GIOVE-A SIS Experimentation and Receiver Validation: Laboratory Activities at ESTEC

Massimiliano Spelat[1], Massimo Crisci[2], Martin Hollreiser[2], Marco Falcone[2]

[1]Politecnico di Torino/Electronics Department
C.so Duca degli Abruzzi 24, 10129 Torino, ITALY
Phone: +39(011)2276436, Fax: +39(011)2276299
e-mail: massimiliano.spelat@polito.it
[2]European Space Agency (ESTEC)
Keplerlaan 1, P.O. Box 299, 2200 AG Noordwijk,The Netherlands
e-mail: Marco.Falcone@esa.int, Martin.Hollreiser@esa.int, Massimo.Crisci@esa.int

Abstract. The European Space Agency (ESA) and the Surrey Satellite Technology LTD (SSTL) have completed the on-orbit preparation and activated the payload of GIOVE-A, the first Galileo satellite launched last December, the 28th. After successful launch and platform commissioning achievement, GIOVE-A started signals transmission on 12 January 2006. For the time being the quality of the signal broadcast by GIOVE-A is under examination by mean of sophisticated equipments and facilities, including the ESA ground station in Redu (Belgium) and the Rutherford Appleton Laboratory (RAL) Chilbolton Observatory in the United Kingdom. It is clear that the European Galileo satellite navigation system is moving into a crucial phase concerning the development process; therefore the possibility of testing and validating hardware/software tools (e.g. user receivers) will play a key role from the manufacturers point of view. In this context the navigation laboratory at ESA's European Space Research and Technology Centre (ESTEC), in the Netherlands, could be considered relevant in the receivers validation procedures, as well as in the Signal-In-Space (SIS) experimentation activity, where the GSTB-v2 Experimental Test Receiver (GETR) plays a key role.

The paper will provide the overview of the set-up available in the navigation laboratory at ESTEC, describing the equipments composing the test bench. The Galileo Signal Validation Facility (GSVF-v2) will be presented pointing out the capabilities in the Galileo-like signal generation. In particular, the Galileo L1 Open Service (OS) signal will be analyzed, and the corresponding GETR tracking performance will be presented in terms of code tracking noise curves, autocorrelation function and multipath envelope. Tracking performance for the Galileo L1 OS signal in multipath environments will be evaluated in terms of static and dynamic contributions.

Finally, some screenshots of the GETR graphical user interface (while tracking GIOVE-A signals) will also be included in the paper, as the prove that the entire set-up has been fully integrated with the Space Engineering's Galileo antenna for the reception and process of live GIOVE-A signals.

1 Introduction

The European navigation satellite system Galileo is now becoming a reality entering the so called *Galileo System Test Bed – phase2* (GSTB-v2) development phase, where live radio-navigation signals are broadcast worldwide by the first of the two test satellites, GIOVE-A [1]. This name stands for *Galileo In-Orbit Validation Element* being part of the future IOV constellation, which will be constituted by 4 satellites. Formerly called GSTB-v2, the GIOVE mission has to secure the frequencies allocated for the Galileo system, characterise the radiation environment of the orbits (the *Medium Earth Orbit* – MEO environment), confirm technologies for the navigation payloads architecture of future operational Galileo satellites and perform the *Signal-In-Space* (SIS) experimentation, where the *GSTB-v2 Experimental Test Receiver* (GETR) developed by Septentrio plays a key role [2]. GIOVE-A has been placed in orbit by a Soyuz-Fregat rocket operated by Starsem on 28 December 2005 from the Baikonur Cosmodrome, with the aim of representing the starting point of the Galileo In-Orbit Validation phase. GIOVE-A has been transmitting Galileo-like signals from the beginning of January 2006, carrying a payload is able to generate and transmit the nominal GALILEO L1, E6 and E5 modulations and multiplexing schemes including the *Binary Offset Carrier* (BOC) modulated signals (e.g. BOC(15,2.5) and BOC(1,1)) as well as the wideband *AlternativeBOC* (AltBOC) modulation [3]. This 600 kg satellite, built by *Surrey Satellite Technology Ltd* (SSTL) of Guildford in the United Kingdom, carries two redundant, small-size rubidium atomic clocks, each with a stability of 10 nanoseconds per day, and two signal generation units, one able to generate a simple Galileo signal and the nominal one, more representative in terms of Galileo signals. These two signals are broadcast through an L-band phased-array antenna designed to cover all of the visible Earth under the satellite. Finally, two on-board instruments are monitoring the types of radiation to which the satellite is exposed during its two year mission.

For the time being the quality of the signals broadcast by GIOVE-A is monitored (continuosly or during specific measurement campaign) by means of several facilities, including the *Rutherford Appleton Laboratory* (RAL) Chilbolton Observatory in the United Kingdom, the *European Space Agency* (ESA) ground station at Redu, in Belgium, and the Navigation Laboratory at ESA's *European Space Research and Technology Centre* (ESTEC), in the Netherlands. As far as the SIS experimentation activity is concerned, it is meant to provide supporting data for the frequency filing, characterise the performance of the Galileo SIS and confirm the GETR performance and consolidate the receiver design. Given the nature of the measurements required by such an activity, the SIS experimentation phase has been designed to be carried out using both the Chilbolton 25m-diameter antenna with high gain, and the L1-E6-E5 Galileo Reference Antenna developed by Space Engineering. In order to prepare and fully support the activities, a dedicated test bench has been set-up in the Navigation Laboratory at ESTEC. The paper gives an overview of this test bench, considering that the procurement of hardware and software has been driven by the necessity to reproduce the SIS experimentation environments for the GETR before the real signal in space was available. The content of the paper is focused on the analysis of results provided by the receiver processing the L1 Opens Service (OS) signal. In particular, results are presented identifying two different phases:

- **Phase1,** functional verification and validation of the equipments employed in the test bench
- **Phase2,** results on the GETR performance validation

The verification and validation of the laboratory setup (**Phase1**) consists in testing the equipments with the aim of getting results that have to match the expected ones (theoretical or simulated). For such a reason both the *Galileo Signal Validation Facility* (GSVF-v2) [4] and the GETR have been carefully tested, and some results in terms of spectrum of the signals, correlation functions, multipath envelopes and code tracking noise curves are presented. The GETR performance validation (**Phase2**) consists in testing the receiver performance under GSVF-2 simulated environment conditions (multipath and interference contributions). The paper analyses the GETR in terms of code tracking error (standard deviation and bias) describing as an example the following user environments: *Rural Vehicle* (RV), *Rural Pedestrian* (RP) and fixed scenarios.

