Latest Developments On The Payload In-Orbit Testing Of Galileo IOV Spacecraft

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BIOGRAPHY

Massimo Ciollaro received his university degree (MSc) in Telecommunications Engineering from University of Naples "Federico II" (Italy) in 2005. In 2008 he received his PhD in Electronics and Telecommunications Engineering from the same university, with a final thesis on the GNSS Multisystem Integrity. In 2008 he worked for NSL in Nottingham, on the GNSS integrity and RAIM algorithms. In 2009 he joined Inmarsat, where he works as Galileo IOT Engineer and is responsible for the integration and validation activities of the Galileo Payload IOT System.

Emanuele Guariglia received his university degree (MSc) in Electronics Engineering from University of Rome in 1984. In 1998 he attained a Master of Business Administration (MBA) at Heriot-Watt University Business School, Edinburgh (UK). From 1985 to 1986 he worked for Selenia as Systems/Project Engineer in the field of tracking radars. From 1986 to 1989 he worked for Ciset as IOT Engineer at ESA Telemetry and Tracking Station of Redu, Belgium. He joined Inmarsat in 1989 and he is now director of Earth Stations Engineering. He has more than 20 years satellite communications experience, with particular emphasis on ground stations, TT&C engineering and operations, and in-orbit testing.

Christian Weber received his university degree (Dipl.-Ing. Univ.) from the Technical University Munich (Germany) in 2004 and joined the German Aerospace Centre (DLR) in 2005. He has been working on the Galileo project for 4 years, first as a researcher with focus on interference detection and mitigation and later in operations as Galileo IOT Engineer. Now he is with the infrastructure department of the private company "DLR Gesellschaft fuer Raumfahrt" (DLR GfR) and located in the Galileo Control Centre where he is involved in several Galileo related operations activities.

Andrzej Baranski is a Senior IOT Engineer in Galileo Project. He obtained his B.Sc. degree in 1971 from Politechnika Bydgoszcz, Poland. Since 1981 he has been working at ESTEC, first as On-board Data Handling Engineer, then as RF Engineer in Telecom Division and recently in the Galileo Project.

ABSTRACT

This paper describes the infrastructure and the functions of the Galileo In-Orbit Validation (IOV) In-Orbit Test (IOT) System to be located at the ESA Redu (Belgium) earth station. This is then followed by a detailed review of the main technical challenges posed by the IOT activity and how the IOV IOT System has been specifically designed to meet them.

INTRODUCTION

The IOV phase covers the launch and characterisation in orbit of four satellites, allowing the system to be properly evaluated before full system deployment. The four Galileo IOV satellites will be launched in pairs and the IOT campaign will be held to ensure that they have survived the launch without damage and their performance is consistent with that measured during ground test.

Inmarsat Global Ltd. is responsible for implementing and operating the Galileo Payload IOT System, which will be located at the ESA Redu earth station. The IOT campaign is expected to be 35 days long.

The functions of the IOT System include RF transmit measurements at C-Band and UHF-Band, RF receive measurements at L-Band, as well as measurements carried out by dedicated Navigation Test Equipment. Inmarsat will deploy a fully automated IOT Measurement System (MS) and three main antennas at Redu: a high gain L-Band receive-only antenna (LBA) for receiving satellite downlink signals, a C-Band transmit antenna (CBA) for sending navigation messages and a UHF transmit antenna (UBA) for up-linking Search & Rescue (S&R) test signals to the satellite. During IOT the satellites will be under the control of the German Aerospace Centre (DLR), which is responsible for the GCC-GCS (Galileo Control Centre – Ground Control Segment).

The IOT System will face design challenges dictated by technical and operational requirements that are uncommon for IOT purposes of conventional geosynchronous satellites:

1) Tracking the Galileo Satellites
2) The constraints dictated by the IOT Timeline
3) Measuring On-Board Clocks Accuracy and Stability
4) Assessing the Quality of Navigation Signals by real-time analysis and post-processing.

The results obtained during the IOV IOT campaigns will represent a benchmark throughout the satellite operational life and will constitute a reference basis across the entire constellation.

1. BACKGROUND

The final Galileo constellation will comprise 30 satellites, each transmitting a range of L-Band navigation signals to users providing a number of navigation services. The payload also contains a transparent Search & Rescue (S&R) transponder, which turns around UHF distress signals and returns these to earth at L-Band. The Galileo satellites will fly in a Walker constellation with three orbital planes at 56°, each containing 9 equally spaced operational satellites plus one spare. Orbit radius is 29600 km and orbital period is 14 hours.

The IOV phase covers the launch and characterisation in orbit of four satellites, allowing the system to be properly evaluated before full system deployment. The four Galileo IOV satellites will be launched in pairs. Following injection a LEOP and IOT campaign will be held during which tests will be performed on the satellites to ensure that they have survived the launch without damage, and that their performance is consistent with that measured during ground test.

A contract is in place between the European Space Agency (ESA) and Deutsches Zentrum für Luft- und Raumfahrt (DLR) for Galileo IOV System Operations, System Integrated Logistic Support, Launch and Early Orbit Phase and In-Orbit Testing (OILI). For this work, DLR heads an industrial consortium of which Inmarsat Global Limited (Inmarsat) is a part. In particular, Inmarsat is responsible for implementing and operating the Payload IOT System. In order to fulfil its IOT Service commitments, Inmarsat has in turn put together an industrial organisation as further detailed below by this paper.

At the time of writing, the Payload IOT System has successfully passed its critical design review and it is now on the way to its integration and validation activities.

