Contact

First Acquisition and Tracking of IOV Galileo Signals

Europe's GNSS program — Galileo — entered a new phase of development with the recent launch of two in-orbit validation satellites, which comprise the first elements of the system's fully operational constellation. In this article, a team of Italian researchers present the initial results of their analysis of the Galileo signals.

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On December 12, 2011, one of the two Galileo in-orbit validation (IOV) satellites launched on October 21 — the Galileo-ProtoFlight Model (PFM) spacecraft — started transmitting its payload signal on the E1 band over Europe.

That same day NavSAS researchers were able to acquire and track the E1 signal (Galileo Code Number 11) begin-

ning at 14:46:15 CET. Two days later, on December 14, the E5 signal became available as well.

The E1 signal was received on December 12 at the Istituto Superiore Mario Boella (ISMB) premises (located in Torino, Italy) with a non-directive antenna, a commercial narrowband RF front-end, and a proprietary software receiver, developed by our research group. The team first received the PFM E5 signal on December 14, using a similar experimental setup.

In this article we will discuss the first acquisition and tracking of the signal broadcast by the Galileo-PFM satellite, on both E1 and E5 bands. We will describe the receiving equipment configuration and present our initial
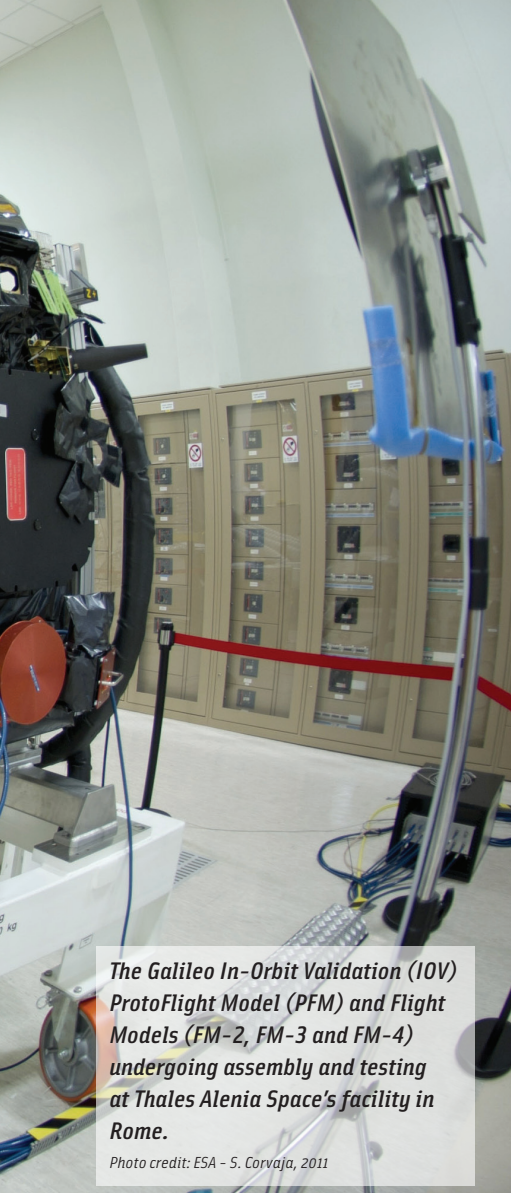
The Galileo In-Orbit Validation (IOV) ProtoFlight Model (PFM) and Flight Models (FM-2, FM-3 and FM-4) undergoing assembly and testing at Thales Alenia Space's facility in Rome.

Photo credit: ESA – S. Corvaja, 2011

results on signal acquisition, tracking, data demodulation and joint PVT (position, velocity, time) solution as a first receiver-side validation of the new Galileo system.

Experimental Setup for Galileo IOV Acquisition

The radio frequency (RF) signal was received by means of two fixed, non-directional rooftop antennas, co-located at ISMB premises in Torino at the following coordinates: latitude = 45°03'54.99" N, longitude = 7°39'32.29" E, height = 311.97 meters.

The Galileo-PFM IOV navigation payload began by transmitting the E1 signal; so, our first acquisition and tracking test focused on this signal.

Using a commercial GPS/Galileo receiver front-end, the RF signal was filtered, amplified, and downconverted to intermediate frequency (IF) while also being converted to a digital format. The front-end features a bandwidth of approximately four megahertz and samples the signal at 16.3676 MHz, using one bit per sample.

The digital IF samples were transferred via a USB interface to a PC, where they could be either stored in memory or processed in real-time with the N-GENE receiver, a prototype fully software receiver developed by our group and used in our research activities. Postprocessing of the stored data collections was done both with N-GENE and with ad hoc routines developed using a commercial high-level technical computing language and interactive environment.

Because the day and time of the IOVs' navigation signal switch-on were unknown, we ran an automatic procedure that searched all Galileo code numbers every 10 minutes. At each search, the N-GENE software receiver calculated the cross-ambiguity function (CAF) of the received signal with local codes and a variable Doppler shift within ±7 kilohertz. When the receiver recognized a valid acquisition peak in the CAF, it displayed an alert message on the PC's screen and a two-minute data collection of raw samples — accurately time-stamped — was stored on disk.

We checked the system in lab during working hours and were able to remotely control the system 24/7. Furthermore, we configured the system to send an alert to NavSAS team members' mobile phones in case of successful signal acquisition.

The front-end used to collect E5 data sets follows the block diagram of **Figure 1** and was built in lab with commercial off-the-shelf (COTS) components (more details can be found in the Manufacturers section near the end of this article).