The paper presents also the reception of ‘live’ GIOVE-A signals. Therefore screenshots of the GETR are included in the paper proving the functionality.

2 Test Bench Description

Considerable amount of data will be collected during this phase in order to confirm and steer the design development of the Galileo program segments. It is clear that a reliable understanding of the results analysis can be achieved only if consolidated reference performance results, obtained in realistic and controlled environments, are available. In this way the isolation of each error contribution becomes possible, and it is useful to prevent possible malfunctioning being able to test the receiver in exhaustive number of environment conditions. That is the idea behind the realisation of the test bench shown in Fig. 1, where both the “Real-Time” and “Post-Processing” branches allow for the acquisition and analysis of GIOVE-A signals, whether they are coming from the satellite or the Galileo RF signal generator.

The Galileo Signal Validation Facility together with the Spirent GPS constellation simulator [5] have been integrated with the early prototype of the Galileo receiver, the GETR, being able to acquire and track the ad-hoc generated SIS and the “live” signal coming from the Galileo User Antenna capable of operating also in the GPS bands (L1, L2 and L5). The quality of these signals can be checked in real-time by means of sophisticated real-time analysis tools such as the spectrum analyser and the digital oscilloscope, or in post-processing storing samples of the signal using the bitgrabber (a flexible digitaliser in terms of sampling frequency and quantisation) jointly with specific software tools.

Considering the equipment shown in Fig. 1, a Matlab®-based tool has been developed in order to process and analyse raw output data of the GETR, being able to characterise the list parameters defined for the SIS experimentation activity. The tool has been called *GETRdat* and was used whether during the functional verification and validation of the equipments or in the GETR performance analysis and validation. An introduction on the architecture of the tool is given in 3, pointing out the capabilities concerning in terms of data analysis.

2.1 Galileo Signal Validation Facility

The Galileo Signal Validation Facility, the GSVF-v2, has been developed by *Thales Research and Technology UK* (TRT-UK) for ESA representing the reference in the

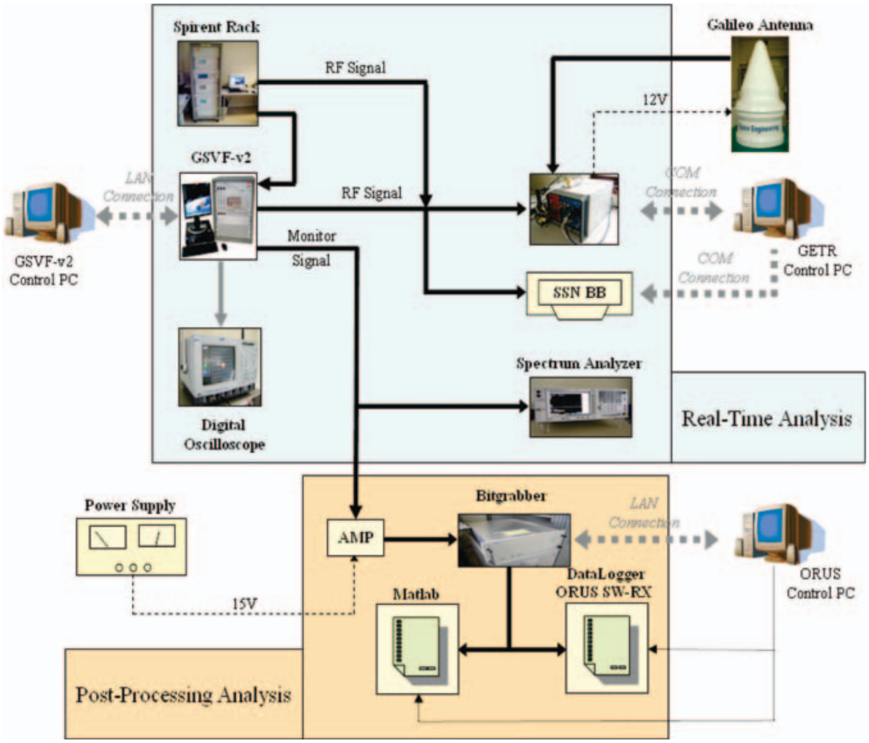


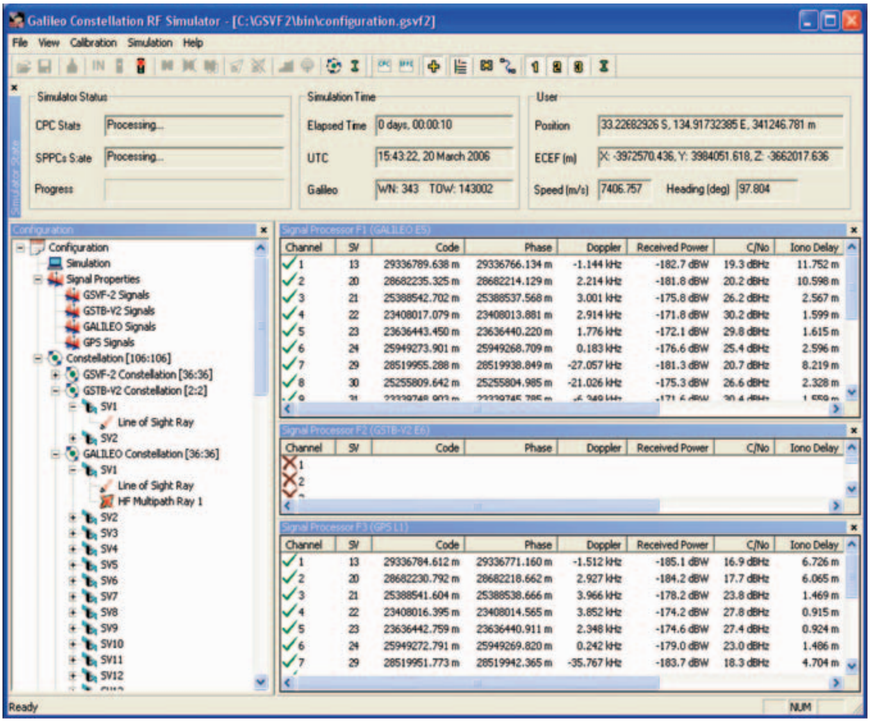
Fig. 1. Test bench in the navigation lab at ESTEC.

