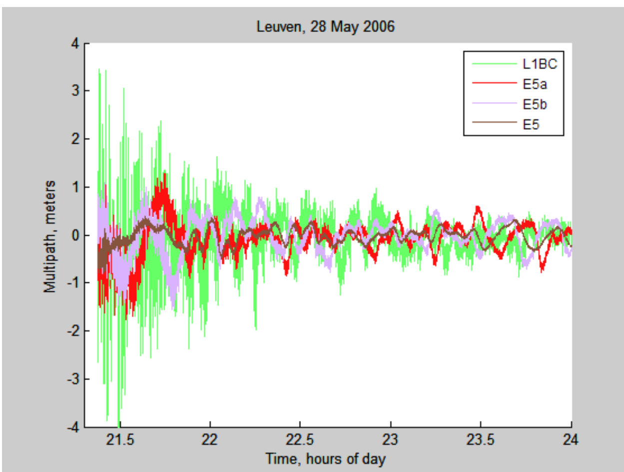

Figure 9. Multipath time series for May 28, 2006

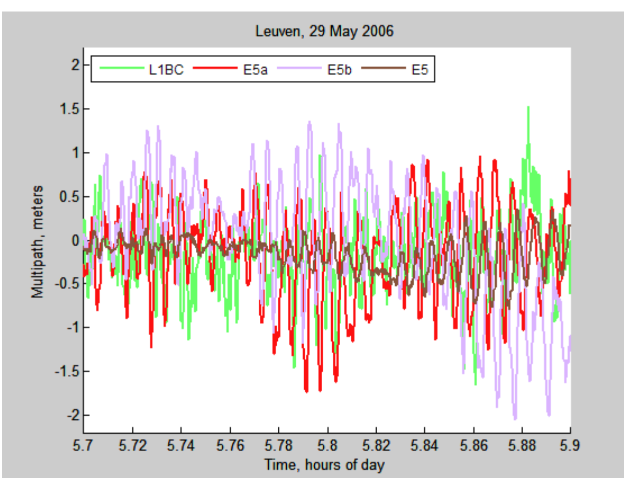

Figure 10. Multipath time series for May 29, 2006

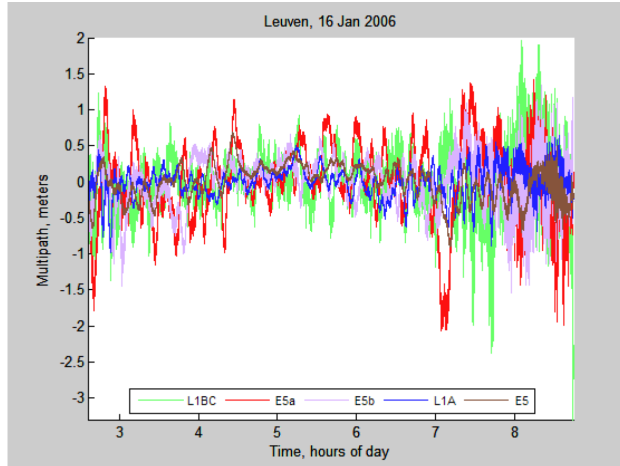

Figure 11. Multipath time series for January 16, 2006

ANTENNA SITE LEUVEN-2 WITH MORE INTENSIVE SHORT-RANGE MULTIPATH

In order to investigate the effect of short-range multipath on Galileo signals, we placed the Galileo antenna at another, more multipath-rich position on the same rooftop. This antenna position was located on the roof floor between the two metal ventilation outlets (identical to these in the right bottom corner of Figure 2). The antenna was located lower than many other reflective objects on the rooftop, so it was expected to get more short-range and middle-range multipath compared to the main site. The comparison of the two sites is presented in Figure 12.

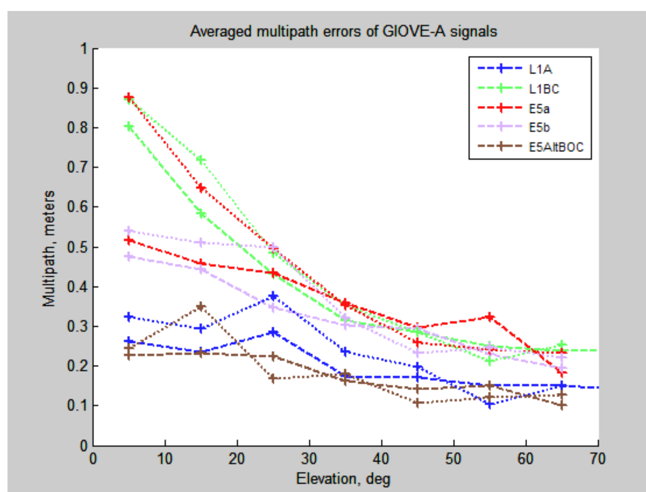

Figure 12. Dotted line : tests of Dec 12,13 at Leuven-2 (multipath-rich site). Broken line : average of tests during March-October 2006 at Leuven-1 (open-sky site).