The RF signal from the antenna was first amplified and filtered, before being converted to an intermediate frequency of 225 megahertz. The signal was then further amplified and sent to the anti-aliasing filter with a bandwidth equal to 18 megahertz. The signal was then sampled at 39 megahertz, quantized over eight bits, and recorded on disk through the USB interface.

The described front-end is a laboratory prototype, that can be configured to receive both E5a and E5b, inserting the proper RF filter and setting the correspondent local oscillator frequency, which in our case was an external local oscillator.

In the following sections, the results of the processing of E1 and E5 Galileo data collections are shown and commented.

E1 Signal Processing Results

This section reports the most relevant results obtained from the E1 signal, recorded during the afternoon of December 12 (CET). We start with the acquisition results, then we show the estimated carrier-to-noise power density ratio (C/N_0) and Doppler profiles. At the end, we discuss the outcomes of navigation message decoding.

Signal Acquisition. Figure 2 shows some of the results obtained performing the signal acquisition over several data sets. The CAFs, plotted on the left column, are computed over the acquisition search space defined along two dimen-
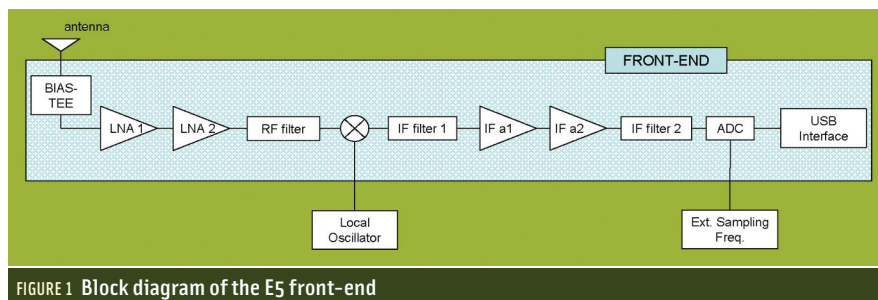

FIGURE 1 **Block diagram of the E5 front-end**

Soyuz lifts off for the first time from Europe's Spaceport in French Guiana on October 21, 2011, carrying the first two Galileo In-Orbit Validation satellites.
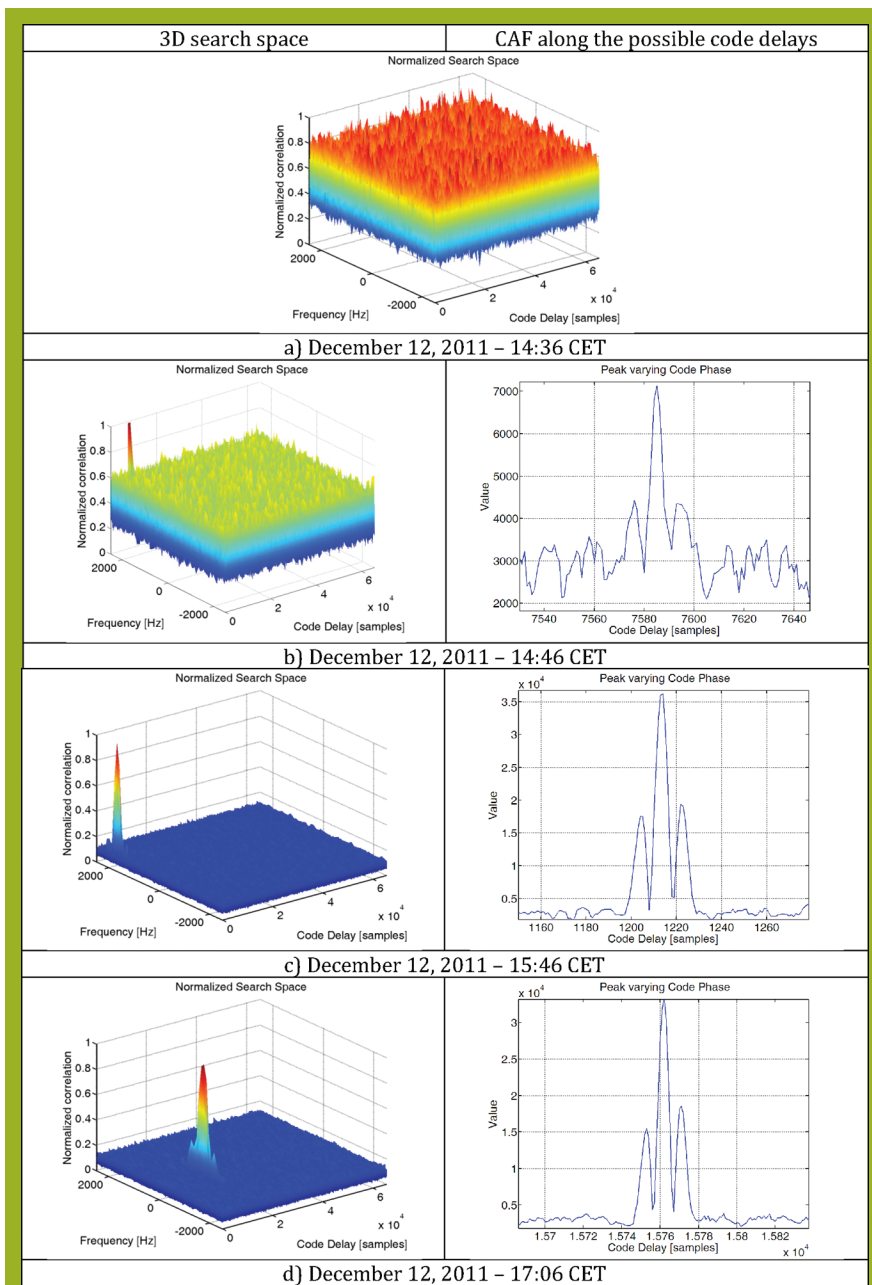
ESA/CNES/ARIANESPACE/Optique Video Du CSG

3D search space	CAF along the possible code delays

a) December 12, 2011 – 14:36 CET

b) December 12, 2011 – 14:46 CET

c) December 12, 2011 – 15:46 CET

d) December 12, 2011 – 17:06 CET

FIGURE 2 Search space of various signal-acquisition runs, along the first transit of the satellite with switched-on navigation payload, on December 12, 2011

sions: code delays and Doppler frequency shifts. These CAFs are obtained performing 11 noncoherent accumulations of four-millisecond coherent integration times.