field of signal generators for Galileo. The GSVF-v2 constellation RF simulator shown in Fig. 2 is capable of generating a single composite L-band signal fully representative for all three Galileo frequencies from all satellites in view of the user. As it is possible to see in Fig. 2, the simulator consists of the *Control PC* (CPC) and a 19” rack, where three embedded PCs are installed for the 50 Hz pseudorange computations, antenna, clock and high-fidelity multipath modelling, and navigation data elaboration and formatting. Each PC drives a dedicated FPGA-based baseband board responsible for generation of code, phase, gain and navigation data updates at 50 Hz. Each baseband board can generate a single baseband signal for up to 16 satellites (channels) [4].

A generic channel implements models for code and chip modulations generation, Doppler and amplitude variations as well as for the *High Power Amplifier* (HPA) distortion. Moreover, each channel has the possibility of generating fading, shadowing and multipath delay on top of the *Line-Of-Sight* (LOS) signal. Finally, the RF signal is generated by the RF up-conversion module, which combines the three baseband signal to L-band with the possibility of mixing external antenna or interferer signals.

Figure 3 shows the *Graphical User Interface* (GUI) of the simulator, which provides the user with an high level of flexibility in configuring the models for the Galileo signal generation. The simulator is fully compliant against Galileo and

Fig. 2. The Galileo signal validation facility.



Simulator Status

CPC State: Processing...

SPPCs State: Processing...

Progress:

Simulation Time

Elapsed Time: 0 days, 00:00:10

UTC: 15:43:22, 20 March 2006

Galileo: WN: 343 TOW: 143002

User

Position: 33.22682926 S, 134.91732385 E, 341246.781 m

ECEF (m): X: -3972570.436, Y: 3984051.618, Z: -3662017.636

Speed (m/s): 7406.757 Heading (deg): 97.804

Signal Processor F1 (GALILEO E5)

Channel	SV	Code	Phase	Doppler	Received Power	C/No	Iono Delay
✓ 1	13	29336789.638 m	29336766.134 m	-1.144 kHz	-182.7 dBW	19.3 dBHz	11.752 m
✓ 2	20	28682235.325 m	28682214.129 m	2.214 kHz	-181.8 dBW	20.2 dBHz	10.598 m
✓ 3	21	25388542.702 m	25388537.568 m	3.001 kHz	-175.8 dBW	26.2 dBHz	2.567 m
✓ 4	22	23408017.079 m	23408013.881 m	2.914 kHz	-171.8 dBW	30.2 dBHz	1.599 m
✓ 5	23	23636443.450 m	23636440.220 m	1.776 kHz	-172.1 dBW	29.8 dBHz	1.615 m
✓ 6	24	25949273.901 m	25949268.709 m	0.183 kHz	-176.6 dBW	25.4 dBHz	2.596 m
✓ 7	29	28519955.288 m	28519938.849 m	-27.057 kHz	-181.3 dBW	20.7 dBHz	8.219 m
✓ 8	30	25255809.642 m	25255804.985 m	-21.026 kHz	-175.3 dBW	26.6 dBHz	2.328 m

Signal Processor F2 (GSTB-V2 E6)

Channel	SV	Code	Phase	Doppler	Received Power	C/No	Iono Delay
✗ 1							
✗ 2							

Signal Processor F3 (GPS L1)

Channel	SV	Code	Phase	Doppler	Received Power	C/No	Iono Delay
✓ 1	13	29336784.612 m	29336771.160 m	-1.512 kHz	-185.1 dBW	16.9 dBHz	6.726 m
✓ 2	20	28682230.792 m	28682218.662 m	2.927 kHz	-184.2 dBW	17.7 dBHz	6.065 m
✓ 3	21	25388541.604 m	25388538.666 m	3.966 kHz	-178.2 dBW	23.8 dBHz	1.469 m
✓ 4	22	23408016.395 m	23408014.565 m	3.852 kHz	-174.2 dBW	27.8 dBHz	0.915 m
✓ 5	23	23636442.759 m	23636440.911 m	2.348 kHz	-174.6 dBW	27.4 dBHz	0.924 m
✓ 6	24	25949272.791 m	25949269.820 m	0.242 kHz	-179.0 dBW	23.0 dBHz	1.486 m
✓ 7	29	28519951.773 m	28519942.365 m	-35.767 kHz	-183.7 dBW	18.3 dBHz	4.704 m

Fig. 3. GSVF-v2 Simulator user interface.

GSTB-v2 SIS *Interface Control Documents* (ICD) for those parts of the specifications which would provide benefits in terms of receiver testing and validation, waiting for the consolidation of the Galileo C/NAV and I/NAV navigation message definition (see Table 1). Anyway, although the implementation of both the C/NAV and I/NAV data streams are not finalised yet, the simulator message contains random data with the appropriate CRC, FEC and interleaving implemented. The GSVF-v2 does not support generation of nominal *Public Regulated Services* (PRS) signals in terms of spreading codes and navigation messages. Since these signals are classified, the simulator emulates them using very long random codes with the correct chip rate and random bits representing the modulated data message [4].

