Data Decoding of the first Galileo IOV PFM satellite and joint GPS+Galileo Positions

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Abstract— **On the 20th of October 2011, the first two satellites of the Galileo constellation have been launched successfully. The possibility to have these two satellites in orbit represented a great opportunity for researchers to receive and monitor the first Galileo signals. After the satellite switch-on, we continuously monitored the signal broadcast by both the satellites, using a software radio receiver. This paper shows the analysis on the navigation message that was broadcast by the IOV-PFM Galileo satellite on the E1 bandwidth, starting from December 2011. In particular, we were able to observe a valid ephemeris data on December 21st and December 22nd. The successful interpretation of the navigation message enabled the first GPS+Galileo experimentations using real signals that were performed in static condition, through code-phase measurements.**

***Keywords*— IOV-PFM, Galileo, I/NAV, ephemeris, joint PVT.**

I. INTRODUCTION

Galileo will be the first European Global Satellite Navigation System (GNSS) and it will give to Europe the independence in satellite navigation, assuring at the same time the interoperability with GPS and GLONASS.

This new system will improve the performance of existing receivers in terms of accuracy, availability and robustness. As far as the availability concept is concerned, it is worth to remember that up to now an effective positioning service is currently only available in 50% of large cities, due to the ‘urban canyon’ effect where buildings limit the reception of satellite signals. Thanks to the Galileo satellites, case of outages will be reduced to only 5%, and will improve indoor satellite positioning capability [6]. The Galileo signals are designed to be robust against interference and errors caused by multipath; in the meanwhile dedicated signals (i.e. those used for Public Regulated and Commercial services) will offer enhanced resistance to jamming and intentional spoofing attacks, and will be suitable to support strategic applications [1], [2], [13]. Another parameter of robustness is the level of performance in low C/N0 environments such as indoor and narrow urban ones. In [15] a performance comparison of the GPS L1C and GALILEO E1 OS data message decoding process is presented, by observing the BER, the WER (Word Error Rate) and the EER (Ephemeris Error Rate) as functions of the C/N0. Eventually, precise ephemerides and the transmission of the navigation message over two frequencies will guarantee that Galileo will be able to provide a positioning accuracy within 1-2 meters [3], [4].

In order to reach the full constellation’s operability, three main phases have been scheduled in the Galileo program: the *In-Orbit Validation* (IOV) phase, the *Initial Operational Capability* (IOC) and the *Full Operational Capability* (FOC) phase [5], [6]. The first monitored and validated the system through the operation of two experimental satellites (i.e. GIOVE-A and GIOVE-B, launched in December 2005 and April 2008, respectively) and a reduced constellation of four operational satellites and ground infrastructures. In [14] authors made some preliminary experimentation by combining GPS and GIOVE measurements. They have shown that a GPS-level accuracy can be reached with GIOVE signals, and all those GNSS signals can be mixed together to get a good PVT with a few meter accuracy. The main difference of our work with respect to [14] is in the unavailability of the GGTO (i.e. the GPS and Galileo Time Offset) parameter that has forced us to build up the final system with an additional unknown in order to take into account the time bias between the Galileo system and the clock of the receiver. Moreover, , according to the IOC phase for the first time we have the chance to deal with a satellite that belongs to the final Galileo constellation and not only with a prototype as the GIOVE one. In fact, the second part of the Galileo program includes the launch of additional satellites to reach Initial Operational Capability (IOC) around mid-decade. A range of services will be then extended as the system is built up from IOC to reach the Full Operational Capability (FOC) by this decade’s end. After the accomplishment of the last part of the Galileo program, the fully deployed Galileo system is expected to have 30 satellites on orbit.

The first two operational satellites (i.e. IOV *ProtoFlight Model* -PFM and IOV *FlightModel2*-FM2) of the IOV phase have been launched on the 20th of October 2011 from the Europe's Space Port in Kourou, French Guiana. Other two IOV satellites are expected to be launched in the first half of 2012. This paper reports part of the analysis performed on the signal broadcast by the IOV-PFM satellite, after its switch on. We performed several data collections using a software radio receiver and we were able to acquire and track the signal in space. Since the PRN of the IOV-PFM satellite was unknown, we have performed a cold start signal acquisition, using all possible ranging codes (i.e. primary code) for each code number reported in the public Interface Control Document (ICD) [8]. We succeeded in the acquisition with a code number equal to 11, tracking both data and pilot channel E1-B and E1-C as shown in [9].