On the right-hand side, the figure displays the signal correlations along the code delay axis, for a fixed value of Doppler shift corresponding to the maximum of the CAF. Here, the profile of the typical BOC(1,1) autocorrelation function is expected to emerge, at least for medium-high values of C/N_0 ratio.

First, Figure 2a shows the CAF over the whole search space during a trial that started at 14:36 CET. No correlation peaks emerge clearly yet.

The following trial (Figure 2b), initiated at 14:46 CET, successfully reveals the presence of the Galileo signal: the correlation peak rises above the noise floor. In this case, the code correlation function (see right-hand panel) is not clear enough to recognize the typical BOC(1,1) autocorrelation shape, as the side peaks are buried in the noise floor.
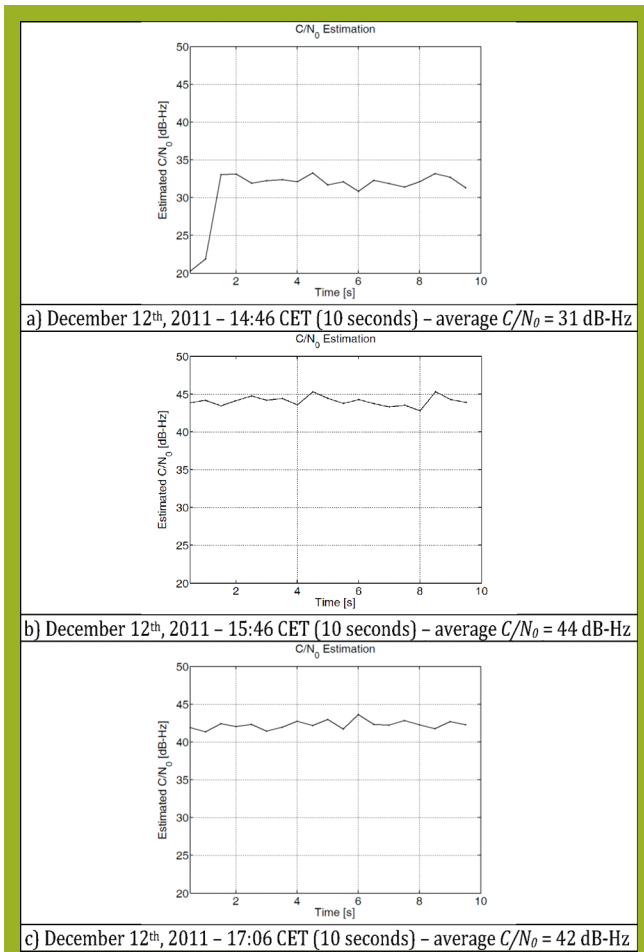
FIGURE 3 Sample profiles of Galileo–PFM E1 signal C/N_0, as measured at the receiving antennas during three data recording sessions
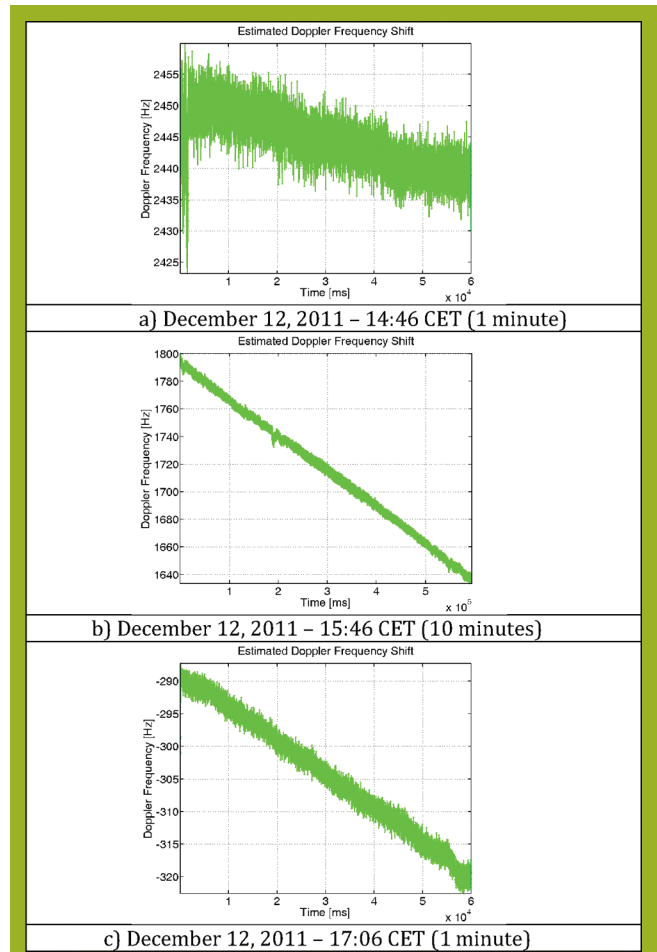

FIGURE 4 Sample profiles of Doppler frequency estimates, measured during three data collections

Consequently, we expected to measure a low C/N_0 for the signal of such a data set.