It is important to remark that the GSVF-v2 environment models are fully inline with the Galileo reference specification documents, including those for the troposphere, ionosphere and multipath. As far as the multipath is concerned, elevation and azimuth-dependent models are supported generating multipath ray delay, phase shift and relative amplitude on the basis of actual site survey data. In addition to these geometrical models, the GSVF-v2 also implements linearly varying periodic multipath ray characteristics, as well as the possibility of reading these characteristics from a file as a time-based series. Since the flexibility in modelling the multipath environment is one of the most important feature, the simulator provides two classes of multipath ray generation:

- High-fidelity, quantising the generated multipath delay in 11.1 ns steps
- Low-fidelity ray, using dedicated hardware resources without restriction in terms of ray modelling

Four low-fidelity rays for each space vehicle are always supported by the simulator, while the maximum configuration using high-fidelity rays is represented by a 47 high-fidelity rays on top of a single LOS (because the number of channels in the simulator is limited to 48, 16 for each baseband board). Rayleigh fading models can be applied to the multipath ray specifying the fading bandwidth in the range 1mHz – 2.4 kHz. Finally, the LOS supports Rician fading settings (configurable mean state duration) for both the "good" or "bad" states controlled by a Markov model.

Table 1. GSVF-v2 signal compliance.

System specifications	E5			
	E5a	E5b	E6	L1
GSVF-v2 Iss.4		Full compliance		
Galileo Iss.11 Rev.2	Full signal And F/NAV compliance	Full signal compliance. Compliant navigation message framing and encoding. E6-A and L1-A PRS codes emulated with random codes.		
GSTB-v2 Iss.2 Rev.2	Full signal and OS compliance	Full signal compliance. Compliant navigation message framing and encoding		

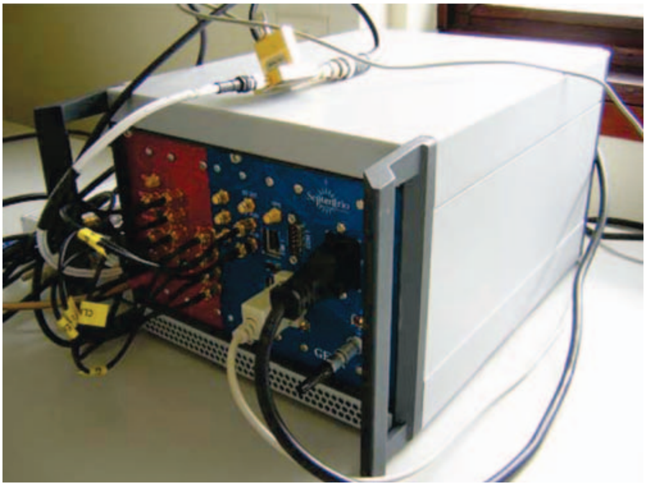


Fig. 4. GSTB-v2 experimental test receiver.

2.2 GSTB-v2 Experimentation Test Receiver

The GSTB-v2 Experimental Test Receiver is an all-in-view dual-frequency GPS receiver, which can simultaneously track up to 7 GSTB-v2 and/or Galileo signals. Fig. 4 shows the GETR, where tracking of Galileo signals as well as of GPS C/A Code is implemented in baseband modules using FPGA technology. The internal architecture of the GETR foresees the presence of the GPS dual-frequency Polarx2 receiver that working in parallel with the GSTB-v2/GPS C/A chipset, allows the synchronisation with the GPS signal. Anyway, the GPS L1 signal is processed by the same front-end and digital logic as the Galileo/GSTB-v2 signal in order to avoid any inter-system bias. As far as the compliance with the GSTB-v2 and Galileo signals is concerned, the GETR is fully representative in terms of modulations, chip length, chip rate and *Binary Offset Carrier* (BOC) sub-modulation, also for the BOC(15,2.5) and BOC(10,5) PRS signals. For each BOC modulation, the GETR supports both the sine and cosine type, with default setting as specified in the SIS ICDs. Six independent channels can be allocated to acquire and track any Galileo/GPS signal, apart form the *Alternative BOC* (AltBOC) modulation; since the AltBOC carries two different data streams, a dedicated channel has been implemented with some shrewdness for the internal architecture point of view [2].

The GETR is capable of producing and storing different type of data. In particular:

- Raw data (code phase, carrier phase, Doppler, C/No, etc. . .)
- Navigation data (message, CRC, Interleaving, etc. . .)
- IF samples of the received signal
- Samples of the autocorrelation function

The *GETRdat* tool has been developed on the basis of these output, being able of testing the receiver functionalities and performance.

2.3 Other Equipments

Apart from the Galileo Signal Validation Facility and the GETR, the test bench shown in Fig. 1 presents other hardware tools playing a key role in the real/simulated GIOVE-A signal, even if they are not used to perform the tests described in this paper. First of all, the set-up includes the Space Engineering Galileo/GPS antenna, see Fig. 5. This is a *Right Hand Circular Polarised* (RHCP) antenna able to receive L1, L2, L5, E6 and E5 signals and to amplify them by means of the internal LNA with 27 dB gain (considering connectors and cables). Another important tool to be cited is the Spirent GPS/Glonass Constellation simulator. It is capable of generating L1, L2 and L5 signals fully in-line with the SIS ICDs [5]. The role of this tool is mainly crucial for the evaluation of intersystem interference, as well as for providing GPS time synchronisation to the GETR.

Considering the diagram of Fig. 1, the section called "Real-Time" analysis is completed by the spectrum analyser and the digital oscilloscope, providing the user with high flexibility for SIS analysis (e.g. examining the spectrum of the GSVF-simulated signal in terms of shape and relative power sharing between different channels in the same band, for instance L1 A,B and C). In particular, the test bench has been equipped with an Agilent E4448A PSA spectrum analyser with 3 Hz – 50 GHz bandwidth, and a LeCroy LC334AM digital oscilloscope with a variable sample rate in the range 2Gsamples/500 Msamples per second depending on the number of channels used.