2. IOT SYSTEM ARCHITECTURE

2.1 System Overview

Following release from the launch vehicle the Galileo satellites will enter an orbit with a 14 hour orbital period.

Because of the selected orbit, the Galileo satellites will only be visible at the IOT ground station for limited periods each day, with visibility typically ranging from 3 to 9 hours.

During IOT the satellite will be under the control of the GCC-GCS, who will use a network of S-band antennas to handle satellite TT&C functions. The IOT System will be located at the ESA Redu site and will have a direct link with the GCC-GCS to receive quasi-real time telemetry as well as other supporting information.

The IOT Service provider will have three antennas at his disposal: an L-band receive only antenna (LBA) for receiving and processing satellite downlink signals, a C-band transmit antenna (CBA) for sending navigation and S&R messages to the satellite payload and a UHF transmit antenna (UBA) for transmitting UHF test signals to the satellite.

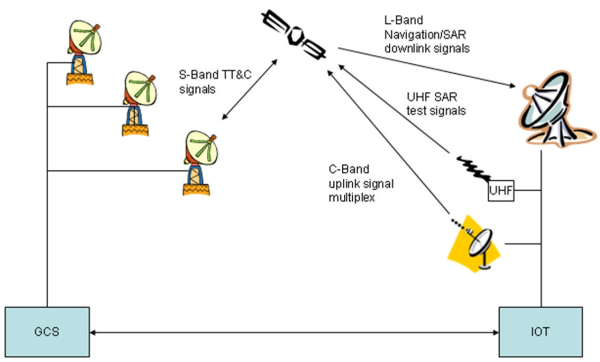


Figure 1: Galileo GCS/IOT Ground Segment Schematic

Figure 1 above presents a simple schematic of the IOT System together with its interfaces with the GCC-GCS, whereas Table 1 below lists the main elements constituting the IOT System and the associated suppliers; status of procurement at time of writing is also shown in the table. The existing INDRA 3.5m GSTB-V2 L-Band receive antenna is also listed as the IOT System will enable to connect it to the Navigation Receiver (part of the Navigation Test Equipment) for additional measurement flexibility.

At the time of writing, the main component of the IOT System, the Measurement System, has successfully passed its critical design review and it is going to be tested in factory, before being shipped to Redu. The three antennas provided within the IOT System have successfully passed their design reviews as well. It should be noted that some components of the LBA and CBA, e.g., ACU and Feed, have already successfully been tested in factory by their respective manufacturers.

Table 1: Main Elements of the IOT System

Element	Supplier	Status
Measurement System	SED Systems (Canada)	Factory Acceptance Test (FAT)
Navigation Test Equipment (NTE)	Siemens Austria (Austria)	delivered & integrated with MS
L-Band Antenna	Vertex (Germany)	Site installation
C-Band Antenna	HITEC (Luxemburg)	FAT
UHF-Antenna	Satimo (France)	Design Review
Existing GSTB-V2 3.5m L-Band Receive Antenna	Indra (Spain)	Existing facility

The Navigation Test Equipment (NTE) includes a Navigation Receiver, developed by IfEN GmbH, and a Navigation Data Modulator and Up-Converter (NDMU), developed by Satellite Services BV (SSBV). In particular, the NDMU can generate and emulate the mission navigation data messages packetized according to the uplink format defined in the MGF (Message Generation Facility). On the other hand, the Navigation Receiver is capable of receiving unencrypted Galileo service signals and supports some of the payload tests. After its successful Factory Acceptance Test (FAT), the NTE has been integrated with the IOT MS.

It is worth noting that a small L-Band rotary horn receive antenna is included in the Galileo IOT System for the purpose of accurately measuring the transmit antenna Axial Ratio of the satellite. The rotary horn consists of a linearly polarised standard L-Band horn and L-band LNA. The rotation of the horn is driven by a step motor. The rotation can be controlled by the IOT Measurement System. This equipment will be mounted on the structure of the large L-Band antenna, behind the sub-reflector.

In addition to the typical measurement functions listed below, the IOT Measurement System also caters for the two following critical functions:

1. Monitor and Control capability of antenna and RF equipment which are part of the IOT System;
2. Handling of program track functionality, in effect acting as a ‘bridge’ between the Flight Dynamics centre at the GCC-GCS and the Antenna Control Units (ACUs) of the various antennas.

It should also be said that in addition to the IOV Beginning-of-Life IOT campaigns proper, it is envisaged that the IOT Measurement System will be used for subsequent re-activations on a planned and/or ad-hoc basis, for periodic payload measurements and/or anomaly investigations. It is also intended to use the IOT Measurement System for an extended IOT campaign on the GIOVE-B spacecraft. Finally, the requirements of the IOT Measurement System mention that there should be no limitation as to the use of the system for the Galileo Full Deployment (FD) phase, which envisages launches of up to 6 satellites in a cluster. Design lifetime of the IOT System is specified at 20 years.

2.2 IOT Measurement System

The IOT Measurement System is based on SED’s latest generation of in-orbit test system products. It is being developed with the following primary requirements in mind:

1. High-speed, accurate measurements. Innovative measurement techniques are provided to maximise the number of measurements that can be performed within a short time period;
2. Automated measurements. Operators can quickly create sequences of measurements, submit them or schedule them for execution, and monitor the results of the measurements either in real-time as they occur or by retrieving them afterwards. Complex sequences of measurements can be created in advance, validated, and stored ready for execution at the time of need;
3. Configurability and expandability. The operator has full freedom to change measurement parameters for individual measurements and to create measurement sequences as needed using the available measurements. Should totally new measurements be required, the software is designed in such a way that the current suite of available measurements can easily be added to (but this would require software work by the supplier).

