ESTIMATION AND PREDICTION OF THE GIOVE CLOCKS

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Abstract

In preparation for the development of the Galileo system, the European Space Agency (ESA) launched in 2002 the development of an experimental ground segment (Galileo System Test Bed Version 1). Within the GSTB-V1 project, tests of Galileo algorithms were conducted processing GPS global data at the Ground Processing Center (GPC) located at ESA/ESTEC in The Netherlands.

In December 2005 and then in April 2008, two experimental Galileo satellites called GIOVE-A and GIOVE-B, respectively, have been launched. They mark the second step in the validation of the Galileo system to be completed with the deployment of the In-Orbit Validation (IOV) satellites. The vapor-cell rubidium (RAFS) atomic clock technology is common to both GIOVE satellites, and GIOVE-B carries also the first-ever orbiting passive hydrogen maser (PHM).

The GIOVE Mission experimentation project is intended to mitigate the Galileo project risks by an early assessment of technical aspects like demonstration 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 on-ground algorithm prototypes, and overall testing of timeliness and operational aspects.

The GIOVE Mission core infrastructure for experimentation consists of a network of 13 Galileo Experimental Sensor Stations (GESS) worldwide distributed that acquire and collect the GIOVE and GPS satellite signals and send pseudo-range and carrier-phase measurements to the upgraded GPC. Satellite Laser Ranging (SLR) stations track both GIOVE satellites as well. One of the GESS is installed at the Time Laboratory located at INRiM, Turin, connected to an active hydrogen maser, located in a controlled environment. The INRiM time reference is used as the basis for Experimental Galileo System Time (EGST).

This paper presents and discusses up-to-date results from the GIOVE Mission experimentation, mainly focusing on the Orbit Determination & Time Synchronization (ODTS) technique and its validation with GIOVE data. After a short description of the GIOVE infrastructure and of the ODTS process, the results obtained with both RAFS and PHM are presented, which is followed by a discussion on the ODTS quality and validity.

INTRODUCTION

In preparation for the development of the Galileo System, the European Space Agency (ESA) began development in 2002 of an experimental Ground Mission Segment (Galileo System Test Bed Version 1). Within the GSTB-V1 project **[1]**, tests of Galileo orbit determination, integrity, and time synchronization algorithms were conducted in order to generate navigation and integrity core products. These tests were based on pre-developments of Ground Mission Segment (GMS) Processing Facilities using 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 **[2]**: GIOVE-A and GIOVE-B. In parallel, a ground mission infrastructure was developed and deployed in order, among others, to validate the algorithms and processes developed under the GSTB-V1 project. The overall GIOVE system architecture includes:

- The space segment is composed of GIOVE-A and GIOVE-B satellites.
- The Ground Control Segment is composed of both GIOVE satellites control centers (in Guildford for GIOVE-A and in Fucino for GIOVE-B)
- The GIOVE Mission Segment is composed of the Galileo Experimental Sensor Stations (GESS) network and the GIOVE Processing Centre (GPC) located in ESA-ESTEC (Noordwijk, The Netherlands) **[3]**.

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 GIOVE Mission Infrastructure includes the GIOVE Processing Centre (GPC), composed of the Data Server Facility (DSF), the interface with the GIOVE A and B Satellites Control centers (GPCI), and the Experimental Orbit & Synchronization processing facility (E-OSPF); a worldwide 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 GPS signals. These GESS data are collected through the Sensor Station Data Servers (SSDS) on the central Data Storage Facility (DSF), and converted to standard RINEX 3.00 **[4]**. In parallel, 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 GIOVE Payload Control Interface (GPCI) facility.

This paper presents the ODTS results obtained for the GIOVE satellites with the GIOVE infrastructure during the GIOVE experimentation period. After a summary of the GIOVE infrastructure and ODTS process and models, its validation with real GIOVE data is described. It is shown that the GIOVE experimentation provides excellent and valuable results that are extremely beneficial for the overall development of Galileo.

THE GIOVE MEASUREMENT SYSTEM

The GIOVE Measurement System is composed by the network of GESS, which track the Satellites L-Band signals, and the Orbit Determination & Time Synchronization (ODTS) software, which process the observations. The Experimental Orbit Synchronisation Processing Facility (E-OSPF) computes the near-real-time orbit and clock information based on session files generated by the DSF operator.

Data from the GESS network, together with GIOVE-A and GIOVE-B optical measurements from the International Laser Ranging Service (ILRS) **[5]**, have been processed since the beginning of the GIOVE mission. During the major part of this period, 13 GESS stations (Table 1) were operational, providing the theoretical geographical coverage shown in Figure 1. In the figure, the colors indicate the number of stations (also called Depth-of-Coverage or DOC) in view of the satellite when GIOVE is flying over a particular location. In order to reduce the estimation uncertainty, the GIOVE clock is calculated when a DOC of at least 2 is available. The GESS network has been designed to minimize the extent of DOC-1 areas (in red in Figure 1).