Finally, the "Post-Processing" section of the test bench is represented by the bitgrabber with some ad-hoc-developed software tools, for instance the *GETRdat* tool. The bitgrabber is a quantiser, being able to sample the RF signal at the input. It guarantees flexibility in the sampling procedure, with the possibility of setting the sampling frequency up to 250 MHz and the quantisation up to 10 bit. It produces a binary output file containing the stream of bits representing the samples of the quantised signal.

It is important to remark that, the software tools designed for the integration with the test bench equipment have been implemented in Matlab®, with the aim of communicating with both the GETR and the bitgrabber output files.

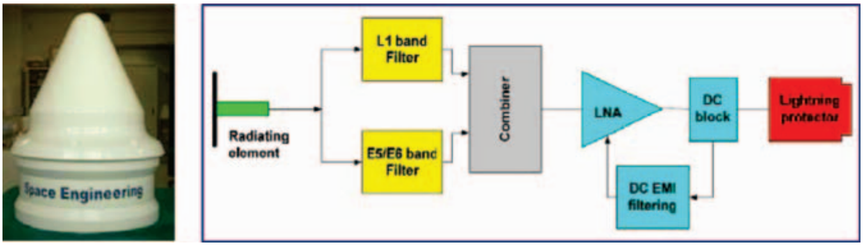


Fig. 5. Space engineering Galileo/GPS antenna.

3 Getrdat Tool

In order to be able to accomplish both Phase 1 and Phase2 described in section 1, which consist in the functional verification and validation of the equipments employed in the test bench as well as the analysis of results on the GETR performance validation, a really flexible software tool has been developed using Matlab® platform. It is also important to remark that the final intent in developing such a tool is to provide a generic user with the possibility of analysing the real GIOVE-A signals in the context of the SIS experimentation activity.

As shown in Fig. 6, the *GETRdat* tool contains 4 different sub-tools:

- *Dual Channel Tool*, to analyse the raw data files generated by the GETR
- *IF Samples Tool*, to process the IF samples of the signal whether they are stored using the GETR front-end or the bitgrabber
- *Correlation Data Tool*, to reconstruct the correlation function by means of processing correlation samples generated by the GETR
- *Navigation Data Tool*, to analyze the navigation data demodulated and stored in the GETR output file

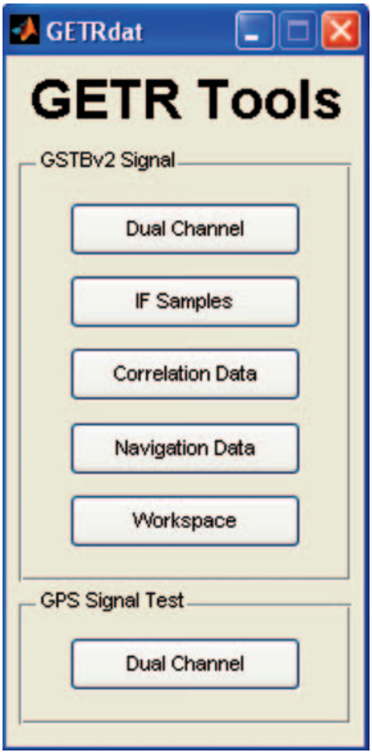
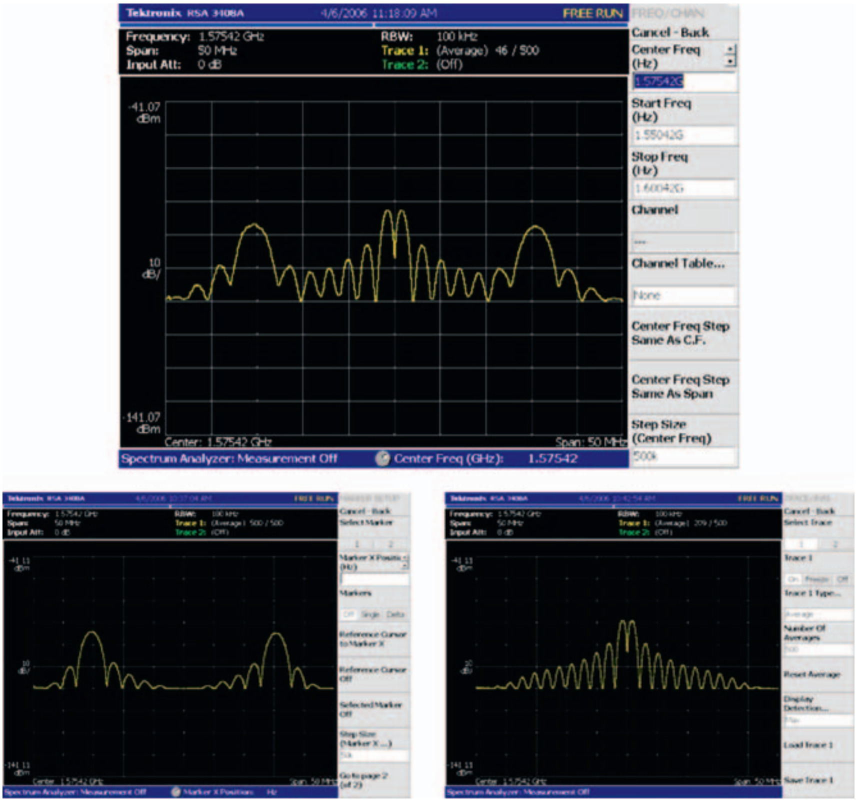


Fig. 6. GETRdat tool.

These sub-tools have been grouped in two sections, on the basis of the signal type (GPS or GSTBV-2) they are suppose to be used with.

