THE GIOVE MISSION – A MAJOR STEP TOWARDS GALILEO

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OVERVIEW

Within the Galileo System Test Bed Version 2 a first Giove-A satellite was launched from the Baikonur cosmodrome by a Soyuz rocket in late 2005 and placed into a Medium Earth Orbit with an altitude of 23260 km. Following the successful platform commissioning phase, payload operations with the transmission of first Galileo signals began in early January 2006 in order to secure the frequency filings.

The GSTB-V2 Mission Experimentation project is intended to mitigate the Galileo project risks by an early assessment of technical aspects like early demonstration and performance assessment of the navigation service (including navigation message generation, uplink and broadcast), validation of critical in-orbit technology (clocks), end-to end analysis of the Galileo Signal-In-Space, assessment of Galileo Test Receiver performance, validation of existing ground algorithm prototypes (from GSTB-V1) and testing of new ones (e.g. ionosphere and Broadcast Group Delay), and overall testing of timeliness and operational aspects.

The GSTB-V2 mission experimentation is supported by a core infrastructure based mainly of a worldwide distributed network of Galileo Experimental Sensor Stations (GESSs) that acquire and collect the GSTB-V2 satellite signals and send pseudorange and carrier phase measurements to a Ground Processing Center (GPC) located at ESTEC. One GESS is installed at the Time Laboratory located at INRiM, Turin, and connected to an Active Hydrogen Maser, located in a controlled environment. The INRiM time reference will be used as the basis for Galileo System Time (GST) in GSTB-V2.

Furthermore Satellite Laser Ranging (SLR) stations from the ILRS network send measurements to the GPC as well.

This paper describes the scope and goals of the GSTB-V2 Mission Experimentation and presents the first GIOVE-A orbit and clock analysis results as well as the lessons learned to be considered for the on-going Galileo development.

1. INTRODUCTION

In preparation for the deployment of the Galileo System, the European Space Agency (ESA) began development in 2002 of an experimental Ground Mission Segment, called Galileo System Test Bed Version 1. Within the GSTB-V1 project, tests of Galileo orbit determination, integrity and time synchronisation algorithms were conducted in order to generate navigation and integrity core products. These tests based on pre-developments of GMS Processing Facilities incl. Galileo-like algorithms and on realistic GPS measurements collected at 1 Hz by a worldwide network of sensor stations.

In 2003 began the second step of the overall Galileo System Test Bed (GSTB-V2) implementation with the development of two Galileo In-Orbit Validation Element (GIOVE) satellites: GIOVE-A and GIOVE-B.

In order to mitigate programmatic and technical risks of the Galileo IOV phase the main objectives of the GSTB-V2 or Giove mission are:

- Secure use of the frequencies allocated by the International Telecommunications Union (ITU) for the Galileo System
- Validate Signal In Space performance in representative environment (RFI and Multipath) conditions
- Characterise the On-Board Clock (RAFS and PHM) technology in space
- Characterise the Radiation Environment for the Galileo Medium Earth Orbit (MEO)
- Collect lessons learned on Ground Mission Segment development, deployment and validation especially as far as Galileo Sensor Station are concerned
- Collect lessons learned on Space Segment on-board units pre-development and in-orbit operations

GIOVE-A and –B are being built in parallel to provide in-orbit redundancy and secure the mission objectives. They provide complementary capabilities.

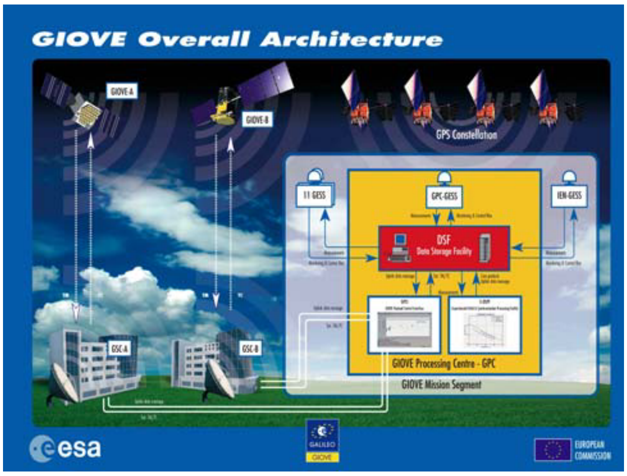


FIG 1. GIOVE Overall Architecture

Figure 1 shows the overall GIOVE system architecture with the necessary components to achieve the above mentioned objectives: the space segment is composed of GIOVE-A and GIOVE-B satellites. In addition, data from GPS constellation is also collected and processed. The Ground Control Segment is composed of both GIOVE satellites control centres (in Guildford for GIOVE-A and in Fucino for GIOVE-B) and of the GIOVE Mission Segment or Core Infrastructure including the Galileo Experimental Sensor Stations (GESS) network and the GIOVE Processing Centre (GPC) located in ESA-ESTEC (Noordwijk, The Netherlands). This infrastructure provides all the necessary facilities and tools for the requested experimentations, covering the data acquisition (also from external providers as IGS, IERS, BIPM and SLRS) and archiving, the operations of the major processing facilities and the management and wide dispatching of the results to internal and external users.

The GSTB-V2 Infrastructure includes the GIOVE Processing Centre (GPC), composed of the Data Server Facility (DSF), the interface with the GIOVE A and B Satellites Control centres (GPCI) and the Experimental Orbit & Synchronisation processing facility (E-OSPF); a word-wide network of Sensor Stations composed of 13 stations and a Communication Network.

The GIOVE signal in space is acquired by the reference stations (GESS), together with the GPS signal. By polling, the Data Server acquires periodically the files with the raw data and converts this to standard RINEX 3.00. In parallel, the GIOVE flight dynamics data and the telemetry and telecommand files acquired by the GSC-A and B are also archived in the Data Server, through the GIOVE Payload Control Interface (GPCI) facility. These data are the basis for the experimentation process, together with other supporting data.

