Performance Assessment of Galileo Ranging Signals Transmitted by GSTB-V2 Satellites

Andrew Simsky, Jean-Marie Sleewaegen, *Septentrio, Belgium*
Martin Hollreiser, Massimo Crisci, *ESA/ESTEC, Netherlands*

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.

Dr. Jean-Marie Sleewaegen is currently responsible for the GNSS signal processing, data analysis and technology development at Septentrio. 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. 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

The ranging signals of Galileo, the new European global satellite navigation system, are using advanced code modulation schemes, which are expected to provide significant improvement of the tracking and multipath performance as compared to current GPS. These expectations can now be verified with the launch of GIOVE-A, the first of the two GSTB-V2 satellites. In this paper we present the first performance analysis of the GIOVE-A measurements, collected with the use of Septentrio's GETR receiver, specifically developed for the reception of GSTB-V2 signals.

This paper presents information on signal power, tracking noise and multipath performance of GIOVE-A ranging signals. The main conclusion is: tracking/multipath performance of all the foreseen Galileo code modulations is significantly better than for existing GPS codes. In agreement with theory, wide-band Galileo codes, which use advanced BOC modulations, show exceptional multipath rejection, especially with respect to the long-range multipath, that is practically eliminated by L1A, E6A and E5AltBOC modulations, the latter being the most remarkable because it brings exceptional multipath performance to open-service users. It is shown that the Galileo signals with lower amplitudes of multipath errors exhibit weaker elevation dependence of multipath noise. For the high-performance E5AltBOC, the total reduction of multipath compared to GPS-CA is, according to our observations, by a factor of about 5.

Multi-frequency signals of GIOVE-A present a unique opportunity to experiment with multi-frequency combinations of observables which are not available with today's dual-frequency GPS. In particular, triple-

frequency combinations of observables can be used for the assessment of phase multipath and also have a number of other uses. Occurrences of false locks on side correlation peaks in L1BC BOC(1,1) code are also discussed.

INTRODUCTION

One of the objectives of the GSTB-V2 (Galileo System Test Bed, version 2) mission is the detailed assessment of the future Galileo signal performances in terms of tracking feasibility, noise and multipath. To support this analysis, the first GSTB-V2 satellite, GIOVE-A was launched on December 28, 2005 and began the transmission of ranging signals on all the 3 frequency bands (L1, E5, E6) early January 2006. The ground reception and performance analysis of the new signals with the help of the purpose-built Septentrio's receiver (GETR [1]) have started immediately as soon as the signal-in-space appeared in the air.

In this paper the results of the first stage of the signal experimentation and assessment activity are summarized. Galileo and GPS ranging code modulations are compared in terms of tracking performance. It is expected that better multipath rejection characteristics and tracking performance of Galileo signals shall lead to significant performance improvements in both range-based and phase-based positioning.

GALILEO SIGNALS AND OBSERVABLES

Galileo spectrum (Figure 1) consists of 4 frequency bands: E5a, E5b, E6 and L1. The design of the Galileo signal structure presents significant user advantages compared to the signals of current GPS:

- Each Galileo signal includes a so-called "pilot" data-less component, which offers several benefits with respect to a data-bearing signal like the GPS CA code, including reduced noise and better tracking robustness at low signal power.
- The novel modulation schemes will result in significant reduction of both tracking and multipath noise for all the code ranges. One of the new modulations, E5-AltBOC will have exceptionally low noise characteristics.
- A more reliable and robust 3-step coding scheme for navigation bits will be used (FEC-encoding, interleaving and improved CRC).

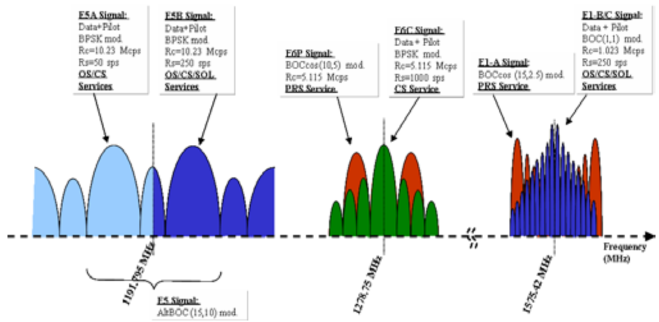

Figure 1. Galileo signal spectrum.

Although the principles of Galileo are quite similar to the principles of GPS, Galileo offers a much greater variety of signals and services. Main parameters of Galileo signal components are presented in Table 1. The complex signal structure, which includes as many as 10 signal components, will serve the needs of 4 Galileo positioning services: Open (OS), Safety-of-Life (SoL), Commercial (CS), and Public Regulated (PRS).

Signal	Modulation	Carrier frequency (MHz)	Data /Pilot	Symbol/s
E5a-I*	BPSK(10)	1176.45	Data	50
E5a-Q*	BPSK(10)	1176.45	Pilot	-
E5b-I*	BPSK(10)	1207.14	Data	250
E5b-Q*	BPSK(10)	1207.14	Pilot	-
E6-A	BOC(10,5)	1278.750	Classified	Classified
E6-B	BPSK(5)	1278.750	Data	1000
E6-C	BPSK(5)	1278.750	Pilot	-
L1-A	BOC(15,2.5)	1575.420	Classified	Classified
L1-B	BOC(1,1)	1575.420	Data	250
L1-C	BOC(1,1)	1575.420	Pilot	-

Table 1. Galileo signal components. Note that E5a and E5b are transmitted as one single wide-band modulation referred to as E5AltBOC (15, 10).

Galileo observables are user measurements provided by Galileo receivers. Each Galileo observable is (similarly to GPS) a set of 4 measurements, which includes a code pseudorange, a carrier-phase measurement, a Doppler (or a range rate), and a C/N_0 (carrier-to-noise ratio).

Galileo observables can be obtained by tracking either pure signal components (rows from Table 1) or combinations of components coherently transmitted within the same frequency band. All the signals which contain pilot and data components allow co-operative tracking of data and pilot, which would result in a doubling of the carrier-to-noise ratio. Due to the E5AltBOC modulation on E5, several tracking options are available for the E5 band. Firstly, receivers can track E5a and/or E5b as two independent BPSK(10) modulations, at center frequencies of 1176.45MHz and 1207.14MHz respectively. Secondly, the E5a and E5b bands can be tracked coherently as one signal, centered at 1191.795MHz, which leads to the high-performance E5AltBOC observable. The main reason for the exceptional qualities of the E5AltBOC modulation is its wide bandwidth, which results in a higher value for the effective modulation rate. The mechanism of E5AltBOC tracking is covered in [2] and an efficient implementation has been patented.

GSTB-V2 SATELLITES

The first step in the development of Galileo is a two-satellite GSTB-V2 constellation (Galileo System Test Bed, version 2). The first GSTB-V2 satellite, GIOVE-A, built by Surrey Satellite Technology Ltd, was launched on Dec 28 2006. GIOVE-A is transmitting signals of all the foreseen frequencies and modulations, but only on two frequency bands at a time. Later in 2006, the second GIOVE-B satellite will join in.

One of the main roles of GSTB-V2 satellites is to test new code modulations foreseen for Galileo. The GIOVE-A signal in space is fully representative of the operational GALILEO system in terms of Radio Frequency and modulations, as well as chip rates and data rates. However, GIOVE-A codes are different from GALILEO codes. The navigation message of GIOVE-A is consistent with the transmission protocol (including interleaving and FEC encoding) but, at the time of writing, the frames do not contain any ephemeris parameters. The ranging signals of GIOVE-A can be used to generate a complete set of GNSS measurements: ranges, carrier phases, Doppler measurements and carrier-to-noise ratios, but they cannot be included in any positional solution, unless some external measurements of GIOVE orbits, such as with laser ranging, will become available.