The time series of code multipath are presented in Figure 13 and Figure 14. It is evident that in both plots the multipath of E5a is unusually high in comparison to all the other tests. The reason for this strange behaviour, different from all the other tests, is not clear. It should be mentioned that because we could use only one antenna at a time, we are comparing the multipath on two different sites at different days. So the differences between the sites are at least partly due to the differences between the passes of GIOVE-A on different days.

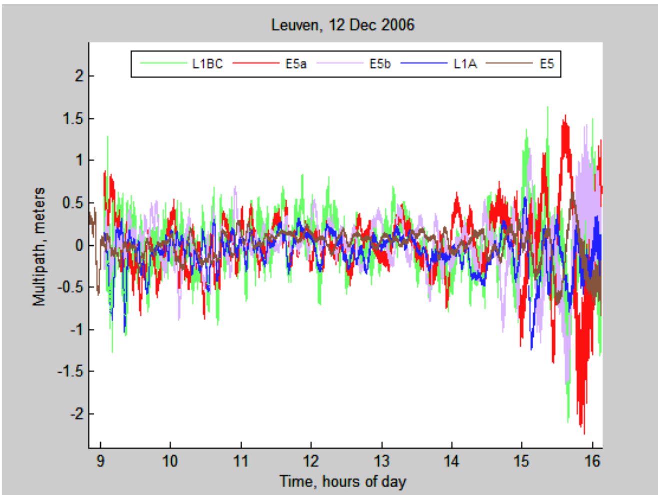

Figure 13. Time series for code multipath at Leuven-2 for December 12, 2006

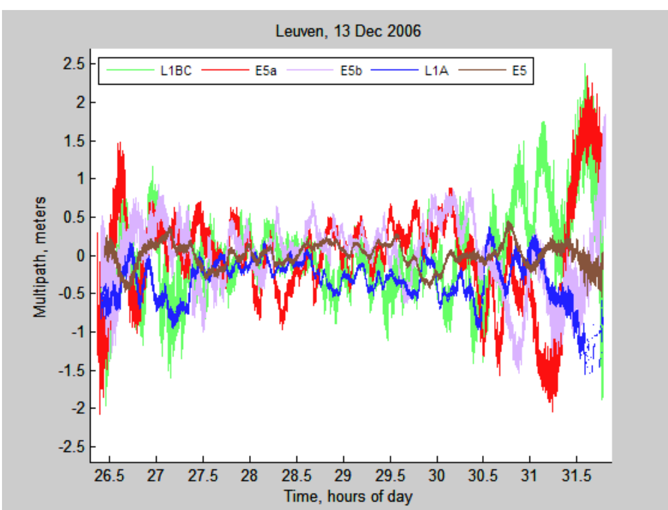

Figure 14. Time series for code multipath at Leuven-2 for December 13, 2006.

STATIC DATA COLLECTED AT LA PLATA AND WUHAN GESS SITES

On top of processing the data collected by ourselves, we also processed the GIOVE-A data collected at 2 other geographic locations and available via GESS network: La Plata in Latin America and Wuhan in China.

Signal	LaPlata 4 days		Wuhan, 4 days	
	>10°	<10°	<10°	>10°
L1BC	0.60	1.0	0.53	0.70
E5a	0.45	0.90	0.42	0.52
E5b	0.32	0.80	0.46	0.48
E6BC	0.50	-----	0.50	0.50
E6A	0.38	-----	0.29	0.16
L1A	0.28	0.45	0.39	0.30
E5AltBOC	**0.21**	**0.22**	**0.20**	**0.20**

Table 2. Multipath (STD) in meters from LaPlata and Wuhan sites based on all the processed data.

The analysis of multipath data from these two sites confirms in broad terms the tendencies reported in the first section. In particular, the superior performance of L1A and E5AltBOC has been confirmed. However, some important differences must be mentioned. First of all, the E6BC signal has unusually high multipath comparable to L1BC (even higher than L1BC at low elevations). Secondly, at the Wuhan site the elevation dependence is much less pronounced than for the rest of the tests, probably due to the peculiarities of local reflectors. Thirdly, the E6A signal shows worse performance than L1A and E5AltBOC. At low elevations it still gravitates to the "high-performance group", while at higher elevations it shows about the same average multipath errors than other signals.