A detailed configuration diagram of the IOT Measurement System is depicted in Figure 2, which includes also the RF connections to the antennas. The colours used in the diagram identify the different components:

- In green, the components that belong to the IOT MS, which are provided by SED Systems.

- In yellow, the components provided by the other Inmarsat subcontractors (e.g. VertexAntennen for the L-Band Antenna).
- In blue, the components provided by the customer not controlled by the IOT System (i.e., Septentrio Receiver).

The measurement system is operated from the operator workstations located in the IOT control room, which in turn is located in the Redu Main Technical Building. In each of the three main antenna hubs a hub box is provided, containing a power sensor and other RF equipment as required. The power sensor is used to measure the transmitted test carrier power in the C-Band and UHF antennas, and the calibration signal power in the L-Band antenna. The existing 3.5 m L band antenna does not include any hub equipment.

Two synthesizers are provided:

1. The vector signal generator can be used to transmit a pair of CW test signals at UHF and as a calibration signal source for the L-band downlink calibration measurement on the large L-band antenna. The vector signal generator can be used to measure the downlink phase response as well.
2. The RF signal generator is used to generate the L-band pilot injection signal at the specific frequencies used during the tests, and the modulated UHF-band signal used to measure group delay. In this latter case the modulation waveform is also passed to the Signal Analyser to allow group delay to be measured.

Another Vector Signal Generator is used to facilitate some limited L-band Navigation Signal simulation function by playing back recorded digital samples of navigation signal.

The main measurement instruments in the L band equipment room are vector signal analyzers. Both analyzers can provide basic spectral measurement capability, but each analyzer is optimized for specific measurements. One of the units is a signal source analyzer (SSA), which provides very fast and accurate phase noise measurements. A high gain filter path optimizes the dynamic range of the phase noise measurements. The other analyzer has the capability to sample the broadband carriers. The samples then can be used for off-line analysis. The analyzer in the C-band shelter is a conventional spectrum analyzer used for spectral measurements of the transmitted signals from either the C Band or UHF Band antennas.

Routing of the signals is performed by SED-manufactured switchbanks. The switches and other devices in the switchbanks are high quality RF components to optimize the stability and repeatability of the measurements. The switchbanks provide all the path selection and conditioning (levels, bandwidths) for the measurement system. The L-band simulator injects the navigation test signals into the navigation downlink from the 20 m L band antenna to support the IOT system validation and testing.

Frequency and timing equipment is provided for the distributing of the station-provided sources, i.e. IRIG-B and 1 PPS timing and 10 MHz frequency reference

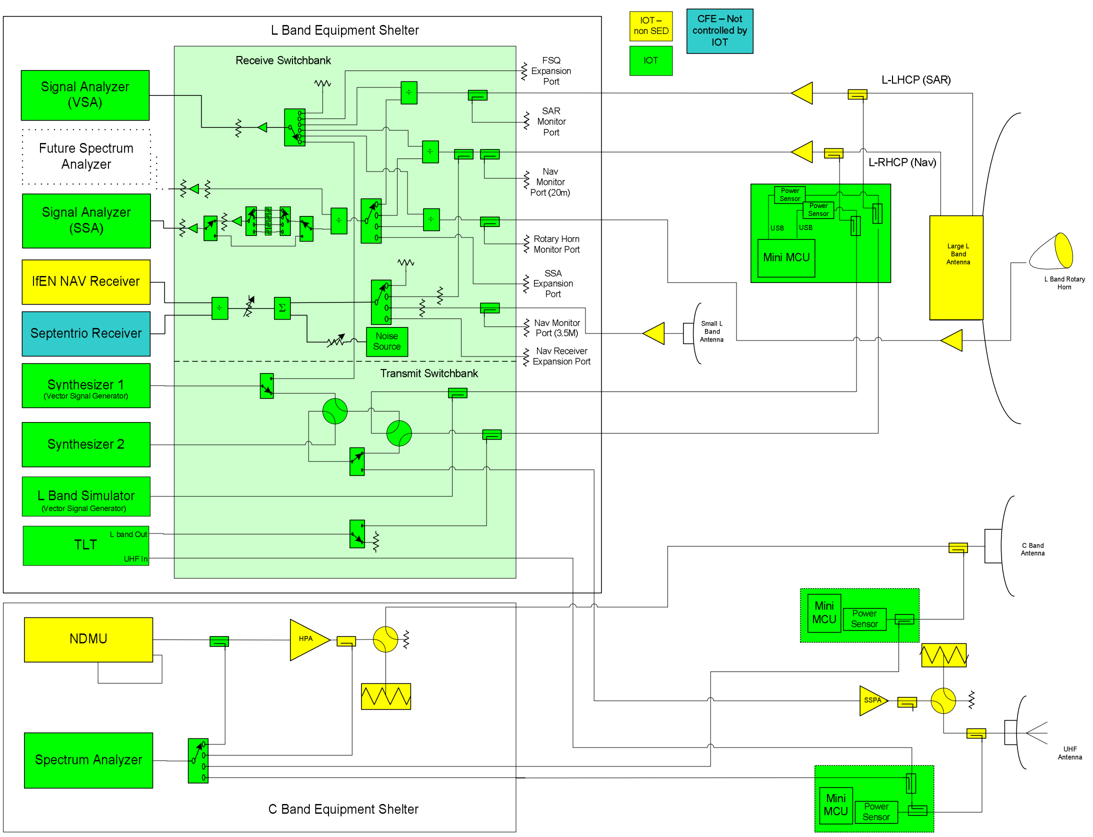


Figure 2: Galileo IOT Measurement System Configuration

(which is also cleaned up). A pulse generator is also provided. The Measurement System will then distribute the time to the other components of the IOT System, e.g., Antenna Control Units (Figure 3).