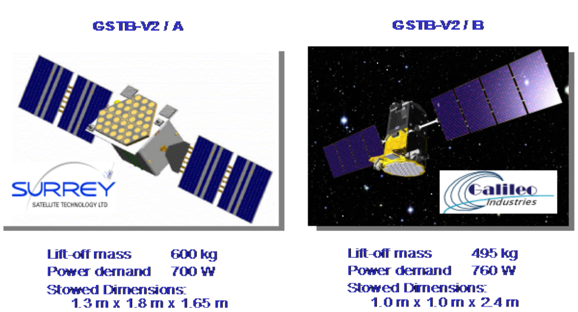

Figure 2. GSTB-V2 satellites

Because the purpose of GSTB satellites is to test various options for code modulations, the signals of GSTB-V2 satellites are flexible: the modulation parameters can be changed from the control station in order to experiment with different modulation schemes. However, during the first months of GIOVE-A operation the transmitted modulation types were fixed: they corresponded to the modulation types preliminarily adopted for the future Galileo as formulated in the draft Galileo SIS-ICD.

Due to weight/power limitations of the payload, GIOVE-A is designed to transmit on only two frequency bands at a time. The subset of signals to be transmitted is determined at the control station, the most typical combinations being L1+E6 or L1+E5. During the initial period of GIOVE-A operation, L1+E6 transmission was alternating with L1+E5 transmission, while for the last 3 months, only L1+E5 has been transmitted.

SEPTENTRIO'S GSTB-V2 RECEIVER

Septentrio has been contracted by ESA to build a GSTB-V2 receiver (in fact, the first operational Galileo receiver ever)[3]. This receiver is called GETR (Galileo Experimental Test Receiver, Figure 3). Soon after its release at the end of 2004, the GETR was used for end-to-end verification of the payloads of the two early versions of both GSTB-V2 satellites. It has also been used for the acceptance of the Galileo Signal Validation Facility (GSVF), an RF Constellation Simulator developed for ESA by Thales TRT UK. After the success of bench testing, GETR was well prepared for the reception of the first real Galileo signal-in-space [9].

The GETR is used by Septentrio, ESA, and other interested parties to monitor GIOVE-A signals. The GETR receiver is able to track simultaneously 6 general Galileo signals + one E5AltBOC signal + 9 GPS satellites (L1+L2). The receiving capabilities of the GETR match the transmitting capabilities of the GSTB-V2 satellites.

The GETR is able to generate and log raw measurements (ranges, phases, Doppler measurements, C/N_0) at a rate of 1 Hz. The raw symbols of the navigation message are also available for logging as well as decoded navigation bits (after de-interleaving and Viterbi decoding). The GETR receiver does not explicitly perform any navigation tasks, but it uses GPS as a time base for epoch sampling and generation of pseudoranges. On the other hand, the GETR offers in-depth signal analysis functionalities like real-time correlation peak monitoring and IF sample logging.

With GETR, the assignment of signals to channels is quite explicit. For each generic channel, the type of the signal, modulation parameters and PRN number are userselectable. In accordance with one of the objectives of GSTB as a signal test bed, the GETR does not implement co-operative tracking of signal components except for E5AltBOC.

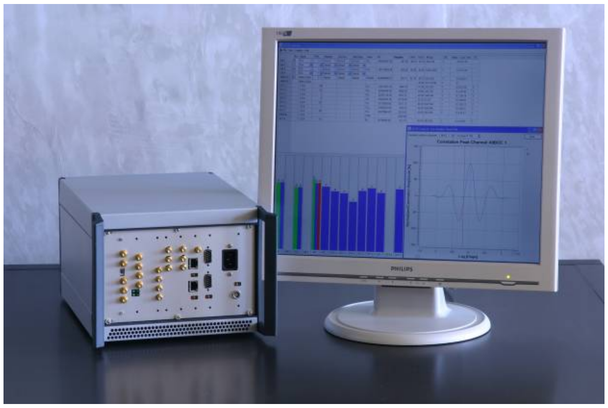

Figure 3. GETR receiver and its typical graphical output. The real-time monitoring of the E5AltBOC correlation peak is displayed on the screen.

OBSERVATION DATA OF GIOVE-A

Signals from GIOVE-A satellite are continuously logged by Septentrio and other interested parties with the use of the GETR receiver. The results presented in this paper are based on sample data sets collected January – June 2006. Most of the static data were collected at the rooftop of Septentrio's office in Leuven, Belgium, with the wide-band GPS/Galileo antenna built by the Italian company "Space Engineering S.p.A.". Kinematic data were collected during a few car tests in and around Septentrio, when the same antenna was mounted on a car.

Unlike GPS, the passes of GIOVE-A have a ground track repeat cycle of 17 orbits (10 days), hence multipath noise from day to day is uncorrelated. The maximal attained elevation angles are also day-dependent.

As it has already been mentioned, the GIOVE-A transmits in only two frequency bands at a time according to the decision of the control center, so different data sets contain different data. For example, on January 15 and March 08 it was transmitting L1+E6, while on January 16 it was transmitting L1+E5a+E5b.

Figure 4. The wide-band Space Engineering antenna, which was used in this work, allows reception of GPS L1, L2 signals as well as Galileo L1, E5, E6.

C/N$_0$ OF TRACKED SIGNALS

The GIOVE-A satellite transmits stable signal fully sufficient for the purposes of signal testing. The carrier-to-noise ratio of GIOVE-A signals received on January 16 is shown in Figure 5. Averaged C/N$_0$ of GIOVE-A signals on the same day is presented in Figure 6 as a function of elevation.

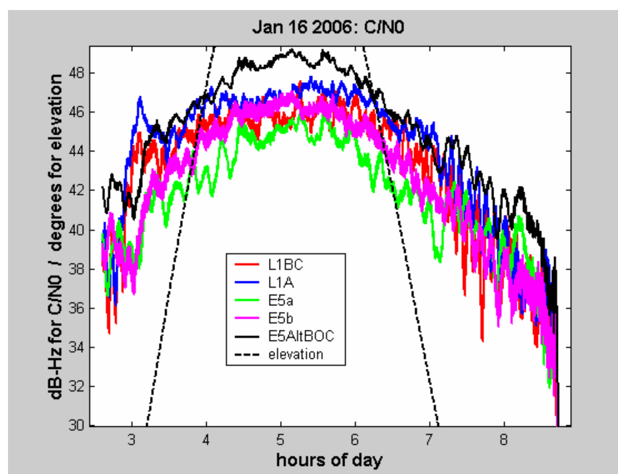

Figure 5. C/N$_0$ for GIOVE-A signals for January 16.