From 14:46 to 17:06 CET, the trials were all successful in terms of valid acquisition peak, recognized in each acquisition run. Figure 2c and Figure 2d present two other examples of CAF, corresponding to the datasets of 15:46 and 17:06 CET respectively.

Note that, in these cases, the BOC(1,1) autocorrelation profile is visible in the code correlation in the right-hand panel. Indeed, in these cases we expect to find higher C/N_0 values.

C/N_0 estimates. Once the receiver began operating in the tracking mode, we were able to estimate the C/N_0 ratio of the satellite signal at the receiving antenna. **Figure 3** shows the time sequence of the estimated C/N_0 during the 10 seconds following signal acquisition for the datasets collected and recorded at 14:46, 15:46, and 17:06, respectively.

One can observe that the profiles are nearly constant throughout the 10-second periods. Furthermore, it is interesting to notice that the average values of the three profiles (namely, 31 dB-Hz, 44 dB-Hz, and 42 dB-Hz) meet our initial hypothesis on the C/N_0 trend, based on the simple observation of the corresponding code correlation profiles in Figure 2.

Doppler Profiles. Figure 4 presents a third measure of the successful tracking experiment by plotting the Doppler frequency as estimated by the phase lock loop (PLL) along a one-minute time interval for the data collections started at 14:46 and 17:06, and along a 10-minute time interval for the data collection that began at 15:46.

In all the three cases the PLL correctly tracks the Galileo signal and provides a good estimate of the Doppler frequency. An incidental note: as the satellite passes through the sky over Torino and the satellite/receiver line-of-sight angle changes accordingly, the estimated Doppler frequency decreases.

Combined observation of C/N_0 and Doppler profiles provided some additional insights about the transmitting satellite. For example, we can see that the Doppler estimate was quite noisy (Figure 4a) in the data collection of 14:46, because the corresponding C/N_0 was low (Figure 3a). In contrast, the data collections of 15:46 and 17:06 show a higher C/N_0 (Figure 3b and Figure 3c) and a more accurate Doppler estimate (Figure 4b and Figure 4c).

Identifying the Transmitting Satellite

Because two IOV satellites — PFM and Flight Model 2 (FM2) — were launched simultaneously on October 21 and were relatively close together in the same
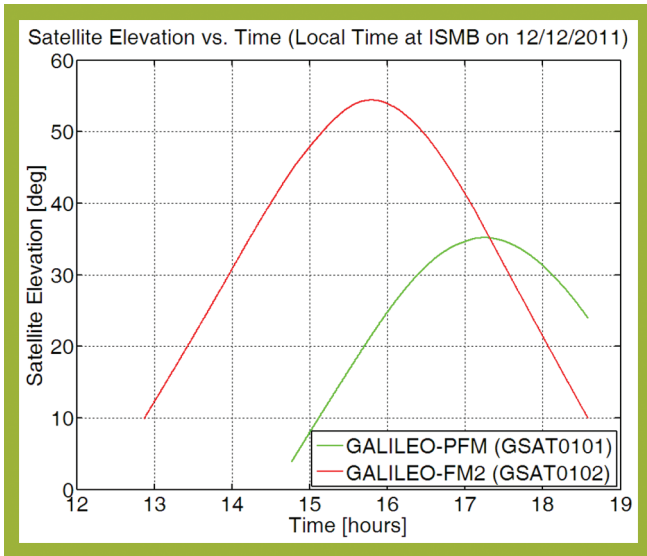
FIGURE 5 Elevation pattern versus CET of the PFM and FM2 satellites over Torino on December 12, 2011
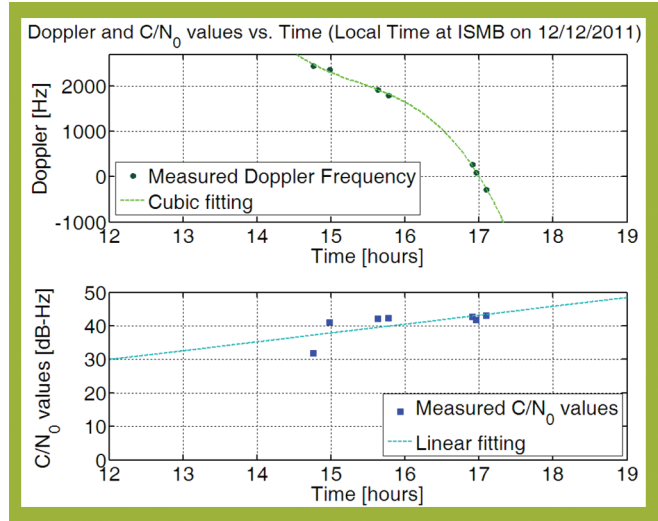

FIGURE 6 Estimated Doppler and C/N$_0$ profiles along several afternoon hours on December 12, 2011

orbital plane, they were both visible at the same time during much of the observation period. However, the rooftop antenna at ISMB used to receive the signal was non-directional and consequently provided no spatial information to help us determine which satellite was likely transmitting.

However, knowing the satellite elevation during each data collection period usually helps to make preliminary assessments of the quality of the received signal. To overcome this lack of information, we tried to get more insight about the identity of the transmitting satellite by observing the estimates of the Doppler and C/N$_0$ profiles with respect to the elevation pattern of the two possible transmitters.

Figure 5 shows the elevation patterns of Galileo-PFM and Galileo-FM2 during the afternoon of December 12, as obtained from prediction visibilities based on NORAD tracking information (two-line elements of Galileo satellites downloaded on 12/12/2011 from the CelesTrack website). **Figure 6** shows both the estimated Doppler and C/N$_0$ profiles during the same time interval.