4 Functional Verification and Validation of the Equipments

As it has been identified in Section 1, the first step in the validation of the test bench is the functional verification of the equipments involved in the integration. This section provides an overview of the set-up validation, mainly focusing the attention on the OS signals with particular reference to the L1 BOC(1,1). The set of results presented are related to GSVF-generated signals, being able to create a controlled environment surrounding the user and the signal path. Fig. 7 shows the spectrum of the signal generated by means of the GSVF-v2, where the components on the Galileo L1 band are clearly visible. The upper part of Fig. 7 shows the L1 A, B and C channels composition, implementing the CASM modulation between the nominal BOC(15,2.5)c and BOC(1,1) for the PRS and the OS signals respectively. The bottom part of the figure presents these nominal sub-modulation independently, using BPSK or QPSK scheme for the generation.



Frequency: 1.57542 GHz
Span: 50 MHz
Input Att: 0 dB
RBW: 100 kHz
Trace 1: (Average) 46 / 500
Trace 2: (Off)
Center Freq (Hz): 1.57542G
Start Freq (Hz): 1.55042G
Stop Freq (Hz): 1.60042G
Channel: ---
Channel Table...: None
Step Size (Center Freq): 500k
Center Freq (GHz): 1.57542

Fig. 7. GSVF-v2 spectrum of simulated GIOVE-A L1 signal.

The GSVF-generated L1 signal has been directly sent to the RF input connector of the GETR, being able of testing and validating some aspects of the receiver. First of all, the code noise tracking error curves for all the nominal GIOVE-A signals has been evaluated analysing the code-carrier phase measurement provided by the GETR. Nevertheless, the paper presents results only in the case of BOC(1,1) signal since it represents the nominal modulation foreseen for L1 OS signals. The signal has been generated sweeping the signal-to-noise ratio at the input of the GETR in the range 29–50 dBHz, considering a clean environment from both the user and signal path points of view. In such a way, it is possible to isolate the error on the code tracking due to the noise. Fig. 8 shows the results for the L1 pilot and data channels, comparing the obtained curves with the theoretical one. In this figure the theoretical curves are derived form the following formula, which represents the variance of the code noise error (expressed in m^2) [6][7]:

$$\sigma^2_{DLL} = T_C^2 \frac{B_L \int_{-\beta_r/2}^{\beta_r/2} G(f)\ \sin^2(\pi f \Delta)\, df}{C/N_0 \left(2\pi \int_{-\beta_r/2}^{\beta_r/2} f G(f) \sin(\pi f \Delta)\, df \right)^2} \times \left[1 + \frac{\int_{-\beta_r/2}^{\beta_r/2} G(f)\ \cos^2(\pi f \Delta)\, df}{T\, C/N_0 \left(\int_{-\beta_r/2}^{\beta_r/2} G(f) \cos(\pi f \Delta)\, df \right)^2} \right]$$

where T_c is chip duration, B_L is the DLL noise bandwidth, $G(f)$ is the spectrum of the signal, C/N_0 is the carrier-to-noise ratio and T is the DLL predetection time.

The second part of the functionalities verification and validation of the equipments has been devoted to the analysis of the autocorrelation function at the output of the GETR's correlators. The stream of correlation samples have been collected and processed by means of the *GETRdat* tool, with the aim of reconstructing the shape of the function checking for possible asymmetries. The left side of Figs. 9 and 10 point out the shape of the correlation function for both the BOC(15,2.5)c and BOC(1,1) modulations considering high C/No scenario (around 50 dBHz).

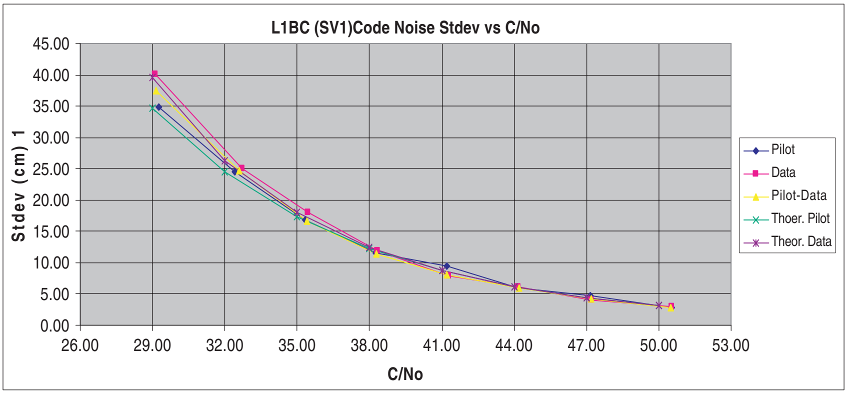


Fig. 8. L1BC code tracking noise error (GETR and theoretical).

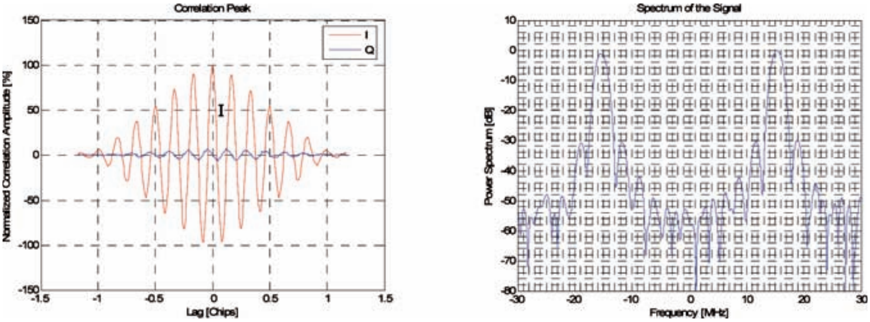


Fig. 9. BOC(15,2.5)c Correlation function and spectrum of the signal.