Table 1. List of GESS stations.

Station Name	Location	Country
GIEN	INRiM, Turin	Italy
GKIR	Kiruna	Sweden
GKOU	Kourou	French Guyana
GLPG	La Plata	Argentina
GMAL	Malindi	Kenya
GMIZ	Mizusawa	Japan
GNNO	New Norcia	Australia
GNOR	ESA, Noordwijk	The Netherlands
GOUS	Dunedin	New Zealand
GTHT	Tahiti	French Polynesia
GUSN	USNO, Washington	USA
GVES	Vesleskarvet	Antarctica
GWUH	Wuhan	China

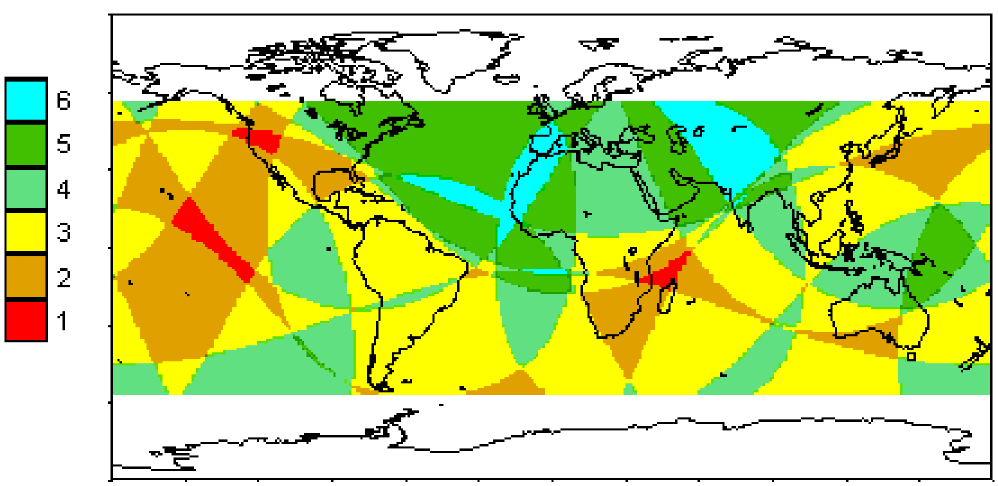

Figure 1. Coverage of the 13-GESS network (colors indicate the number of stations in view of GIOVE).

During the GIOVE-M experimentation, both RAFS on board GIOVE-A and PHM on board GIOVE-B were estimated and predicted through the ODTS process. During the same period, various types of observables were experimented (L1+E5 and L1+E6) in order to assess signal performances. The Galileo Experimental Test Receiver (GETR) within the GESS station has seven Galileo channels, configured to generate the pseudorange and phase observables. All the receivers in the GESS network are configured in the same way. Depending on the actual payload configuration, the L1-E5b or L1-E6 iono-free code and phase combinations have been selected for clock characterization, and are used together with the P1-P2 and L1-L2 iono-free code and phase combinations from the GPS constellation.

The reference clock for the GIOVE experimentation is a free-running active hydrogen maser (AHM) connected to the GIEN station at the Italian national metrological laboratory (INRiM) in Turin. All clocks in GIOVE system 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 technique used for clock characterization is the ODTS process (explained in next section). The ODTS processes undifferenced iono-free GIOVE and GPS code and phase combinations together with GIOVE SLR measurements. 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.).

Figure 2 summarizes the main clocks, reference points, and components of the Measurement System.