Direct comparison of Figure 5 and Figure 6 enabled us to observe a quite clear correspondence of the signal measurements with the elevation pattern of Galileo-PFM: as long as the satellite raises over the horizon, the Doppler estimate decreases from about 2300 Hz to
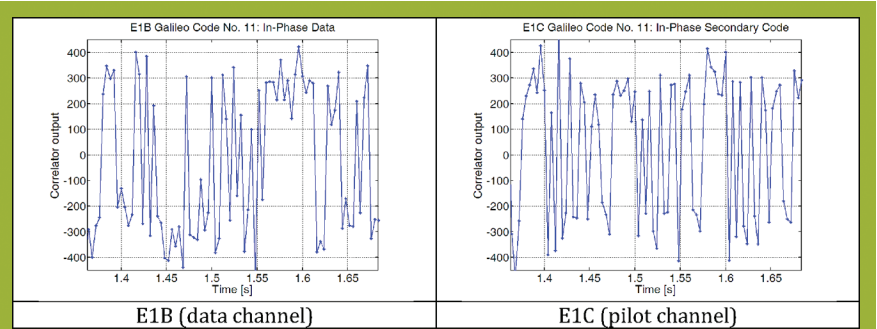

E1B (data channel)   E1C (pilot channel)

FIGURE 7 Galileo signals navigation data samples

a) December 14, 2011 – E5a-I – 10:53 CET

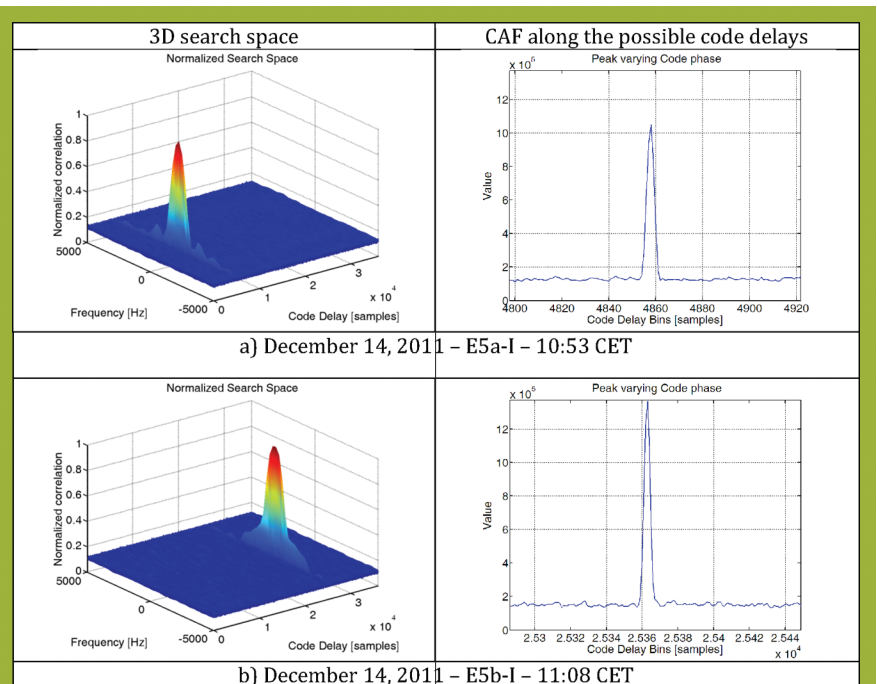b) December 14, 2011 – E5b-I – 11:08 CET

FIGURE 8 Search space of different acquisition runs, along the passage of the satellite with switched-on payload, on December 14, 2011

Description from ICD	Test at GATE	Test of IOV signal
Word 2	Word 2	Reserved (word type 63)
Word 4	Word 4	Reserved (word type 63)
Word 6	Word 6	Reserved (word type 63)
Word 7 or 9	Word 7 or 9	Reserved (word type 63)
Word 8 or 10	Word 8 or 10	Reserved (word type 63)
Reserved	Reserved	Word 0 (Spare)
Reserved	Reserved	Word 0 (Spare)
Reserved	Reserved	Word 0 (Spare)
Reserved	Reserved	Word 0 (Spare)
Reserved	Reserved	Word 0 (Spare)
Word 1	Word 1	Reserved (word type 63)
Word 3	Word 3	Reserved (word type 63)
Word 5	Word 5	Reserved (word type 63)
Word 0 (Spare)	Word 0 (Spare)	Word 0 (Spare)
Word 0 (Spare)	Word 0 (Spare)	Word 0 (Spare)

TABLE 1. Comparison of navigation message structures.

less than -100 Hz, while the C/N_0 estimates increase from about 30 dB-Hz to about 43 dB-Hz. On the contrary, these patterns are incompatible with the path of GALILEO-FM2.

Navigation Data & Message Decoding

Figure 7 shows a sample of the tracking output, namely the in-phase part of the "prompt" correlation of both E1B and E1C signals.

Table 1 reports the results of navigation message decoding on E1B and the comparison with the structure of a complete frame of the navigation message described in the Galileo interface control document (ICD).

In order to have another term of reference, we also compared the results with those obtained processing a data set taken at the Germany's Galileo Test and Development Environment (GATE) several months ago, using the same software receiver.

In the signal received from the Galileo satellite, the receiver demodulated two types of page only: reserved (word type field with value 63) and type 0 (spare). Word 0 contains information about the Galileo system week number (WN) and time of week (TOW). The receiver found a WN equal to 642 and an initial TOW equal to 136047. In **Table 2**, a sample text log of the decoding procedure is also included.

Processing the E5 Signal

The following section will present some results obtained from processing the stored data collections recorded in the morning of December 14, 2011, on the E5 band.