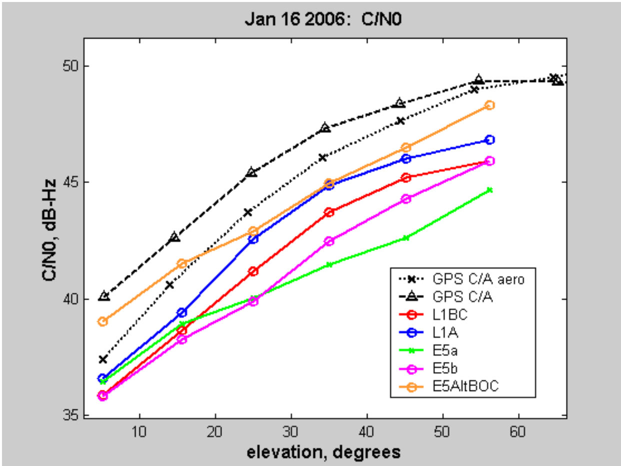

Figure 6. Averaged C/N$_0$ of GIOVE-A signals for January 16.

In Figure 6 and subsequent Figure 8 and Figure 10, the C/N$_0$ of C/A code signals tracked with the GETR receiver is obtained through averaging for all the PRNs. The C/N$_0$ of the C/A code marked "aero" refers to the data obtained with the AERAT2775_42 antenna, used as a reference.

This plot shows that the C/N$_0$ of the received GIOVE-A signal on L1 and E5 frequency bands is lower than the C/N$_0$ of the GPS L1-C/A code signals received by the same receiver and with the same antenna. However, the power of GIOVE-A signals is sufficient to test the quality of the signals, which is their main purpose. The power of real Galileo navigation signals, according to the draft ICD, will be similar to the power of GPS-C/A. This means that the excellent results demonstrated in this paper with actual GIOVE-A signals shall further improve with a greater signal power of the future Galileo.

The measured carrier/noise ratio of tracked signals is a complex function of all the HW elements in the chain "satellite-antenna-receiver". The signal power of the C/A code obtained with the geodetic AERAT2775_42 antenna can be compared in Figure 6, Figure 8, Figure 10 to the signal power of the same C/A code received with the wideband all-signal Galileo/GPS antenna used in our GIOVE-A data collection. The difference between the two plots reflects the differences in the radiation patterns of both antennas. The AERAT2775_42, a geodetic antenna for professional use (i.e., optimized for L1/L2 usage) has apparently stronger suppression of low-elevation signals, and, hence, better multipath rejection than the experimental Space Engineering antenna that is covering much wider bandwidth. Multipath rejection characteristics of the AERAT2775_42 and Space Engineering antenna can be directly compared in the multipath statistics plots presented in Figure 19 and Figure 20. It is expected that low levels of multipath errors of Galileo signals demonstrated in this paper shall further decrease with geodetic-grade user Galileo antennas of the future, which shall be designed to optimize multipath rejection on certain frequencies.

Figure 6 and Figure 10 show the advantages of using the E5AltBOC signal. It can be seen that the C/N$_0$ for E5AltBOC is about 3dB higher than the C/N$_0$ of either E5a or E5b separately. This is explained by the fact that the tracking of E5AltBOC involves combining both E5a and E5b signals together, thereby doubling the available power.

Figure 7 and Figure 8 show signal power for the session of March 08, where L1 and E6 signal was transmitted. On March 08, a maximal elevation angle close to 90° was achieved, so the signal power for almost the whole range of elevations was available. The same is true of the session of May 28 (Figure 9, Figure 10)

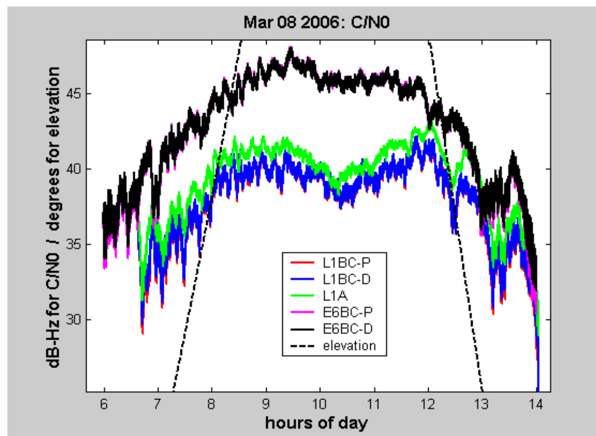

Figure 7. C/N$_0$ for GIOVE-A signals for March 08.

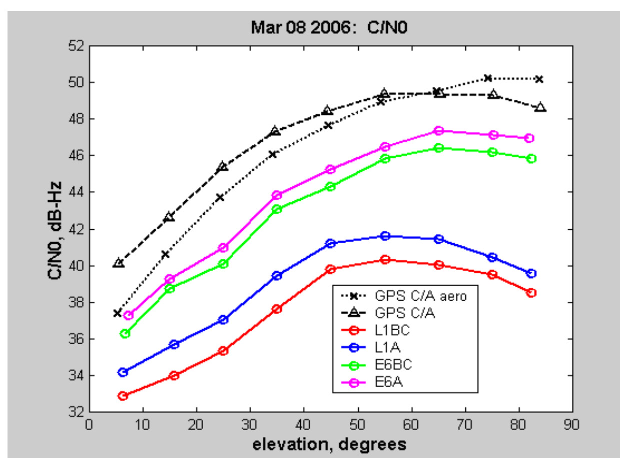

Figure 8. Averaged signal power of GIOVE-A signals for March 08.

It can be seen in Figure 8 that the received signal power for L1 has a maximum at an elevation of about 55° and then goes down by 1-2 dB for higher elevations. This behaviour causes visible minima of received power for L1 signals at highest elevations in Figure 7 and Figure 9.

This could be explained either by the peculiarity of the radiation pattern of the Space Engineering antenna or by the behaviour of the transmitting antenna of the GIOVE-A satellite.

The AERAT2775_42 apparently has a maximum of received power at zenith.

Figure 9 and Figure 10 show signal power for May 28. On that day, GIOVE-A was transmitting the same set of signals as on January 16th, but the elevation angle of almost 90° was achieved.

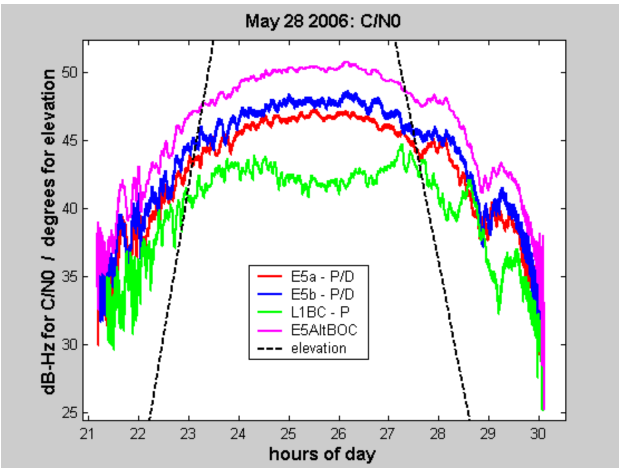

Figure 9. C/N$_0$ for GIOVE-A signals for May 28.

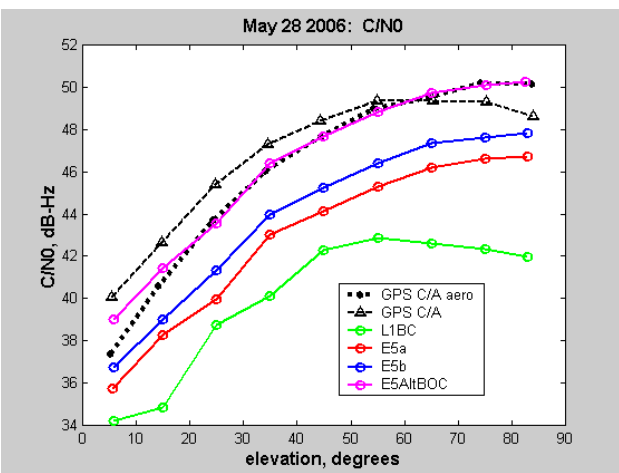

Figure 10. Averaged signal power of GIOVE-A signals for May 28.