The computer equipment in Redu consists of two measurement computers/servers, two operator workstations with related peripherals and one further server used for post-processing and data archiving. The measurement servers operate in a warm standby redundancy configuration; they communicate with all the equipment and external entities via LAN or RS-232. The measurement algorithms execute on these server computers. They are server class computers and contain the master database. The SED software on these computers executes on the Linux operating system.

The measurement servers communicate with a number of external systems over the LAN:

- Telemetry Interface
- Orbital and Attitude Interface
- Meteorological Data Interface
- L-band Antenna ACU
- L Band Antenna LNA Controller
- C-band Antenna ACU
- C Band HPA
- UHF Antenna ACU
- UHF Antenna HPA
- 3.5m L-band Antenna ACU

The user interface runs on the operator workstations, which are Windows based PCs that communicate with the server computer via LAN. The user interface software is written in the Java programming language and can be installed on additional customer provided PCs.

2.3 Measurements, Pro-Formas and Test Cases

During the IOT Campaign, the IOT System will be required to execute specific measurements both in the downlink and uplink paths. These measurements, called Test Cases, have been identified in the Space Segment provided "Satellite Commissioning and IOT Plan" document. These Test Cases include three categories of measurements: 1) Functional; 2) RF; 3) Baseband.

The IOT Functional tests shall be capable of verifying that the fundamental functions of the PL units have survived the launch phase. This test category is mainly performed via S-Band TC and TM verification in order to check each PL unit health status in different PL configurations. Only limited and simplified functional verification are performed on functionalities available through L-band downlink and UHF and C-band uplink.

The main purpose of the RF test category is to perform RF measurements on the L and C-bands in the different PL configuration.

The main purpose of the Baseband test category

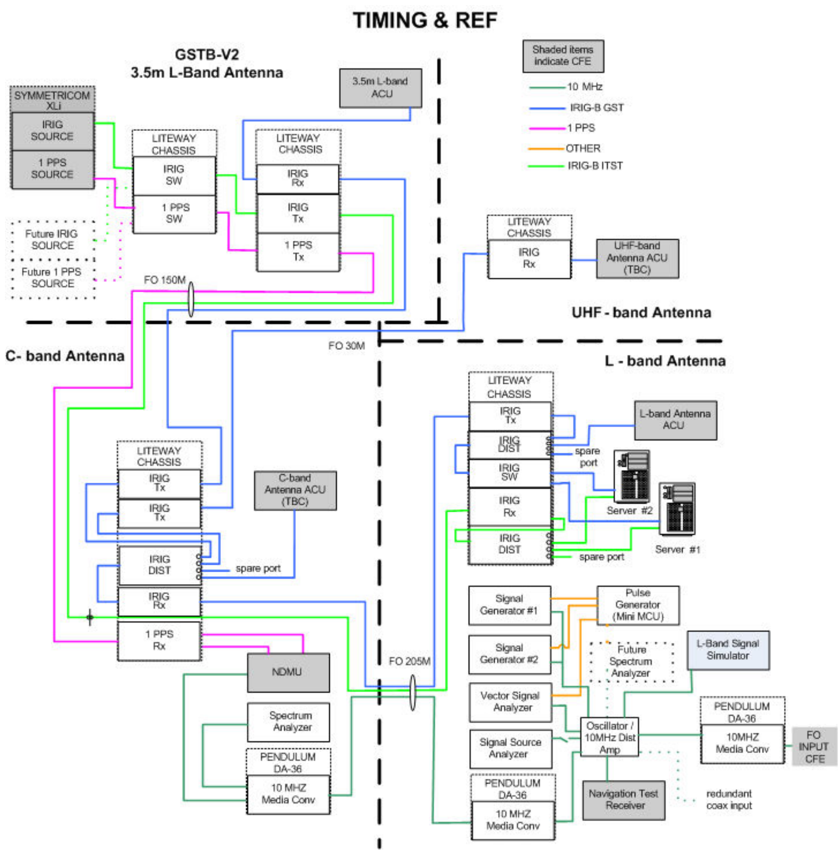


Figure 3: Reference and Timing Block Diagram

consists of demodulation and extraction of Navigation and return S&R message data from L-band.

Moreover, additional Navigation Test Cases covering the navigation signal have been identified and they will be performed in some cases by using the Navigation Receiver of the NTE and in some other cases in post-processing by using the ESA provided OASIS software.

Table 2 below presents the list of measurements and pro-formas provided by the IOT Measurement System. Through various combinations of measurements and pro-formas it is possible to cover all the required IOT Test Cases. In most cases the mapping between measurements and Test Cases is direct. In others the Test Case is satisfied by a set of measurements that are entered into a measurement sequence. Finally, pro-formas are not as directly applicable to any one Test Case and are used to support multiple tests.