In parallel to the off-line experimentation, an on-line experimentation is performed continuously in routine mode: the evaluation and generation of the GIOVE navigation message. In a two-hour basis, the ODTS processing facility evaluates the orbit and clock parameters needed for the generation of the navigation message. Once generated, this navigation message is sent to the GSC for uplink to the GIOVE satellites.

The results of the data acquisition process, the results of the experimentations, the status of the mission, and other important information is distributed to the GNSS community using via the GIOVE web page (http://www.giove.esa.int/).

2. GSTB-V2 MISSION ARCHITECTURE

The GIOVE Ground Infrastructure consists of two main elements: the world wide located Galileo Experimental Sensor Stations (GESS) and the GIOVE Processing Centre (GPC) located at ESTEC, Noordwijk.

A total of 13 GESS stations are located all over the world (see figure 2) to assure the continuous acquisition of GIOVE and GPS signals and to assure a minimum depth of coverage of 2 for the GIOVE satellite as shown in the following figure 3.

The colours indicate the number of stations in view of the GIOVE satellite over a particular area. This figure is also defined as the so called Depth-Of-Coverage (DOC). A DOC-1 means that the satellite is in view of at least 1 station over a particular area (here red colour). A DOC-2 means that the satellite is in view of at least 2 stations over a particular area (here orange colour), etc.

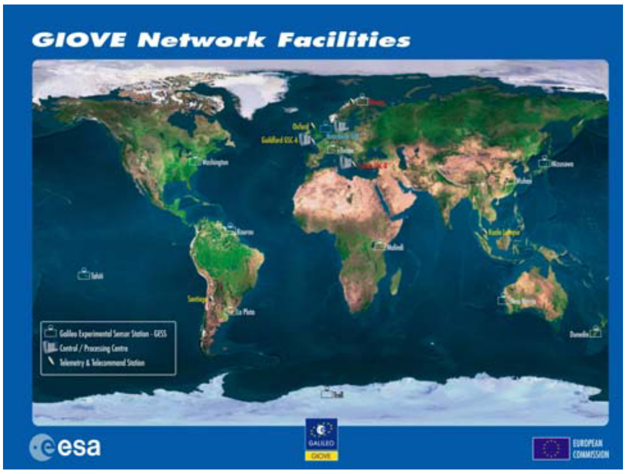


FIG 2. GIOVE Network Facilities.

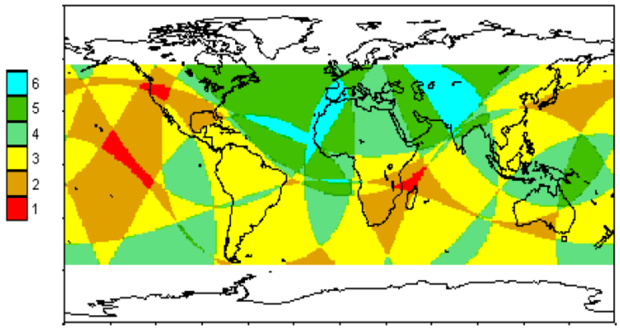


FIG 3. Depth-Of-Coverage (DOC) for the 13-station network.

The GIOVE Processing Centre contains the following elements as can be seen in Figure 4:

- The Data Server Facility (DSF): it is the central facility of the GPC managing data acquisition and dissemination, the monitoring and control of the system, the execution of the routine processes and the user access. Four servers and the disk array compose the DSF.
- The Experimental Orbit and Synchronisation Processing Facility (E-OSPF): it hosts the major processing and it is responsible for the calculation of the GIOVE products. Two work stations are used for the E-OSPF:
  - the first one is computing the near real-time orbit and clock information and also the navigation messages to be broadcasted by GIOVE satellites;
  - the second one is used for off-line processing of the data and specific experimentation campaigns.
- The GIOVE Payload Control Interface (GPCI) constituting the interface between the GIOVE Satellite Control (GSC A/B) centre and the GPC, where operation, telemetry, flight dynamics and navigation data is exchanged and telemetry analysis are possible.

- The GPC communications means, based on hot-backup routers firewalls and switches.

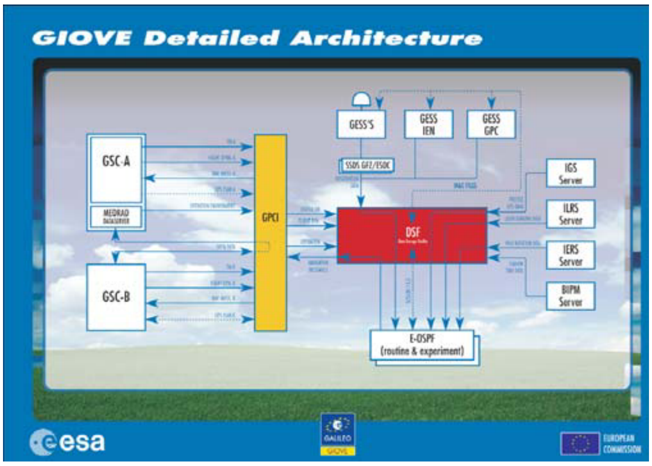


FIG 4. GIOVE detailed architecture.

These elements and functions are representative of the future Galileo system architecture, nevertheless the GIOVE Core Infrastructure will not be used in the final Galileo system, but as a means to bring added value in terms of confidence, design and performances consolidation. Therefore the Core Infrastructure is composed of prototypes for the Galileo Mission Segment algorithms and is not to be considered safety critical.