MEASUREMENT TRACKING NOISE

Tracking noise of Galileo signals was first measured using Septentrio's custom-built signal generator [1]. These simulated results, presented in Table 2, confirmed the high potential of Galileo code modulations and agreed well with theoretical expectations. As compared to GPS, the code tracking noise improves from dm-level to cm-level values. In particular, E5AltBOC brings superior tracking performance to open-service users.

Code Type	**Tracking Noise Sigma (cm)**	
	Code	Phase
GPS L1-CA	*11.0*	*0.07*
L1-BC	6.0	0.07
L1-A	1.0	0.07
E6-BC	4.8	0.08
E6-A	1.4	0.08
E5a	3.7	0.09
E5b	3.6	0.09
E5 AltBOC	0.9	0.09

Table 2. Code/phase tracking noise at the C/N$_0$ of 45 dB-Hz.

The simplest and most direct way to extract tracking noise for those signals which contain pilot and data components is by subtracting the pilot from the data measurements. This method is based on the fact that with identical tracking loop settings all the error sources, including multipath and group delays, are exactly identical for pilot and data tracking, while thermal noise is independent for both but has the same statistical characteristics. Hence, thermal noise is the only source of differences between Pilot and Data observables.

This noise estimation method is equally applicable to all kinds of measurements (ranges, carrier phases, Doppler measurements) and works equally well for all types of data (live as well as simulated, static as well as kinematic). However, it requires the presence of a Pilot and a Data channel, and therefore cannot be applied to GPS C/A code and L1A and E6A signals of GIOVE-A. Figure 11 illustrates the behavior of code tracking noise for all the signals that have pilot and data components.

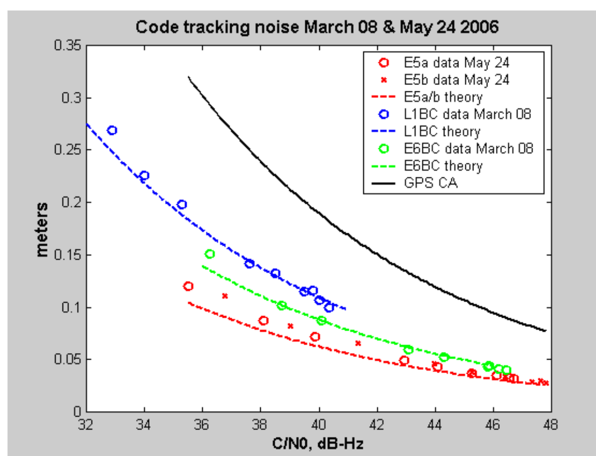

Figure 11. Code tracking noise for OS/CS signals according to the data of March 08 and May 28.

Figure 11 demonstrates that all the new Galileo modulations have lower tracking noise in comparison with the current GPS C/A code, and shows the good agreement with the theoretical curves. Those signals that are not covered in Figure 11 have even lower tracking noises, which can be seen in Table 2. Measuring of the code tracking noise for these signals requires data collection in a zero-baseline setup, which was not done within the framework of this first data collection campaign.

The tracking noise of phase measurements is, according to theory, independent from the modulation scheme and hence about equal for all kinds of ranging signals and GNSS systems. To be more precise, the phase noise is equal when measured in cycles and is proportional to the wavelength when measured in units of length. The phase noise for the GIOVE-A signals that have pilot and data components is presented in Figure 12.

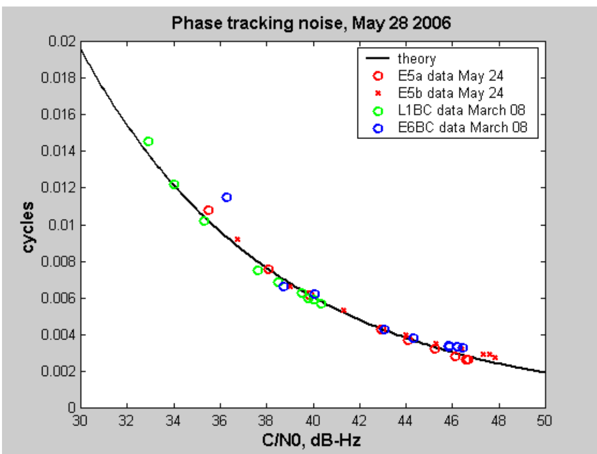

Figure 12. Phase tracking noise for OS/CS signals according to the data of March 08 and May 28.

CODE MULTIPATH

Figure 13 represents the theoretical multipath error envelopes for different types of GSTB/Galileo modulations, and for GPS C/A. Multipath envelopes represent the maximal positive and negative ranging errors for a single multipath ray at a given delay with respect to the line-of-sight signal, and for a given signal-to-multipath ratio (in the case of the figure, this ratio is 6dB).

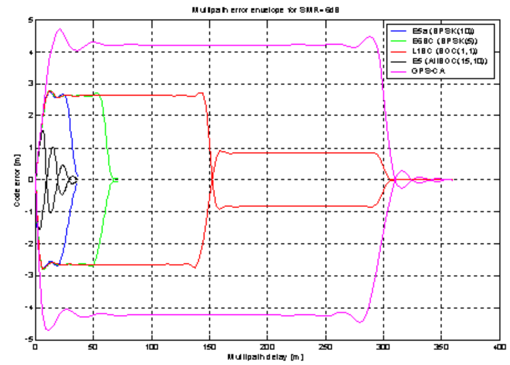

Figure 13. Multipath error envelopes for selected Galileo codes and GPS-C/A.

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. Actually, from all currently known Galileo and GPS signals, the E5AltBOC has by far the lowest multipath sensitivity. The Galileo L1A and E6A signals intended for PRS exhibit multipath performances approaching those of the E5AltBOC.

Figure 13 shows that the Galileo modulations (except for L1BC) virtually suppress the long-range multipath errors, i.e. errors from multipath rays with a delay larger than about 60m. Such long-range multipath mostly affects low elevation satellites, and hence this is where the improvement is expected to be the largest.

Signal	Chip rate, Mhz	Jan 15		Jan 16		May 24	
		>10°	<10°	>10°	<10°	>10°	<10°
CPS-C/A	*1.023*	*0.60*	*1.19*	*0.60*	*1.21*	*0.58*	*1.18*
L1BC	1.023	0.49	0.98	0.40	0.65	0.38	0.84
E5a	10.23	-----	-----	0.54	0.59	0.25	0.45
E5b	10.23	-----	-----	0.33	0.44	0.27	0.53
E6BC	5.115	0.28	0.28	-----	-----	----	----
L1A	2.5575	0.25	0.23	0.21	0.20	---	---
E6A	5.115	0.24	0.24	-----	-----	----	
AltBOC	10.23	-----	-----	0.25	0.23	0.14	0.20

Table 3. Multipath of Galileo signals as compared to GPS C/A code; STDs of multipath noise are presented for high-elevation (>10°) and low-elevation (<10°) observations. The data for C/A code are obtained by averaging for all the GPS satellites. The grouping of modulations is shown with colors (the best group at the bottom).

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

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

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.

In accordance with both theory and observations, multipath on pilot and data signals is identical. The estimates of multipath presented in this paper are based on pilot observations.