Table 2: SystemMeasurements and Pro-Formas

No.	Measurement or Pro-forma Name
	Measurements
1	Satellite Gain, Translation Frequency and G/T – G/T is an option, accurate translation is an option
2	Single Carrier Gain Transfer/Crosspol Isolation/Axial Ratio
3	Frequency Response
4	Linearity/3rd Order Intermod
5	Uplink a Signal (CW) / Terminate CW Signal
6	Forward Group Delay – Absolute
7	Forward Group Delay – Response
8	Spurious
9	Uplink a Signal (NDMU)
10	Uplink Carrier Level Adjustment (NDMU)
11	Uplink Carrier Frequency Adjustment (NDMU)
12	Modulated Satellite Carrier EIRP and Power Spectrum
13	CW Satellite EIRP and Signal Frequency (with optional triggering on signal, and optional accurate frequency, optional plot of sweep result)
14	I/Q Relative Power
15	Read Nav Observables and Calculate Parameters
16	S-curve Bias (post-processing)
17	Modulation Scatter Plot (post-processing)
18	Correlation Loss (post-processing)
19	Phase Noise
20	Axial Ratio
21	Antenna Patterns
	Pro-Formas
1	EIRP in a BW
2	Telemetry Check
3	Configure Equipment/Paths
4	Read SA
5	Record I/Q Samples
6	Configure Nav Receiver/Check State – optionally includes setting C/No
7	Read Nav Receiver Data / Stop Reading Nav Receiver Data
8	SA Calibration
9	Power Sensor Zero
10	Cold Sky Noise
11	Downlink Gain and Gain Response
12	Uplink Noise Calibration
13	Swept Analyzer Filter Noise Bandwidth Calibration
14	Post-processing
15	Vector Path Calibration
16	Compare Uplink C-band and Navigation Message Data
17	NAV Signal BW Using Stepped CW Signal

2.4 Payload IOT Mission Procedures

Inmarsat is responsible for the development of the *Payload IOT Mission Procedures*, which will cover all the Test Cases and additional Navigation Test Cases described in the previous section. For every specific Test Case to be run there will be a distinct IOT Procedure for each defined spacecraft configuration on which that measurement type needs to be run. The IOT Procedures will typically be paper-based (Microsoft Word) documents containing an initial descriptive section (with test pre-requisites, assumptions, objectives, cautions, methodology, ground requirements, etc.), followed by a section describing the applicable spacecraft configuration, and followed by an operator script with numbered steps and associated operator instructions. A print-out of these procedures will be used during IOT execution to manually record information relevant to the progress of the test including date and time of execution, engineers present, equipment versions, etc. Data entry boxes shall be included to record specific information as required. Each IOT Procedure will act as 'master procedure' for the following two lower level procedures:

1. The first will be the associated *Payload IOT Flight Procedure* (groups of satellite commands and associated TM residing on the satellite control system at the GCC-GCS, used to change payload configuration under manual initiation. These sequences may comprise multiple commands or groups of commands which are issued by DLR as GCC-GCS operator as a timed sequence);
2. The second will be the associated *Payload IOT Measurement Sequence* (electronic sequence of software-based measurement steps implemented within and invoked by the IOT Measurement System). The IOT Measurement Sequences are constituted of measurements and pro-formas with operator-defined control parameters (e.g. test equipment settings, frequency levels etc.), as defined in Section 2.3 above.

The two above lower level procedures will be tightly linked with the master Payload IOT Mission Procedures, and they will strictly follow the same step numbering.

The PL IOT Mission Procedures developed by Inmarsat will follow a thorough validation process in order to declare the IOT System capable of successfully executing all the IOT Test Cases and thus ready to perform the IOT Campaign.

3. TRACKING THE GALILEO SATELLITES

The Galileo telemetry beacon is in S-Band, which is not supported by any of the antennas of the Galileo IOT System in Redu as they cover different payload bands. Therefore, it will not be possible for the IOT antennas to track the Galileo satellites using the auto-track mode. Program track will be used instead.

In order to guarantee the measurement accuracy requirements, the following two aspects become fundamental:

1. Antenna pointing accuracy;
2. Accuracy of the predicted orbital elements information provided by the GCC-GCS to the IOT System.

The GCC-GCS Flight Dynamics team will provide predicted orbital elements information to the IOT System via the data link connecting Oberpfaffenhofen in Germany with Redu in Belgium. Such data will be provided via a file-based mechanism; each file will cover at least one visible pass and the files will be made available at least half an hour before the start of each visible pass from the IOT site. The IOT Measurement System will receive the orbital elements data, process it, where necessary, to extract pointing angles and acting as a hub it will distribute the pointing information via the internal IOT LAN to the ACUs of all the IOT antennas.
System-level analysis established that to meet overall measurement accuracy requirements, during program track operation the antennas shall be kept pointing in the direction predicted by the selected file, to an accuracy of no worse than 0.1 dB for satellites moving at up to 0.2°/s (this includes antenna gain variations as a function of elevation angle and includes the error attributable to the antenna pointing accuracy). In addition to this antenna specific error contribution, orbital elements prediction accuracy has to be considered in the overall error analysis.

Table 3 below shows the resulting Antenna Pointing specification applicable to each of the antennas (differences between antennas are accountable to the different antenna sizes and frequency bands, and hence beamwidths). For each of the antennas, Table 3 also shows the preferred format of prediction file together with the accuracy achievable by the derived pointing angles. Note that at time of writing, it is understood that such accuracy requirements on direct predictions cannot be met all the time: as a result, estimated achievable accuracy of each directly predicted data will be indicated, and a schedule for the estimated accuracy of the orbital parameters may be provided by the GCC-GCS a few hours ahead of time.