We were also able to acquire the signal either on the E5b-I, E5a-I bands. However, in this paper we focus the analysis of the E1-B data decoding only. In particular we show how we monitored the data content over December 2011 and January 2012, observing the evolution toward the valid message. Moreover, when we recognized valid ephemeris, we performed a joint GPS/Galileo Position Velocity and Time (PVT) computation, assessing the improved accuracy with the inclusion of the IOV-PFM in the navigation solution.

The paper is organized as in the following. Section II recalls the general structure of the Navigation Message broadcast on the OS Galileo E1 band. Section III deals with the analysis of the data content of the IOV-PFM satellite performed over the whole period of observation. Section IV shows some tests in a combined GPS+Galileo PVT computation, while Section V concludes the paper.

II. Overview of the Galileo E1 navigation message and insights on data decoding

The Galileo signal-in-space carries three different type of data message: the F/NAV, the I/NAV and the C/NAV messages. Each type of message provides different information and is transmitted on a different band [4]. In this paper we focus on the I/NAV message, which is the only one broadcast on the E1-b band.

Let's start analyzing the structure of such Galileo message through a rough comparison with that embedded in the GPS C/A signal. Both Galileo and GPS navigation data are organized in the typical frame-subframe-page layout: the way the two messages' elements are structured is very similar and only some minor differences can be denoted, like the message length, the number of frames and the page length. These values are reported in the block diagram of Fig. 1.

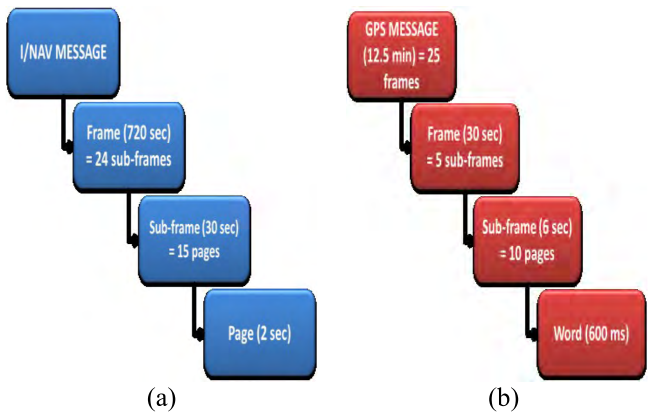


Figure 1. Navigation Message Structure for Galileo OS on E1-B (a) and GPS (b).

A quite significant difference between Galileo and GPS is in the transmission of time information: in the GPS navigation message the transmission time, namely the Time Of Week (TOW) can be recovered from the Hand Over Word (HOW) in each subframe. On the contrary, in the Galileo navigation message, only some pages contain the time information. Galileo introduces another new characteristic, which consists in the transmission of two different types of pages: the Alert Page and the Nominal Page [8]. All the ephemerides, essential to compute the user's position, are within the Nominal pages. Alert pages do not carry any navigation data and are transmitted only in case of detected failures in order to preserve the transmission integrity. Each Nominal page is formed by two parts of 250 symbols, the odd and the even part. The Galileo navigation message includes 11 types of Nominal pages (marked as type 0 to type 10). On the basis of the content of the Data field, the Nominal words can be divided in 4 sub-groups:

- Ephemeris, clock corrections parameters, Signal in Space Accuracy (SISA) and the Satellite ID (SvID) (words 1, 2, 3 and 4);
- Ionospheric correction, Broadcast Group Delay BGD, signal health, data validity status and the GPS to Galileo System Time conversion GST-UTC (words 5 and 6);
- Almanac (words 7, 8, 9 and 10);
- I/NAV Spare (word 0).

In order to decode the navigation message and understand the type and content of each word, receivers have to implement algorithms able to recognize odd and even parts of the same page. Similarly to what happens in GPS, a 10 symbols preamble ("0101100000") marks the beginning of each part. Once the preamble is detected, a proper de-interleaver and decoder has to be used, since every part of the page is transmitted interleaved and encoded with a convolutional code, with a rate equal to ½ (that is two output symbols per each bit of information). Details on the de-interleaving block and the parameters of the convolutional code can be found in [8]. Note that the 10 symbols preamble is not coded, therefore, after the preambles are removed and the page is decoded, the length of the page decreases from 480 symbols to 240 bits (i.e. every part is 120 bits long). These 240 bits include also a CRC code for error detection.

