VERSITA

ANNUAL OF NAVIGATION 19/2012/part 1

10.2478/v10367-012-0009-5

DAVIDE MARGARIA, MAURIZIO FANTINO
Navigation Technologies Research Area, Istituto Superiore Mario Boella, Italy

LUCIANO MUSUMECI
Dept. of Electronics and Telecommunications, Politecnico di Torino, Italy

ACQUISITION AND TRACKING OF GALILEO IOV E5 SIGNALS: EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

ABSTRACT

An assessment of the Galileo In-Orbit Validation (IOV) signals on the E5 band is presented in this paper, investigating the signal features compared with the expected characteristics as described in the Galileo Interface Control Document (ICD) specifications. In detail, the results in terms of signal acquisition and tracking during multiple satellite passes are discussed, providing also a description of the experimental setup used in order to separately receive and process E5a and E5b signals. The analysis covers the received signal strength versus the satellite elevation, the modulation format, and the presence of navigation data and secondary code chips. Since at time of writing both the two Galileo IOV satellites (PFM and FM2) are broadcasting E5 signals, the results obtained processing their E5a and E5b signals are discussed. In addition, these signals are also compared with those currently transmitted by the two experimental Galileo satellites, GIOVE-A and GIOVE-B.

Keywords:
Galileo, validation, signal-in-space.

INTRODUCTION

The Galileo programme, the European initiative for the development of a new Global Navigation Satellite System (GNSS), has achieved an important milestone on October 21, 2011, when two IOV satellites have been successfully launched from the spaceport in French Guiana. These IOV satellites expanded the Galileo constellation, previously composed only by the first two experimental Galileo satellites: GIOVE-A and GIOVE-B, launched in 2005 and 2008 respectively, allowed to reserve radio frequencies set aside for Galileo by International Telecommunications Union and to test key Galileo technologies.

The growing interest on the new Galileo signals and on the development of GNSS receivers is clearly demonstrated by the fact that several research laboratories and also receiver manufacturers have started to analyse the IOV signals as soon as the IOV satellite payloads were switched on. Among the others, the Navigation Signal Analysis and Simulation (NavSAS) group, a joint team of Istituto Superiore Mario Boella and Politecnico di Torino in Italy, was one of the first research groups able to successfully acquire and track these new signals. In detail, the signals transmitted on the E1 band by the first IOV satellite — the Galileo Proto-Flight Model (PFM) spacecraft, also known as GSAT0101 — were received by NavSAS researchers for the first time on December 12, 2011. This satellite has begun transmitting signals also on the E5 band using the Code Number 11 defined on the Galileo Interface Control Document [4] on December 14, 2011 [10]. On the other hand, the E1 signal of the second IOV satellite — the Galileo Flight Model 2 (FM2) spacecraft, also known as GSAT0102 — has been successfully acquired and tracked by NavSAS researchers on January 17, 2012 [2]. It must be pointed out that, at time of writing, the FM2 satellite has already started transmitting navigation signals on the E5 band using the Code Number 12 and the first results related to these signals are presented in this paper.

The paper is organized as follows: the main features of the Galileo E5 signal are briefly outlined in next Section, focusing on the expected received signal strength of each channel. The experimental setup used in order to separately receive and process E5a/E5b signals is then described. Finally, the obtained comparative results between the signals received from the Galileo satellites and the conclusions are presented.

GALILEO E5 SIGNAL FEATURES

The Galileo signals on the E5 band (1164-1215 MHz) are attracting special interest from the navigation community due to the novel modulation scheme (the *Alternative Binary Offset Carrier* — AltBOC) which is employed. As pointed out in several articles in literature [6, 9], the constant envelope AltBOC(15,10) modulated signals could lead to excellent performances for high-end receivers able to process the entire E5 band. In fact, these receivers can fully exploit the 4 channels (conventionally denoted as *E5aI*, *E5aQ*, *E5bI* and *E5bQ*) transmitted by each Galileo satellite on the E5 band. Two of these channels, *E5aI* and *E5bI*, are called data channels, since they carry navigation data and integrity information respectively for the *Open Service* (F/NAV) and the *Safety-of-Life Service* (I/NAV), whereas *E5aQ* and *E5bQ* are data free signals also called pilot channels [4].

Another interesting AltBOC modulation feature is that it allows to separately receive and process as QPSK-like modulated signals the 2 sidebands around the E5 carrier frequency, which are conventionally denoted as E5a and E5b sidebands as shown in fig. 1 [8, 9].

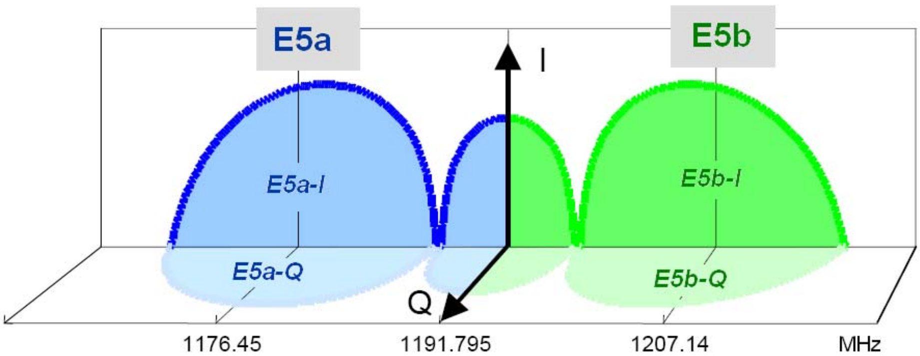

Fig. 1. Spectral scheme of the Galileo AltBOC(15,10) signal on E5 band [11]

Focusing on the ranging code properties, another important characteristic is the tiered codes construction of the Galileo E5 codes [4]. This means that the Galileo E5 codes are built from so-called primary and secondary codes: successive repetitions of a primary code period (with a length of 1 ms) are overlaid with a secondary code such that one chip of the secondary code corresponds to one entire period of the primary code. In this way long spreading codes can be generated (up to 100 ms for the pilot channels), simply composing short primary codes and secondary codes.