Signal Acquisition. Figure 8 shows results obtained by performing signal acquisition on two sets of E5 data, from the data channels E5a-I and E5b-I, respectively. The CAFs, plotted in the left-hand panels, are computed over the 2D acquisition search space; on the right side, the figure shows signal correlations along the code delay axis for a fixed value

```
WORD 2: EPHEMERIS (2/4)
        IOD: 9
        omega_0: 1.33001
        i_0: 1.06465
        omega: 0
        iDot: 1.07147e-12
WORD 4: EPHEMERIS (4/4) and CLOCK
CORRECTION PARAMETERS
        IOD: 9
        prn: 2
        C_ic: 5.58794e-09
        C_is: 1.02445e-07
        C_oc: 288180
        a_f0: -0.000547382
        a_f1: 2.42821e-10
        a_f2: 0
WORD 6: GST-UTC CONVERSION
PARAMETERS
WORD 9: ALMANAC FOR SVID2 (2/2)
        SVID3: 33
WORD 10: ALMANAC FOR SVID3 (2/2)
and GST-GPS CONVERSION PARAMETER
        A_0G: -8.76607e-08
        A_1G: 0
        t_0G: 288000
        WN_0G: 3
RESERVED WORD
RESERVED WORD
RESERVED WORD
RESERVED WORD
RESERVED WORD
WORD 1: EPHEMERIS (1/4)
        IOD: 9
        t_oe: 288000
        M_0: 2.02479
        e: 0
        sqrtA: 5.440617e+03
WORD 3: EPHEMERIS (3/4) and SISA
        IOD: 9
        omegaDot: -4.79163e-09
        deltan: -1.54399e-09
        C_uc: -3.67872e-06
        C_us: 2.12528e-06
        C_rc: 153.062
        C_rs: -135.562
        SISA: 120
WORD 5: IONOSPHERIC CORRECTION,
BGD, SIGNAL HEALTH and DATA VALIDITY
STATUS and GST
        T_GD: -3.86499e-08
        WN: 579
        TOW: 288295
        SatStatus: 0
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 579
        TOW: 288297
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 579
        TOW: 288299
```

```
RESERVED WORD
RESERVED WORD
RESERVED WORD
RESERVED WORD
RESERVED WORD
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 642
        TOW: 136811
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 642
        TOW: 136813
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 642
        TOW: 136815
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 642
        TOW: 136817
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 642
        TOW: 136819
RESERVED WORD
RESERVED WORD
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 642
        TOW: 136827
SPARE WORD 0: EPHEMERIS (1/4)
        WN: 642
        TOW: 136829
RESERVED WORD
RESERVED WORD
RESERVED WORD
RESERVED WORD
RESERVED WORD
```

TABLE 2 Sample text log of the decoding procedure for the GATE (left) and the IOV signal (right)

a) December 14, 2011 – E5a – 10:53 CET (8 seconds) – average C/N_0 = 34 dB-Hz

b) December 14, 2011 – E5b – 11:08 CET (8 seconds) – average C/N_0 = 36 dB-Hz
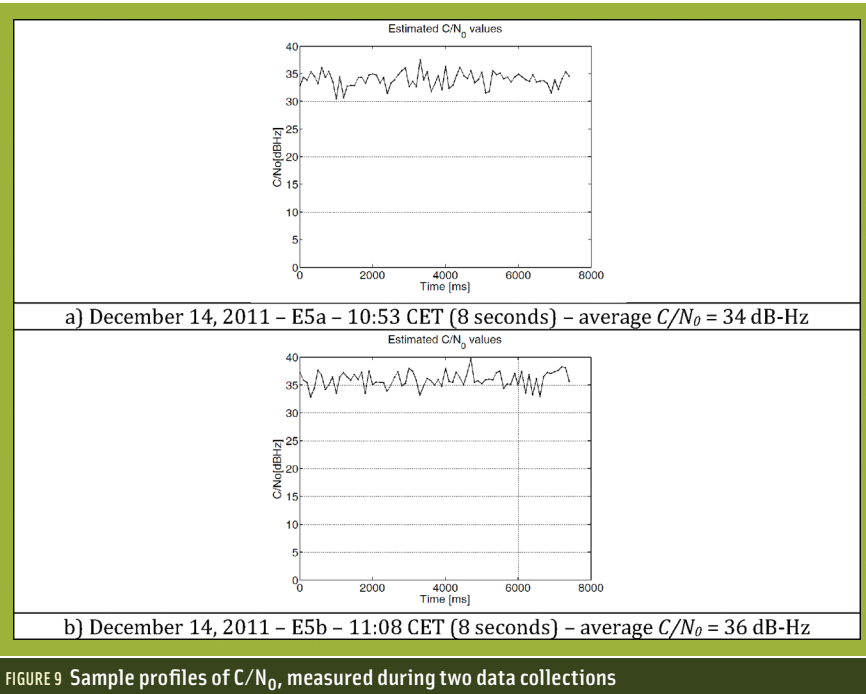
FIGURE 9 Sample profiles of C/N_0, measured during two data collections

of Doppler shift corresponding to the CAF maximum.

In particular, Figure 8a shows the acquisition results over the whole search space obtained processing the dataset on E5a-I, starting at 10:53 CET; Figure 8b shows the same plot related to the data acquired on E5b-I, at 11:08 CET.

Both the trials reveal the presence of the Galileo signal, in terms of valid acquisition peaks. It is worth noticing that, in these cases, the BPSK autocorrelation profile is visible in the code correlations in the right-hand panels.

