Use of SLR observations to improve GIOVE-B orbit and clock determination

I. Hidalgo, A. Mozo, P. Navarro, R. Piriz (1)**, D. Navarro-Reyes** (2)

(1) GMV, Madrid, Spain
(2) ESA - ESTEC, Noordwijk, Netherlands

pfnavarro@gmv.com, Daniel.Navarro-Reyes@esa.int

Abstract

GIOVE-A and GIOVE-B (Galileo In Orbit Validation Elements) are experimental satellites that have been launched by ESA in order to verify some of the critical technologies of the future Galileo system, such as on-board atomic clocks and the generation of the navigation signal, in addition to characterizing the processing of the Galileo signal by user receivers, all in the frame of the GIOVE Mission.

As a primary tool in the experimentation activities, the GIOVE Mission E-OSPF software (Experimental Orbitography and Synchronization Processing Facility) receives the navigation observations gathered by a network of dual GPS/Galileo receivers and estimates the orbit and clock offsets of the GPS and GIOVE satellites. The inclusion of GPS satellites is necessary to achieve the required level of redundancy in the clock estimation. The clock offsets are obtained every 5 minutes, and their time series is essential to characterize the behavior of the on-board atomic clocks, both the RAFS (Rubidium Atomic Frequency Standard) and the Passive Hydrogen Maser clock (PHM) of GIOVE-B, the most stable clock ever flown in space.

The main problem in the determination of the offsets of the on-board clocks is that the radial error in orbits and the clock offsets are highly correlated, so that it is difficult to disentangle them. A good way of overcoming this effect is to have a complementary means to compute the estimated orbits, such as SLR measurements. The GIOVE satellites are equipped with laser reflectors, and dedicated campaigns of laser tracking are being carried by ILRS in coordination with ESA. The E-OSPF is able to process SLR observations together with the navigation ones. In this way, the orbit determination can be improved and decorrelated from the clock estimation.

This paper describes the process of orbit and clock determination from the navigation signal, and how the SLR measurements can be added to have better orbits and a better observability of the on-board clocks. It presents the results of the experimentation carried to characterize the behavior of the GIOVE-B PHM, with the help of SLR measurements, and to assess the improvement obtained by using them.

Introduction

In preparation for the deployment of the Galileo System, the European Space Agency (ESA) initiated in the late 90ies the development and industrialization of two on-board clock technologies: Rubidium Atomic Frequency Standard (RAFS) and Passive Hydrogen Maser (PHM). In 2004, both technologies successfully passed ground environmental qualification tests (including vibration, shock, radiation, etc). In 2005, 6 RAFS and 2 PHM flight models were delivered for first in-orbit validation.

In parallel, ESA began development in 2002 of an experimental Ground Mission Segment, called Galileo System Test Bed Version 1. Within the GSTB-Vl project, tests of Galileo orbit determination, integrity and time synchronization algorithms were conducted in order to generate navigation and integrity core products based on GPS data.

In 2003 the second step of the overall Galileo System Test Bed (GSTB-V2) implementation began with the development of two Galileo In-Orbit Validation Element (GIOVE) satellites: GIOVE-A (launched on 28th December 2005) and GIOVE-B (launched on 27th April 2008). 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 the 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 multi-path) conditions
- Characterize the On-Board Clock (RAFS and PHM) technology in space
- Characterize 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
- Early demonstration and performance assessment of the navigation service (including navigation message uplink and broadcast)
- Validation of ground algorithm prototypes (evolved from GSTB-Vl) and testing of new ones
- Overall testing of timeliness and operational aspects (including data collection from GESS, data processing, message generation and uplink)

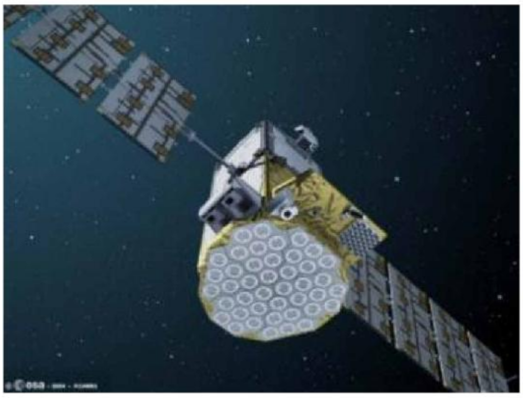


Figure 1. Artist's view of GIOVE-B satellite

The overall GIOVE system architecture with the necessary components to achieve the above mentioned objectives are as listed here:

- The space segment is composed of GIOVE-A and GIOVE-B satellites
- The Ground Control Segment is composed of both GIOVE Ground Control Centers (GSC), in Guildford for GIOVE-A and in Fucino for GIOVE-B
- The GIOVE Mission Segment infrastructure

The present paper focuses in one of the aforementioned objectives of the GIOVE mission: the characterization of the PHM clock of GIOVE-B. From the user point of view, the stability of the on-board clocks is essential, since the computation of the navigation solution is partly based on the prediction of the satellite clock offsets. An unstable clock cannot be accurately predicted, and leads to a degradation of the user performances. On the other hand, the PHM clock onboard GIOVE-B sets a new standard of stability on a satellite, which has to be assessed as part of the GIOVE Mission activities.
The analysis of the satellite clock behavior is based on the determination of the clock offsets with respect to a very stable reference, obtained by processing the microwave measurements gathered from a network of stations. As will be explained in more detail below, the precise estimation of these offsets is hindered by the strong correlation between orbit and clock errors. The use of SLR measurements, that are only dependent on the orbit of the satellite, is expected to help separating both components, and hence improving the accuracy of the clock offsets estimation.

The GIOVE Mission Segment

The GIOVE Mission Segment provides all the necessary facilities and tools for the requested experimentations, covering the data acquisition (from external providers such as IGS [Dow 2005], IERS, BIPM and ILRS [Pearlman 2002]) and archiving, the operations of the major processing facilities and the management and wide dispatching of the results to internal and external users. The GIOVE Mission Segment includes:

- GIOVE Processing Center (GPC) located in ESTEC (Noordwijk, The Netherlands), composed of the Data Server Facility (DSF), the interface with the GIOVE-A and -B Ground Control Centers (GPCI) and the Experimental Orbit & Synchronization Processing Facility (E-OSPF)
- A word-wide network of 13 Galileo Experimental Sensor Stations (GESS), each of which operates a GIOVE/GPS dual receiver connected to an atomic clock, and a Communication Network

A key element of the GPC is the Experimental Orbit Determination and Time Synchronisation Processing Facility (E-OSPF). This element processes pseudo-range and carrier phase measurements collected from the GESSs in order to provide GIOVE orbit and clock estimations and predictions and generate the experimental navigation message to be broadcast by the satellite. The E-OSPF features sophisticated Orbit Determination and Time Synchronisation algorithms, similar to the algorithms that will compute the Galileo navigation message in the operational system. Since these algorithms are based on the processing of data from several satellites and stations simultaneously, complementary GPS data have to be used. This brings some difficulties (such as the need for dual GIOVE/GPS receivers and the existence of so-called Inter-System Biases - ISBs -) that have to be tackled.

The GIOVE orbit and clock estimations and predictions generated by the E-OSPF are input to a number of operational and experimental activities, such as:

- Generation of experimental GIOVE navigation messages in a routine basis
- Assessment of navigation performances
- Characterization of the on-board clock performances