Comparing the specifications of E5 signals currently transmitted by the GIOVE-A and B satellites in [5] and the IOV signal features described in [4], apart from the fact that different code sequences are used in order to distinguish each satellite signal, the same modulation scheme will be used with the same tiered code structure, featuring the same periodicity of the code sequences and the same symbol rate for the data channels. However, a difference of about 3 dB is expected on the received strength of IOV satellite signals with respect to GIOVE-A/B signals, as summarized in table 1.

Table 1. Minimum and maximum expected received power levels for Galileo E5 signals, at the output of a hypothetic 0 dBic RHCP lossless user antenna, for elevations above 10° and on earth surface, assuming 0 dB losses due to propagation effects; values computed from [5] and [4]

Galileo E5 Signal Component	***GIOVE-A/B Min Rx Power***	***GIOVE-A/B Max Rx Power***	***PFM/FM2 Min Rx Power***	***PFM/FM2 Max Rx Power***
E5aI, E5aQ, E5bI or E5bQ	–161.78 dBW	–157.28 dBW	–158.01 dBW	–155.01 dBW

METHODOLOGY AND EXPERIMENTAL SETUP

The E5a/E5b data collections at Intermediate Frequency (IF) have been performed with a flexible Front-End (FE) prototype designed and assembled by the NavSAS researchers with Commercial Off-The-Shelf (COTS) components. The FE configuration, depicted in fig. 2, allows to separately receive the two sidebands E5a and E5b.

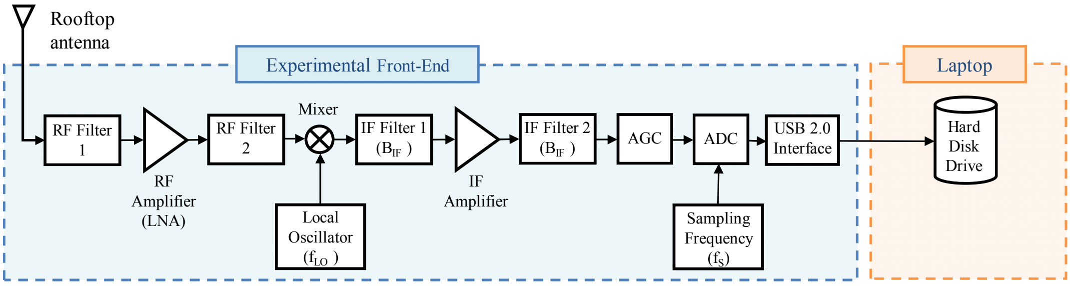

Fig. 2. Block diagram of the front-end used in the experimental setup [own study]

The Galileo Radio Frequency (RF) signals have been received with a fixed non-directional rooftop antenna, located at ISMB premises in Torino at latitude = 45°03'54.99" N, longitude = 7°39'32.29" E, height = 311.97 m. The RF signal from the antenna is first amplified and filtered and then down-converted to IF ($f_{IF,analog}$ = 225 MHz). After a further amplification stage, the IF signal is filtered by using an IF centred filter with a bandwidth equal to 18 MHz. Finally, the received signal is sampled using a sampling frequency (f_S) equal to 39.15 MHz, quantized by using an 8 bit Analog to Digital Converter (ADC) and sent from the USB interface to an Hard Disk Drive (HDD) of a laptop, as shown in fig. 3.

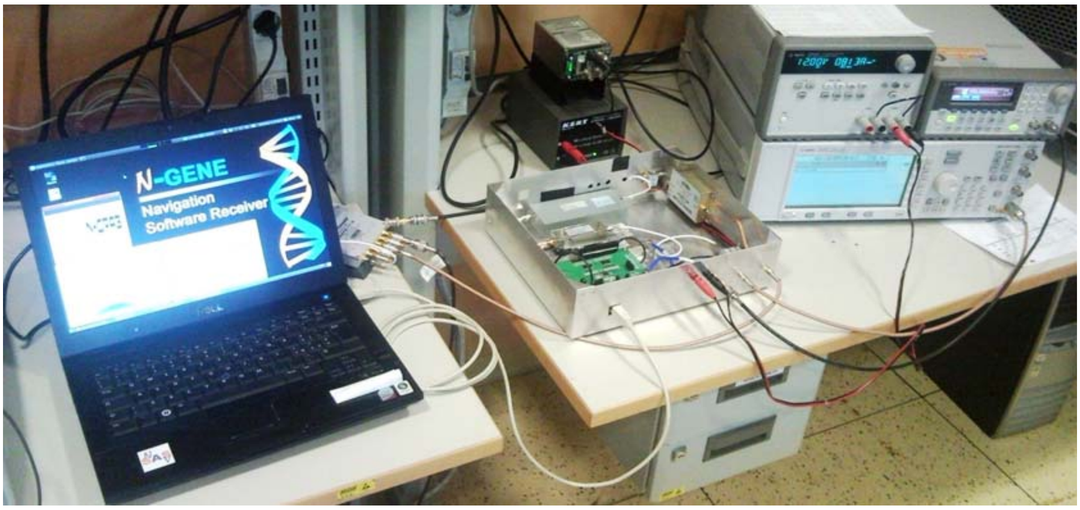

Fig. 3. Picture of the experimental setup (including the laptop for the raw data storage, the discrete component front-end, the power supply and the local oscillators) [own photo]