2.1. GIOVE Experimental Sensor Stations (GESS)

The design drivers of the GIOVE Experimental Sensor Stations (GESS) have been to acquire continuously GIOVE and GPS satellites signals in an unattended way and to be able to configure and control the station remotely from the GPC. These objectives have been mainly achieved with the architecture consisting mainly of the following components, as depicted in figure 5:

- A wide-band experimental Space Engineering GPS /Galileo active antenna tracking L1 signals as well as L2 signals (GPS) and E5/E6 signals (Galileo). The design guarantees an excellent gain over the Galileo frequency band. It is highly stable over temperature and environmental conditions and allows for multipath mitigation.
- A Septentrio Galileo Experimental Test Receiver (GETR) designed as a dual-constellation GPS/Galileo receiver that can be configured to simultaneously track Galileo as well as GPS satellites in multi-frequency mode. All Galileo frequencies and modulations are supported, which allows to track code/carrier GPS L1, L2 and L5 and Galileo L1, E5a, E5b, E5 (AltBOC) and E6 signals. The GETR contains 6 generic Galileo/GPS channels, one AltBOC channel, and 9 dual-frequency (L1&L2) GPS channels. Each generic channel can track the pilot and data component of all currently Galileo defined BOC(m,n) and BPSK signals including Sine and Cosine BOC types, QPSK and interplex multiplexing modes. These channels can be assigned to different Galileo and GPS satellites. This large flexibility in signal types and the configurability of the tracking behaviour (DLL and DLL bandwidths, pre-detection times, C/No tracking threshold, etc.) together with the raw data output (code, carrier phase, Doppler, C/No, navigation data) allows extensive evaluation and experimentation with the new Galileo signals.
- A commercial Rubidium Atomic Frequency Standard (RAFS) manufactured by Temex Time for most of the GESS in the network.
- Connectivity to an external clock for the two master clock stations, to take advantage of a time laboratory high quality clocks. These two GESS have been installed in INRiM (National Institute of Metrological Research in Turin, Italy) and USNO (United States Naval Observatory) sites and are used as time reference for the GIOVE Mission (INRiM as baseline, USNO as backup).
- The GESS Core Computer is an Industrial PC and manages the data collection from the GETR, the data conversion and storage, the Monitoring & Control activities and the communication with the GIOVE Processing Centre (GPC).
- An Uninterruptible Power Supply (UPS): GESS are unattended and in case of electrical failure are able to operate 90 minutes and warn the GPC before the controlled shut down sequence is initiated.

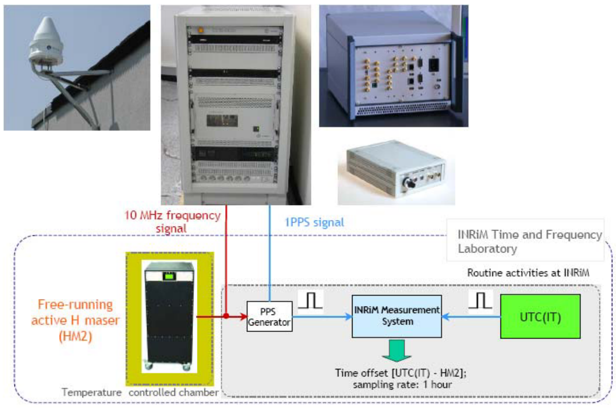


FIG 5. Elements of the GESS.

The GESS are continuously delivering 15 minutes raw data files to the GPC as well as their status information.

Most of the stations are located in hosting entities sites of ESA European Space Operation Centre (ESOC) in Damstadt) and GeoForschungsZentrum (GFZ) Potsdam who provides the infrastructure and communication means to link them to the GIOVE Processing Centre. These organisms own an extensive site network all over the world and have been responsible for the installation of the GESS.

The stations are mainly connected to the GPC through the two Sensor Stations Data Servers (SSDS) of ESOC and GFZ except for two of them that are directly linked to the GPC: the station located at INRiM (National Institute of Metrological Research in Turin, Italy) premises and the station in the GPC which is inside the laboratory internal network.

The INRiM station is also connected to a free-running Active Hydrogen Maser (AHM) acting as time reference for the GIOVE Core Infrastructure, ie. all clocks in the GSTB-

V2 mission segment are synchronised to this AHM.

The two SSDS are acting as a gateway between the GPC and the GESS and ensure bidirectional connectivity between these elements with nearly no impact on the performances of the communication channel; they transfer raw data and command files between both ends keeping a log of the operations and storing all files during 10 days.

2.2. Communications Network

GIOVE Mission communication network allows the data exchanges between all GIOVE Ground Segment elements. It is mostly based on the public internet and has to cope with the following interfaces:

- GPC – GESS provides the communication between the Sensor Stations and the GIOVE Processing Centre and can be established via a direct link or through the Sensor Stations Data Servers. The GPC-INRiM and GPC-ESOC data rate is 2 Mbps and the GPC-GFZ data rate is 32 Mbps.
- GPC – GSCs: Giove A and Giove B Control Centres are directly connected to GPC by a VPN. This allows the secured interchange of the satellite telemetry data and operation plans.
- External Data Providers - GPC: the external data for the Giove experimentation is downloaded from the SLRS, IGS, IERS and BIPM servers.
- External Users - GPC: the GPC firewall allows different types of user access to the data archived in the File Repository. Authorised users can connect to the FTP server of the public DMZ network or to the internal GPC network to download stations data or GIOVE mission processed products and experimentation results. These operations can also be done through the GIOVE web pages.

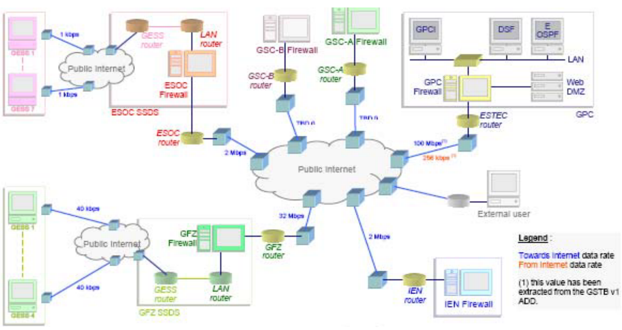


FIG 6. GIOVE Mission Communication Network

2.3. Data Server Facility (DSF)

The Data Server Facility (DSF) is the central point to collect, store and distribute all GIOVE mission related data, allows monitoring the status of the system elements and provides the interface for the internal and external users.