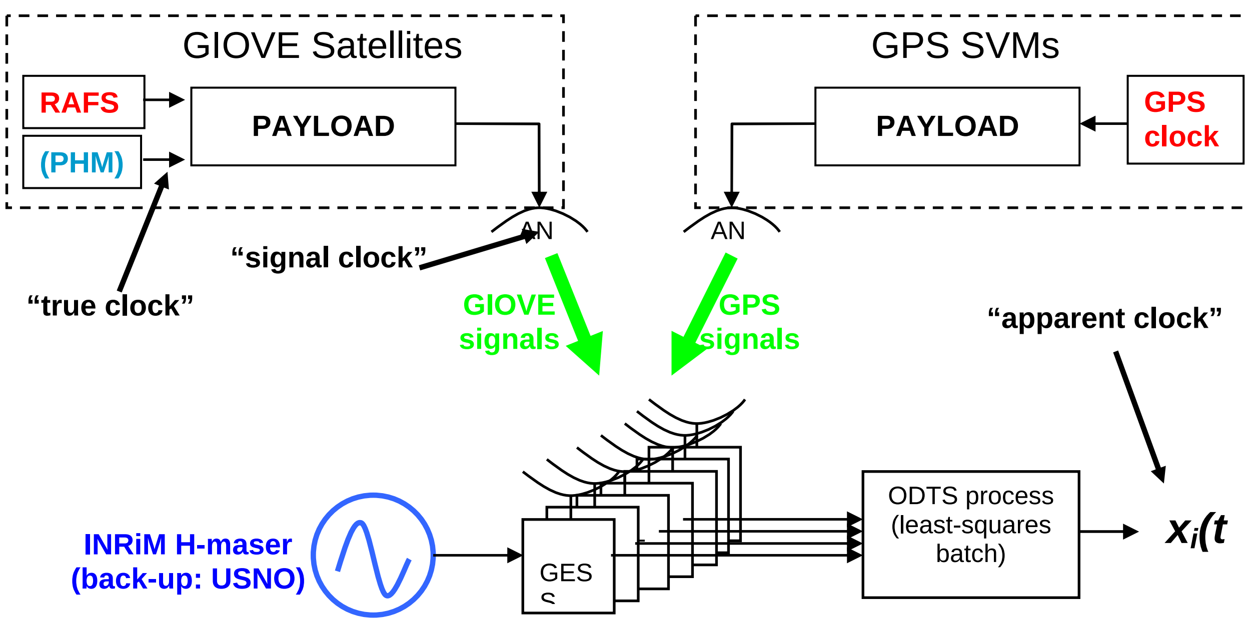

Figure 2. Performance assessment method.

Any biases or mis-modeling of the involved deterministic effects by the ODTS software would be propagated together with other the noise across the different estimations with unclear effects. As a consequence, the apparent clock behavior estimated as phase offset will not coincide with the real physical clock behavior, since it includes stochastic and deterministic residuals errors introduced by the Measurement System.

ODTS METHODOLOGY

In the classical network adjustment used for orbit determination, orbits are estimated at the center of mass, while observations are referred to the transmitting antenna phase center; therefore, dedicated *a-priori* information for the Phase Center Offset (PCO) and Phase Center Variation (PCV) are required or need to be computed. Coordinates are previously estimated in an International Terrestrial Reference Frame (ITRF) realization. The troposphere wet effect is estimated piece-wise and mapped to the slant direction using empirical mapping functions. Ionosphere first-order effects are eliminated by Linear Combinations (LC). Satellite Inter-Frequency Satellite Biases (IFB) are included in the clock bias for the LC used, while receivers' IFB and Inter-System Bias (ISB) are computed once per day (except for the reference station).

ESTIMATION

The technique used for clock estimation is called Orbit Determination & Time Synchronization (ODTS), a batch least-squares algorithm that processes iono-free GIOVE and GPS code and phase combinations together with GIOVE SLR measurements. The 1-second code measurements are smoothed with phase using a Hatch filter. The ODTS solves for orbits, clocks, troposphere, and the so-called station inter-system bias (ISB).

The estimation of the onboard clock is significantly enhanced by the use of Satellite Laser Ranging (SLR), a high-precision technique for orbit determination that is independent of the navigation signal generation. The technique is described in **[6]**. Given the high GIOVE altitude and the reduced size of the laser retro-reflector on board, the satellite is regularly tracked by a limited number of stations (around 15).

Another particular aspect of the ODTS process is the use of a simplified Solar Radiation Pressure (SRP) model for GIOVE and all GPS satellites. The SRP model is an all-GNSS one adapted from existing GPS and Glonass literature on the subject **[7, 8]**, and is based on the estimation of five coefficients that best fit the orbit. The model requires no *a-priori* information about the satellite geometrical and reflectivity properties, only approximate mass and area values are needed. No empirical accelerations are estimated in ODTS; in total only 11 dynamic parameters are estimated per satellite (position, velocity, and five SRP coefficients).

The estimation of a station inter-system bias (ISB) is required when using observations from a dual GPS/Galileo station, due to the different internal delays inside the GESS. The inter-system bias must be understood as the offset (at station level) between the Galileo C1C-C7Q iono-free code observations and the GPS P1-P2 iono-free code observations. The inter-system bias is estimated relative to the reference station (GIEN, which is assumed by convention to have a zero inter-system bias); therefore, it is actually a differential inter-system bias. The estimation of the reference station inter-system bias is not possible in ODTS, since such bias is fully correlated with the GIOVE clock offset and, therefore, undistinguishable from it. The inter-system bias is estimated as a constant daily value.

The ODTS experimentation setup for the GIOVE Mission Clock and Orbit Performance assessment is done with the execution of consecutive and overlapping ODTS arcs (as illustrated in Figure 3), with the detailed configuration shown in Table 2. The length of the ODTS determination arc is 5 days. Two consecutive ODTS arcs have a 1-day overlap.

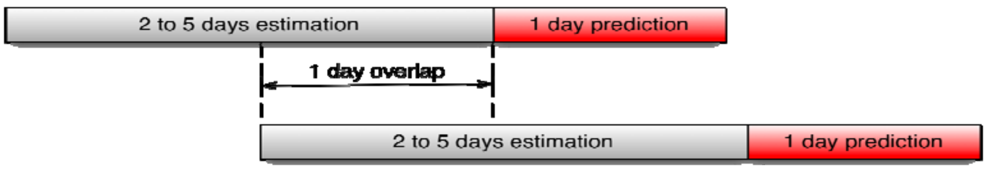

Figure 3. ODTS overlapping arcs.