The NavSAS N-GRAB software has been used to collect the data which have been used for the results presented in this paper. The post processing of the IF data-sets has been carried out with a fully software GNSS receiver developed again by the NavSAS researchers called N-GENE [3] and with several ad-hoc developed MATLAB® routines. It must be highlighted that the data collections on the two sidebands have been performed in different time instants but under similar signal conditions (same antenna location and similar satellite elevation), just modifying the flexible experimental setup in order to receive the desired sideband according to the parameters in table 2. More in detail, only the RF filter and local oscillator frequency (f_{LO}) have been changed within the experimental setup shown in fig. 3: the proper RF filter (centred on E5a or E5b) has been used and the correct frequency for the local oscillator has been selected in order to down-convert the RF signal to the desired analog IF ($f_{IF,analog}$ = 225 MHz) and digital IF ($f_{IF,digital}$ = 9.9 MHz).

Table 2. RF frond-end parameters of the frequency plan for receiving Galileo E5a/E5b signals [own study]

Galileo Sideband	f_{RF} [MHz]	$f_{IF,analog}$ [MHz]	f_{LO} [MHz]	f_S [MHz]	$f_{IF,digital}$ [MHz]	B_{IF} [MHz]
E5a	1176.45	225	951.45	39.15	9.9	18
E5b	1207.14	225	982.14	39.15	9.9	18

Taking into account the expected received power levels listed in table 1, the noise figure of the experimental setup has been assessed in order to compute the expected C/N_0 value of each received signal. The obtained values are then summarized in table 3.

Table 3. Minimum and maximum expected C/N_0 values for Galileo E5 signals, taking into account the features of the active antenna (noise figure of 2.6 dB, 6 dBi gain for signals coming from the zenith, up to 39 dB of LNA gain, sky temperature equal to 100 K and 0.5 dB atmospheric losses) and the characteristics of the front-end (equivalent noise figure of 4 dB, operative temperature equal to 290 K) [own study]

Galileo E5 Signal Component	***GIOVE-A/B Min C/N_0***	***GIOVE-A/B Max C/N_0***	***PFM/FM2 Min C/N_0***	***PFM/FM2 Max C/N_0***
E5aI, E5aQ, E5bI or E5bQ	47.0 dB-Hz	51.5 dB-Hz	50.8 dB-Hz	53.8 dB-Hz

EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

The results obtained using the experimental setup introduced in previous section are presented in the following paragraphs. The results in terms of E5a/E5b signal acquisition and tracking during multiple satellite passes will be discussed, focusing on the analysis of the received signal strength versus the satellite elevation and comparing the signals received from the two Galileo IOV satellites with those from GIOVE-A and GIOVE-B. In addition, the modulation format of the E5a/E5b received signals will be investigated, checking the scattering diagrams of the signal received from the two IOV satellites. Finally, the presence of navigation data and secondary code chips on the received signals will be discussed.

Signal acquisition and tracking results

A first data collection was performed on April 4-5, 2012, configuring the experimental setup in order to receive and store E5b signals during a complete pass of the two Galileo IOV satellites and GIOVE-A and GIOVE-B. In fact, as shown in fig. 4, the four satellites were in view from the Navigation Technologies Laboratory antenna (ISMB, Italy). Taking advantage of N-GRAB features, 512 MB of raw samples (approx. 13 seconds) have been automatically received and stored every 30 minutes, for a total of 16 hours.

(a) (b)

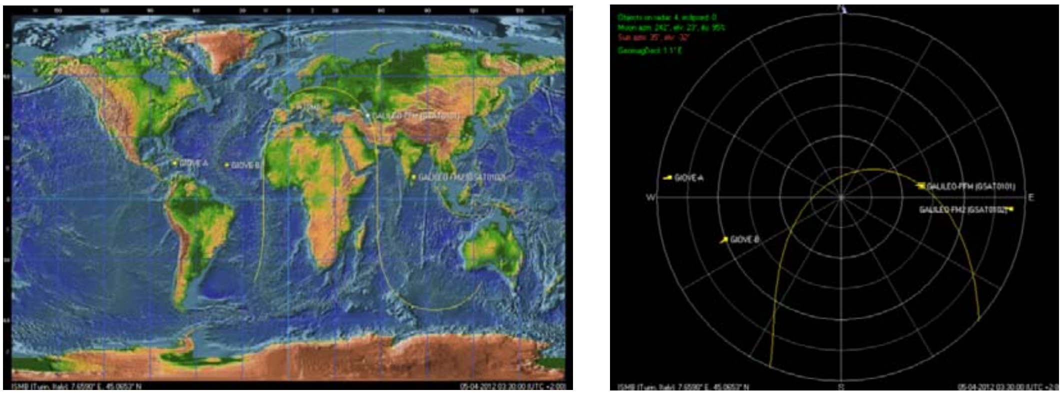

Fig. 4. Satellites orbits (a) and skyplot (b) showing the two Galileo IOV satellites and GIOVE-A and B during one of the data collections (performed on April 05, 2012, at 3:30 AM) [own study]