Averaged multipath noise for the heretofore processed data is presented in **Table 3**. These data confirm that all the Galileo signals have significantly lower multipath noise than GPS C/A. The expected high degree of rejection for low-elevation long-range multipath by wide-band Galileo codes is illustrated by the fact that the differences between the magnitude of high-elevation and low-elevation multipath for all the Galileo codes except for L1BC are smaller than for GPS-C/A. According to Table 3, for GPS C/A the amplitude of low-elevation multipath is about twice as high as the amplitude of the high-elevation multipath, while for the best Galileo modulations, such as E5AltBOC and L1A the amplitudes of low-elevation and high-elevation multipath are about equal. It should be noted that the multipath performance of GPS L2C is equivalent to GPS CA [4].

Representative examples of multipath signatures for different modulations are to be found in Figure 14, Figure 15 and Figure 16. For static multipath in open-sky conditions, the long-range multipath results in typical short-term high-amplitude oscillations of multipath errors mostly at low elevations. This oscillation is clearly seen in the figures for the L1BC code. It is reduced for the E5a and E5b codes, and is reduced even greater for the E5AltBOC and L1A codes.

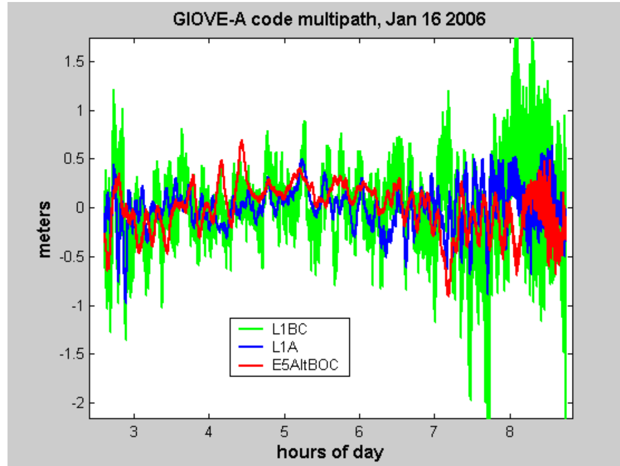

Figure 14. Multipath of E5AltBOC code as compared to L1BC and L1A.

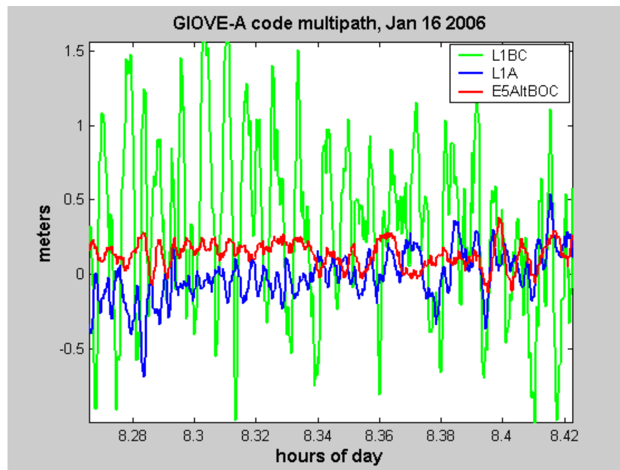

Figure 15. Zooming into the low-elevation portion of Figure 14 clearly demonstrates superior performance of E5AltBOC and L1A modulations.

From the data presented in **Table 3** it can be seen that both GPS C/A codes and Galileo L1BC comprise a group of modulations with relatively high average multipath values and a significant difference between low-elevation and high-elevation multipath.

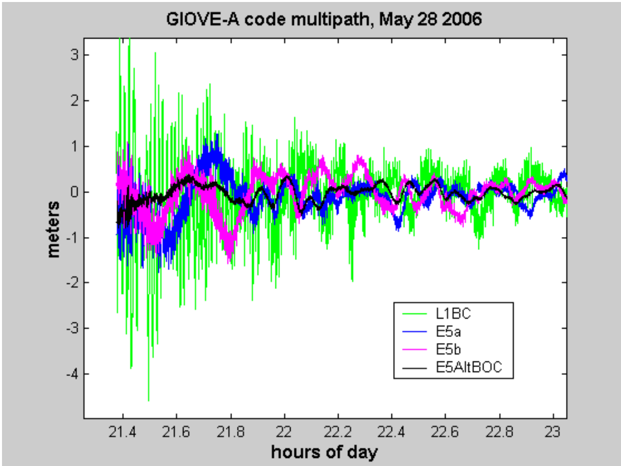

Figure 16. Low-elevation portion of multipath data for May 28. Low multipath noise of E5AltBOC can be clearly seen.

All the other Galileo modulations can be further divided into a group of low-multipath modulations (E5a, E5b and E6BC), and a group of modulations with exceptional multipath suppression, which includes E5AltBOC and both PRS modulations (L1A and E6A). The low-multipath modulations show much lower values of multipath errors and much less difference between low-elevation and high-elevation multipath, The 3 modulations of the last group (E5AltBOC, L1A, E6A) show practically no angular dependence of multipath and a very low high-frequency multipath component.

Although we believe the above classification to be true - at least in a rough sense - these results may be modified when more data is analyzed, especially for E6. On our site, the main multipath reflector was an adjacent building at a distance about 50m to the North, and the results are quite different between days depending upon the azimuth of rising and setting of GIOVE-A, the southern direction being the most multipath-rich. The fact that our results do not show the expected advantage of E5a/E5b compared to E6BC may be attributed to these day-dependent variations or to a greater sensitivity of the Space Engineering antenna to multipath in the E5 band. Unfortunately, with GIOVE-A direct comparison of E5 and E6 signals is impossible.

In the particular case of the E5AltBOC multipath, it is interesting to see how the multipath error of E5AltBOC compares to that of E5a and E5b. In particular, it has been suggested that computing the average of E5a and E5b pseudoranges would yield a multipath reduction approaching that of the E5AltBOC modulation. The fact that it is not true is illustrated in Figure 17, where it can be seen that although averaging the E5a and E5b pseudoranges results in some reduction of multipath, the true E5AltBOC observable still outperforms it.

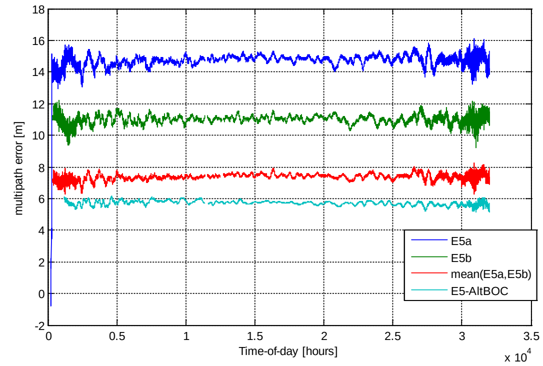

Figure 17. Comparison of AltBOC multipath error with the average of the E5a and E5b multipath errors. The offset between the 3 curves is introduced for visibility.

The Galileo signals not only show lower multipath errors, but also the multipath error patterns in the time domain and their spectra is quite different. Dramatic reduction of high-frequency component - clearly visible in time plots - is confirmed by the results of spectral analysis presented in Figure 18. It can be seen that although the low-frequency limits of the spectra are quite close for all the Galileo signals, the high-frequency limit for E5AltBOC is by 20 dB lower than for L1BC and about 10 dB lower than for E5a and E5b. E5a and E5b modulations form an intermediate group, in agreement with their place in the classification presented in **Table 3**. The spectral peak that corresponds to the main quasi-period of multipath on E5 (about 25 seconds) is lower in E5AltBOC by about 8dB as compared to E5a and E5b.