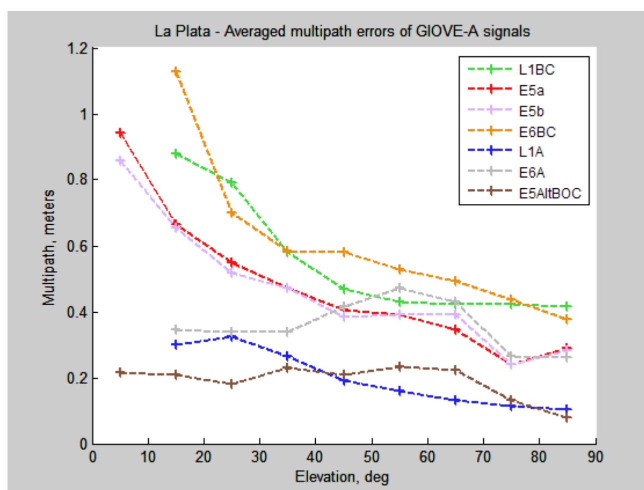

Figure 15. Multipath performance at the La Plata GESS site

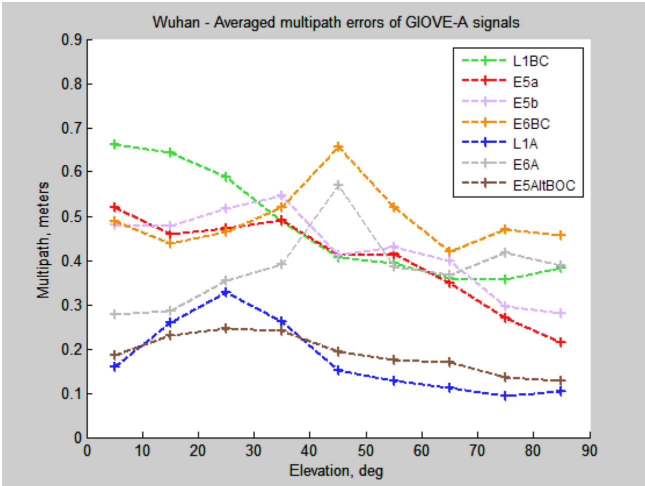

Figure 16. Multipath performance at the Wuhan GESS site

Peculiarities of these sites can also be illustrated by the time series of multipath errors (Figure 17 - Figure 20). Figure 17 illustrates relatively high multipath errors for E6BC. Figure 19 and Figure 20 show that the multipath for the Wuhan stations has indeed atypical elevation dependence: at lower elevations the frequency of the variations of multipath are increasing while their amplitude remains the same. The multipath results for different stations depend of course upon the peculiarities of the multipath environment, in particular upon the presence of reflectors oriented in a certain way relative to the GIOVE-A lines of sight at its rising and setting.

Figure 21 demonstrates how different the multipath environments indeed are at different stations. At La Plata station, the multipath is generally the highest (almost a double at high elevations compared to Leuven), while at Wuhan the multipath is not only higher in general, but also its elevation dependence is flatter. Logically enough, the biggest differences can be seen for L1BC, where multipath errors are the highest, while for E5AltBOC, where multipath errors are significantly suppressed, the differences are almost undetectable (Figure 22).

Investigation of the reasons for site-dependent differences is beyond the scope of this paper. It should only be mentioned that some part of the blame for the unusually high multipath of the La Plata site should be attributed to the fact that the signal power on this site is systematically lower than in Leuven and Wuhan (compare Figure 3, Figure 23, Figure 24). The photos of La Plata and Wuhan antenna sites from public IGS sources show significant amount of local reflectors. The La Plata site (Figure 25) resembles a park and is surrounded with high trees which are apparently responsible for high multipath and masking of the signal at low elevations. The Wuhan site (Figure 26) is on the rooftop of a two-storied building and is surrounded by remote trees which are likely to serve as a source of scattered signals. The multipath caused by scattered signals is expected to be present at all the elevations and may be responsible for the flatter elevation dependence of multipath at Wuhan (Figure 21).