These data sets have been used for post-processing analysis and all the E5b signals received from the four in-view satellites have been successfully acquired and tracked. As an example, the signal acquisition and tracking results for the Galileo PFM satellite are depicted in fig. 5. In detail, the acquisition of the E5bI data channel of the Galileo PFM satellite (Code Number 11) has been performed using a coherent integration time of 1 ms (equal to 1 primary code period) and 11 non-coherent accumulations: the obtained search space is shown in fig. 5(a). A peak can be clearly seen also on in fig. 5(b), where a zoom around the peak allows to notice the known *sinc* shape in the Doppler domain [7] and a nearly-triangular correlation peak on the code delay domain of the acquisition Ambiguity Function (AF). An estimated Doppler frequency of –1000 Hz has been obtained from the acquisition engine. This initial value has been confirmed and refined by the tracking routine, obtaining a value of –1099.4 Hz (with an estimation standard deviation $\sigma \approx 0.7$ Hz) for both the E5bI and the E5bQ channels, as shown in fig. 5(c). The correct lock of the code tracking loop can be noticed in fig. 5(d), where the Early/Prompt/Late correlation results are reported in the lower subplot. In addition, the upper subplot in fig. 5(d) shows the same estimated C/N_0 value (52.6 dB-Hz, with $\sigma \approx 0.6$ dB-Hz) for both the E5bI and the E5bQ channels.

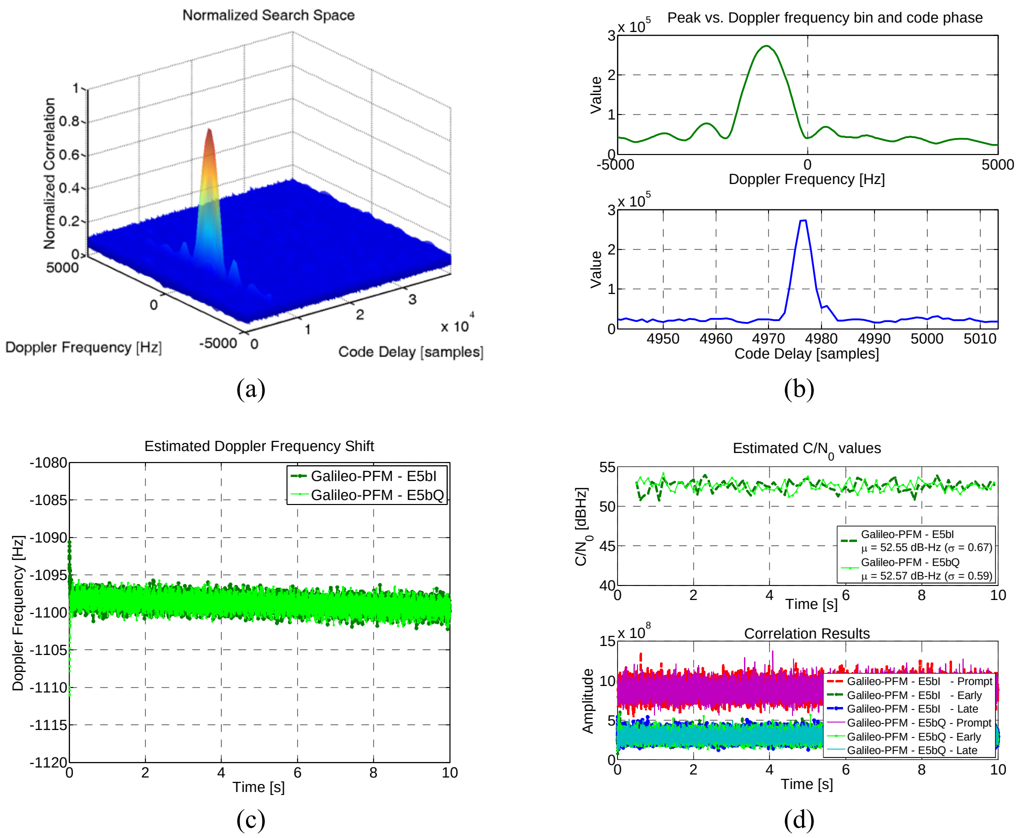

Fig. 5. Results in terms of signal acquisition and tracking obtained processing the E5b data collected on April 05, 2012, at 3:30 AM, during a satellite pass of the Galileo PFM satellite: search space (a) and zoom on the peak (b) of the successful acquisition of the E5bI channel, estimated Doppler values (c) and estimated C/N_0 and correlation values (d) obtained tracking both the E5bI and E5bQ channels for 10 seconds [own study]

The signal acquisition and tracking routines have been executed multiple times on the data sets collected on April 4–5, in order to analyse the strength of all the received E5b signals versus the elevation of the four in-view satellites. Fig. 6(a) shows the elevation patterns of the Galileo satellites obtained from prediction visibilities based on the NORAD tracking information (two-line elements of Galileo satellites) obtained from [1]. This figure shows how all the four satellites reached their maximum elevations near to the zenith (ranging from 77.7 to 82.7 degrees) during the 16 hours of the data collection, thus fairly comparing their signal characteristics in similar geometrical conditions. The obtained results in terms of estimated Doppler frequency and C/N_0 values for all the E5b signals (data and pilot channels) are also reported in fig. 6.