The DSF hardware architecture is composed of Central Archive Server, File Repository RAID disks, Monitoring and Control Server, GIOVE Data Quality Server and DMZ server, which have the following functions and role inside the GIOVE Mission:

- The Data acquisition function collects the sensor station data (ESOC SSDS, GFZ SSDS, INRIM-GESS and GPC-GESS) and other related external file servers (from BIPM, IERS, SLRS and IGS) by means of a programmatic FTP based on a predefined schedule or from off-line media. Furthermore the results and core products are retrieved from the GIOVE Mission Processing Facilities (ie. E-OSPF). In addition the GIOVE satellites telemetry, flight dynamics and other relevant data are retrieved from the GPCI. Each single file collected is stored in the File Repository and catalogued according to its type to make it available to the authorised users.
- The stations raw data delivered on a 15-minutes basis are converted to 1-hour RINEX 3.0 observation and navigation files. The RINEX files are archived and can be made available to the authorised users.
- The Routine Navigation Message generation function is automatically triggering every two hours the generation of the routine E-OSPF products such as the orbits, clocks and the navigation message to be uploaded to GIOVE satellites. The routine processed data is properly archived and the navigation message is sent to the GPCI where it will be transferred to the GSCs for upload.
- GIOVE website is hosted in the DSF, based on an internal web service (in the Central Archive Server) and on an external one (in the DMZ Server).
- All users are authenticated when attempting to log in the DSF, with a username and password. A LDAP server is used for the authentication and authorisation.
- The Monitoring and Control function for the entire Core Infrastructure in order to retrieve information about the availability of station files, interface errors, processing facilities alarms, etc. is centralised in the DSF. This function provides also the interface to send commands to the GESS. Those commands are used to get the stations status information, to reconfigure the station or the receiver and they can be time tagged for a future execution. Due to the experimental nature of the GIOVE mission, this feature is especially important to adapt the receiver tracking behaviour or channels allocation according to the experimentation needs. The capability to remotely upgrade the GESS or GETR software is also essential.
- The DSF is also in charge of generating data quality analysis on the received GIOVE data. This analysis contains the availability of observables (pseudorange, carrier phase for L1A, L1B, L1C, E5a, E5b, E5, E6A, E6b and E6C) per station and satellite, the multipath error and cycle slips per frequency for each GIOVE RINEX file and the results are presented on the GIOVE web pages.

FIG 7. GIOVE Official Web site

2.4. GIOVE Payload Control Interface (GPCI)

The GIOVE Payload Control Interface (GPCI) provides an interface between the GIOVE Satellite Control Centers (GSCs) and the Data Server Facility (DSF) to support requests for transfer of data from the DSF to the GSC and the ingestion of data from the GSC into the DSF. This includes retrieval of telemetry and telecommands from the GSC, retrieval of flight dynamics from the GSC and forwarding of navigation messages and satellite operation requests to the GSC. GPCI is also the facility in GPC that allows Giove telemetry analysis.

GPCI facility is build upon a Spacecraft Control System (SCOS-2000) and a Mission Utility and Support Tools (MUST) implemented on two industrial PCs.

The SCOS-2000 Spacecraft Control System is conceived as a scaleable distributed system that can be used in a variety of configurations. The system is data driven; therefore very little adaptation needs to be made when applying the system to a new mission. The system supports CCSDS telemetry and telecommand packet standards, and the ESA packet utilization standard (PUS). SCOS-2000 system has been customised to cope with the different GIOVE-A and GIOVE-B data formats. It allows for Telemetry extraction, processing and display (e.g. alphanumeric, graphic, scrolling, mimics and variable packet displays) and the Mission Planning System is used to create Satellite Operations Requests.

The Mission Utility & Support Tools, developed for the European Space Agency (ESA) is a collection of tools that supports the analysis, visualization, exploration and exportation of telemetry and ancillary mission data. In the GPCI facility the data is imported from the SCOS database and the calibrated parameters are stored in an offline repository. The MUST clients connect to this repository to retrieve and process the data independently from the processes running in the SCOS-2000 system. The user can retrieve, display, explore, analyse and export all the data (TM, orbit, radiation) stored in the MUST database of a selected time window and can either plot a number of parameters against time (in the same or in different windows) or he can plot one parameter against another one. Furthermore the data can be exported in ASCII and in Matlab format for further processing in Matlab, Excel or other tools.

2.5. Experimental Orbit & Synchronisation Processing Facility (E-OSPF)

The Experimental Orbit and Synchronisation Processing Facility (E-OSPF) is conceived to be a mock-up of the basic functions that will be implemented in the operational Galileo OSPF in the future. It has been designed with a view to produce orbit, clock and SISA data emulating most of the functions that are currently envisaged for the final OSPF.

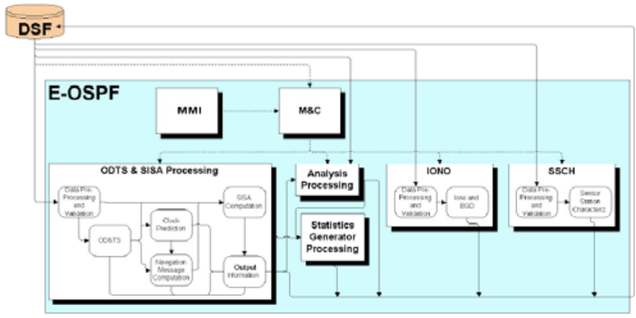


FIG 8. E-OSPF functional diagram

The E-OSPF functional architecture is shown in Figure 8. The three main modules are:

- The OD&TS and SISA Processing are in charge of generating the “basic” products, such as the determined and predicted orbit and clocks, the navigation message and the SISA. It supports the following functions:
    - GPS & GIOVE data pre-processing and validation.
    - Satellite Laser Ranging (SLR) data acquisition and validation from around 10 SLR stations, which provides data on a regular basis.
    - Orbit Determination and Time Synchronisation determines the precise orbits for all GPS and GIOVE satellites in a batch least-squares estimator that processes in the same estimation arc the iono-free GIOVE and GPS observations and GIOVE SLR measurements (when available). The code measurements are smoothed with phase to a five-minute sampling interval using a Hatch filter. Furthermore, the ODTS solves the so-called station inter-system bias (ISB), which is the differential delay between the GPS and Galileo signal paths within the stations. The determination of this delay allows aligning the GPS and GIOVE-A observations to the common station clock. The ISB concept is depicted in figure 9.