The main products from ODTS are estimated orbits (for GIOVE and all GPS satellites) and estimated clocks (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 offset relative to the INRiM reference clock, and at a nominal output rate of 5 minutes. The E-OSPF calculates snapshot clock estimations over the whole observation arc of the Orbit Determination and Time Synchronization (ODTS) process. These clock estimations are obtained at every valid measurement epoch, and are directly referred to the reference time (E-GST). The estimates at different epoch are considered independent, in the sense that no dynamical filtering or clock modeling is applied to them. The clock estimate as seen through the ODTS algorithm is not the "pure" clock as tested on the ground, but the "apparent" clock as seen through the complete onboard signal generation chain (that gives the "signal" clock), the space propagation, the receiver network, and the ODTS algorithm. The clock estimations coming from ODTS are the basis for the so-called clock characterization. Figure 4 presents two examples of Apparent Clock estimation for GIOVE-A (left) and GIOVE-B (right) for 5 days, starting the 1 November 2008. Results of the GIOVE clock characterization are presented in **[9]**.

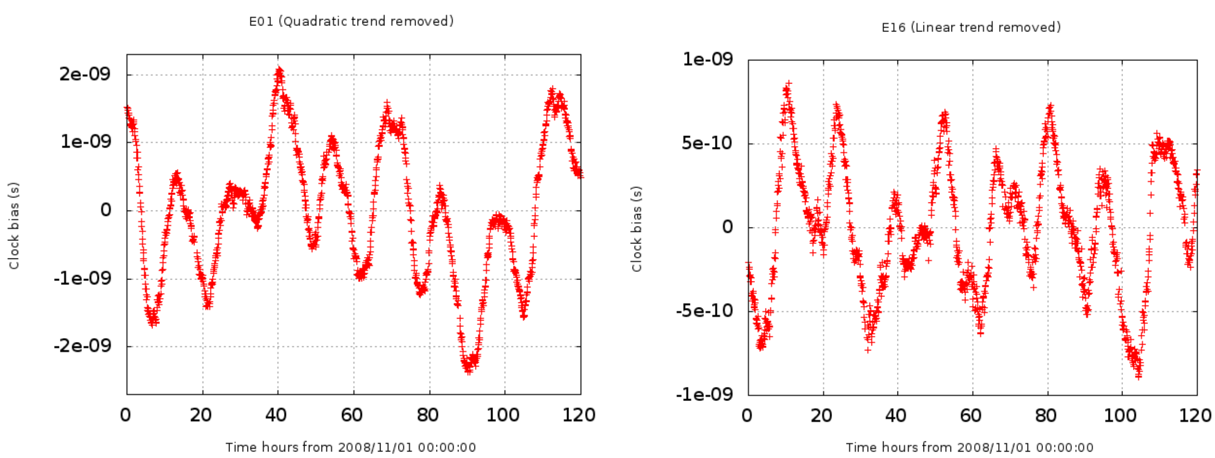

Figure 4. GIOVE Apparent Clock examples.

Table 2. Estimation strategy used by the ODTS.

PRE-PROCESSING	
GPS raw observables	Code: P1-P2, Phase: L1-L2
Galileo raw observables	Code: C1C-C7Q, Phase: L1C-L7Q Code: C1C-C6C, Phase: L1C-L6C
Basic observable	Un-differenced iono-free (code + phase)
Sampling rate of raw observables	1 Hz
Code smoothing	Hatch filter, interval 1000 s
Sampling rate after preprocessing	5 min
SLR	GIOVE

PROCESSING	
Number of Stations	9-13
Processed Satellites	ALL (GPS+Giove)
Processed GSS clocks	ALL except GIEN
Basic observable	Un-differenced iono-free (code + phase)
Elevation cut-off angle	15 °
Weight of smoothed-code	30 cm
Weight of phase	10 mm
Weight of SLR	∞ (deweighted) or 5 cm (weighted)
Weighting	Elevation-independent
Reference clock	GIEN (fixed to zero)
Reference ISB	GIEN (fixed to zero)
Inter-system bias estimation	Per arc
Ambiguity fixing	Float
Station Coordinates	Fixed to ITRF2005, a priori values computed by PPP using IGS products, then re-estimated by ODTS fixing GPS orbits (but not clocks) to IGS solutions
Orbits	5 days orbital arcs, initial orbit position and velocities, and 5 empirical SRP.
ERP	Fixed to IERS solutions
Ionofree	First order effect removed by ionofree combination.
Tropospheric refraction	Estimated at zenith as piece-wise constants at 2 hours interval, using Saastamoninen as a priori model and Niell mapping function.
Satellite antenna PCO	GPS Fixed to latest IGS values, GIOVE to ground test
Satellite antenna PCV	No
Receiver antenna PCV	No