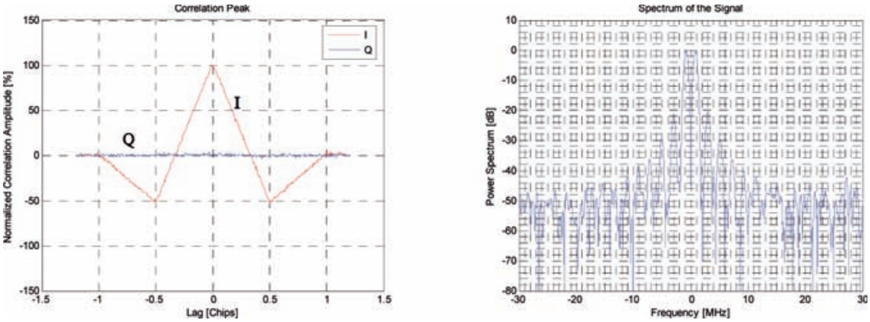


Fig. 10. BOC(1,1) Correlation function and spectrum of the signal.

The plots do not present any relevant asymmetry in the lobes amplitude, which could results in fixed bias on the pseudorange computation. Figures 9 and 10 show also the spectrum of both the modulations, derived through post processing operations on the correlation functions. The main lobes of the spectrum are clearly recognisable, with the correct distance from the central frequency (identified with 0 MHz) and nominal bandwidth.

Finally, the GETR functionalities under multipath conditions have been analysed and validated in terms of multipath envelope. The shape of the envelope derived directly from the GETR for the nominal signals (except the PRS ones) are shown in Fig. 11, where the zoom on the first 80 meters of ray delay with respect to the LOS is also presented in the case of multipath-to-signal ratio of 6 dB. Code phase error amplitudes versus multipath ray delay are in line with the expectations.

5 GETR Performance Results

This section describes results about the characterization of the receiver performance in presence of multipath. Only the tracking performance has been analyzed since it is considered the first and most important step towards the assessment of the

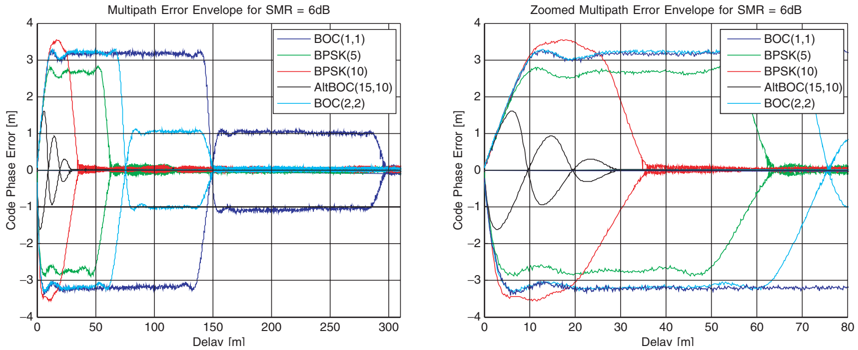


Fig. 11. GETR multipath envelope, SMR = 6 dB.

positioning performance. As a first approximation, the position performance can be simply derived including the satellite to user geometry, and projecting in the position domain the standard deviation of the error in the range domain. Thus the starting point becomes the ranging accuracy. Only multipath and noise contributions are considered for this analysis. No other errors (ionosphere, troposphere, interference, etc.) have been included. The measurement are performed in a high (around 50 dBHz) and low (around 34 dBHz) C/N0 conditions. Only L1 BOC(1,1) signal performances are shown.

To better understand and evaluate the obtained results in terms of static and dynamic errors, the added multipath is generated according to the model of Fig. 12. The GSVF-v2 multipath model that has been used to perform the test includes a Direct Path (Shadowing and Fading) and multipath (Fading), where the

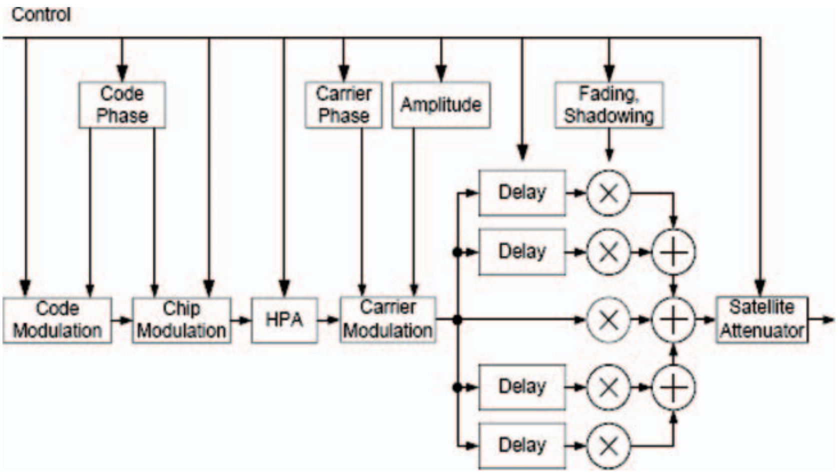


Fig. 12. Satellite path.

computation of the complex path scale factor to implement the fading and shadowing is according to

$$A = G \cdot \frac{K + \frac{X + jY}{\sqrt{2}}}{\sqrt{1 + K^2}} \cdot e^{\frac{S}{20 \cdot \log_{10}(2)} \cdot Z} \cdot e^{j\Phi}$$

where A is the complex scale factor, $X/Y/Z$ are band-limited unit variance Gaussian noise values, G represents the required path gain (in linear units), K is the Rice factor (in linear units), S is the standard deviation of the shadowing in dB and Φ is an additive phase for static multipath.

The model consists of 4 multipath rays with fixed delays and randomly varying phase added to the line of sight. The mean power relative to the line of sight of the Rayleigh fading is specified in Table 2. Rician fading is also applied to the line of sight. The delay, the Rician fading factor and the Bandwidth of the fading process are also specified in Table 2.

The parameters of the model have been selected according to Table 2, in line with Galileo Reference multipath model. The values selected constitute only one of the possible infinite choices, and they are considered representative of an average multipath scenario for the indicated type of environment (rural) and user category (pedestrian, fixed and vehicle).