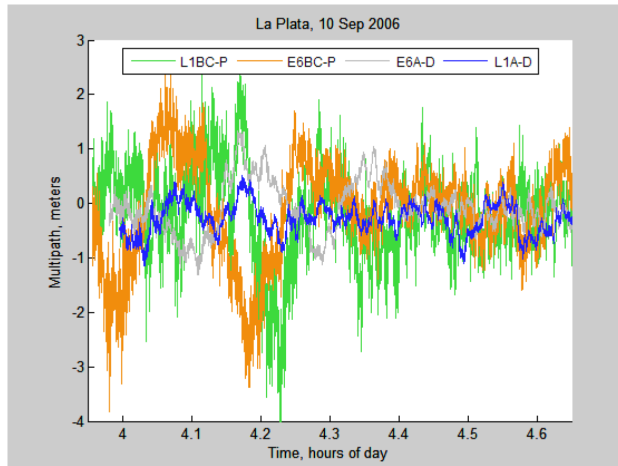

Figure 17. Time series of code multipath for La Plata, Sep 10 2006

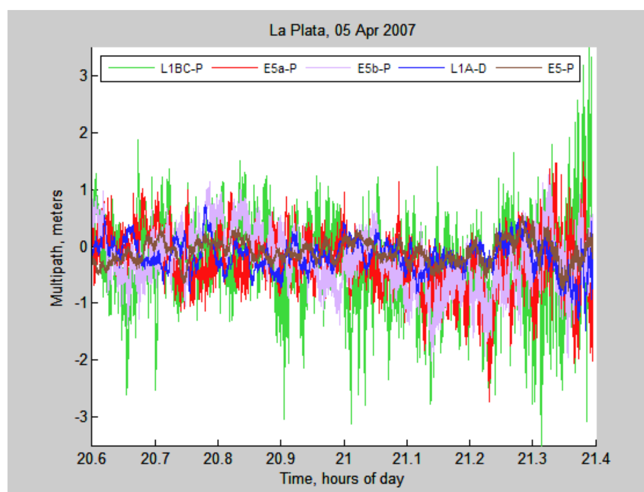

Figure 18. Time series of code multipath for La Plata, April 05, 2007

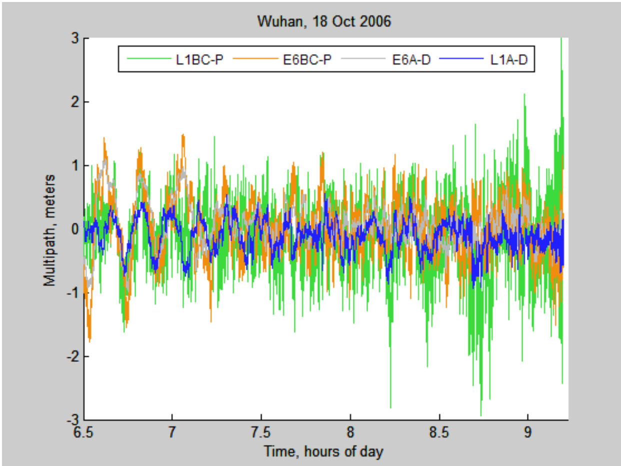

Figure 19. Time series of code multipath for Wuhan, 18 Oct 2006

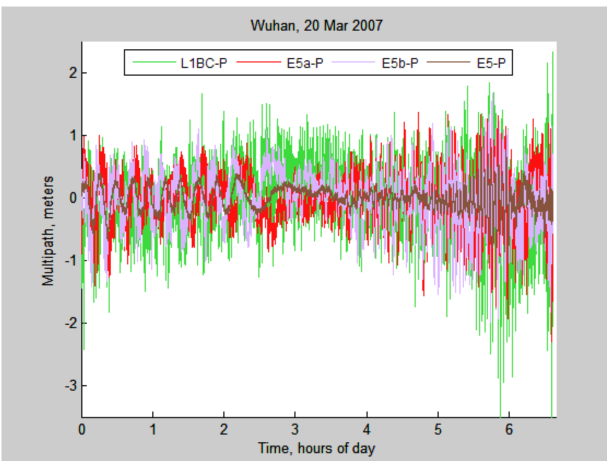

Figure 20. Time series of code multipath for Wuhan, March 20, 2007

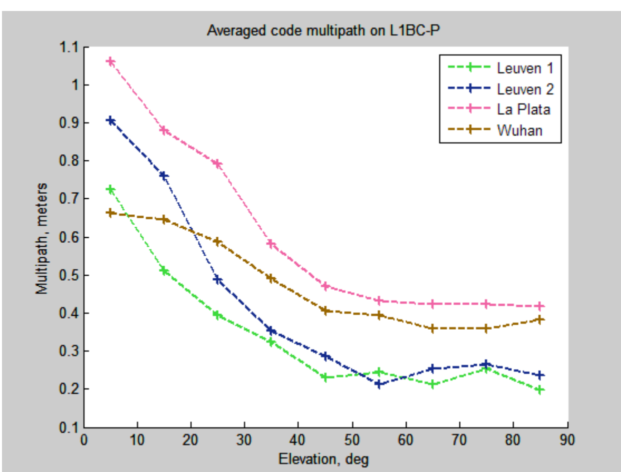

Figure 21. Code multipath on L1BC at 4 locations. Here Leuven-1 an open-sky antenna site (Figure 2). Leuven-2 is more multipath-rich site located between the ventilation outlets (see previous section)