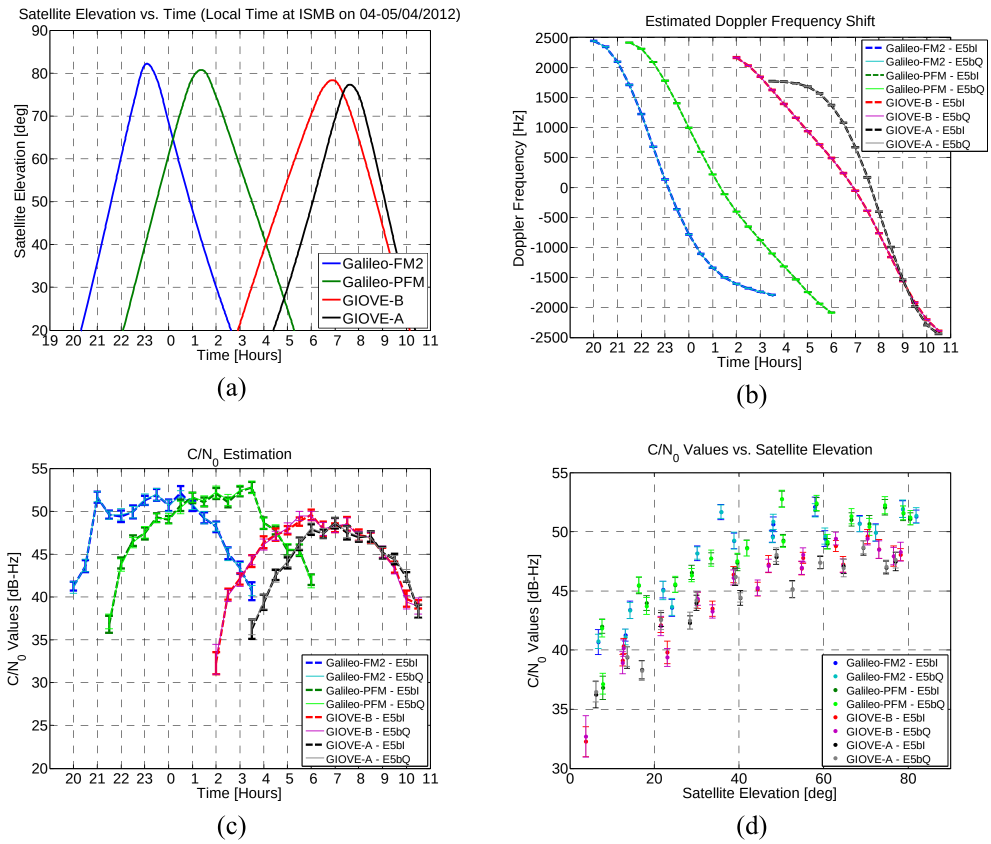

Fig. 6. Results obtained analysing the E5b signals (data and pilot channels) collected on April 4–5, 2012, from the four Galileo satellites: satellite elevation plot (a), estimated Doppler frequency (b), C/N_0 values during the data collection (c) and received signal strength (C/N_0) versus satellite elevation (d) [own study]

From fig. 6(c) it is possible to notice that the trends of the estimated C/N_0 values agree with the satellite elevations plotted in fig. 6(a): in fact, depending also on the radiation pattern of the receiving antenna, satellite signals with low elevation result attenuated. This trend is also confirmed in fig. 6(d). As an additional remark, fig. 6(c) allows also to confirm that the PFM and FM2 satellites are broadcasting E5b signals with similar strength and, as expected, the estimated C/N_0 values for those satellites at the maximum elevation are approximately 3 dB higher with respect to GIOVE-A and GIOVE-B signals in similar conditions.

The same analysis and performance evaluation has been repeated also for the E5a signals on April 11–12, 2012, performing a second data collection in similar conditions of April 4–5, 2012. The experimental setup has been reused in order to receive and store E5a signals during a complete pass of the four satellites lasting in total 17 hours. The received E5a signals have been assessed, as reported in fig. 7, obtaining similar results with respect to the E5b signals (compare with fig. 6).