After the decoding stage has been performed using the Viterbi algorithm, the receiver can access the content of a page, but the correct order of the two parts needs to be checked at first. The CRC is computed over 240 bits to verify that the two parts belong to the same page and that are received according to the right sequence. If the CRC fails, either some bits have not been recovered correctly or the two parts do not correspond to the same page. In order to discern between the two possibilities, the same procedure is repeated on the subsequent 250 bits stream. If the new check of the CRC ends successfully, the receiver is able to detect the beginning of the page and can start interpreting the navigation message, recovering the ephemerides. On the other hand, the page has to be discarded and the procedure repeats until the CRC

computation gives a positive feedback. The diagram reported in Fig. 2 shows a possible implementation of the described procedure, in terms of a state machine for software architectures.
The state machine is composed by 4 states:

- Search_first_preamble
- Read_page_part
- Control_new_preamble
- Decode data

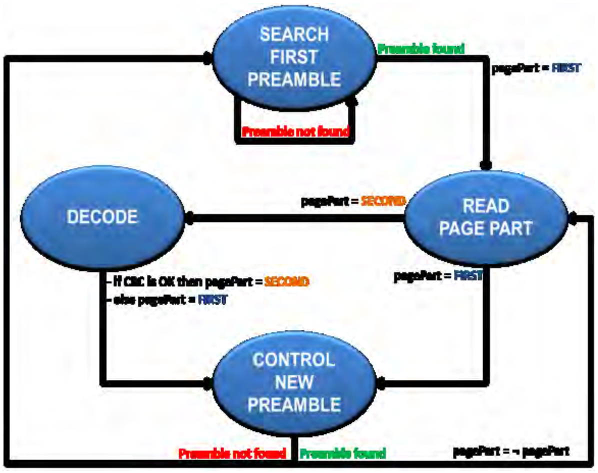


Figure 2. Block scheme of the state machine used for the I/NAV Galileo message's data decoding.

The *Search_first_preamble* state is the starting point of the state machine. Here the symbols at the output of the In Phase Prompt correlator are processed until a preamble is found. When a preamble is detected the process passes to the *Read_page_part* state. Here, symbols of the A_0 page are read. After that, the process enters a new state, the *Control_new_preamble,* where a new synchronization preamble is expected at the end of the page part A_0. If a new preamble is found, the process goes back to the *Read_page_part* state where the symbols of the second page part, named B_0, are processed.
When B_0 has been read, the machine enters the *Decode state* where the following operations are executed:

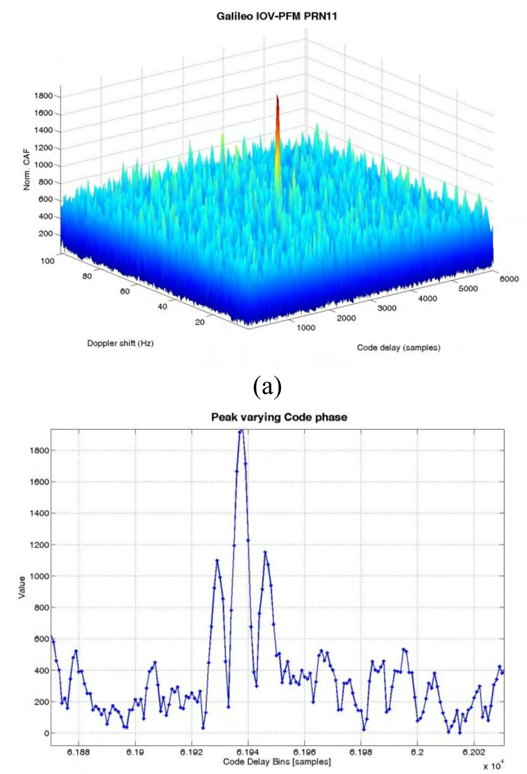
- Polarity correction (if necessary) over A_0 and B_0
- De-interleaving of A_0 and B_0
- Viterbi decoding of the symbols of A_0 and B_0
- CRC checksum on the content of A_0 and B_0

At this point, if the CRC computation succeeds, the data message decoding can continue passing to the *Control_new_preamble* state in order to decode two new page parts A_1, B_1. Otherwise, the old second page part, B_0, becomes the new first page part and the machine takes in consideration a new page part, A_1, which becomes the new second page part. B_0 and A_1 are processed together and a new checksum is calculated. If this CRC ends successfully, the receiver can recover the navigation ephemeris, otherwise the B_0 stream is discarded and the process goes back to the *Control_new_preamble* stage.