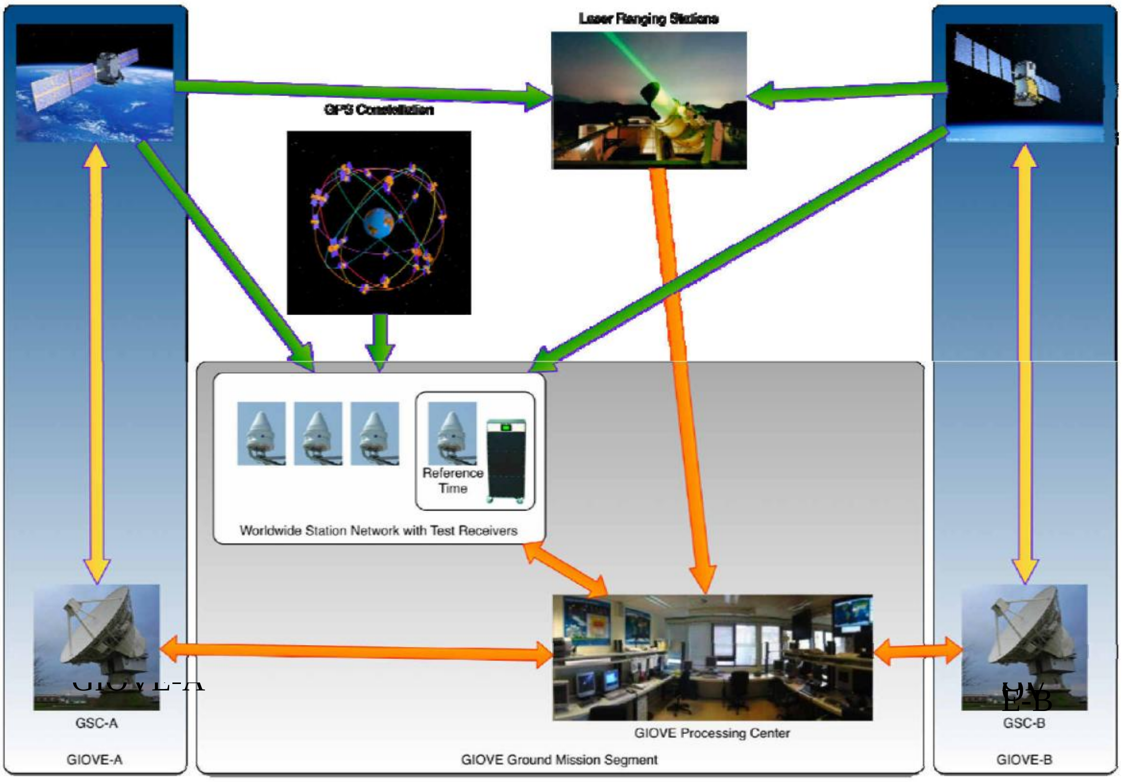


Figure 2. Overview of GIOVE Mission Architecture

Experimentation Setup

The GIOVE signal in space is continuously acquired by the GESS network, together with the GPS signals. The DSF acquires periodically the data files and converts them to standard RINEX 3.00 format. In addition, the GIOVE flight dynamics data and the telemetry and telecommand processed by the GSC-A and -B are also archived in the Data Server, through the GPCI. Finally, GIOVE laser ranging data collected from the International Laser Ranging Service (ILRS, [Pearlman 2002]) are also retrieved and stored. These data are the basis for the routine generation of experimental GIOVE navigation messages at the GPC, as well as for the off-line experimentation process.

The time span covered in this experimentation ranges from 29th August to 8th September 2008. The satellites processed were 25 GPS plus the GIOVE-B. During this period, GIOVE-B used the PHM clock for the signal generation. Unfortunately, the experimentation period could not be extended to the end of September, as initially foreseen.

The sensor station network of the GSTBV2 includes 13 GESS stations distributed as the following map and table show:

Table 1. GSTB-v2 GESS list

Site Code	Site Name	Country
GIEN	INRiM, Turin	Italy
GKIR	Kiruna	Sweeden
GKOU	Kourou	French Guyana
GLPG	La Plata	Argentina
GMAL	Malindi	Kenya
GMIZ	Mizusawa	Japan
GNNO	New Norcia	Australia
GOUS	Dunedin	New Zealand
GTHT	Tahiti	French Polynesia
GUSN	USNO, Washington	USA
GVES	Vesleskarvet	Antarctica
GWUH	Wuhan	China

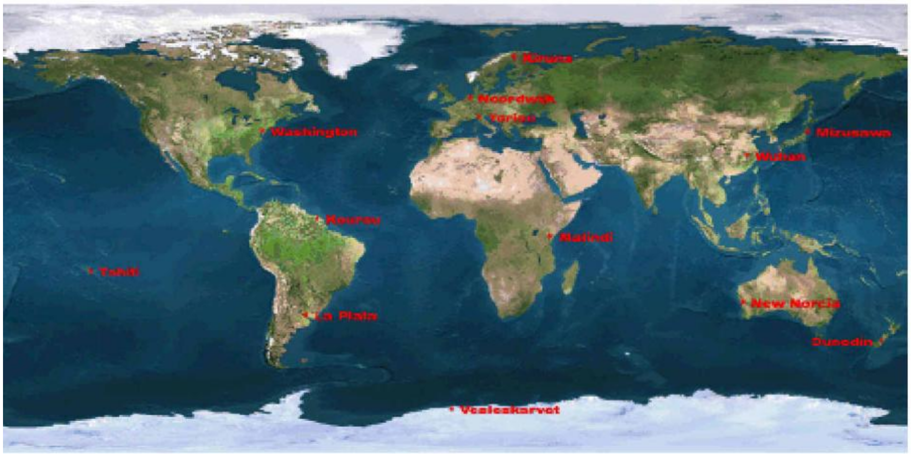


Figure 3. GSTB-v2 GSS network distribution

The SLR stations that have been employed in the experimentation are the following:

Table 2. GSTB-v2 SLR stations list

Site Code	Site Name	Num. Obs.
7237	Changchun	15
7839	Graz	50
7105	Greenbelt	20
7840	Herstmonceux	16
7308	Koganei	5
7110	Monument Peak	5
7825	Mount Stromlo	6
7406	San Juan	41
8834	Wetzell	4
7090	Yagardee	32
7810	Zimmerwald	34

Note that the number of available SLR measurements is low, so that they cannot be expected to have a big impact in the performances.