Table 3: Antenna Pointing and Orbital Predictions Accuracy Requirements

Antenna	Antenna Type/Size	Specified Antenna Pointing Accuracy	Format of Prediction File	Accuracy of Prediction
L-Band Antenna	20m Cassegrain	0.02 degrees rms (*)	State Vectors	0.02 degrees
C-Band Antenna	3.6m Cassegrain	0.09 degrees rms (*)	Two Line Elements	0.1 degrees
UHF-Antenna	Array of seven 4-element yagis	1 degree rms (*)	Two Line Elements	0.1 degrees
GSTB-V2 3.5m L-Band Antenna	3.5m Prime focus	Existing antenna	Two Line Elements	0.1 degrees

(*) For 99% of the year, under local environmental conditions

4. THE IOT TIMELINE

A test window of 30 to 40 days will be available to complete LEOP, platform IOT and clear-mode Payload IOT of the Galileo IOV satellites. The operational planning of the Payload IOT Timeline (both advance/offline preparation and real-time adaptation and modification in response to unplanned circumstances) is a highly complex task that needs to take into account numerous constraints some of which are listed below:

1. Number of simultaneous satellites to test: two for IOV, up to six for the Full Deployment (FD) phase;
2. Allocated time window for testing in clear-mode will also be used for LEOP activities and for platform IOT testing;
3. Availability of S-Band TT&C Stations: the IOT Timeline must take into account that whenever it is required to uplink payload commands or to receive real-time spacecraft telemetry, there should be visibility from at least one of the S-Band TT&C stations. In certain cases payload configuration can be commanded in advance of measurement execution if this is advantageous;
4. Frequency co-ordination and interference avoidance: in particular, any uplink in the UHF-Band must be carefully co-ordinated so as to avoid interference with the operational COSPAS-SARSAT Search & Rescue (S&R) satellite system. In practice no transmission can occur whenever a LEOSAR satellite is visible from Redu, and transmission levels and antenna pointing angles will have to be carefully monitored to avoid radiating excessive power towards visible GEOSAR satellite(s). The uplink UHF radiation constraint may also apply to Galileo satellites which are already flying. Moreover, interferences from other satellites (e.g., GPS satellites, Inmarsat satellites, etc.) and celestial bodies (i.e., Sun, Moon and Radio Stars) shall be avoided;

5. Satellite and payload health and safety considerations: in particular, equipment warm-up times recommended by the payload manufacturer shall be strictly adhered to whenever applicable (this is particularly relevant to the on-board clocks - see Section 5 below);
6. Antenna horizon profiles and azimuth/elevation masks: in particular the antenna horizon profiles depend on the particular location of the antennas and on the profile of the ground. Several obstacles (e.g., trees, walls, other antennas, etc.) contribute to further reduce the available time slots (Figure 4).
7. Methodology to carry out the Antenna Pattern measurement: a 'piecemeal' approach (with reconstruction in post-processing) would enable more efficient use of available time slots. On the other hand continuous cuts would likely deliver better accuracy but would result in longer measurement duration.

In order to improve the efficiency of the operation, the IOT System is being developed to allow measurements to be performed in parallel whenever the available resources (i.e. antennas and test instruments) can be shared. A typical case where the parallel measurement capability would be extremely useful is for Navigation and RF performance tests. The small 3.5m antenna coupled with the Navigation Test Equipment (NTE) could be used for the former whereas the large L-Band antenna and the UHF antenna together with the rest of the instruments could be assigned to RF performance and SAR tests.

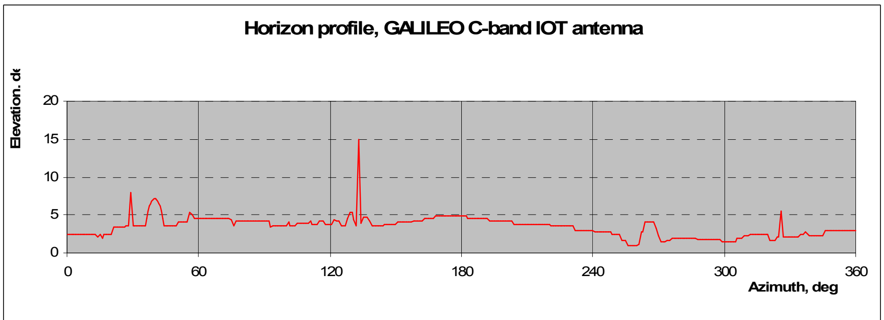
It is clear from the above that controlled and efficient time management becomes a key to the success of IOT campaigns within the allocated time window. Indeed, during each pass of a Galileo IOV satellite, one or more measurement sequences can be executed from the IOT site. However, during a pass the above described constraints can affect the duration of valid time slots available for measurements from the IOT site.

Therefore, an IOT Planning Assistant Tool (IOT PAT) will be used to calculate in advance, for each pass of the Galileo IOV satellites, the available time slots during which one or more measurement sequences can be executed from the IOT site. This tool is intended to be highly configurable, in order to let the operator decide which constraints should be applied for each specific test sequence. Nevertheless, the IOT PAT is not intended to be a scheduling tool, but it has to aid the operator to plan, for each Galileo IOV satellite, the time allocation of the test sequences to be executed during the IOT campaign.

Two different strategies of test planning will then be considered:

- **Long term planning**, in which, starting from the same initial input and configuration data set (i.e., orbital parameters and constraints), time slots for the whole IOT campaign are calculated (typically 35 days). This computation provides only a rough approximation of the available time slots, because the propagation of orbital parameters for such a long time and possible satellite manoeuvres can negatively affect the accuracy of the computation. Therefore, these results serve as a basis for a short term planning, which shall then provide a more accurate computation.
- **Short term planning**, in which visibility time slots are recalculated typically every 24 hours starting from daily updated orbital parameters and constraints. In this way, the capability to review the timeline and implement real-time modifications and changes will be provided, to take into account delays, contingencies, and ad-hoc/new tests or retesting requirements.