C/N_0 estimates. As in the previous case, described in Section 2, once the receiver entered the tracking mode, we could estimate the C/N_0 ratio of the satellite signal at the receiving antenna. **Figure 9** shows the estimated C/N_0 during eight seconds of the data collections recorded at 10:53 and 11:08, respectively. Again, one can observe that the profiles are nearly constant throughout the collection period.

Pilot Verification. The E1C signal contains a periodic pilot sequence of 25 secondary code chips. We verified the consistency of the tracking output over the

received signal (see Figure 7) with the pilot sequence described in the ICD. A graphical representation of such a comparison is shown in **Figure 10**.

Joint GPS+Galileo Position Solution

In order to check both the accuracy of the ephemeris broadcast by the Galileo satellite and the possibility of combining GPS and Galileo observations to obtain a joint position, velocity, and time (PVT) solution, we performed a data collection in static condition on December 21, 2011, at 09:48:00. A snapshot of all the satellites in view at the time of the experiment and used for the PVT is reported in **Figure 11**.

As we can see from Figure 11, the elevation of the Galileo satellite was of 40.9 degrees; its decoded ephemeris has been reported in Table 2.

By using our N-GENE software receiver we were able to test the joint PVT computation algorithm. 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, 30) were taken into account, on the basis of the best GDOP (geometrical dilution of precision) obtainable, while in the second case also the Galileo PFM satellite was included. This inclusion led to a slight improvement of the overall GDOP.

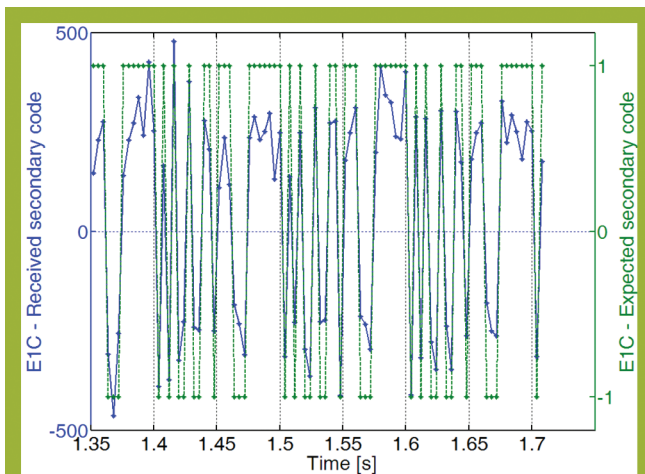**Figure 12** reports the estimated position computed by using the two afore-

FIGURE 10 Comparison between the secondary code in the received signal and the expected one.
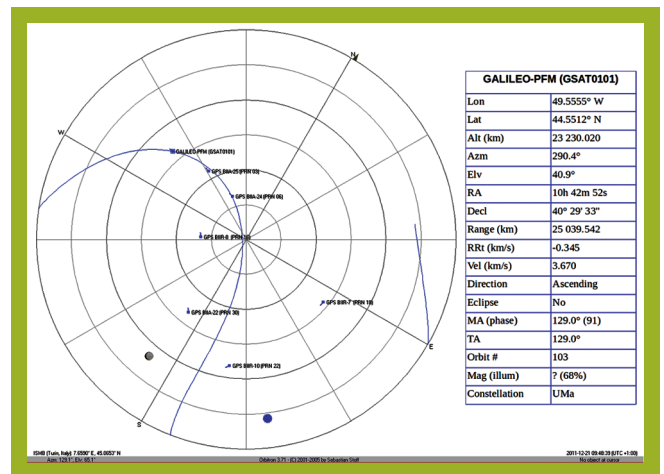

GALILEO-PFM (GSAT0101)	
Lon	49.5555° W
Lat	44.5512° N
Alt (km)	23 230.020
Azm	290.4°
Elv	40.9°
RA	10h 42m 52s
Decl	40° 29' 33"
Range (km)	25 039.542
RRt (km/s)	-0.345
Vel (km/s)	3.670
Direction	Ascending
Eclipse	No
MA (phase)	129.0° (91)
TA	129.0°
Orbit #	103
Mag (illum)	? (68%)
Constellation	UMa

FIGURE 11 GPS and the Galileo–PFM satellite (red circle) acquired on December 21, 2011, at 09:48:00 CET. Orbit information of the Galileo PFM is shown on the right side.

mentioned satellites scenarios, as well as the error of the PVT solution with respect to the position of the georeferenced antenna, placed on the roof of the ISMB building. Notice that the position solution provided by N-GENE was based on code-phase measurements only: this is the reason for a certain spread of the obtained estimates.

Figure12b clearly shows how the Galileo measurements contribute to reducing the error of the PVT solution with respect to the case of the GPS stand-alone, thanks to the additional satellite that improved the global satellite geometry. In the case of a combined GPS+Galileo PVT solution, the error is always confined within six meters, while in the GPS-only scenario we have instants where the estimated position is more than eight meters away from the true position.

More studies need to be carried out to really understand the benefit of using a Galileo satellite in the PVT, but, from now on, a Galileo-ready GNSS receiver has the opportunity to take one more satellite in the PVT computation and it can decide whether to exploit it or not.

Conclusions

In this article we have shown the first results from working with the IOV Galileo signals. We verified the transmission of the Galileo Code Number 11 from the Galileo-PFM satellite in the afternoon of December 12, 2011. We also demonstrated successful acquisition, tracking, and data demodulation of the E1 signal on both data and pilot channels, using a GPS+Galileo software receiver, whereas the navigation message, although compatible with the ICD structure, were in dummy mode.

Thanks to our observations, we were able to detect also the presence of the signal on the E5 band in the morning of December 14, 2011. We received the signal with a lab front-end prototype, storing raw samples on disk for post processing analysis. We were able to successfully acquire and track the signals on both E5a and E5b bands.