Table 2. GSVF-v2 Multipath model configuration.

Rural Pedestrian	LOS ray
Enable LOS Ray	YES
Mean Time in Good State (s)	1.0
Enable Good State Fading	YES
Rician Fading Factor (dB)	13.71
Enable Bad State Fading	NO
Fading Bandwidth (Hz)	4

	Relative power (dB)	Path delay (ns)	Dynamic bandwidth (Hz)
Ray 1	−13.91	20	4
Ray 2	−14.11	40	4
Ray 3	−14.46	75	4
Ray 4	−14.86	115	4

Rural Vehicle	LOS ray
Enable LOS Ray	YES
Mean Time in Good State (s)	1.0
Enable Good State Fading	YES
Rician Fading Factor (dB)	13.71
Enable Bad State Fading	NO
Fading Bandwidth (Hz)	140

	Relative power (dB)	Path delay (ns)	Dynamic bandwidth (Hz)
Ray 1	−13.91	20	140
Ray 2	−14.11	40	140
Ray 3	−14.46	75	140
Ray 4	−14.86	115	140

Fixed	LOS ray
Enable LOS Ray	YES
Mean Time in Good State (s)	1.0
Enable Good State Fading	YES
Rician Fading Factor (dB)	13.71
Enable Bad State Fading	NO
Fading Bandwidth (Hz)	0.0025 (0.1)

	Relative power (dB)	Path delay (ns)	Dynamic bandwidth (Hz)
Ray 1	−13.91	20	0.0025 (0.1)
Ray 2	−14.11	40	0.0025 (0.1)
Ray 3	−14.46	75	0.0025 (0.1)
Ray 4	−14.86	115	0.0025 (0.1)

The GETR was configured with a PPL and DLL bandwidth of 10 Hz and 0.25 Hz respectively, while the predetection time was 10 ms for the PLL and 100 ms for the DLL. A non-coherent dot-product power discriminator for the code phase tracking:

$$\Delta\tau = I_{E-L} I_P + Q_{E-L} Q_P$$

where I_E, I_P, I_L represent the early, punctual and late replicas of the in-phase correlators output, while Q_E, Q_P, Q_L are the output of the correlators on the quadrature branch. Table 3 summarises the characterisation of the multipath contribution on L1 BOC(1,1) signal. The static contribution on the tracking error is calculated as the difference between the code measurements of two cloned satellites; one affected by multipath the other one in a multipath-free scenario. In fact in order to accurately isolate the MP contribution (bias plus standard deviation) from the code phase, a cloned satellite is generated (same orbit, same clock etc) but with a different PRN

Table 3. Multipath contribution on L1 BOC(1,1) signal.

Rural pedestrian			C/No ~ 34 dBHz
SV 1	PRN 1	No MP Model	Std = 19.59 cm
SV 2	PRN 2	Yes MP Model	std = 40.20 cm
			bias = 50 cm
Rural vehicle			C/No ~ 34 dBHz
SV 1	PRN 1	No MP Model	std = 25.14 cm
SV 2	PRN 2	Yes MP Model	std = 26.41 cm
			bias = 1 cm
Fixed			C/No ~ 34 dBHz
SV 1	PRN 1	No MP Model	std = 17.5 cm
SV 2	PRN 2	Yes MP Model	std = 166.58 cm
			bias = 41 cm

Rural pedestrian			C/No ~ 50 dBHz
SV 1	PRN 1	No MP Model	std = 3.85 cm
SV 2	PRN 2	Yes MP Model	std = 34.07 cm
			bias = 51 cm
Rural vehicle			C/No ~ 50 dBHz
SV 1	PRN 1	No MP Model	std = 5.98 cm
SV 2	PRN 2	Yes MP Model	std = 6.96 cm
			bias = 2 cm
Fixed			C/No ~ 50 dBHz
SV 1	PRN 1	No MP Model	std = 3.27 cm
SV 2	PRN 2	Yes MP Model	std = 162.5 cm
			bias = 42 cm

and without applying the multipath model; in other words, this space vehicle is used as a reference. Both standard deviation and bias can then be computed.

The results show the impact of multipath for the scenarios considered, RV, RP and fixed user. The dynamic of the user as well as the bandwidth of the fading determine the presence and the amount of the bias in the error, which cannot be filtered or averaged away. These preliminary results are also in line with the expectations, as specified in the requirements for the L1 OS signal in case of both the rural pedestrian, rural vehicle and fixed.

6 GIOVE-A SIS Acquisition and Tracking

As it has been introduced already in Section 2, the test bench set-up was finally integrated with the Galileo user antenna, being able of tracking real GIOVE-A and GPS signals. Fig. 13 shows an example of tracking, while the GETR was receiving and processing real signals from GIOVE A using the Space Engineering Antenna. The final results of such an integration is making comparison between real and simulated data possible, as well as validating the reference models (e.g multipath for fixed users).

Fig. 13. GETR operating with real GIOVE-A SIS.

References

[1] http://www.esa.int/esaNA/galileo.html

[2] A. Simsky, J. Sleewaegen, W. De Wilde, F. Wilms, "Overview of Septentrio's Galileo Receiver Development Strategy", *ION-GNSS (Long Beach)*, September 2005.

[3] J. W. Betz, "Binary Offset Carrier Modulation for Radionavigation", *Navigation*, Volume 48, pp. 227–246, Winter 2001–2002.

[4] P. J. Harris, M. Spelat, G. J. Burden, M. Crisci, "GSVF: The Galileo Reference Constellation RF Signal Simulator", *ENC-GNSS (Manchester),* May 2006.

[5] http://www.spirentcom.com

[6] E. D. Kaplan, C. J. Hegarty, "Understanding GPS, Principles and Applications", Second Edition, 2006.

[7] J. W. Betz, "Extended Theory of Early-Late Code Tracking for a Bandlimited GPS Receiver," *Navigation: Journal of the ION*, vol. 41, no. 3, pp. 211–226.