PREDICTION

The E-OSPF generates 1-day long orbit and clock predictions in each ODTS arc (see Figure 3). The clock estimations from each arc are used to fit the clock model parameters. The model can only account for the deterministic clock behavior; therefore, a straight line or a parabola is typically used. The choice for one or the other will depend on the actual clock behavior and the desired prediction validity time. The prediction performances will depend also on the measurements' noise (i.e., the quality of the clock estimation). The so-computed clock model parameters are used to predict GIOVE clock offsets in the future. Such offsets can be then compared to the estimations obtained in the following ODTS arc in order to assess prediction performances. Usually, the clock estimates from the last day of the ODTS determination arc are used to fit the parameters of a linear or quadratic model. This model is used to generate predictions for 1 day. The generation of 1-day predictions is a particular need of the GIOVE mission, in which the navigation messages on board the GIOVE satellite cannot be updated frequently (as they will be in Galileo).

The prediction performances have been evaluated as described above along several ODTS arcs. Usually, the clock estimates from a last period of the ODTS determination arc are used to fit the parameters of a linear or quadratic model. This model is used to generate predictions for 1 day; the final Galileo IOV model is optimized for 100 minutes, with flexible fitting intervals which can further improve these results. The instantaneous prediction error at 100 minutes (i.e. not averaged over 100 minutes) is close to or below 2 ns (60cm) for GIOVE-A RAFS clocks and around 0.3 ns for GIOVE-B PHM Clock. These results can be compared with the target of the contribution to UERE from orbits and clocks for Galileo IOV (130cm 2σ). Therefore, GIOVE onboard clock performances are really promising in view of the Galileo required navigation performances (130 cm for orbit and clock at user level, 95%).

Examples of prediction results at 1 day are shown in Figure 5, where one can see that the PHM Prediction Error (left-hand plot) for 1 day is less than 1.5 ns.

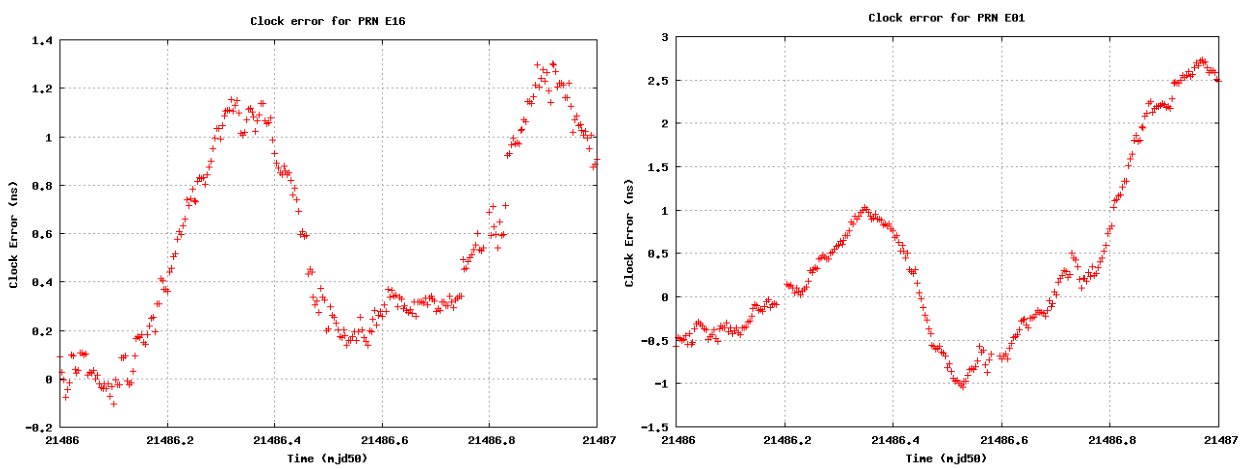

Figure 5. GIOVE clock 1-day prediction examples.

SYSTEM VALIDATION

Different strategies are then used in order to assess the quality of the ODTS process, namely:

- Analysis of measurement residuals and SLR residuals
- 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)
- Comparison of ISB -> ODTS vs. IONO algorithm.

MEASUREMENT RESIDUALS

A first indicator of the quality of ODTS results is measurement residuals, i.e. the difference between real data and the measurements as modeled by the processing algorithms. For optimal results, measurement residuals should be small and randomly distributed, showing only the unmodeled error contained in the data (for example code multipath). Typical ODTS residuals RMS are 40 cm for code measurements, 1 cm for phase, and 3 cm (one-way) for SLR.