Finally, on December 21, 2011, we were able to observe a complete and valid navigation message and to successfully perform the first joint GPS+Galileo PVT solution.

Manufacturers

The commercial GPS/Galileo front-end used in the experimental setup for E1 signal acquisition was a SE4120L GNSS radio front-end IC from **SiGe Semiconductor, Inc.**, Andover, MA, Canada (now **Skyworks Solutions, Inc.**, Woburn, Massachusetts, USA). The prototype front-end for the E5 data recording sessions was built at the Nav-SAS lab with COTS components from **Mini-Circuits, Inc.**, Brooklyn, New York, USA, and **TTE, Inc.**, Los Angeles, California, USA.

Some of the data presented in this article was plotted using MATLAB from
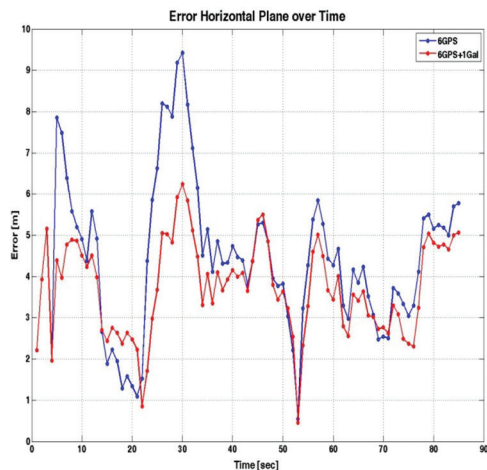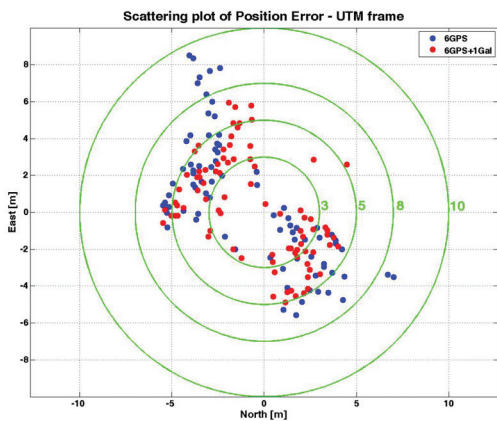
a)   Google Earth plot of the computed position of the two satellites' scenario (only GPS in blue and GPS+Galileo in red)

b)   Horizontal error of two different PVT solutions over time(only GPS in blue and GPS+Galileo in red)

c)   Scattering diagram of the error in UTM coordinates with respect to the location of the antenna.

FIGURE 12 Results of a joint GPS+Galileo PVT (in red) compared with a stand-Alone GPS PVT (in blue)

The Mathworks, Inc., Natick, Massachusetts, USA. The aerial imagery in Figure 12 used Google Earth, from Google, Inc., Mountain View, California, USA.

Additional Resources

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

[2] Falletti, E., and M. Pini, L. Lo Presti, and D. Margaria, "Assessment on Low Complexity C/N0 Estimators Based on M-PSK Signal Model for GNSS Receivers," in *Position, Location and Navigation Symposium, 2008 IEEE/ION,* pp. 167–172, May 5–8, 2008

[3] Fantino, M., and A. Molino and M. Nicola, "N-GENE GNSS Receiver: Benefits of Software Radio in Navigation," in *Proceedings of the European Navigation Conference ENC 2009,* Napoli (Italy), May 3–6, 2009

[4] Fernandez-Prades, C., and L. Lo Presti and E. Falletti, "Satellite Radiolocalization from GPS to GNSS and Beyond: Novel Technologies and Applications for Civil Mass Market," in *Proceedings of the IEEE,* vol. 99, no. 11, pp. 1882–1904, November 2011

[5] Galileo Test and Development Environment website: http://www.gate-testbed.com

[6] *Galileo Open Service Signal in Space Interface Control Document (OS SIS ICD),* Issue 1.1, September 2010

Authors

The Navigation, Signals Analysis, and Navigation (NavSAS) group, a joint team of the Istituto Superiore Mario Boella and Politecnico di Torino, Italy, include 26 people, among them the authors of this article. The authors are grateful to all the other members of the group, without the support of which these results would have been hardly achieved. In particular, a special acknowledgement is addressed to Prof. Letizia Lo Presti, for her constant encouraging and brilliant guidance.

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NICOLA LINTY is a Ph.D. student in the Electronics and Telecommunications Department at Politecnico di Torino, Italy. His research interest is mainly focused on the development of architectures for high performance GPS and Galileo receivers.

ALFREDO FAVENZA received the Master of Science in computer science from the Università degli Studi

A photo of the NavSAS group (December 2011)

di Torino. His research activity is focused on software defined radio technologies applied to GNSS receivers.

MARIO NICOLA received a Ph.D. degree in electrical and communications engineering from Politecnico di Torino, Italy. His activity is focused on the implementation of algorithms for fully software GPS/Galileo receivers.

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GIANLUCA FALCO received a B.S. in telematics engineering and an M.S. in communication engineering and a Ph.D. degree. Since 2008 he has been with the NavSAS group of Istituto Superiore Mario Boella where he developed a loosely-coupled and tightly-coupled approach for a GPS/INS integration. His interest has been mainly focused on multi-sensors fusion, particularly between GPS and inertial navigation systems, as well as on processing techniques for GNSS-reflectometry and remote sensing.

EMANUELA FALLETTI holds a Ph. D. degree in electrical and communications engineering from Politecnico di Torino, Italy. Her current research interests cover digital signal processing for GNSS receivers, in particular signal quality control in the presence of interference and multipath, and signal simulation.

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