The microwave channels processed are listed in the table below:

Table 3. Processed microwave channels

	Frequency Band	Frequency (Mhz)	Code	Phase
GPS	L1	1575.42	P1	L1
	L2	1227.60	P2	L2
GIOVE-B	L1	1575.42	C1C	L1C
	E5b	1207.140	C7Q	L7Q

ODTS Processing Overview

The orbit and clock determination is mainly based on the microwave measurements from the GESS network. Since they involve the positions and the clock offsets of the satellites, both orbits and clocks have to be estimated in the same process. The estimation algorithm (ODTS: Orbit Determination and Time Synchronisation) is a batch least-squares algorithm that is able to process microwave and SLR measurements. The code measurements, coming at l-second rate from the tracking stations, are smoothed with the phase observations using a Hatch filter. The ODTS process solves for orbits (dynamics parameters, i.e. parameters of a high-accuracy orbit model), clocks, troposphere, and the so-called station inter-system bias (ISB), following a dedicated strategy in order to deal with different effects (ionosphere, troposphere, relativity, phase center offsets, phase wind-up, tides, site displacements, ocean-atmosphere loading, etc).

Unlike SLR, the use of microwave measurements requires a good number of satellites and stations to be processed simultaneously, to attain a reasonable level of accuracy. It does not make sense to configure one or two GIOVE satellites alone in ODTS. A sound approach is to include the GPS satellites in ODTS, although this will make necessary to estimate an intersystem bias per receiver, as explained below. On the receiver side, the results will be better if the GESS network is enlarged, but at the time of the experimentation there were only thirteen stations available.

The E-OSPF implements a version of the ODTS algorithm. But for the current experimentation, the tool magicODTS (GMV) has been used, that provides additional features as the capability of fixing orbits and clock of certain satellites to the values taken from input files (like IGS products). Nevertheless, it has been checked that for the conventional mode, both tools provide similar results.

The experimentation is carried out by executing consecutive and overlapping ODTS arcs. The length of the arcs has been chosen to be 2 and 3 days, with 1 day of overlapping. Longer arcs have not been considered, since for the short period of data available, there were to few overlaps for the analysis.

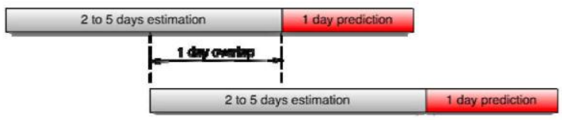


Figure 4. ODTS Overlapping Arcs

While the GPS satellites solutions can be compared with the IGS reference, there is no direct way to assess the quality of the GIOVE orbit and clock estimations. However, a good indicator is the differences in the overlap of successive ODTS estimation arcs.
Additionally, when the clock estimation errors dominate over the clock instability, an improvement in the solutions should carry a better fit to a quadratic model. So, a useful metric is the RMS of the residuals of the quadratic fit.

In summary, the following metrics are used in the analysis of the results:

- Comparison of orbits and clocks from consecutive arcs in the overlapping period
- Comparison of GPS estimated orbits and clocks with those computed by the International GNSS service (IGS)
- Analysis of the residuals of the clock estimation to a quadratic fit.
- Analysis of SLR residuals

The whole experimentation set-up is depicted in the figure below:

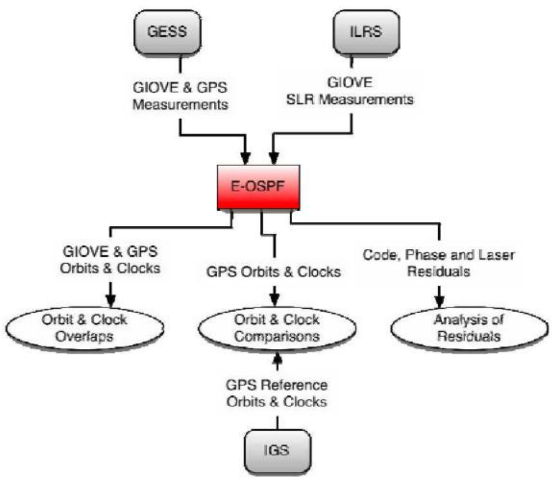


Figure 5. ODTS Experimentation Setup

Clock bias estimation

The microwave measurements are sampled at fixed intervals (every 5 minutes). At each such epoch, a clock bias is estimated for all the satellite and receiver clocks. However, the measurements do not provide enough information to fix a global reference for the clock estimation, the associated system of equations being degenerate. The solution adopted is to use the clock of a GSS as reference, constraining its bias to zero. So, what is finally estimated is the clock difference of all stations and satellites with respect to this reference clock. The reference clock for the GIOVE experimentation is a free-running Active Hydrogen Maser (AHM) connected to the GIEN station, a GESS at the Italian national metrological laboratory

(INRiM) in Turin. All clocks in the GIOVE segment are synchronized to the INRiM master clock. The AHM output signal, both 10 MHz and 1 Pulse Per Second (PPS), is fed to the GIEN station as an external reference time scale. The clock is continuously monitored versus the ensemble of atomic clocks of INRiM and also compared versus external reference time scales as the Universal Coordinated Time (UTC) realized by the BIPM.

The clock estimated by ODTS is not the 'true' clock connected to the satellite or the receiver, but an 'apparent clock' that is the sum of the clock signal plus some hardware delays of the satellite/receiver due to different effects (clock connection to the signal generator on board of the satellite, path from the signal generator to the transmitting antenna array, cable from the antenna to the receiver, etc). These delays are not the same for code and phase observations, or for different frequencies or satellites, but can be safely ignored as far as:

- The biases are stable (close to a constant value during ODTS estimation intervals).
- At each receiver, the delays introduced for different satellites are similar, with negligible differences.

If the latter is not true, an inter-satellite bias has to be estimated for each receiver-satellite link, as is the case when GLONASS satellites are configured. However, the dual receivers of the GESS have similar delays for satellites of the same constellation (GPS or GIOVE), so it is enough to estimate the bias between GPS and GIOVE satellite clocks. This parameter is called inter-system bias, and is typically estimated at constant by intervals (24 hours long, or the whole estimation arc). Even if the code and phase hardware delays are not the same, there is no need to estimate an inter-system bias parameter for the phase measurements, since the ambiguity parameters can absorb the constant difference. As in the clock estimation, all the inter-system bias values obtained in ODTS are relative to the master GSS.

The above scheme works in a proper way if the hardware delays are very stable and remain approximately constant in the term of several hours. Nevertheless, if this assumption is not fulfilled, there will be a negative impact in the performances. Since the GIOVE-B is the only GIOVE satellite processed, ODTS will tend to set the clock biases to the values that best suit the GPS satellites, while the GIOVE-B residuals will tend to absorb most of the modeling error. Hence, the errors derived from the instability of the inter-system bias will mainly affect the GIOVE-B satellite estimations.

The satellite clock estimation is better when more ground stations are tracking the satellite. The number of stations in view from a satellite, when the satellite is flying over a particular area, is called. Depth-of-Coverage (DOC). At least a DOC-2 is required to have a minimum quality in the estimation but it is better to have higher values. The following picture shows the geographical coverage provided by the 13-GESS network.