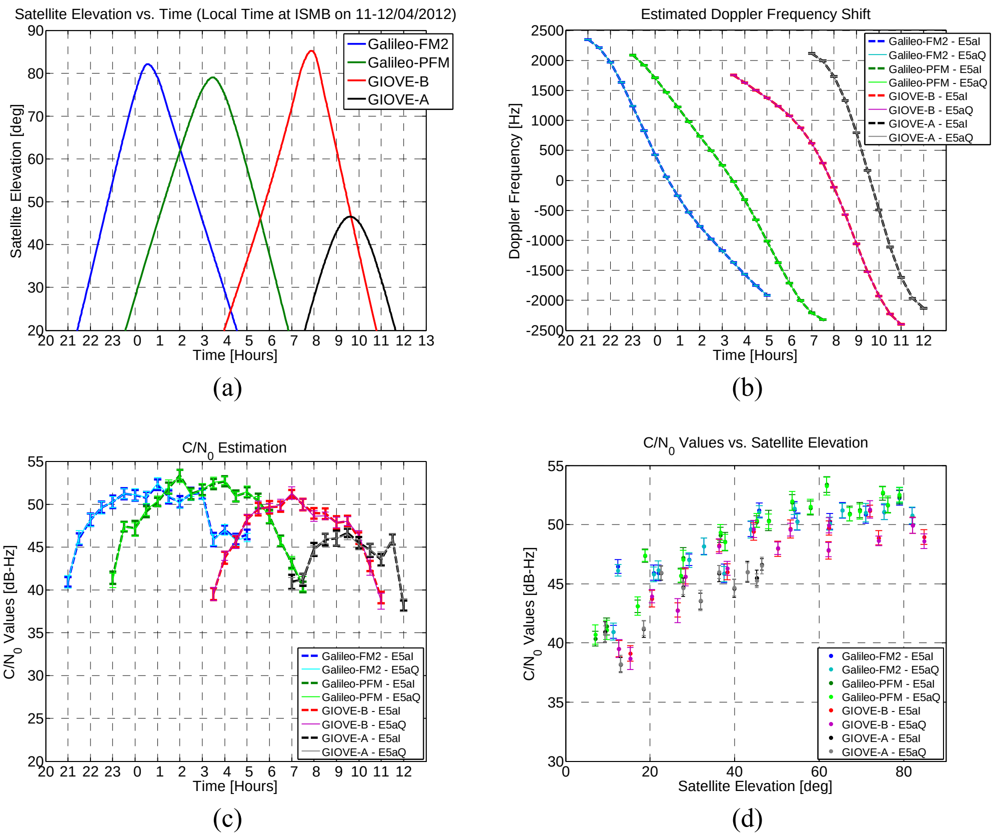

Fig. 7. Results obtained analysing the E5a signals (data and pilot channels) collected on April 11–12, 2012, from the four Galileo satellites: satellite elevation plot (a), estimated Doppler frequency (b), C/N_0 values during the data collection (c) and received signal strength (C/N_0) versus satellite elevation (d) [own study]

Unlike of the previous data collection, where GIOVE-A satellite reached a maximum elevation of 77.7 degrees, during this data collection the GIOVE-A satellite reached a maximum elevation of 46.5 degrees, as shown in fig. 7(a), whereas other satellites reached maximum elevations near to the zenith (ranging from 79.1 to 86.6 degrees). Thus, this is the reason of the lower C/N_0 value obtained from GIOVE-A signals in fig. 7(c) and fig. 7(d). Apart from this minor problem, from fig. 7(c) and fig. 7(d) it is possible to remark how the E5a signals of PFM and FM2 satellites have been received with similar strength, with estimated C/N_0 values of approximately 3 dB higher with respect to GIOVE-B signals at the maximum elevation. In addition, all the obtained C/N_0 values near to the zenith shown in fig. 6(d) and fig. 7(d) agree with expected values previously listed in table 3.

Modulation format analysis

The modulation format of the E5a/E5b received signals has been investigated, checking the scatter plots of the signal received from the two IOV satellites. Fig. 8 shows the results obtained correlating the received signals with the primary codes of all the corresponding data and pilot channels and plotting the outputs of the prompt complex correlators (1 ms coherent integration time).

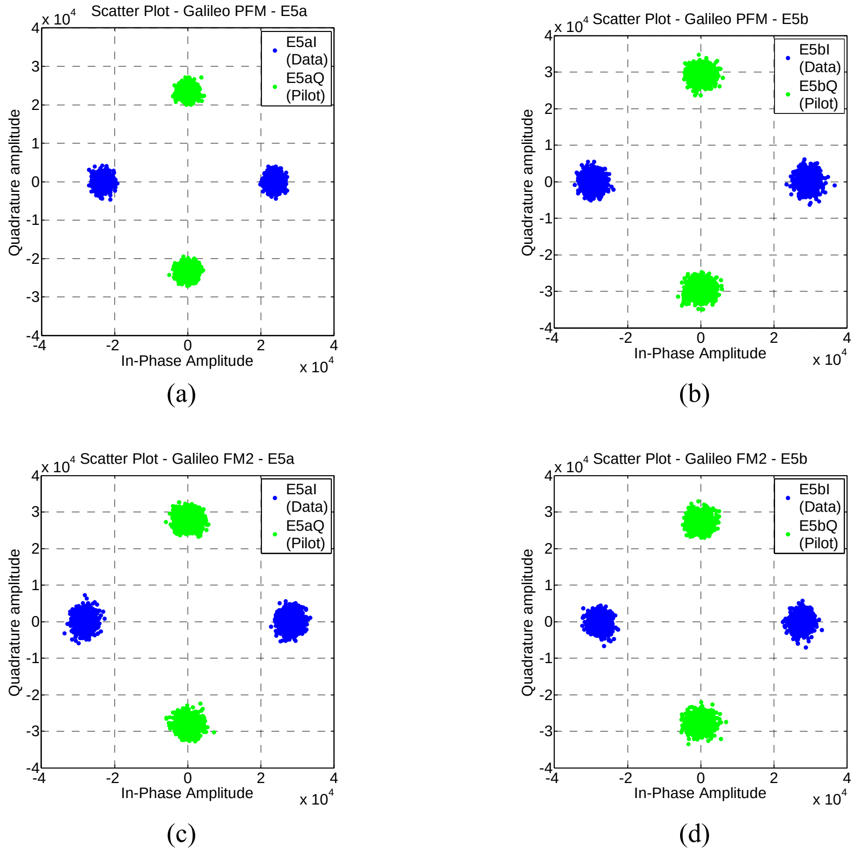

Fig. 8. Results obtained analysing the modulation formats of E5a and E5b signals (data and pilot channels) received from the two Galileo IOV satellites: scatter plots showing the E5a (a) and E5b channels (b) of the PFM satellite (Code No 11) and the E5a (c) and E5b channels (d) of the FM2 satellite (Code No 12) [own study]