      Another particular aspect of the ODTS process is the use of a five-coefficient empirical solar radiation pressure (SRP) model for GIOVE-A and the GPS satellites. This model is adapted from existing GPS and GLONASS literature on the subject. The model requires no a priori information about a satellite’s geometric and reflectivity properties; only approximate mass and crosssectional area values are needed. In total, only 11 dynamic parameters are estimated per satellite (position, velocity, and five SRP coefficients).

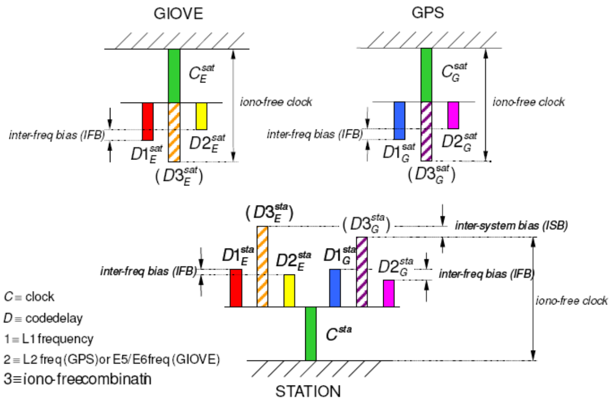


FIG 9. Relationships between GIOVE and GPS station signal-path delays.

- Estimation of the onboard and sensor station clock bias with respect to the INRiM time reference.
- Precise orbit prediction for the GPS and GIOVE satellites.
- Clock prediction which fits the estimated clock biases into a certain model among several possible ones.
- Navigation message computation containing the ephemeris, corrections and almanac parameters and generation of the navigation messages to be uploaded.

- The Iono Processing is in charge of generating the “Ionosphere” products. It includes the following functions:
  - Support functions for data pre-processing and validation and for the generation of geometry and ambiguity free combination of phase and code observables needed for the Inter Frequency Bias (IFB) estimation.
  - Inter Frequency Bias Estimation determines the IFB’s for all the stations and all the GPS and GIOVE satellites with respect to the INRiM GESS reference based on a Kalman filter.
  - Azimuth Coefficients Estimation determines Az coefficients (A0, A1, A2) which correspond to the second order polynomial that describes the Az parameter function of modified dip latitude for each site using the NeQuick model for the Ionosphere.
  - Ionosphere Disturbance Flag (IDF) Computation determines the IDFs, which indicate whether the estimated Az values are valid or not for each configured region.
  - Iono Navigation Data Generation builds the Ionosphere products for the navigation message.
- The Sensor Station Characterisation Processing performs the statistical characterization of the configured sensor stations. It includes the following functions :
  - Support functions for data pre-processing and validation
  - Measurement Statistics Computation.
  - Receiver Noise and Multipath Statistics Computation.
  - Station Clock Statistics Computation.

In addition the following support functions are implemented:

- The Man Machine Interface (MMI) and Monitoring and Control (M&C) modules to control and trigger the execution of the different internal modules and to control the interface with the DSF.
- The Analysis Processing is in charge of generating the final OD&TS and SISA Core Products:
  - Computation of Orbit and Clocks differences based on a comparison of the OD&TS predictions with a reference, which are either the estimations from a previous OD&TS and SISA processing cycle or the IGS products.
  - SISE Computation computes the satellite ephemeris and clock errors.
    - SREW Computation estimates the SISE for the worst user location.
    - UERE Computation computes the UERE w.r.t. the ephemeris and clock error.
  - SISE and SISA Comparison compare the SISE and the SISA values to compute the SISA bounding status.
- The Statistical Generator Processing performs the statistical analyses for SISA Core Products (which require the processing of outputs from several OD&TS and SISA Processing cycles).

The E-OSPF software functions are implemented on two Sun Work Stations connected to the GPC internal LAN in order to support the parallel execution of the continuous routine on-line experimentation and the campaign driven off-line experimentation.

The ODTS routine processing is shown in picture 10 and can be summarised as follows:

- ODTS “arc” duration is 5 days
- 1-day overlapping arcs when possible (depends on signal continuity)
- 1-day orbit + clock predictions (nav. message performance)
- Reference station clock is GIEN (optionally GUSN)
- Iono-free observables: Orbit + Clock + Tropo + ISB
- Smoothed code + phase + SLR
- “Simple” dynamics: state vector (6) + SRP parameters (5)
- Inter-System Bias (ISB) constant per arc (ref. GIEN)
- Main products:
  - Estimated and predicted orbits (SP3)
  - Estimated and predicted clocks (CLK), normally at 5-min rate

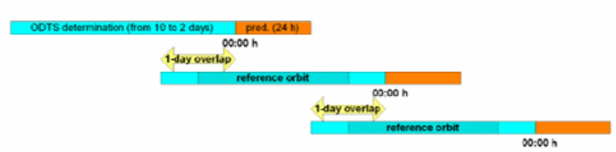


FIG 10. ODTS Routine Processing

3. EXPERIMENTATION AND RESULTS

In satellite navigation, the position accuracy of a user is driven, among others, by the performance of the navigation message broadcast by the satellites, the satellite clock stability, and the user's receiver and environment. Wrong assumptions on the impact of each of these drivers can be catastrophic for the overall performance of GALILEO. Therefore Experimentation with real data is essential for the Galileo Project and is part of the ESA's system verification and risk mitigation approach.

The experimentation results presented in this paper are based on data from the GESS network, with a sampling interval of one second, and satellite laser ranging (SLR) data from the International Laser Ranging Service (ILSR) collected between October 2006 and January 2007, when 12 GESS were operational. To reduce the estimation uncertainty, the GIOVE-A clock is calculated when the satellite is visible by at least two stations (DOC-2).