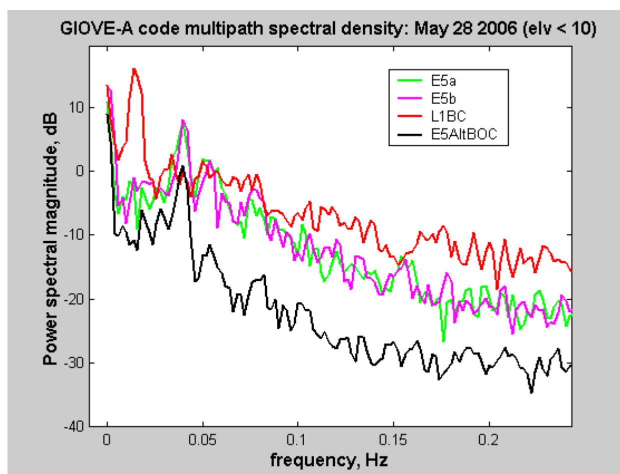

Figure 18. Spectra of code multipath errors, May 28.

To conclude this section, Figure 19 and Figure 20 contain the plots of averaged multipath (RMS values) as a function of elevation. These plots clearly show that the modulations with lower total values of multipath errors also have a flatter angular dependence, that is, smaller differences between high-elevation and low-elevation behavior. The best modulations (E5AltBOC and L1A) show very weak elevation dependence.

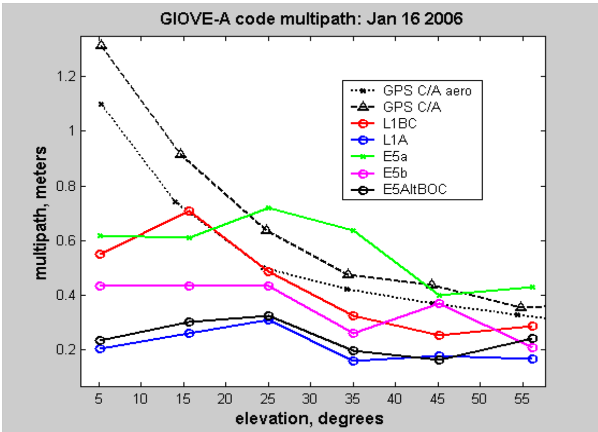

Figure 19. Averaged multipath (RMS) at different elevations for GIOVE-A signals and GPS C/A code for January 16. The curve for the C/A code marked "aero" refers to the data obtained with the AERAT2775_42 antenna.

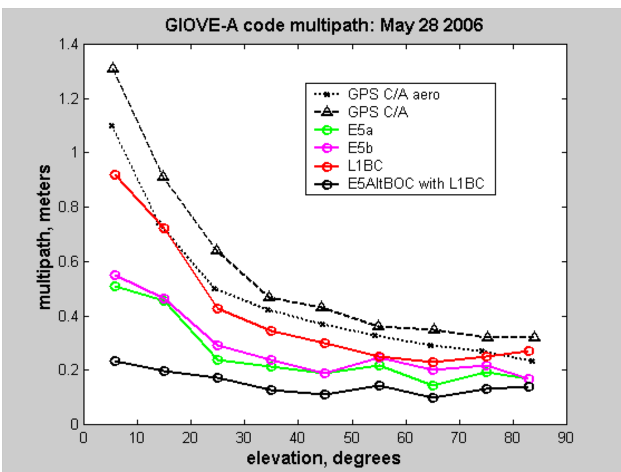

Figure 20. Averaged multipath (RMS) at different elevations for GIOVE-A signals and GPS C/A code for May 28.

Because our multipath statistics for GIOVE-A are based on the data for only one satellite with no daily repeatability of multipath, Figure 19 and Figure 20 are representative of real tendencies only in a broad sense. Visible differences in the details of the plots for the same modulations (for example, for L1BC and E5a) are an illustration of this statement. It can be clearly seen that multipath statistics for GPS which is based on the averaging for the whole constellation is a lot more stable and repeatable.

Figure 19 and Figure 20 contain also a plot of C/A code multipath obtained with the help of a AERAT2775_42 antenna. In accordance with the behaviour of the radiation patterns of both antennas (Figure 6, Figure 8, Figure 10), this antenna shows greater multipath rejection than the Galileo antenna that we used. Please note that our current Galileo antenna is an experimental wideband antenna, and its multipath performance was a compromise between several important performance parameters. This means that with future Galileo antennas, which shall come close to the today's professional dual-frequency GPS antennas, the multipath performance of Galileo signals can only be improved relative to the data presented in this section.

It has to be noted that the multipath levels shown here correspond to intrinsic signal immunity to multipath: no dedicated multipath mitigation method has been employed. It can be expected that multipath performance can be significantly improved by multipath mitigation methods such as APME [5]. As it has already been stressed in [5], APME can effectively suppress both short-range and long-range multipath. The expected reduction of multipath is by about 40% according to the results obtained in [4] for GPS C/A and L2C codes.

To end with, it should be added that although it is our belief that the presented results are quite indicative of actual tendencies, they are still based on a limited amount of data and may be generalized only with caution. More work is required for fully decisive conclusions.

TRIPLE-FREQUENCY GEOMETRY-FREE IONO-FREE COMBINATIONS

It is well known that by making linear combinations of phase or code measurements at 2 different frequencies, geometry-free and iono-free observables can be obtained, but not both at the same time. For example, geometry-free combination of phases is a simple difference (Φ_1 -Φ_2), but it contains ionosphere delays. It is shown in [6] that by adding the third frequency, it is possible to make a triple-frequency observable, which is geometry-free and iono-free at the same time:

$$M_{\Phi 123} = \lambda_3^2(\Phi_1 - \Phi_2) + \lambda_2^2(\Phi_3 - \Phi_1) + \lambda_1^2(\Phi_2 - \Phi_3) \quad (2)$$

This formula is a linear combination of three geometry-free observables (Φ_i – Φ_j), which all contain ionosphere delays. In (2), ionosphere delays cancel out. $M_{\Phi 123}$ 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.

Similar combinations can also be derived for code and Doppler measurements. Possible uses of triple-frequency combinations in future GNSS are considered in more detail in [6]. In particular, formula (2) leads to similar relationships between phase ambiguities, which can be used as constraints in multi-frequency ambiguity resolution algorithms. An analogue of (2) also exists for code measurements and can be used in the analysis of code multipath, although it is less convenient than formula (1).

The derivation of both formulas (1) and (2) is based on the same assumption that second-order ionosphere effects are negligible, hence ionosphere delays are assumed to be proportional to λ^2.

PHASE MULTIPATH

The linear combination (2) is particularly valuable for the assessment of phase multipath. Although GIOVE-A transmits only in 2 frequency bands at a time, the E5 band contains GNSS observables on 3 different center frequencies: E5a, E5b, and E5AltBOC. This means that if the signals on L1 and E5 are available, an appreciable number of different 3-frequency combinations of signals can be obtained. One of these combinations, the one which includes E5a, E5b and L1BC is shown in Figure 21.