In detail, a modified tracking loop has been used in order to investigate the carrier phase relations between the data and pilot channels transmitted by each satellite in each sideband. The 4 scatter plots in fig. 8 confirms the fact that each of the four channels (E5aI, E5aQ, E5bI and E5bQ) transmitted by each Galileo satellite can be processed as an independent BPSK-like modulated signal. Moreover, in each sideband (E5a or E5b) every satellite broadcasts a pair of orthogonal data and pilot channels, as in-phase and quadrature components respectively, and thus resulting in a QPSK-like modulated signal.

Secondary code chips and navigation data analysis

As a final analysis, the presence of navigation data and secondary code chips on the received signals has been analysed. The results obtained analysing the four data and pilot channels received from the Galileo PFM satellite are presented in fig. 9, where the outputs of the prompt correlators (1 ms coherent integration time) are plotted and compared with the known secondary code sequences, as reported in [4].

Focusing on the E5aI data channel, it must be noticed that the corresponding secondary code, that is the $CS20_1$ sequence as reported in [4], has a period of 20 chips (20 ms) and is expressed in hexadecimal as [842E9] or as [–1+1+1+1+1 –1+1+1+1+1 –1+1 –1 –1 –1+1 –1+1+1 –1] in signal levels. Two periods of this sequence are shown in the lower subplot of fig. 9(a) and can be compared with the obtained correlation values. It is possible to observe how the sign of the first 20 values perfectly match with the known secondary code sequence. The following 20 values have a reversed sign: this can be explained with the fact that a +1 data symbol can be demodulated from the first 20 values and a –1 is present on the subsequent 20 values. This analysis has been repeated also on the sequent correlation values, confirming the match with the expected secondary code sequence and the presence of the navigation data symbols on the E5aI channel with the expected rate of 50 symbols/s.

Similar results have been obtained also for the E5bI data channel, as shown in fig. 9(b). However, this channel has a shorter secondary code sequence of just 4 chips (4 ms), denoted as $CS4_1$ *in* [4] and expressed as [E] in hexadecimal symbols or [–1 –1 –1 +1] in signal levels. In fig. 9(b) it is possible to see the presence of 2 data symbols with +1 sign and then perfect match with the 4 chips of the secondary code sequence, followed by a –1 symbol (4 values with reversed sign, from the millisecond 1009 to the millisecond 1012), another –1 symbol and then three +1 symbols.

On the other hand, the Galileo E5 pilot channels present longer secondary code sequences (100 chips, corresponding to a period of 100 ms) and they do not carry navigation data. In detail, the secondary code sequence for the Code Number 11 of the E5aQ channel is $CS100_{11}$ in [4] and is expressed in hexadecimal symbols as [1FC32410652A2C49BD845E567]. The code corresponding to the E5bQ channel is the $CS100_{61}$ sequence, expressed as [0366AB33F0167B6FA979DAE18] in hexadecimal symbols. Both these code sequences have been correctly identified with the correct periodicity (100 ms) on the Galileo PFM signal, as demonstrated in fig. 9(c) and fig.(d).