Once the receiver is able to decode correctly the navigation message transmitted by the satellite, an analysis of the orbital parameters broadcast by the Galileo and their reliability can be performed.

III. Analysis of the Navigation Message Broadcast by the IOV PFM Satellite

We started monitoring the IOV-PFM on December 12th, 2011, when the satellite switched on its payload and started transmitting on the E1 band over Europe. We performed several data collections approximately from 14:25: CET to 17:06: CET when the satellite was in view at an elevation ranging from 38° to 53° over Turin. In Fig. 3 the output of search space of the acquisition stage is shown for a data set collected that day.
As we can see from Fig. 3, from 14:58:57 CET we were able to successfully acquire Galileo PFM satellite. After the rough estimation of the code-phase and the frequency Doppler offsets performed by the signal acquisition, the satellite's signal was processed by the tracking loops to refine the estimation of such parameters, enabling the data decoding. The tracking loops were set with an integration time of 4 ms. The navigation data are plot in Fig. 4(b), that shows the data symbols at the output of the In Phase Prompt correlator, while the C/N0 ratio and the outputs of the Early, Late and Prompt correlators are depicted in Fig.4(a) over time.

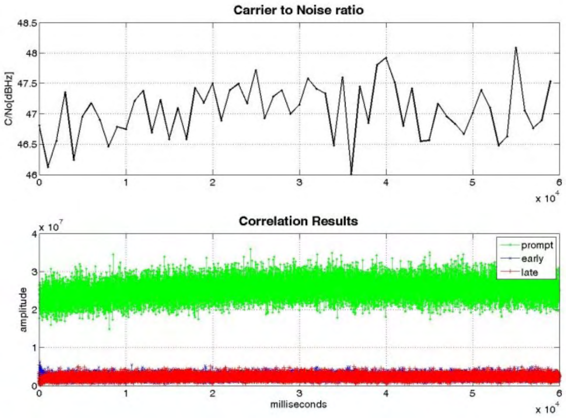


(a)

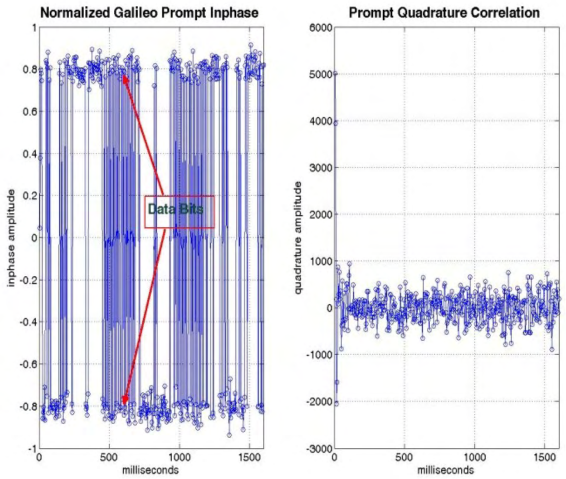
(b)

Figure 3. Search Space of acquisition performed on December 12, 2011 at 14:58:57 (a) and a zoom of the peak by varying the code-phase delay (b) for Galileo IOV-PFM # PRN 11.

After the recovery of the data symbols, we performed the data demodulation according to the process described in the previous section.



(a)



(b)

Figure 4: Tracking results of the Galileo IOV-PFM acquire on December 12, 2012. C/N0 and correlators' output in (a) and data dispreading in (b).

Unfortunately, the signal broadcast by the satellite at that time did not contain any valid navigation information (i.e. ephemeris) and we found that the message was dummy as all the data belonged to the Word type 0 or to the Reserved word.

We repeated the data collection one week later on December 20th at 6:28:00 CET when the IOV-PFM had an elevation of more than 70°.