The tool that will be used for this planning is STK Professional®, developed by Analytical Graphics Inc. (AGI). This software provides the capability to generate different scenarios, each containing:



List of obstacles above 5 deg:			
29		Lightning protection tower	
40		GALILEO L-band IOT antenna	
58	92	Trees	Can be cut. Inside the station territory.
128	131	Single trees	Can be cut. Inside the station territory.
133		Calibration tower	
326		Lightning protection tower	

Figure 4: CBA Horizon Profile at Bunker Roof

- Group of applicable constraints
- The antenna (L-Band, C-Band, UHF) or the group of antennas to be used to execute the measurements

Moreover, STK allows a manual configuration of most of the constraints and the operator can enter specific values for each of the relevant parameter.

5. MEASURING ON-BOARD CLOCKS ACCURACY AND STABILITY

Each of the Galileo satellites is equipped with redundant Passive Hydrogen Maser (PHM) and redundant Rubidium Atomic Frequency Standard (RAFS) on board as reference clocks for the rest of the payload. The performance of those clocks is fully tested for systematic errors and random deviations on ground before the satellites are launched. Testing during the IOT phase is necessary to verify that no degradation has occurred due to the launch and the orbit positioning manoeuvres of the satellites, and to test possible space environmental effects such as the variations of temperature, magnetic field and radiation dose.

However, the IOT Measurement System will not check the performance of the clocks using a time domain measurement during payload IOT. Indeed, the fact that the overall time slot allocated to each payload IOT Campaign for two satellites in a pair is only around 30 to 40 days, that each visible pass only lasts a few hours, that possible interruptions due to other satellite activities such as manoeuvres may arise, and that Doppler effect, environmental parameters and ionospheric effects will add to the uncertainty, would make it difficult to draw any meaningful conclusion from such test, not to mention the logistics of having to maintain a Hydrogen Maser Reference at the IOT site.

Instead, the IOT Measurement System will measure the phase noise of the transmitted CW carrier from the satellite. This is another way of characterising the performance of the clocks. The result can be used to carry out a comparison with the outcome of the ground test and it is also possible to convert this frequency domain measurement to a time domain measurement by adopting the models of the Power-law noise processes (IEEE Std, 1999). This conversion will be done off-line, once the results from the phase noise measurement are available.

The big advantage of the frequency domain measurement over the time domain measurement is that ionospheric effects on the transmitted signal are much less important and the measurement can be made in a very short time.

However, one difficulty when making frequency domain measurement on the satellite is accurate Doppler shift compensation, and another one is to achieve the required high sensitivity and accuracy. The selected instrument to measure the phase noise is the Agilent E5052B signal source analyser, which is a vector signal analyser optimised for phase noise measurements and is equipped with an internal tracking loop for Doppler compensation as well as with Cross-correlation process to reduce the instrument noise due to the internal reference. Preliminary tests have shown that the Agilent E5052B signal source analyser allows meeting the required high sensitivity and accuracy (Table 4).

Table 4: Phase Noise Measurement Requirements

PHASE NOISE MEASUREMENT REQUIREMENTS	
SSB Sensitivity in case of SSA, 1 correlation (dBc/Hz)	**Accuracy (dB)**
1Hz: -54 10Hz: -90 100Hz: -110 1KHz: -120 10KHz: -130 100KHz: -140 1to 46MHz: -150	1 to 100Hz: <+/-4 100 to 1KHz: <+/-4 1K to 1 MHz: <+/-2 1M to 40 Mhz: <+/-3

Figure 5 shows the phase noise of Agilent E8267A Synthesizer measured by Agilent E5052A. Measured phase noise at offsets 1, 10 and 100 Hz was -62.5, -92.4, -110.6 dBc respectively. The synthesizer was set at a frequency of 1.5 GHz and at a level of 14 dBm.

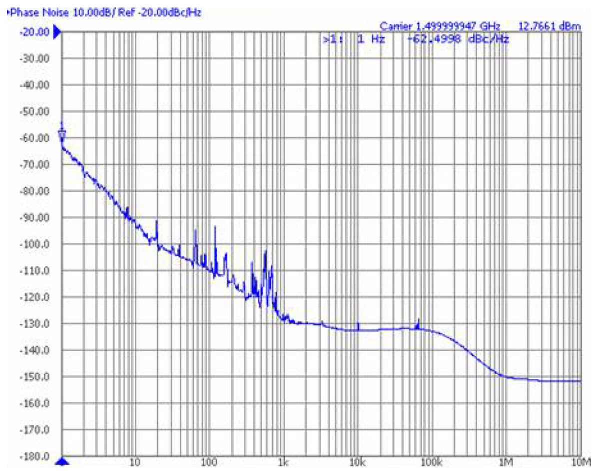


Figure 5: Agilent E5052B - Measurement of E8267A signal

It is possible to evaluate the delta-performance of the two clocks on board using the on-board Phase Meter, which measures the phase difference of the two clocks with a resolution better than 360 x 2^{-12} degrees, and the parameter can be made available on the ground via satellite telemetry. The Phase Meter needs to be initialised during the Payload IOT Campaign and the burden on the IOT Measurement System is to measure the delta frequency of both clocks to the accuracy of $1x10^{-11}$. This implies that high accuracy for orbit prediction will be required for the correction of the Doppler shift change. The requirement on the accuracy of orbital predication could be eased however depending on how quickly the spacecraft can be reconfigured.