Frequency Band	Frequency (MHz)	Pilot/ Data	Pseudo Range	Carrier phase
L1	**1575.420**	Data	C1A	L1A
		Data	C1B	L1B
		Pilot	**C1C**	**L1C**
E5a	1176.450	Data	C5I	L5I
		Pilot	C5Q	L5Q
E5b	**1207.140**	Pilot	**C7Q**	**L7Q**
E5a+b (AltBOC)	1191.795	Pilot	C8Q	L8Q

TAB 1. GIOVE RINEX3.0 observables.

During the Data analysis period mentioned above, GIOVE-A was configured to transmit the L1 and E5 signals using the nominal payload chain, driven by the RAFS Flight Model 4 – one of the two onboard clocks. The Galileo Experimental Test Receiver (GETR) within all GESSs uses seven Galileo Channels, configured to generate the observables shown in table 1.

The three-character code (pseudo-range) and carrier-phase observables in the table follow the RINEX 3.0 standard. The C1C-C7Q and L1C-L7Q ionosphere-free code and phase combinations have been selected for clock characterisation and are used together with the P1-P2 and L1-L2 ionosphere-free code and phase combinations from the GPS constellation.

The characterisation of the onboard clock is significantly enhanced by the use of SLR, a high-precision technique for orbit determination that is independent of the navigation signal generation, but on the other hand limited due to the high GIOVE-A altitude of 23260 km in combination with the small size of its laser retroreflector and weather conditions, so that the satellite is regularly tracked by only a limited number of ILRS stations (around 10).

3.1. ODTS results and Clock characterisation

The main products from ODTS are estimated orbits (for GIOVE-A and all GPS satellites) and estimated clock phase offsets with respect to the reference clock (for all satellites and all stations, except for GIEN which is the reference clock). The clocks are generated in clock-RINEX (CLK) format as phase offsets relative to the INRiM reference clock, and at a nominal output interval of five minutes.

The clock estimate as seen through the ODTS algorithm is not the "pure" clock as tested on the ground, but rather an "apparent" clock as seen through the complete onboard signal generation chain, the space propagation path, the receiver network, and the ODTS estimation algorithm.

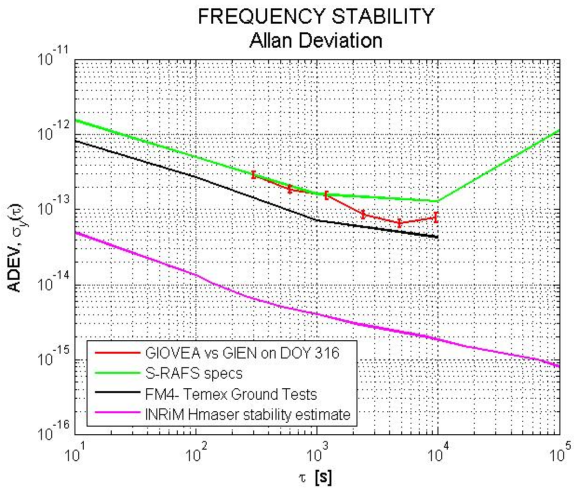


FIG 11. Stability of the GIOVE-A "apparent" clock with respect to the GIEN master clock on a "quite" day (no anomalous behaviour)

Figure 11 illustrates the stability of the GIOVE-A apparent clock with respect to the GIEN master clock, computed for a regular "quiet" data period. The stability of the GIOVE-A apparent clock in the short to medium term is within specifications. The stability reported as "S-RAFS specs" is the specified stability of the pure clock, so the results indicate that, during the most stable period, the apparent clock seen through ODTS is as stable as a pure clock.

Further analysis over longer data periods has shown that the apparent clock sometimes exhibits frequency jumps. These frequency jumps are clearly visible in figure 12, where the GIOVE-A apparent clock frequency data are reported for the period from October 28 to November 18, 2006. The red lines indicate frequency jumps. A GIOVE-A payload switchoff occurred on November 15, so during the period between November 15 (day of year (DOY) 319) and November 18 (DOY 322) the clock was in its warm-up phase.

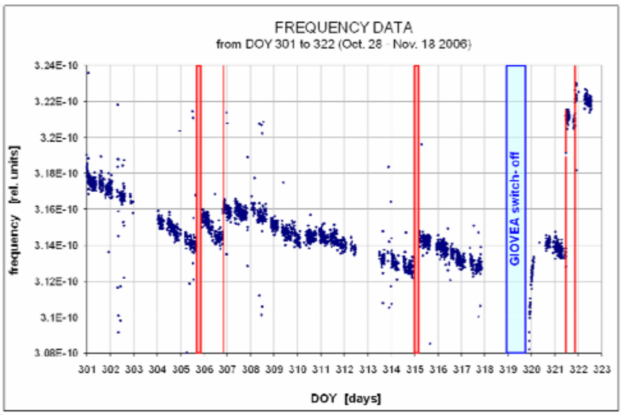


FIG 12. GIOVE-A “apparent” clock frequency from 28.10.06 – 18.11.06. Frequency jumps are indicated by red lines.

To further investigate the shape of the jumps and to obtain a better estimation of the epochs at which the jumps occurred, clock “zooms” around the frequency jumps were estimated by ODTS running at a 10-second sampling interval. Figure 13 shows an example of a zoom of the GIOVE-A clock phase offset (second order polynomial removed), which occurred on December 12, 2006.

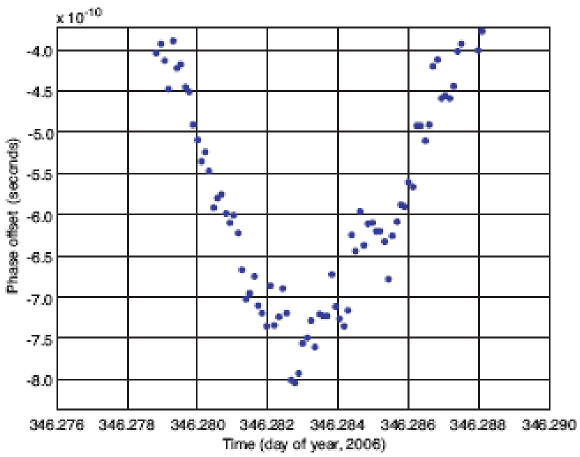


FIG 13. GIOVE-A clock phase offset on 12.12.06.