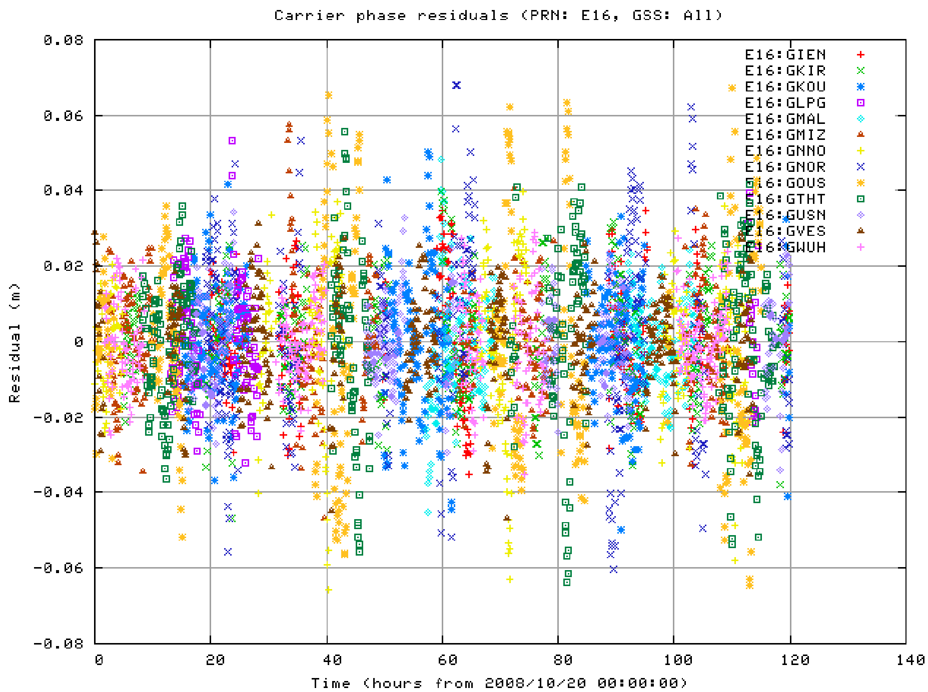

Figure 6. Carrier-phase residuals.

OVERLAP CONSISTENCY

The accuracy of the estimated orbits and clocks must be assessed prior to clock characterization. Although orbit results are not the primary subject of this paper, it is important to have an idea of the error in the orbit estimation, since the estimation of the radial component of the orbit is correlated with the clock estimation error. The estimation error of GIOVE products is calculated to be at the level of 15 cm (RMS) in the radial direction for orbits, and 0.3 ns (1-σ) for clocks, as we can see in the examples of Figure 7. These figures are consistent with GPS satellite orbit and clock comparisons against precise products from the International GNSS Service (IGS) **[10]**, as we are going to see in the next paragraph.

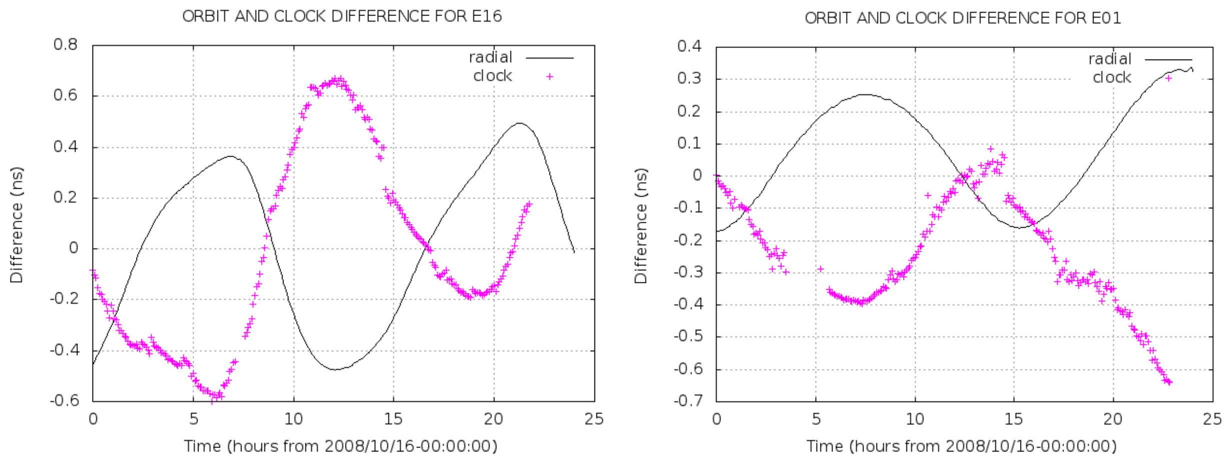

Figure 7. GIOVE orbit and clock overlap consistency.

QUALITY ASSESSMENT WITH GPS

The GIOVE ODTS process provides also GPS estimated orbits and clocks. The comparison of these with the final IGS products, considered as "truth," is a good indicator of the quality of the process, as poor GPS orbits and clocks indicate that one cannot expect good performances on GIOVE. Typical values for orbit and clock accuracy are computed for the entire GPS constellation and used as performance indicators. In Figure 8, these values have been plot for the different ODTS arcs: the projection of the orbital error at WUL, and the clock error. The values obtained (typically 8-cm orbit error at WUL and 0.3-ns clock error) are considered quite good, considering the limited size and distribution of the GIOVE-M tracking network. Prior to this comparison in the GPS clocks, the Experimental Galileo System Time (EGST) scale (reference scale in the estimated ODTS clocks) and the IGS time scale are aligned in order to get these figures for the clocks. This suggests the adequateness of the models implemented in the ODTS software, which are mostly common to GPS and GIOVE.