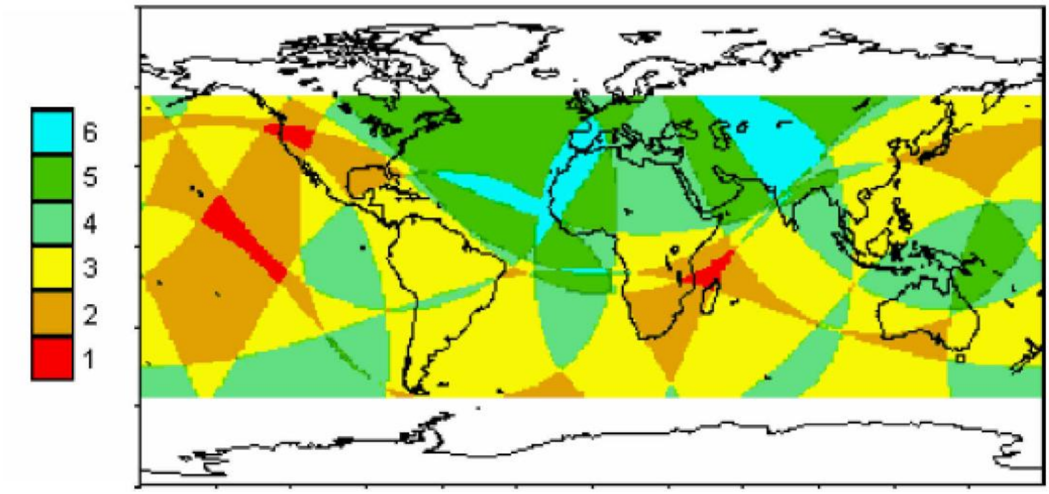


Figure 6. DOC provided by the GSTB-v2 GSS network

One of the difficulties in the current scenario is the reduced GESS network, which provides a poor DOC coverage.

Use of IGS solutions

In order to improve the results, the ODTS process can be forced to use the orbit and clock estimations provided by IGS for the GPS satellites. Meanwhile, the GIOVE solutions and the station clocks, tropospheric zenith delay and Inter-system biases are still estimated. This improves the quality of the station and GIOVE satellites parameters estimation, and hence of the GIOVE-B clock determination. Note that the 25 GPS satellites weight much more than a single GIOVE satellite in the receivers clock and troposphere estimations. Hence, the results based on this technique are similar to those obtained by fixing these parameters to the solution obtained from the GPS IGS products only, and later using them to process the GIOVE satellite.

Use of SLR measurements

The use of thirteen stations and thousands of microwave measurements does not necessarily give very accurate solutions, in contrast with SLR processing, where a smaller number of observations is required. Two reasons for this fact are:

- the need to estimate a large amount of clock parameters at each observation epoch.
- the high correlation between the radial part of the orbital error and the clock error.

To illustrate the second point, the figure below shows an overlap difference of two orbit and clock solutions of satellite GIOVE-B, where in particular the (radial+clock) and (radial-clock) error components are depicted. The observation of the satellites from the ground stations privileges the radial direction over the transversal ones (along-track, cross-track), but the radial component is highly correlated with the clock, so that:

- the (radial+clock) combination is well observed, since it is the essential contribution to the observations;
- the (radial-clock) is not well determined, and this is the main source of the radial and clock errors, where it appears with opposite sign. So, any technique used to improve the clock determination has to reduce this component, either directly or indirectly.

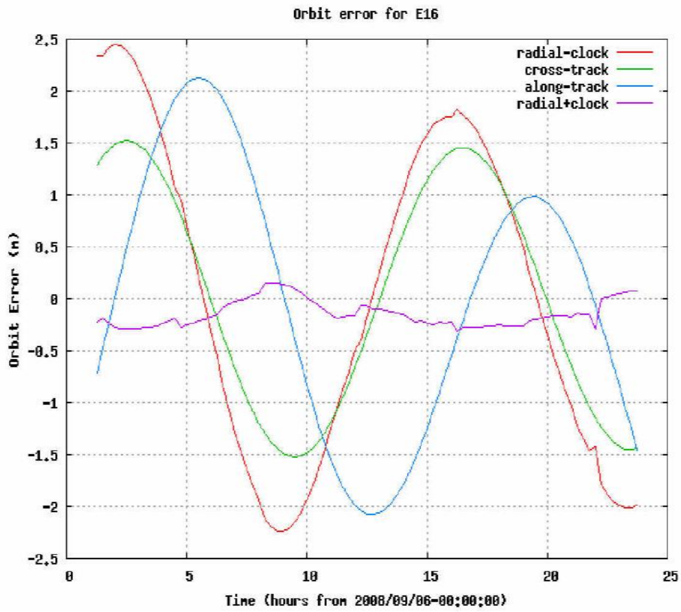


Figure 7. Overlap difference of two consecutive GIOVE-B estimations

On the other hand, the SLR measurements are independent of the satellite clock, so they can improve the accuracy of the satellite orbit alone. But a better determination of the orbit in the radial direction will imply an improvement in the determination of the (radial-clock) component, and hence in the clock estimation.

GIOVE-B Orbit and Clock Determination Results

As a first step, the scenarios have been run including SLR measurements with a negligible weight. Then the solution are based in the microwave signals only, but ODTS computes the SLR residuals.
The following tables summarize the results obtained by running arcs 2 and 3 days long. The performance metrics are obtained either by comparing the estimation of GPS orbits and clocks with the IGS final products, or by comparing the results of two consecutive ODTS runs in the 1-day overlapping period. The final value is the RMS of the orbit or clock differences (in the case of the orbits, the typical RMS).