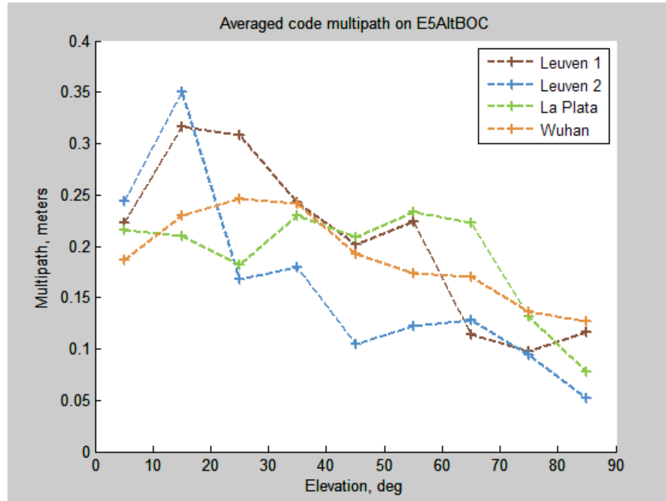

Figure 22. Code multipath on E5AltBOC at 4 locations. Here Leuven-1 is our main open-sky antenna site (Figure 2). Leuven-2 is more multipath-rich site located between the ventilation outlets (see previous section)

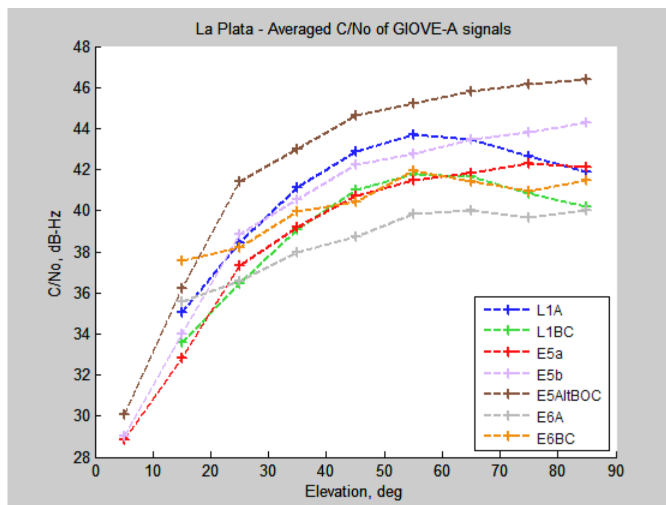

Figure 23. Signal power at La Plata station. It is systematically lower as compared to Leuven (Figure 3) and Wuhan (Figure 24)

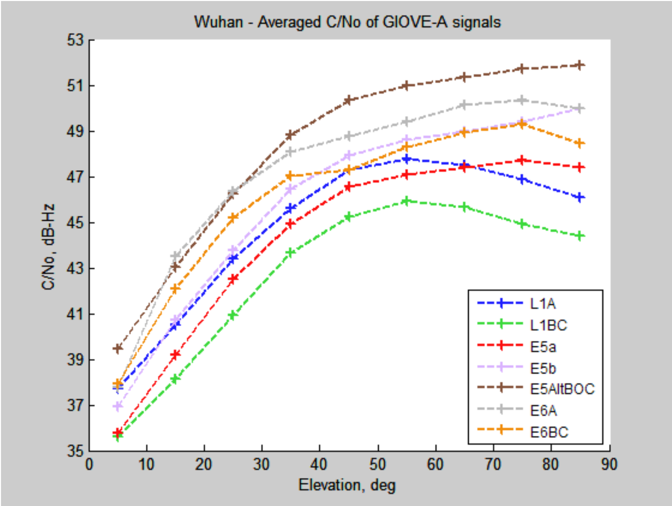

Figure 24. Signal power at Wuhan station.

The total statistics of multipath for all the processed data for La Plata and Wuhan is presented in Table 2. The averages presented in this table illustrate the same tendencies already visible from the plots, in particular the weak elevation dependence of multipath at the Wuhan site.

Figure 25. Environment at the La Plata antenna site.

Figure 26. Environment at the Wuhan antenna site.

COMPARISON OF TWO BPSK(5) SIGNALS: GIOVEA-E6BC AND GLONASS- L2P

It is quite remarkable that GLONASS L2 signals use exactly the same BPSK(5) modulation as Galileo E6BC. This means that both signals generate the same code multipath. Therefore investigation of GLONASS L2 may shed additional light on the multipath performance of Galileo E6BC.

Direct comparison of the multipath of GIOVEA-E6BC and GLONASS-L2P is complicated not only by the fact that the two signals are not transmitted by the same satellites but also by the fact that we currently don't have a receiver that can track both signals. Therefore the performance of these two signals can be compared only in a relative sense, by comparing the performance gains of both signals relative to some other signal, for example to GPS-CA. We can still use the same antenna for all the signals, namely the Space Engineering antenna, which frequency range is broad enough to cover complete GLONASS-L2 band.

For this comparison we used two receivers: the GETR receiver that can track both GPS-CA and GIOVEA-E6BC, and the AsteRx2 (new Septentrio's GPS/GLONASS receiver), which can track both CPS-CA and GLONASS-L2P. The goal is to compare the performance gain of GIOVEA-E6BC relative to GPS-CA when both are tracked by the GETR receiver to the performance gain of GLONASS-L2P relative to GPS-CA when both are tracked by AsteRx2.