Concerning the accuracy of the GIOVE predicted orbits and clocks contained in the navigation message, it can be said that as a result of the good orbit estimation accuracy and the high-fidelity dynamic model, the orbit prediction is excellent, with errors below 50 cm in the worst user direction even after 24 hours of prediction. Figure 14 shows an example of a typical 24-hour orbit prediction, as compared to the orbit estimated a-posteriori (considered as the truth).

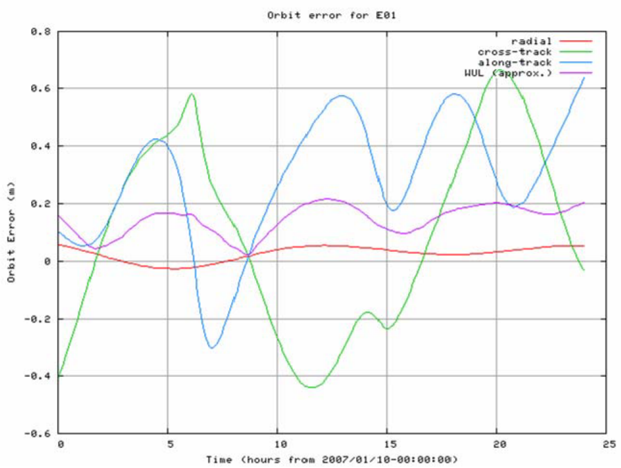
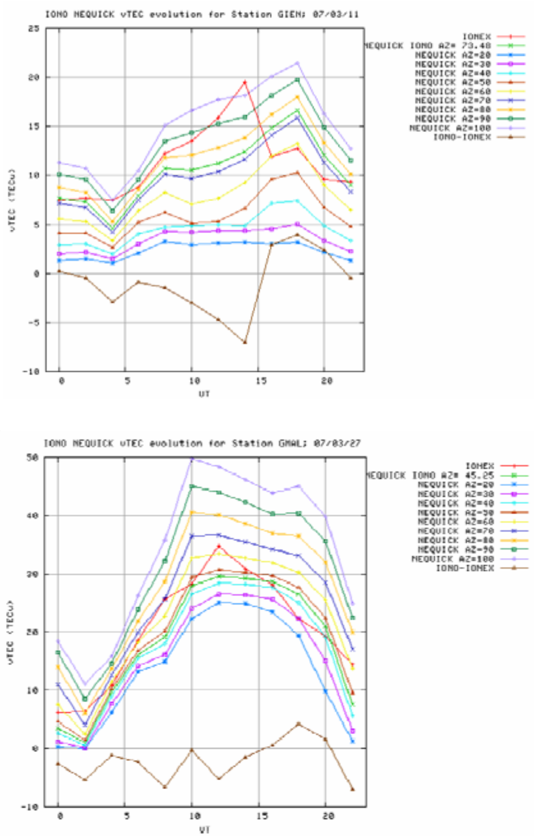


FIG 14. Typical GIOVE-A orbit prediction error.

3.2. IONO results

Figure 15 shows examples of local Az estimation for stations at different latitudes: GMAL (Malindi, 2.99° S). GIEN (Turin, 45.9°) and GKIR (Kiruna, 67.86°). Each graphic shows the IONEX file vTECdaily evolution, the NeQuick vertical TEC daily evolution for different values of the effective ionization level Az, the IONO vTEC daily evolution (using the previous estimated Az coefficients) and the differences between IONO and IONEX vTEC daily evolution. IONEX files from IGS are used as true ionosphere for comparison with the IONO results.



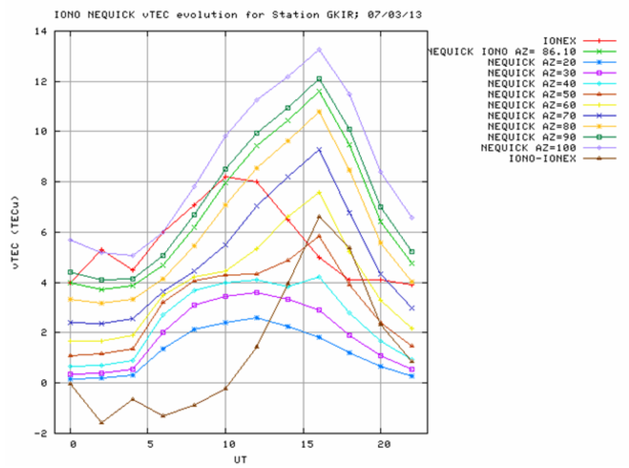


FIG 15. IONO vTEC profile over different latitudes.

The IONO – IONEX vTEC difference generally is smaller than 10 TECu (where 1 TECu = 10 16 e/m-2), which means, for a single frequency user, a position error of 1.6 meters. It is also important to point out that one of the main limitations of this methodology is that in general the NeQuick vertical TEC daily evolution shape is different from the IONEX one. Consequently it is not possible for IONO software to reproduce the IONEX evolution only changing the Az value, which is the only NeQuick model parameter to be changed in the optimization method.

The calculation of the station ISBs using geometry-free GIOVE-A and GPS code and phase combinations, which contain ionospheric total electron content (TEC) information and satellite and station inter-frequency biases. The calculated stations ISB values (every two days), depicted in figure 16, show good stability and are in agreement with the values calculated by ODTS (at the nanosecond level).