Table 4. Orbits and clocks results for 2 days arcs

	GPS satellites	**GIOVE-B**
Estimated GPS Solutions		
Orbit error wrt IGS (2 days RMS)	10.1cm	--
Clock error wrt IGS (2 days RMS)	0.60ns	--
Orbit overlap (1 day RMS)	10.2cm	14.5cm
Clock overlap (1 day RMS)	0.25ns	0.56ns
GPS fixed to IGS solutions		
Orbit overlap (1 day RMS)	--	14.6cm
Clock overlap (1 day RMS)	--	0.46ns

Table 5. Orbits and clocks results for 2 days arcs

	GPS satellites	GIOVE-B
Estimated GPS Solutions		
Orbit error wrt IGS (3 days RMS)	10.6cm	--
Clock error wrt IGS (3 days RMS)	0.61ns	--
Orbit overlap (1 day RMS)	14.3cm	10.1cm
Clock overlap (1 day RMS)	0.29ns	0.40ns
GPS fixed to IGS solutions		
Orbit overlap (1 day RMS)	--	8.8cm
Clock overlap (1 day RMS)	--	0.38ns

The most relevant conclusions are:

- The orbit overlaps for GIOVE-B give results of the same order as the GPS satellites. However, the GIOVE clock overlaps are worse, due to variations in the estimations of the inter-system bias.
- The use of estimation arcs of 3 days lead to better results for the GIOVE-B satellite, while the GPS results are very similar in both configurations. This is probably related to the inter-system bias, which is more consistently estimated in longer arcs.
- The overlap results for clocks are better for GPS than the comparison with IGS. This is because the differences with IGS show average offsets that are cancelled out in the overlaps. As these constant offsets do not affect the clock stability analysis, they can be neglected, and the clock overlap RMS taken as a valid indicator.
- The use of IGS solutions for the GPS satellites brings a small improvement.

The next step has been to run the scenarios again, but assigning a proper weight to the SLR measurements. The scenarios with the GPS solutions fixed to IGS as reference, has been chosen as a reference for the comparison. The following tables present the values of several performance metrics with and without the use of SLR measurements:

Table 6. SLR values for 2 days arcs

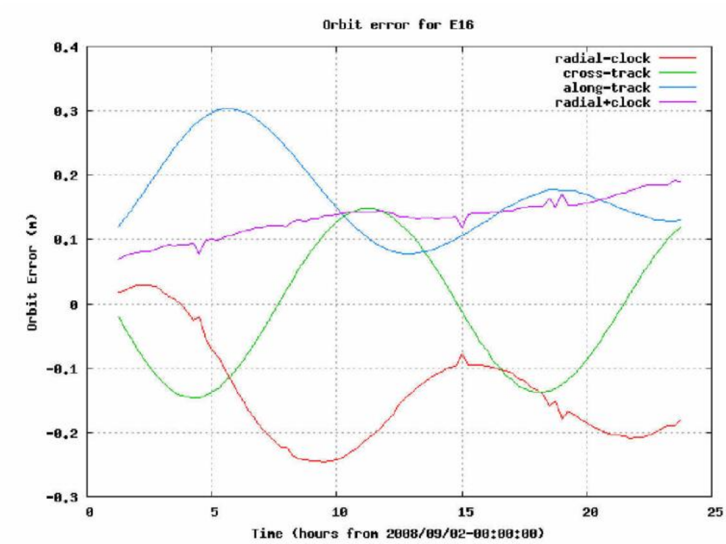
	Without SLR	With SLR
Orbit overlap (RMS)	14.5cm	12.6cm
Clock overlap (RMS)	0.46ns	0.39ns
(Radial – clock) overlap (std)	12.1cm	10.1cm
GIOVE-B clock fit residuals (RMS)	0.29ns	0.21ns

Table 7. Metrics values for 3 days arcs

	Without SLR	With SLR
Orbit overlap (RMS)	8.8cm	8.6cm
Clock overlap (RMS)	0.38ns	0.38ns
(Radial – clock) overlap (std)	8.5cm	8.0cm
GIOVE-B clock fit residuals (RMS)	0.26ns	0.23ns

As a main conclusion, the use of SLR measurements brings an improvement in the case of estimation arcs of 2 days, but not in the longer 3 days scenarios. This is not unexpected, since the microwave-only performance is clearly better in the latter case, and the SLR contribution is possibly not enough to make a difference.
It must be stressed that during the period analyzed, only 228 SLR measurements were available, which are too few. This is due to the small size of the GIOVE-B LRA. A larger number would be required to have a significant effect in the results. But the previous analysis shows a promising tendency that could be used in the future to better assess the quality of the GIOVE/Galileo on board clocks, if the appropriate SLR campaigns are performed.