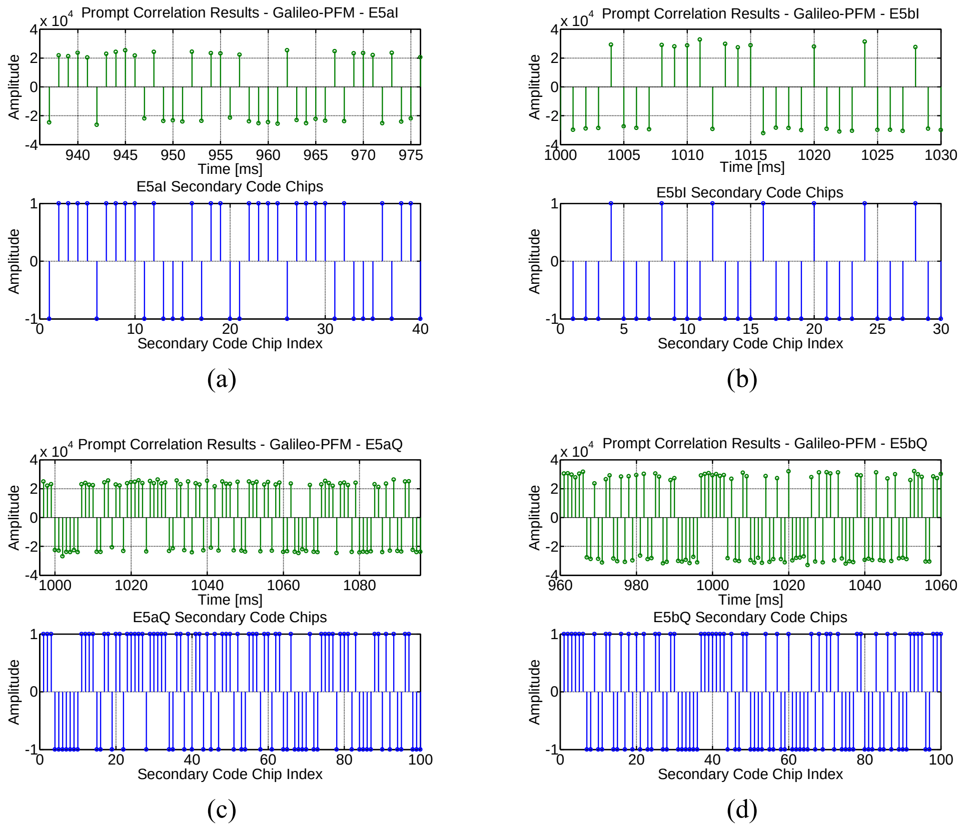

Fig. 9. Results obtained analysing the presence of secondary code chips and navigation data on the four channels received from the Galileo PFM satellite on the E5a and E5b sidebands: E5aI data channel (a), E5bI data channel (b), E5aQ pilot channel (c), E5bQ pilot channel (d) [own study]

Similar results have also been obtained processing both the E5a and E5b signals received from the Galileo FM2 satellite, confirming the presence of the secondary code chips as well as of the navigation data symbols, but are not reported here for the sake of shortness.

As final remark, the content of the navigation data currently transmitted by the Galileo IOV satellites has been checked decoding the I/NAV messages on the E5b band (E5bI channel). As a preliminary result, it must be noticed that valid messages (with correct CRC and Galileo System Time) has been decoded from both PFM and FM2 satellites, including valid page types. On the other hand, at time of writing, the F/NAV messages (transmitted in E5a band) have not been checked due to the lack of an ad-hoc E5aI navigation data parsing routine.

CONCLUSIONS

An experimental assessment of the E5a/E5b signals of the two Galileo IOV satellites (PFM and FM2) have been performed in this paper, comparing these signals with those currently received from the GIOVE-A and GIOVE-B satellites. The obtained results confirm that the PFM and FM2 satellites are broadcasting E5a/E5b signals with similar strength and, as expected, the estimated C/N_0 values for those satellites at the maximum elevation are approximately 3 dB higher with respect to GIOVE-A and B signals in similar conditions. In addition, the other signal features have been confirmed to agree with the characteristics described in the Galileo ICD specifications (modulation format, presence of secondary code chips and navigation data).

Future work will be oriented on the setup of a wideband front-end in order to coherently receive the entire E5 band, fully exploiting and assessing the potential performance of the AltBOC modulation. Furthermore, also the content of the F/NAV data pages currently transmitted by the Galileo satellites on E5a band will be checked.

Acknowledgments

The authors would like to express their gratitude to all the other members of the Navigation, Signals Analysis, and Simulation (NavSAS) group. Among the others, a special acknowledgement is addressed to Marco Pini, Gianluca Marucco, Mario

Nicola and Alfredo Favenza for their collaborative support for the experimental setup.

The authors would also like to acknowledge the free software tool Orbitron (© by S. Stoff), that has been used for plotting fig. 4.

REFERENCES

[1] CelesTrack website, NORAD Two-Line Element Sets, current data for Galileo satellites, available at: http://www.celestrak.com/NORAD/elements/galileo.txt, URL accessed on April 12, 2012.

[2] Dovis F. et al., NavSAS Group Acquires, Tracks Second Galileo IOV Satellite, GPS World website, Top Story, January 17, 2012, available at: http://www.gpsworld.com/gnss-system/galileo/news/navsas-group-acquires-tracks-second-galileo-iov-satellite-12517.

[3] Fantino M., Molino A., Nicola M., N-Gene GNSS Receiver: Benefits of Software Radio in Navigation, in Proc. of ENC GNSS 2009, Naples, Italy, May 2009.

[4] Galileo (European GNSS) Open Service Signal in Space Interface Control Document (OS SIS ICD), Issue 1, Revision 1, September 2010, available at: http://ec.europa.eu/enterprise/policies/satnav/galileo/open-service/index_en.htm.

[5] GIOVE-A+B Navigation Signal In Space Interface Control Document, GIOVE-A+B Public SIS ICD, ESA-DTEN-NG-ICD/02837, Issue 1, Revision 1, August 8, 2008, available at: http://www.giove.esa.int/.

[6] Lestarquit L., Artaud G., Issler J.-L., AltBOC for Dummies or Everything You Always Wanted to Know About AltBOC, in Proc. of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008), pp. 961–970, Savannah, GA, September 2008.

[7] Lo Presti L., Motella B., The math of ambiguity: what is the acquisition ambiguity function and how is it expressed mathematically?, in Inside GNSS, Vol. June 2010, pp. 20–28.

[8] Margaria D., Mulassano P., Dovis F., Receiver, method and corresponding computer program product for demodulating AltBOC-modulated signals, European Patent EP 2012488 B1, Application No. 07425412.9, July 05, 2007.

[9] Margaria D., Dovis F., Mulassano P., Galileo AltBOC Signal Multiresolution Acquisition Strategy, IEEE Aerospace and Electronic Systems Magazine, Vol. 23, No. 11, pp.4–10.

[10] NavSAS Group, Contact! — First Acquisition and Tracking of IOV Galileo Signals, Inside GNSS, January/February Issue, 2012, Vol. 7, No. 1, pp. 46–55.

[11] Soellner M., Erhard P., Comparison of AWGN Code Tracking Accuracy for Alternative-BOC, Complex-LOC and Complex-BOC Modulation Options in Galileo E5-Band, in Proc. of ENC GNSS 2003, Graz, Austria, April 2003.

Received May 2012
Reviewed July 2012