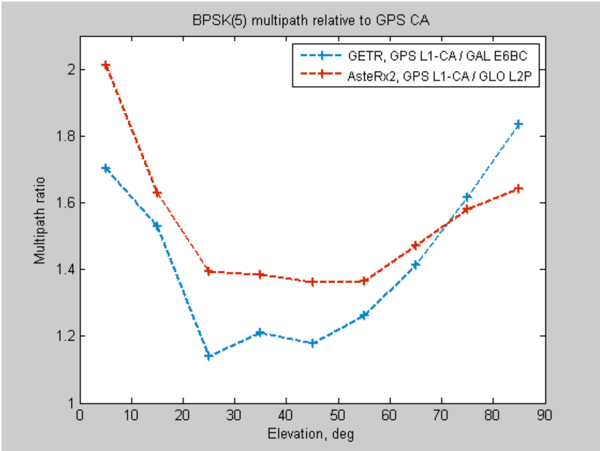

Figure 27. The performance gain of two BPSK(5) signals relative to GPS-CA, i.e., BPSK(1).

The ratios of averaged multipath errors of GPS-CA (BPSK(1)) to BPSK(5) signals are shown in Figure 27 as a function of elevation. In other words, this plot shows the gains in multipath performance achieved by the use of BPSK(5) compared to BPSK(1). It is clear that in both cases the behaviour of the performance gain is quite similar with an average gain of about 50%. The performance gain is the highest at low elevations due to the domination of long-range multipath and even comes close to the factor of 2.

Investigation of GLONASS-L2P as a close analogue of GIOVEA-E6BC may prove quite useful as a way to get additional insight into the behaviour of E6BC in future real-life Galileo applications.

KINEMATIC TESTS

The code multipath errors for kinematic tests with GIOVE-A signals where first presented in [1]. The kinematic multipath is very different from a static one in that its variations are dominated by fast changes of the reflectors due to movement, and that a high degree of multipath suppression is achieved at the tracking level due to averaging of the rapid oscillations of in-phase/out-of-phase multipath. The time series of kinematic multipath consist of random structure-less variations, where the differences between the modulations are much less pronounced that in the static case.

In this paper we present the results of two car tests performed in different environments: rural and urban. Separate statistics was computed for the periods when the car was static and the periods when the car was moving. As shown in Table 3, the signal availability during the tests was different: during the urban test, L1 and E6 were being transmitted, while during the rural test L1 and E5 signals were available.

	Rural Static	Rural Movement	Urban Static	Urban Movement
GPS-CA			1.19	0.23
L1BC	0.27	0.15	0.40	0.18
E6BC			0.50	0.22
E5a	0.20	0.16		
E5b	0.26	0.15		
E5AltBOC	0.10	0.11		

Table 3. Multipath statistic for car tests (meters)

Although the static portions of the car tests still show the same tendencies as the data collected on the rooftop, the data collected during the movement demonstrates much smaller values of multipath errors, much smaller advantage of Galileo modulations as compared to GPS-C/A, and much smaller differences between Galileo modulations. The differences between static and kinematic multipath can be clearly seen in Figure 28, Figure 29. Figure 30 illustrates that code multipath during the urban test was generally somewhat higher due to obviously greater amount of reflectors in the urban environment.

In particular, the results of the car tests suggest that the replacement of L1 BOC(1,1) with MBOC shall not have any significant impact on the multipath performance in the automotive environment. Indeed, MBOC is expected to show the performance intermediate between L1BC and E6BC, while both modulations have about the same intensity of kinematic multipath according to Table 3.

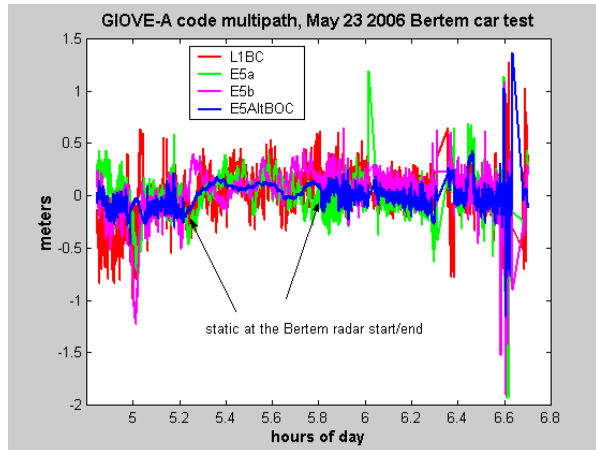

Figure 28. Code multipath during the rural car test.