In this case we found out that the satellite was transmitting a complete navigation message and that all the word types (i.e. word 1-4) necessary to the orbit's determination of the Galileo satellite were filled with data. Table I shows the result of the ephemeris as we got by decoding the navigation message. After a more careful analysis, it was odd seeing that we found a decoded PRN equal to 5, even if we acquired and tracked the IOV-PFM with a spreading code corresponding to the code number 11. This mismatch made us suspicious and we considered the hypothesis that the data included in the message could be erroneous. The proof of such hypothesis was clear when we computed the satellite's position in ECEF coordinates:

$$X_s = 24406.8226099098\ \mathrm{m}$$
$$Y_s = 9109.57597616321\ \mathrm{m}$$
$$Z_s = 1776.1442189745\ \mathrm{m}$$

TABLE I. NAVIGATION MESSAGE BROADCAST BY IOV-PFM ON DECEMBER 20, 2011

Navigation message broadcast by Galileo IOV-PFM on December 20, 2012.		
WORD	**TYPE**	**PARAMETERS**
1	Ephemeris (1/4)	IOD: 276 t_0e: 77100 M_0: 0.12319971187679741587 e: 0.0098039215663447958765 sqrtA: 1.60627450942993164062e+02
2	Ephemeris (2/4)	IOD: 532 omega_0: 0.49279884750718966346 i_0: 0.49279884750718966346 omega: 0.49279884750718966346 iDot: 4.5894768844196773129e-10
3	Ephemeris (3/4)	IOD: 276 omegaDot: 4.6996957611925886686e-07 deltan: 1.8357907537678709252e-09 C_uc: 9.5739960670471191406e-06 C_us: 9.5739960670471191406e-06 C_rc: 160.625 C_rs: 160.625 SISA: 20
4	Ephemeris (4/4)	IOD: 532 PRN: 5 C_ic: 2.3934990167617797852e-06 C_is: 2.3934990167617797852e-06 C_oc: 19260 a_f0: 0.031862744561486716632 a_f1: -1.1102823418200000248e-08 a_f2: 8.6736150000000002039e-18
5	Ionospheric Correction	T_GD: 3.7252902984619134008e-08 WN: 286 TOW: 303145

It was immediately clear these values were not correct since a Galileo satellite is planned to have a circular orbit at an altitude of almost 23000 km. Therefore, the decoded ephemeris could not be used for a valid satellite orbit's computation and a joint GPS+Galileo PVT.

One day later, we performed a new data collection at 9:48:39 CET. In Table II it is summarized the navigation message we decoded using the same method of the previous days.

In this case all the parameters seemed reasonable and matched our expectations (e.g. the code number, IOD values and the square root of the radius of the satellite's orbit). This time the satellite's position was:

$$X_s = 13696090.6737061\ \mathrm{m}$$
$$Y_s = \text{-}16001540.4179182\ \mathrm{m}$$
$$Z_s = 20792749.2507184\ \mathrm{m}$$

Hence, it was compatible with the expected satellite's altitude over the Earth. Using such decoded ephemeris, we were able to perform the first joint GPS and Galileo position.

The results of this GPS+Galileo solution will be shown in the next Section.

TABLE II. NAVIGATION MESSAGE BROADCAST BY IOV-PFM ON DECEMBER 21, 2011

Navigation message broadcast by Galileo IOV-PFM on December 21, 2011 at 9:48:39.		
WORD	**TYPE**	**PARAMETERS**
1	Ephemeris (1/4)	IOD: 261 t_0e: 86400 M_0: 6.0606433328645223924 e: 0.00010852864943444727496 sqrtA: 5.44060267639160156250e+03
2	Ephemeris (2/4)	IOD: 261 omega_0: 0.73184192186787599965 i_0: 0.95453139050952806599 omega: 1.0311038260473941452 iDot: -2.6179661916572947105e-10
3	Ephemeris (3/4)	IOD: 261 omegaDot: -5.7373818421258903838e-09 deltan: 3.4390718225740909781e-09 C_uc: 0 C_us: 0 C_rc: 178.96875 C_rs: -66.15625 SISA: 25
4	Ephemeris (4/4)	IOD: 261 PRN: 11 C_ic: 0 C_is: 0 C_oc: 86400 a_f0: 0 a_f1: 0 a_f2: 0
5	Ionospheric Correction	T_GD: 0 WN: 643 TOW: 291025

Referring to Table II, it is important to stress that most of the parameters of the ephemeris were still set to zero and the calculated satellite's orbit was approximated. Therefore, the precise ephemeris that will be one of the benefits of new Galileo satellite system could not be evaluated at the time of the experiment and they will be a topic of investigation in the next future when the Galileo satellites will provide a complete navigation message.