Finally, as an example, the orbit and clock differences in the overlap period for two typical arcs with SLR is shown in Figure 8.



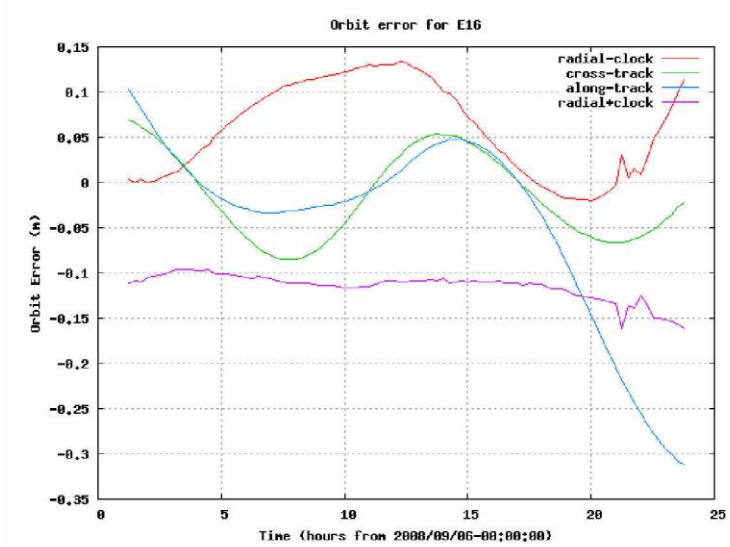


Figure 8. GIOVE-B Orbit and Clock Overlaps Examples

SLR Measurement Residuals

Table 8 shows the statistics of SLR residuals in the ODTS arcs, in the 3 days long scenarios. As expected, the results are better when the SLR observations contribute to the solution, although it is remarkable that the improvement is so evident with so few SLR measurements available. As SLR gives clock-free observations completely independent from the navigation signal, these residuals provide a good indication of the orbit performances: around 10cm in the radial direction, which is in line with the observed internal orbit consistency.

Table 8. SLR two-way residuals

	Microwave only	Microwave + SLR
3 days /est GPS	16cm	12cm
3 days / fix GPS	18cm	14cm

Conclusions

The on-board Passive Hydrogen Maser clock of GIOVE-B represents an important step in the testing of the new technologies that will be integrated in Galileo. The assessment of the stability of the clock is done from the products of an orbit and clock determination process, based on the measurements gathered by the GESS network that is part of the GIOVE Mission. Due the expected level of performance of the PHM, the accuracy of the clock determination has to be as high as possible, in spite of the limited size of the GESS network. A way of improving the quality of the estimations is to use the SLR measurements as a complementary mean to fix the GIOVE satellite orbits and help disentangling orbits and clock solutions.

Several SLR stations from the ILRS are tracking the GIOVE satellites. For the present paper, experimentation has been carried out by processing microwave together with SLR measurements, to confirm the viability of using laser ranging to improve the accuracy of the GIOVE-B clock estimations. The main conclusions are:

- Microwave and SLR observations show a good consistency between them, thus confirming the very good performance of the orbit and clock determination performed in the GIOVE Mission.
- For GIOVE-B, the use of arcs of 3 days has shown a clear improvement over two-day arcs.
- There is a clear improvement in the results when using SLR together with the microwave measurements, for the 2 days scenarios, even if there are very few SLR observations available. For longer arcs (3 days), the improvement is smaller.
- Due to small size of the GIOVE-B LRA, the number of SLR measurement is limited. The improvements could be much more significant if the number of SLR measurements per day were higher.

The processing of longer periods of data should give more conclusive results.

References

J.M. Dow, R.E. Neilan and G. Gendt: *The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade,* Adv. Space Res. 36 vol. 36, no. 3, pp. 320-326,2005. DOl: 10-1 06/J.ASR.2005.05.125

M.R. Pearlman, J.J. Degnan and J.M. Bosworth: *The International Laser Ranging Service,* Advances in Space Research, Vol. 30, No.2, pp. 135-143, July 2002, DOl: 10.1016/S0273-1177(02)00277-6