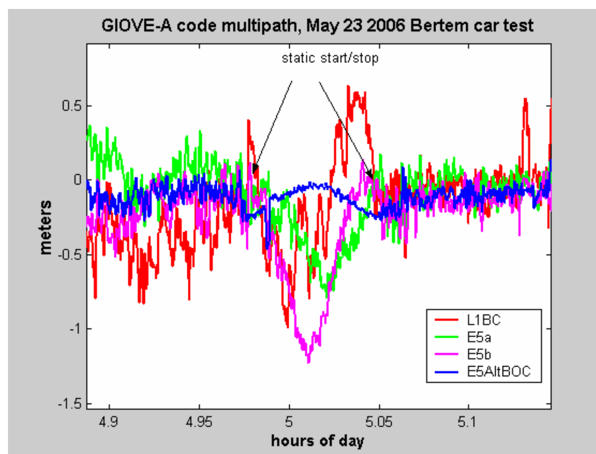

Figure 29. Zoom into one of the static portions of the rural test

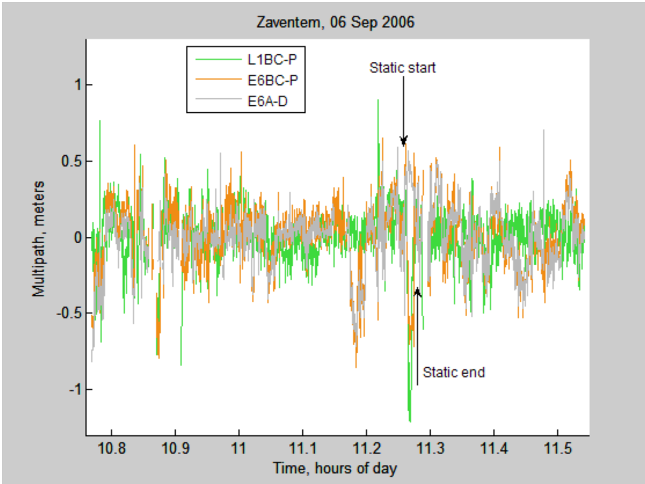

Figure 30. Code multipath during the urban test.

PHASE MULTIPATH

Simultaneous availability of 3 frequencies allows direct evaluation of phase multipath from triple-frequency iono-free geometry-free combinations of phase measurements [1, 9]:

$$M_{\Phi123} = \lambda_3^2(\Phi_1 - \Phi_2) + \lambda_2^2(\Phi_3 - \Phi_1) + \lambda_1^2(\Phi_2 - \Phi_3)$$

This formula is a linear combination of three geometry-free observables ($\Phi_i - \Phi_j$), which all contain ionosphere delays. As it has been shown in [9], in this formula ionosphere delays cancel out. $M_{\Phi123}$ contains a mix of phase multipath and tracking errors for the same satellite on 3 different frequencies and can be used as a global indicator of phase multipath severity. It can be used in particular to study elevation dependence and site dependence of phase multipath.

In this paper we used one particular combination (`E5a - 1.128*E5b + 0.128*L1BC`) as an indicator of phase multipath. Figure 31 contains elevation dependence of this phase multipath indicator for all the static sites covered in this paper. The elevation dependence shows significant variability and does not indicate with certainty any differences between the sites.

The nature of phase multipath is in general quite different from code multipath. In particular phase multipath for different signals is not expected to show significant differences. It has already been demonstrated in [1] that the phase tracking noise is identical for all the GIOVE-A signals. Phase multipath is generally much less studied than code multipath, so it is difficult to predict what the behaviour of phase multipath should be. The time series of our phase multipath indicator are presented in Figure 32, Figure 33..

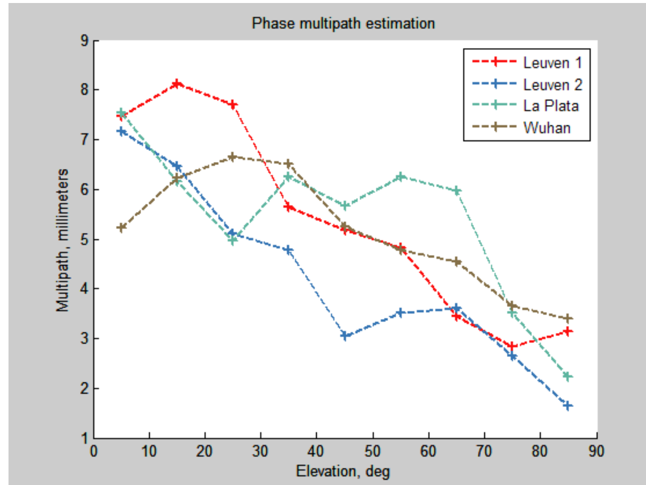

Figure 31. Phase multipath at 4 locations. Here Leuven-1 is our main open-sky antenna site (Figure 2). Leuven-2 is a more multipath-rich site located between the ventilation outlets (see previous section)