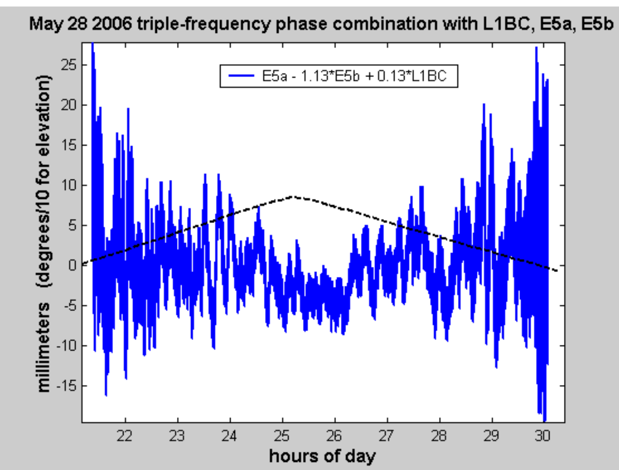

Figure 21. Triple-frequency phase combination of L1BC, E5a, E5b.

This combination can be interpreted as a difference E5a-E5b corrected for ionosphere delays by using L1BC. This combination contains roughly equal portions of E5a and E5b multipath and can be used to characterize the differential multipath between both frequencies.

It can be seen that this combination contains not only short-term noise, but also some minor systematic component. According to the order of magnitude of this variation, it could be attributed to second-order ionosphere effects [7] although it may as well be caused by mm-level thermal drifts of some HW parameters in the GETR or in the antenna.

Another way to assess phase multipath in GIOVE-A measurements would be by differencing phase between pairs of signals that have the same frequency but different modulations (such as L1BC/L1A or E6BC/E6A). However this method shall not be available to open-service users of the future Galileo.

MULTIPATH IN KINEMATIC TESTS

For kinematic tests, the Space Engineering antenna was attached to the rooftop of the passenger car, and a few routes around Leuven were completed. One of the routes included a static session in close vicinity of the airport radar facility in Bertem (near the Brussels International airport). Most of the car tests were performed in May 2006 with the logging of L1BC, E5a, E5b, and E5AltBOC signals. During the latest car tests in September 2006 we logged L1BC, E6A, and E6BC. As an example, we present here the results of the Bertem car test, done on May 23, 2006. This test included kinematic and static portions of about equal duration and provides an opportunity to compare static and kinematic multipath. During this test, GIOVE-A was at a quite high elevation (about 60°), so the availability of the signal was quite good even in the urban environment.

The time series of code multipath are presented in Figure 22. The test consisted of two kinematic periods and one long static in the vicinity of the Bertem radar. The purpose of this static period was to test for the interference from the radar. As we could see from the recorded data, the interference from the radar had almost no visible impact on the measurements.

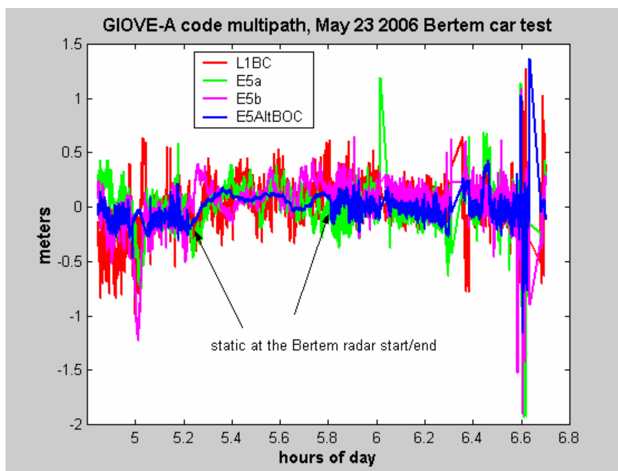

Figure 22. Time series of code multipath for the Bertem car test.

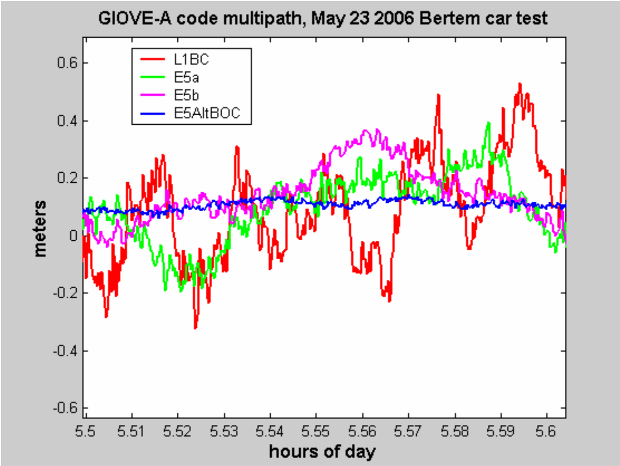

Figure 23. Typical pattern for static multipath of GIOVE-A signals. The time span of the plot is 6 min.

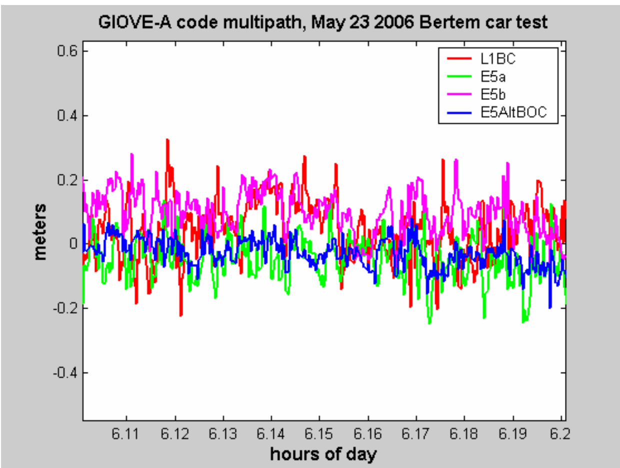

Figure 24. Typical pattern for kinematic multipath of GIOVE-A signals. The time span is 6 min.

Typical patterns of static and kinematic multipath are presented in Figure 23 and Figure 24 respectively. For L1BC, the static multipath is characterized by quasi-regular patterns of relatively high amplitude and a quasi-period of about 1 minute, while kinematic multipath is characterized by an irregular pattern with higher frequencies but lower amplitudes. Lower amplitudes of multipath in the movement can be explained by the averaging of quickly alternating in-phase and out-of-phase conditions for reflected signals. High frequency and irregularity of multipath errors during the kinematic part are due to the quick variation of multipath environment due to the movement.

This behaviour of L1BC multipath is qualitatively similar to the well-known behaviour of GPS C/A code. The patterns of low-multipath E5AltBOC are quite different, especially for the static part. For this static part, the multipath of E5AltBOC consists of a cm-level high-frequency component and a very slowly changing dm-level component (with the characteristic period of about 30 min). The kinematic multipath of E5AltBOC in fact looks similar to all the other signals but its amplitude is visibly lower than for L1BC and other signals. The patterns of E5a and E5b are intermediate between L1BC and E5AltBOC. The obvious reason why kinematic patterns look similar for all the signals is the dominating impact of the quick changes in multipath environment.

The contrast between static and kinematic multipath patterns can also be observed in Figure 25. It can be clearly seen that the multipath of L1BC significantly increases when the car stops. Similar behaviour is always observed for GPS: in city driving tests the largest outliers caused by multipath always occur at traffic lights. The behaviour of E5AltBOC is visibly different from L1BC. E5a and E5b modulations behave similarly to L1BC but with somewhat lower amplitude.