6. ASSESSING THE QUALITY OF NAVIGATION SIGNALS

Inmarsat will make use of common IOT measurements which are usually applied to communication satellites, but furthermore will apply sophisticated test techniques specifically designed to test the Galileo navigation downlink signals. These have been carefully selected and implemented into the IOT Measurement System in close interaction between ESA, DLR, Inmarsat and SED. The relevant test cases are:

- I/Q relative power test
- Code-Carrier/Code-Code/Carrier-Carrier coherency tests
- S-Curve Bias
- Modulation Scatter Plot
- Correlation Loss

The coherency tests will be carried out by the IfEN Navigation Receiver and further post processed by the IOT Measurement System. Despite the possibility to use the 20m LBA, the best C/N_0 will be 60 dB-Hz as this is the maximum input for the receiver. Usage of the small GSTB-V2 Antenna for this purpose is possible as well and opens the possibility for concurrent measurements.

The remaining measurements above will be carried out by post processing captured I/Q samples using the high gain LBA downlink path and will lead to extraordinarily pure signal samples. The post-processing will be performed using OASIS, a specific software tool developed by ESA. OASIS was extensively used for analogous measurements during the GIOVE-B IOT campaign. It should be noted that all post-processing measurements will be run on a dedicated server to ensure real-time operation for the rest of the system.

The main driver of the post-processing accuracy performance is the C/N_0 at the VSA input when the samples are recorded. The raw samples are processed and the final accuracy achievable depends on the algorithms used by OASIS. Therefore, a complete end-to-end analytic calculation of the accuracy can not be performed. The alternative approach that will be followed is to process ideal navigation signal samples using OASIS, then replay these samples with the L-Band Signal Generator through the whole IOT System and finally process again the recorded samples using the OASIS software. In this way, the degradation induced by the system and the simulator can be assessed.

The following table shows the calculated downlink power values for the individual frequencies at the VSA input.

Table 5: Carrier to Noise Density for high gain path

Parameter	L1	E6	E5	Units
Frequency	1.57542	1.27875	1.191795	GHz
Antenna Diameter	20.00	20.00	20.00	m
Antenna Efficiency	55.00	55.00	55.00	%
Antenna Gain	47.77	45.96	45.35	dBi
Min Signal at Earth	-152.00	-152.00	-152.00	dBW
System Noise Temp	120.00	120.00	120.00	K
G/T	26.98	25.17	24.56	dB K
C/No	103.58	101.77	101.16	dB Hz
Signal at LNA input	-74.23	-76.04	-76.65	dBm
Noise at LNA input	-177.81	-177.81	-177.81	dBm/Hz
LNA Gain	60.00	60.00	60.00	dB
Signal at LNA Output	-14.23	-16.04	-16.65	dBm
Noise at LNA output	-117.81	-117.81	-117.81	dBm/Hz
C/No at LNA output	103.58	101.77	101.16	dB Hz
IFL Length	48.00	48.00	48.00	m
IFL Loss	9.60	8.64	8.16	dB
Switchbank Gain	15.00	15.00	15.00	dB
Signal Level at Analyzer	**-8.83**	**-9.68**	**-9.81**	**dBm**
Noise Level at Analyzer	-112.41	-111.45	-110.97	dBm/Hz
FSQ Noise Level	-150.00	-150.00	-150.00	dBm/Hz
Total Noise	-112.41	-111.45	-110.97	dBm/Hz
C/No	**103.58**	**101.77**	**101.16**	**dB.Hz**

Table 6: Carrier to Noise Density for individual signals using the high gain path

	A	B	C	
Signal Relative Power - L1	-2.23	-7.25	-7.25	dB
C/No	**101.35**	**96.33**	**96.33**	**dB.Hz**

Signal Relative Power - E6	-3.33	-6.36	-6.36	dB
C/No	**98.44**	**95.40**	**95.40**	**dB.Hz**

	E5a-I	E5a-Q	E5b-I	E5b-Q	
Signal Relative Power - E5	-6.71	-6.71	-6.71	-6.71	dB
C/No	**94.45**	**94.45**	**94.45**	**94.45**	**dB.Hz**

CONCLUSIONS

The In-Orbit Tests of the Galileo IOV satellites is of key significance for the success of the Galileo mission. Indeed, the results obtained during the IOV IOT campaigns will represent a benchmark throughout the satellite operational life and will constitute a reference basis across the entire constellation.

The successful design reviews of the PL IOT System and of the PL IOT Subsystems (i.e., MS, LBA, CBA and UBA) represent key milestones on the Galileo mission. However, the next phases that include the integration of the subsystems and the final validation of the complete IOT system represent the last great challenges before starting the IOT campaign. It is therefore of paramount importance that the development of the IOT System will be strictly in line with its successful design and that the highest accuracy will be achieved for each individual measurement with every possible source of error minimised and accounted for. This process will be guaranteed by a comprehensive validation activity in order to declare the IOT System capable of performing the IOT campaign.

The Inmarsat response to the challenges posed by the Galileo IOT is a combination of state-of-the-art technology and a highly skilled and motivated engineering and operations team backed by more than 20 years experience in this kind of activities, supported by a strong industrial team of key sub-contractors ranking Vertex, SED Systems, Siemens Austria, Hitech and Satimo. The support of the European Space Agency and DLR will be instrumental in ensuring that all the Galileo IOT objectives are met to the highest achievable standards.

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REFERENCES

IEEE Std 1139-1999 (1999). IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology – Random Instabilities.