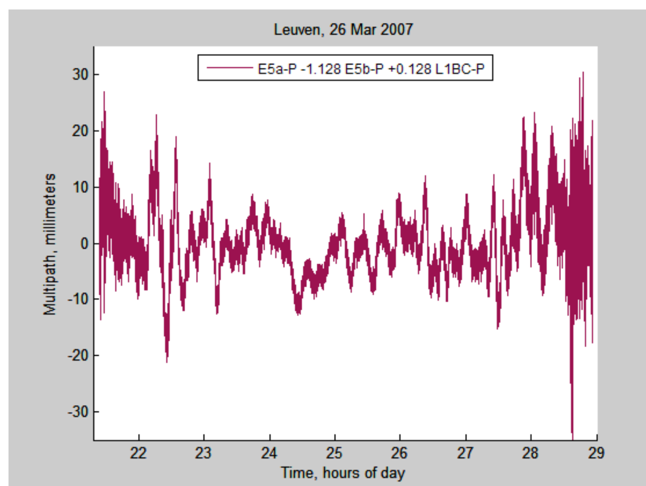

Figure 32. Phase multipath indicator (triple-frequency phase combination of L1BC, E5a, E5b) at Leuven site

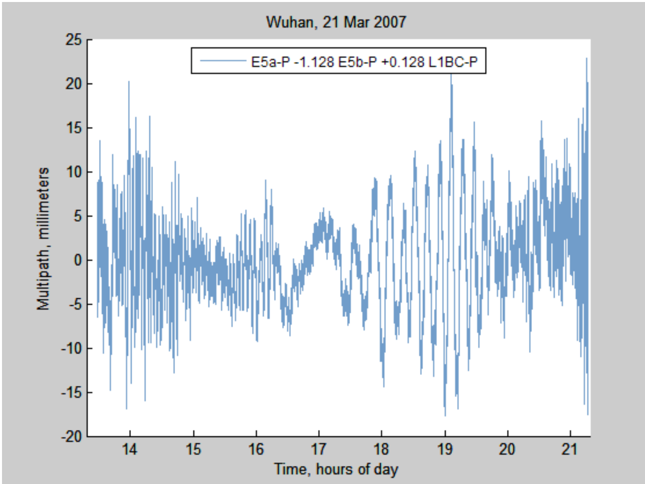

Figure 33. Phase multipath indicator (triple-frequency phase combination of L1BC, E5a, E5b) at Wuhan

The elevation dependence of phase multipath is generally flatter and more variable that with the code multipath. There exist significant long-term variations, which have impact on the elevation-dependent statistics in a way of making it less stable. The pattern pf phase multipath is quite different between the sites (compare Figure 32 and Figure 33).

CONCLUSIONS

Field experience with GIOVE-A signals has demonstrated stable reception in a variety of external conditions and confirmed the theoretical expectations as to superior multipath rejection of wide-band Galileo modulations. Multipath performance results for static and kinematic tests have been reported.

Comparison of the static data from different sites shows significant variability of the multipath performance for most of the Galileo signals. It seems that only the behaviour of E5AltBOC is truly stable and repeatable for all the tests: in all the tests the E5AltBOC demonstrates the highest multipath suppression as compared to other signals and very low values of average multipath errors, down to the values about 0.2m.

For all the other signals we can talk about the tendencies which manifest themselves on average, but with significant site-dependent variations. The most important of these tendencies is the classification of all the modulations in groups shown in Table 1. According to this classification, E6A+L1A+E5AltBOC form the group of high-performance signals, while the E5a, E5b, E6BC signals belong to the medium group; the performance of L1BC is the lowest.

This classification, which agrees with theoretical predictions and computer simulations, can be accepted as a general rule, although in some tests E6BC and E5a show performance similar to L1BC, and E6A in the others shows performance more typical to the medium group. Peculiarities of real-life multipath apparently present such a variety of multipath conditions that hardly any rule can be expected to work in all the cases. Only accumulation of much greater statistic could help to formulate the trends in a more reliable and detailed manner. One possible way of further research is to look in more detail into specific multipath conditions and types of reflectors at different sites.

The kinematic tests have demonstrated a lot smaller values of multipath errors and a much less significant dependence of multipath upon code modulations. This means in particular that any further changes in the signal definition of Galileo signals are not likely to bring any significant improvement to dynamic applications, such as automotive, although modulation changes may have impact on static applications.

We presented here the comparison of GLONASS-L2P and GIOVEA E6BC signals, which use both the same modulation pattern BPSK(5). It is demonstrated that GLONASS L2P can be used as a close analogue of E6BC in order to get more information about the behaviour of this signal designed for the future Commercial Service of Galileo

The phase multipath statistics for GIOVE-A signals is presented.

ACKNOWLEDGEMENTS

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