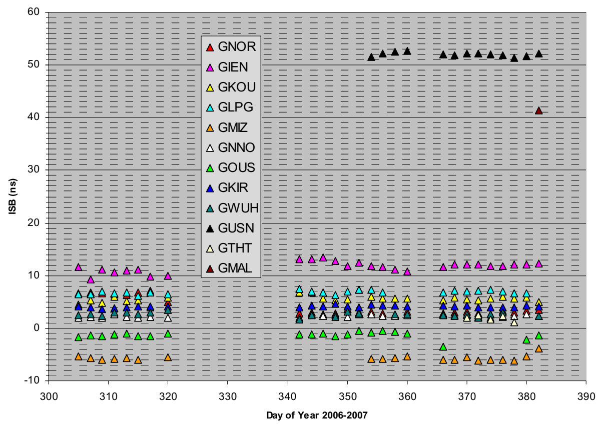


FIG 16. The inter-system station biases for 12 GESSs.

3.3. Quality control

The quality of the ODTS results can be initially assessed through an examination of the measurement residuals; that are the differences between real data and the values as modelled by the processing algorithms. For optimal results, measurement residuals should be small and randomly distributed, showing only the un-modelled error contained in the data (eg. code multipath). Typical ODTS residuals are 40 cm for code measurements, 1 cm for phase and 3 cm (one-way) for SLR. A systematic elevation-angle dependent pattern is observed on code residuals. This effect is under investigation but is believed not to significantly affect the experiment results.

The accuracy of the estimated orbits and clocks must be assessed prior to clock characterization, because the orbit estimation error is largely correlated with the clock estimation error. The estimation error of GIOVE-A products is calculated to be at the level of 5–10 cm root-mean-square (RMS) in the radial direction for orbits, and 0.4 nsec (one standard deviation) for clocks. These figures are consistent with the comparison of GPS satellite orbit and clock estimates against precise products from the International GNSS Service (IGS).

Another validation exercise consists of evaluating the behaviour of the GSTB-V2 ground reference clock, the INRiM AHM, to check that its noise and drift levels are well below those of the onboard clock.

This is done with two almost independent techniques. First, since two active H masers are included in the GESS network — one at INRiM and one at the United States Naval Observatory, Washington, D.C. (station GUSN) — ODTS can estimate their respective phase offset. This clock-phase comparison has high quality in spite of being based on only 12 ground stations (mostly equipped with a rubidium clock) and is robust to missing GPS observations. Second, the Natural Resources Canada precise point positioning (PPP) algorithm is used to process the GPS observations gathered at the same two stations, estimating also the same clock-phase difference. An example of results is reported in figure 17 for the period January 5–17, 2007. The two estimation techniques agree to a remarkable extent. However, the stability of the PPP method is affected by missing GPS observations, which can increase the noise sometimes causing small jumps in the phase.

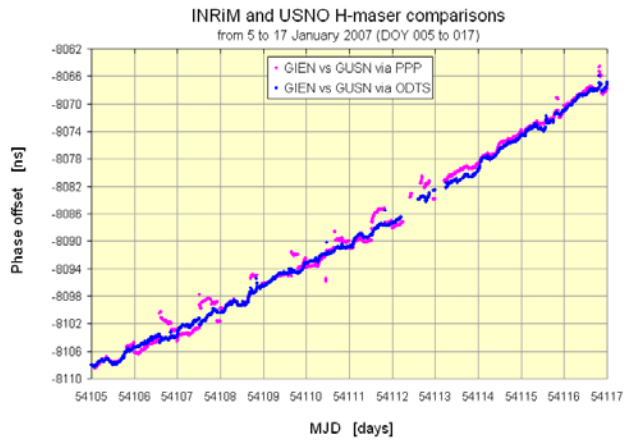


FIG 17. Phase offsets between the active hydrogen maser clocks at INRiM (GIEN) and USNO (GUSN), January 5-17, 2007, computed using precise point positioning (PPP) and the ODTS software.

Since the overall behaviour of the INRiM and USNO H-masers is in line with the expected behaviour of a maser (low noise and low frequency drift), the GIEN clock is a good reference clock for characterizing the GIOVE-A clock.

4. CONCLUSION AND LESSONS LEARNED

The GSTB v2 Mission Core Infrastructure is a prototype of the final Galileo Mission Segment that allow the verification of the critical items of the Galileo system, like the on-board clocks or the reference stations installation requirements.

The infrastructure is based on a network of world wide distributed sensor stations with a DoC of 2, which is providing 15-min GIOVE-A SIS raw data files based on secure FTP using existing internet links. These files, converted to RINEX 3.0, together with other data acquired from the public servers (eg. SLR, IGS), are the basis for the experimentation and the evaluation of the navigation message related parameters that are uplinked to the GIOVE satellites.

Experimentation is a key element of the Galileo validation phase and these early results are bringing much valuable information that extends well beyond the orbit and clock performance and behaviour assessment. First, it is now demonstrated that the rubidium clock has been operating nominally for more than one year in orbit and, outside of a few sporadic frequency jumps, the clock has met performance specifications. This also proves that the noise of the measurement method is not affecting the results. Second, these results also demonstrate that the GIOVE-A environment is well mastered as it does not significantly affect the clock performance. Finally, they show indirectly that the GIOVE Mission segment and its associated infrastructure is fully functional and operating according to its specification.

As far as frequency jumps are concerned, several hypotheses have been identified and analyzed. As exemplified by the extensive literature on the topic, such events are not surprising with this technology and remedial actions have already been put into place and are being validated on the ground. Furthermore, in February 2007, GIOVE-A was switched to the redundant rubidium clock (FM5) to verify whether these frequency jumps are also observed or whether they can be explained by the limited accumulated on-ground tests. Preliminary results have revealed no FM5 frequency jumps so far.

In the near future, further data will be processed, both from FM4 and FM5, to gather as many results as possible. This will also be an excellent opportunity to further validate the whole GIOVE Mission segment and prepare for the characterization and assessment of the passive hydrogen maser onboard GIOVE-B.

The entire GIOVE experimentation can be considered as highly successful and the lessons learned are widely used by the project for the on-going development and deployment of the Galileo System.

5. LITERATURE

[1] The Architecture of the Galileo System Test Bed (GSTB-V2 Mission Infrastructure, P. Durba et. TimeNav2007, 29.5-1.6, Geneva, Switzerland
[2] Time for GIOVE-A, GPS World, May2007
[3] http://www.giove.esa.int/