On January 2012, new data collections have been made when the Galileo PFM satellite had a good visibility. What we found out was that during the week from the 10th to the 16th of January the satellite was not transmitting at all and the acquisition could not detect any peak in the search space. On the contrary, from the 17th of January the satellite was transmitting only dummy messages and it could not be used in the PVT calculation. In Table III there is a complete summary of the data collections that we made in the lab of the Istituto Superio Mario Boella in Turin with the characteristics of the navigation message that we decoded.

From Table III we can gather that the IOV-PFM broadcast a valid navigation message for a couple of days while for most of time it has been kept turned off or in test mode.

TABLE III. SUMMARY OF THE VALIDITY OF THE NAVIGATION MESSAGE BROADCAST BY THE GALILEO IOV-PFM AND COLLECTED AT THE ISMB LAB FROM DECEMBER 2011 TO JANUARY 2012.

History of the Navigation messages broadcast by Galileo IOV-PFM from December 21, 2011 to January 17,2012.			
DATE	**TIME**	**ACQUIRED**	**MESSAGE**
12/12/11	14:25:33	No	N.A.
12/12/11	14:46:15	Yes	Dummy
12/12/11	14:58:57	Yes	Dummy
20/12/11	06:28:00	Yes	Not valid
21/12/11	08:37:20	Yes	Valid
21/12/11	09:48:39	Yes	Valid
21/12/11	23:56:00	Yes	Valid
22/12/11	16:35:00	Yes	Valid
10/01/12	10:53:00	No	N.A.
16/01/12	05:44:00	Yes	Dummy
17/01/12	11:54:10	No	N.A.
17/01/12	11:59:03	Yes	Dummy
17/01/12	12:06:46	Yes	Dummy

We expect that in the next months this satellite will be fully operational and the navigation message will be always available and reliable

IV. JOINT GPS+GALILEO PVT EXPERIMENTATION

In this Section, we discuss the results of the combined GPS+Galileo PVT computation relative to the data collection in static condition performed on the 21th December 2011 at 09:48:00. This experiment has the aim to check both the accuracy of the ephemeris broadcast by the Galileo-PFM satellite and the improvement of the combined solution.

A snapshot of all the satellites in view at the time of the experiment and used for the PVT computation, is reported in Fig. 5.

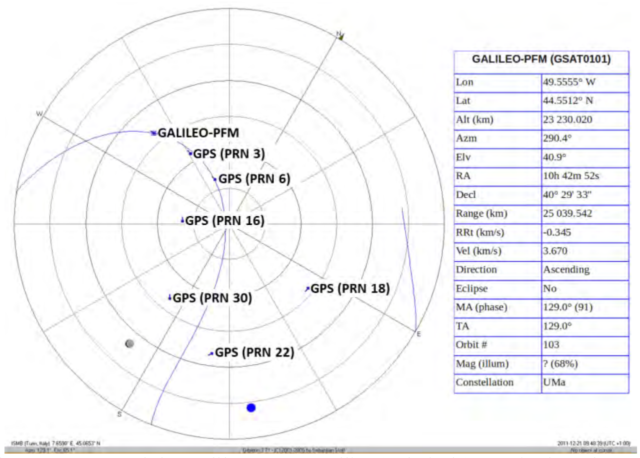
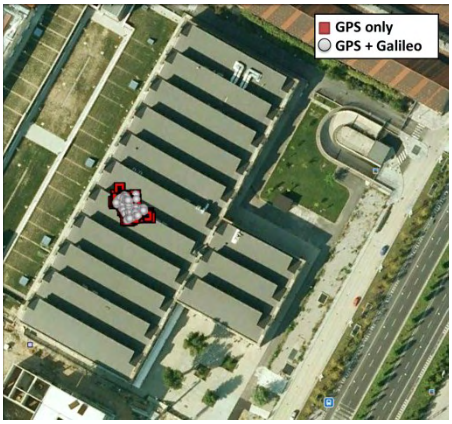