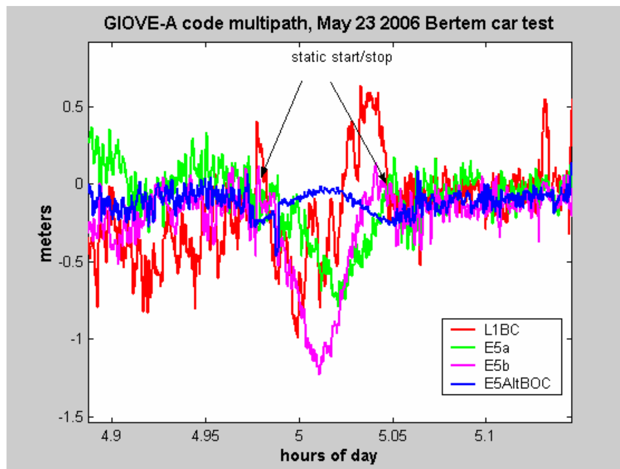

Figure 25. Behaviour of multipath during a short 3-min stop

Statistics of code multipath for the Bertem car test is presented in Table 4. It can be seen that the difference between static and kinematic multipath is quite significant for L1BC and E5b (almost by a factor of 2) and is somewhat smaller for E5a. The E5AltBOC stands out: for E5AltBOC the average magnitudes of the static and kinematic multipath are almost equal.

Signal	total	movement	static
L1BC	0.22	0.15	0.27
E5a	0.18	0.16	0.20
E5b	0.21	0.15	0.26
E5AltBOC	0.11	0.11	0.10

Table 4. Standard deviations of code multipath for Bertem car test.

Two factors must be taken into account when comparing the static results for the car test presented in Table 4 with the statistics for the roof data presented in Table 3.

Firstly, the elevation angle of GIOVE-A during the Bertem car test was fairly high (about 60 degrees), so it is quite natural that the statistics presented in Table 4 for the static period show lower values than the high-elevation columns of Table 3. Notice that in that table the column for "high-elevation multipath" is an average of all the values above 10 degrees. The high elevation angle of GIOVE-A has a major impact here, even though the multipath environment in the car test was more multipath-rich.

The duration of the session is shorter for the car test, which also has an effect in a way of reducing the standard deviation of multipath errors. From the multipath time series it can be seen that long static sessions always contain some long-term component (with characteristic time of hours). This long-term component makes a particularly significant contribution in the case of E5AltBOC due to much lower amplitudes of short-term multipath variations for this modulation. In the data analysis of short sessions the impact of these long-term variations is reduced with the removal of the constant offset.

It is worth noting that the 3 signals (L1BC, E5a, and E5b) have almost the same value of multipath in the movement. The advantage of E5AltBOC relative to other codes is also less pronounced in the movement: the improvement factor is only by 50% for kinematic multipath, while for the static multipath the improvement factor is more than 2.

The main conclusion is that the kinematic test has confirmed high multipath rejection of Galileo codes demonstrated in the static tests. The 10 cm value of the standard deviation of the E5AltBOC multipath is an exceptionally low value and has in fact the same order of magnitude as the thermal tracking noise of the GPS C/A code.

HANDLING MULTIPLE CORRELATION PEAKS OF BOC(M,N) MODULATION

It is well-known that the BOC modulation leads to multi-peak correlation functions, and hence can potentially lead to a false lock on one of the side peaks. Several techniques have been published to tackle this problem and make sure the correct peak is tracked. These algorithms have been extensively validated by simulations, but so far, never tested with real signals.

With GIOVE-A, BOC modulations have been transmitted for the first time on a civil signal, offering the first possibility to validate these algorithms in real life. The GETR receiver uses the well established bump-jumping algorithm presented in [8].

In our data analysis, a special focus has been put on the L1 BOC(1,1) signal to identify false lock situations. In BOC(1,1), two potential false lock points are located 150m before and after the correct lock point. If a false lock event occurs, it is therefore evident in the L1 pseudorange by an error of +/- 150m.

According to reported simulations and theoretical results, such false locks are extremely rare. Surprisingly enough, a few occurrences of this phenomenon have been recorded, all at very low values of elevation angles and carrier-to-noise ratios.

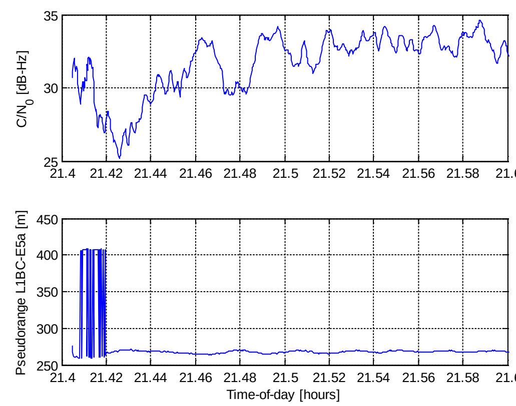

Figure 26. Example of the jumps caused by a false lock of the code loop to the side BOC(1,1) correlation peak.

Figure 26 shows an example of a series of such spurious jumps between the main peak and one side peak. The figure represents the difference between the L1 and E5a pseudorange, the latter being unaffected by the false lock problem because it uses a BPSK modulation. Note that the large offset of about 260m between the E5a and L1 pseudoranges is due to the differential group delay in the GIOVE-A satellite.

The cause of this false lock is probably linked to a combination of very large multipath and low signal power. This behavior indicates that additional effort will be needed to ensure stability of the tracking of multi-peak correlation functions, especially in real-life environments typical for kinematic applications, which are characterized by frequent losses-of-lock, high multipath and signal attenuation.

The problem has been recorded on L1 BOC(1,1), and is likely to be even more severe on L1A (BOC(15,2.5)) and E6A (BOC(10,5)). The MBOC optimization of the L1C modulation, currently under investigation, will also introduce additional side peaks, and increase the probability of a false lock.

The robust detection of the side peak tracking is one of the challenges that the designers of BOC and MBOC receivers will face.

SUMMARY

The GIOVE-A satellite is transmitting ranging signals modulated with Galileo spreading codes in all the Galileo frequency bands. The data heretofore collected by the Septentrio's custom-built receiver indicate stable reception and tracking of all the foreseen Galileo signals. In accordance with theoretical expectations, high rejection of long-range multipath and superior multipath performance have been demonstrated for wide-band Galileo signals, in particular for open-service E5AltBOC and also for L1A and E6A intended for PRS. The multipath noise for these signals at low elevations is lower by a factor of 4-5 as compared to GPS-C/A code. Standard deviations of the multipath noise for E5AltBOC are 10-20 cm in different tests. These values are unusually low for the code multipath and have in fact the same order of magnitude as the tracking noise for the GPS C/A code.

It is shown that the multipath noise patterns of the best Galileo codes are distinctly different from the well-known behaviour of GPS-C/A and L2C codes, which is characterized by significant high-frequency noise component, attributable to long-range multipath typical for low-elevation data. For the best Galileo modulations this high-frequency component almost disappears, and the differences between high-elevation and low-elevation multipath errors are much smaller than for GPS C/A. Superior multipath characteristics of Galileo modulations will lead to significantly increased accuracy of range-based positioning as well as shorter times of ambiguity fixing.

Finally, spurious false locks on side-peaks of the BOC autocorrelation function have been reported, even when using well-documented bump-jumping algorithms. It appears that robust tracking of the main peak of the BOC modulation still remains a challenge for the designers of Galileo and GPS L1C receivers.

ACKNOWLEDGEMENTS

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