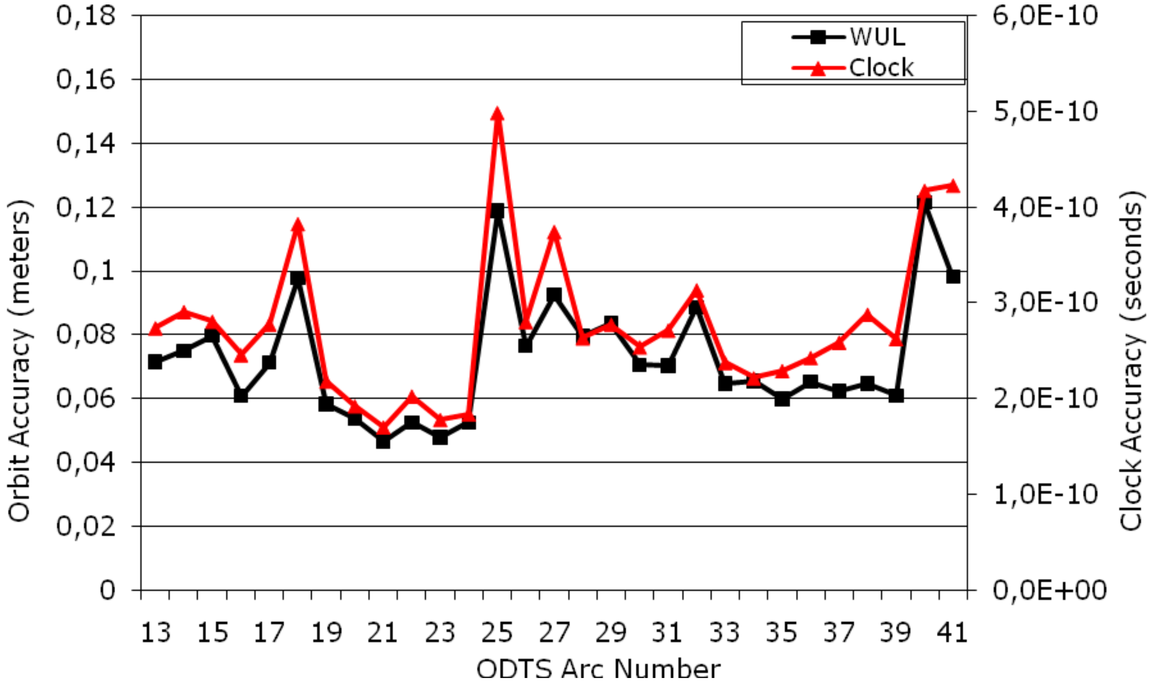

Figure 8. GPS orbits and clocks: ODTS vs. IGS.

INTER-SYSTEM BIAS ASSESSMENT: ODTS VS. IONO RESULTS

A successful determination of the GIOVE clock offset with respect to the master clock depends to a large extent on the correct determination of the aforementioned station inter-system bias (ISB). This is essential in particular to avoid satellite clock jumps when GIOVE flies over different ground stations. Since satellite ISB are included in the iono-free GIOVE clock estimation, the station ISBs and the GIOVE clocks are clearly correlated (they are both obtained from code measurements from a single satellite). As a result, it is not so obvious how the ODTS software should correctly separate clock and station ISB contributions from the GIOVE measurements. The ISBs calculated by ODTS over the data analysis period show a good stability, but their values are in principle meaningless to the experimenter. No phase jumps are observed on the GIOVE clock, which is also a good sign of correct ISB estimation.

An alternative method has been envisaged to calculate station ISBs using geometry-free GIOVE and GPS code and phase combinations processed by a dedicated algorithm called IONO. Geometry-free measurements contain ionospheric Total Electron Content (TEC) information and satellite and station inter-frequency bias (IFB). The IFB is the difference between the P1 and P2 code delays (for GPS), and between the E1 and E5 (or E6) code delays (for GIOVE), both at satellite and station level. The station ISB is calculated as the difference between the station E1-E5 or E1-E6 IFB (GIOVE-A chain) and the P1-P2 IFB (GPS chain), assuming that the delay on L1 codes (L1 and P1) is approximately the same for both systems. In order to calibrate the whole IFB system in the IONO software, the average of satellite P1-P2 IFBs (GPS) has been fixed to 6 ns (from the navigation message TGD values **[11]**) and the satellite E1-E5 and E1-E6 IFBs (for GIOVEs) has been fixed to the values calibrated by the satellite manufacturer. The station ISBs values calculated by IONO (every 2 days) are depicted in Figure 9. They show a good stability and are in agreement with the values calculated by ODTS (at the ns level).