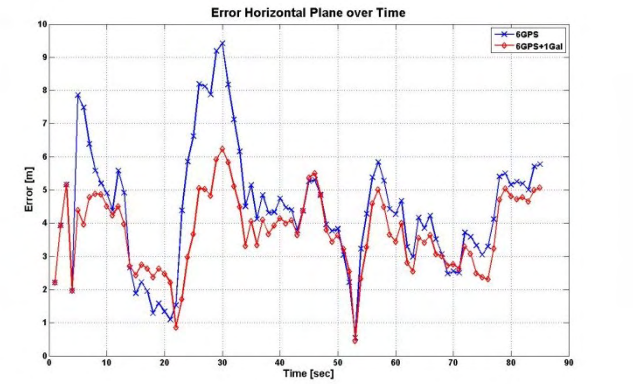
Figure 5: GPS and the Galileo-PFM satellite (red circle) acquired on the 21th December 2011 at 09:48:00. Orbit information of the Galileo PFM is shown on the right side.

As we can see from Fig.5, the elevation of the Galileo satellite was of 40.9° and its decoded ephemeris has been reported in Table II.

By using the N-GENE software receiver [10], [11] we were able to perform a PVT computation both including and excluding the Galileo PFM satellite in the solution. In details, two different scenarios have been considered for the PVT solution: in the first one, only the GPS satellites (PRN #3, #6, #16, #18, #22, and #30) were considered, while in the second case, also the Galileo PFM satellite was included. It is important to stress that the positions' solution reported in this paper is based on code-phase measurements only. As far as the PVT computation is concerned, we used a Kalman filter whose specifications can be found in [12]. In Fig. 6 the estimations of the position are reported for both the two aforementioned satellites' scenarios. Also the error of the PVT solution with respect to the position of the geo-referenced antenna placed on the roof of ISMB building is included.



(a)



(b)

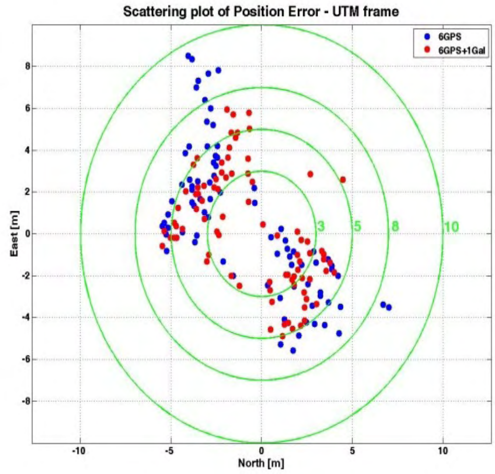
By looking at Fig. 6.b it is evident how the Galileo satellite contributes to reduce the error of the PVT solution with respect to the case of the GPS Stand-Alone. In fact in the case of a combined GPS+Galileo PVT, the error always falls within 6 meters while in the GPS-only scenario we have instants where the estimated position is more than 8 meters far from the true position as highlighted in Fig.6.c.

V. Conclusions

In this paper, some of the results obtained elaborating the signal from the first satellite of the Galileo constellation are reported, with emphasis on the navigation message's decoding and the inclusion of the evaluated pseudorange in the combined GPS+Galileo PVT. The paper shows also the results of several experiments performed over one month aimed at observing the content of the Galileo navigation message, starting from the satellite switch on.

The error in the position with respect to a geo-referenced antenna both in case of a Stand Alone GPS and a joint PVT solution has been shown, demonstrating some advantages from the inclusion of this new satellite in the PVT computation.

At the same time, emphasis was given on the fact that the Galileo system has not reached the full operability (e.g. the number of operational satellites is limited to two at the time of the experiment), consequently more measurements need to be carried out to really understand the real benefits introduced by Galileo.



(c)

Figure 6: Results of a joint GPS+Galileo PVT (in red) compared with a Stand-Alone GPS PVT (in blue). Google Earth plot of the computed position by using two sets of satellites (a). Horizontal error of two different PVT solutions over time (b). Scattering diagram of the error in UTM coordinates with respect to the location of the antenna (c).

In any case, through the N-GENE software receiver, we demonstrated that the first Galileo signal in space can be used yet to enhanced current GPS receivers' performance.

Moreover, through this experiment we had the opportunity to add a new software architecture to the N-GENE receiver able to process the Galileo signals, to recover its navigation data and to perform a joint GPS+Galileo PVT computation in real time.

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