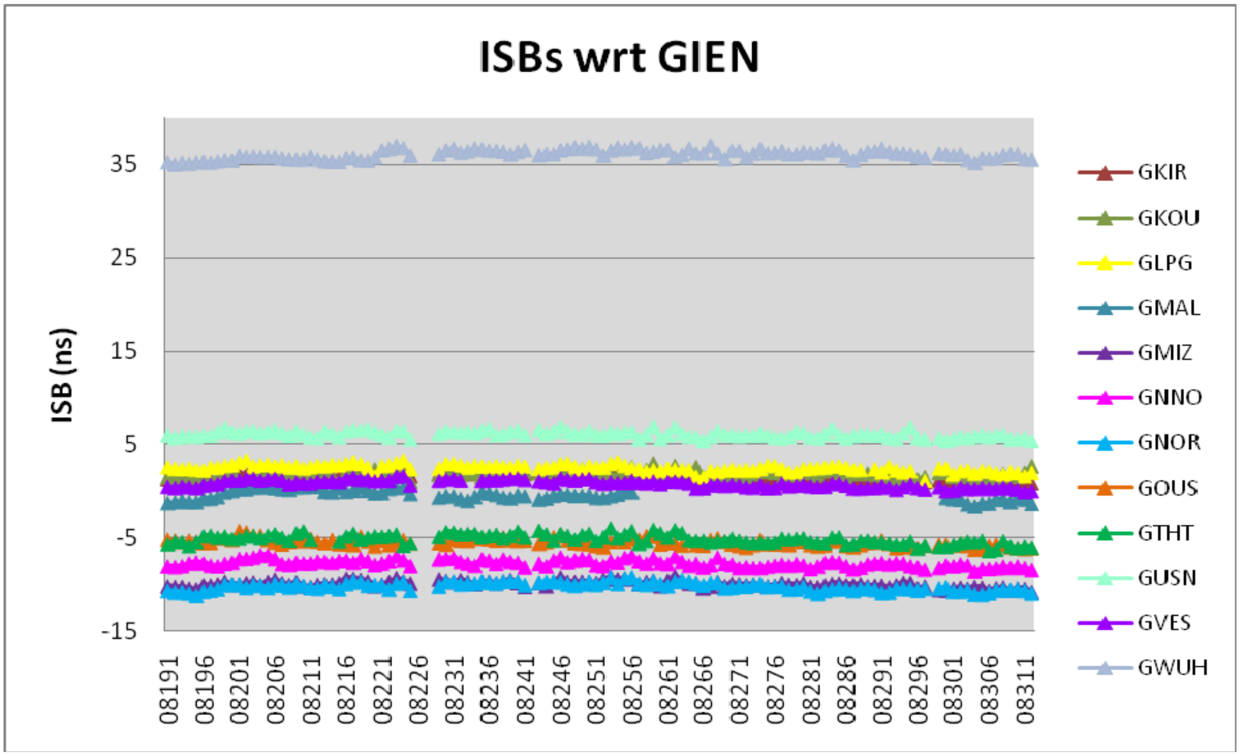

Figure 9. The inter-system station biases for 13 GESSs as calculated with the IONO algorithm using geometry-free GIOVE and GPS code and carrier-phase combinations.

CONCLUSIONS

The GIOVE-M represents an important step forward in the development of Galileo. GIOVE-A is operating for 3 years, and critical technologies such as the navigation payload, the space-qualified rubidium frequency standard and test user receivers have been developed, operated, and tested, showing excellent results. The second satellite, GIOVE-B, was launched on 27 April 2008, and this has allowed to test new technologies, such as the onboard passive hydrogen maser clock and new signal modulations.

The GIOVE-M Ground Segment has been successfully deployed and operated on a routine basis for 3 years, providing the infrastructure needed by GIOVE experimenters to undertake their activities, in terms of data collection and distribution, and algorithm implementation. Within these activities, extensive ODTS experimentation has been carried out, and excellent results have been obtained:

- The deployed ODTS algorithms have shown to provide very good results, allowing the estimation of GIOVE and GPS orbits and clocks with very good performances, considering the limitations of the available tracking network.

- The ODTS performances have been assessed using overlaps, comparison with IGS products and analysis of residuals (including laser ranging residuals). All the strategies have shown consistent results.

- The orbit predictions show good stability over 1 day, and the prediction accuracy in nominal situation is below 30 cm.

The GIOVE onboard clock performances presented in **[9]** and in this paper demonstrate that the PHM on board GIOVE-B is the most stable of all clocks currently in orbit, resulting in a really good prediction (around 1 ns for 1 day). The estimation of the PHM onboard GIOVE-B is actually limited at the short term by the clock accuracy estimation (0.3 ns) and by a combination of payload delay variation and orbital model errors at half of the orbit period. RAFS technology of GIOVE-A is also performing well, as its frequency stability is meeting its requirements and also the prediction requirements. All this work is very useful for the next development and deployment phase of the Galileo Program.

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