The First Months of the Galileo Timekeeping and Time Dissemination: The Role of the Time Validation Facility

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BIOGRAPHIES

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Giovanna Signorile received her M.S. in Telecommunication Engineering from Politecnico di Torino in 2011. Currently she works at the Italian Metrology Institute (INRIM) and she is actively involved in the Galileo Time Validation Facility (TVF) project. Research interests: time scale algorithms, GNSS timing systems, navigation and related applications.

Giancarlo Cerretto has a degree in Communication Engineering and a PhD in Metrology, both achieved at Politecnico di Torino. He is now working with the Italian Metrology Institute (INRIM) as a scientist, involved in the Institute’s “Time and Frequency” and “RadioNavigation” Laboratories maintenance and development activities. He is currently involved in the development of the European Navigation System Galileo.

Elena Cantoni got a degree in Physics and a PhD in Science and High Technology at the University of Torino, Italy. Her early studies were devoted to Cosmic Ray Physics, working on advanced data analysis of Extensive Air Showers at the KASCADE-Grande Experiment. At present she works on Time Transfer Techniques at the Italian Metrology Institute (INRIM) and she is involved in the Galileo Project, performing data monitoring and analysis with the Galileo Time Validation Facility Team.

Patrizia Tavella got a degree in Physics and a Ph.D. in Metrology, she is now senior scientist with the Italian Metrology Institute, INRIM, Torino, Italy. Her main interests are mathematical and statistical models mostly applied to atomic time scale algorithms. She chaired the working groups on “International Atomic Time” and “Algorithms” of the Consultative Committee of Time and Frequency. She is deeply involved in the development of the European Navigation System Galileo.

Alice Cernigliaro received an M.Sc. degree in Communication Engineering from Politecnico di Torino, in 2008, with a thesis on the metrological characterization of clocks in space and GPS/Galileo interoperability. In 2012 she got the PhD in Metrology, from Politecnico di Torino, in cooperation with the Italian Metrology Institute (INRIM). Research interests are timing algorithms, atomic clocks and time scales in Global Navigation Satellite Systems. She is involved in the Galileo Project since 2008, particularly for what concerns the metrological characterization of the space clocks. She is software engineer at aizoOn, working on Aerospace Projects and she currently collaborates with INRIM for the development of the Time Validation Facility.

Andrea Samperi is a software engineer for aizoOn. He received an M.S. degree in Communication Engineering and a Master degree on Navigation and Related Applications, both from the Politecnico di Torino. Since 2006, he has been working in the frame of Galileo project, in particular on the Precise Time Facility and in the last 3 years on the Time Validation Facility at the Italian Metrology Institute. He was involved in the prototyping of timing algorithms, software design and development, assembling, integration and validation, and maintenance.

Abstract

In the last 15 years, the Italian Metrology Institute (INRIM) has been deeply involved in the development of the Galileo project, from the early study phase through all the experimental phases. INRIM designed and developed the Time Validation Facility (TVF), a key timing element of the ongoing Galileo In Orbit Validation (IOV) phase.

This paper presents the TVF, whose role in the IOV phase is the validation of all the timing aspects including space and ground clocks, the time dissemination through the navigation message, and the synchronization and steering of the Galileo System Time versus UTC.
Introduction

Galileo is a global navigation satellite system (GNSS) currently being built by the European Union (EU) and the European Space Agency (ESA). The aim of Galileo is to provide a high-precision positioning as well as high accurate time dissemination system. Some results in timing were recently presented [3,4,5].

Since 1999 different timing activities at INRIM (formerly IEN G. Ferraris) are devoted to the development of the Galileo System, in collaboration with European metrological institutions, space industries, and ESA. In fact time metrology is of fundamental importance in GNSS as it covers various aspects: from the research on compact and highly stable clocks, to the definition of a reference time scale, to the algorithms suited to characterize the clock behavior, to the understanding of the time measurement system.

The development of the Galileo program has been structured according to four main phases: Galileo System Test Bed (GSTB), In-Orbit Validation (IOV), Initial Operational Capability (IOC) and Full Operational Capability (FOC) phases.

In 2002 the Galileo System Test Bed Version 1 (GSTB-V1) project validated the on-ground algorithms for orbit determination and also for the time synchronization aspects. INRIM together with PTB and NPL supported this phase with the experimental Precise Timing Station generating the experimental Galileo Systems Time. This project has provided fundamental understanding to develop the mission segment of the Galileo system.

In the frame of the Galileo System Test Bed Version 2 (GSTB-V2), then named GIOVE mission, the first experimental satellite, GIOVE-A, was launched in 2005 and was followed by a second test satellite, GIOVE-B, launched in 2008. The GIOVE Mission segment exploited these two satellites to provide experimental results based on real data to be used for risk mitigation for the IOV satellites that followed on from the test-beds. INRIM had the role to test the on board and ground clocks to validate their performance in the space system.

The test-bed satellites were followed by four IOV Galileo satellites that are much closer to the final Galileo satellite design. The first two Galileo In-Orbit Validation satellites were launched by Soyuz from Guiana Space Centre on October 21st, 2011, and the remaining two on October 12th, 2012. This reduced satellite constellation and its related ground infrastructure enables key validation tests, and in particular the first determination of a ground location using Earth-based receivers. Also the capability of Galileo to disseminate UTC standard time is under test.

Once this IOV phase is completed, the IOC stage will bring the batch of satellites to 18 (4 IOV + 14) and will provide Open Service, the Search And Rescue service and the Public Regulated Service. The remaining satellites will be then launched to reach the Full Operational Capability.

The IOV Time Validation Facility

Based on the heritage of Galileo System Test Bed V1 and V2, and GIOVE mission, the Time Validation Facility has been defined in 2010 to provide an independent assessment and characterization of all the timing aspects in the frame of a new facility named Time and Geodetic Validation Facility (TGVF), under the overall coordination and responsibility of ESA Galileo system team.

The aims of the TVF are:

- to act as a preliminary Galileo Time Service Provider (TSP) during IOV phase, allowing the Galileo Mission Segment (GMS) to steer the Galileo System Time (GST) to the international reference time UTC (mod 1s);
- to validate the IOV timing infrastructure, including space and ground clocks and Galileo System Time (GST) performances.

Both the objectives have been reached thanks also to the contributions and the efforts of some European laboratories, namely IT, NPL, OP, ORB, PTB, ROA and, recently, SP, providing high quality UTC(k) national time scales and other capacity in calibration, monitoring, and data cross-check.

Two successive qualified versions of the TVF have been delivered in the frame of this program:

- TVF v1, delivered in July 2011, supported the Galileo In Orbit Test (IOT) activities and allowed the first tests as the TSP by steering an INRIM Active Hydrogen Maser acting as the GST master clock;
- TVF v2, delivered on June 2012, supported the GMS external interface verification and the IOV campaign. This version has been deployed on accredited site at INRIM, in order to allow secure connection with Galileo operational system.

Additionally, an intermediate not qualified version called TVF v0 was delivered on May 2011, ensuring the TVF connectivity with the system TGVF and the functionality of the clock characterization tools.

Validation Of The Galileo System Time

To fulfill its tasks the TVF makes use of data coming from different external sources not part of the TGVF, such as BIPM, and a number of European metrological laboratories involved in IOV.

In particular, to estimate the differences UTC(k)–GST, the TVF is gathering daily the measures obtained by the Galileo PTF and the UTC labs with the Two Way Satellite Time and Frequency Transfer (TWSTFT).
stations and the GPS timing receivers with which the All in View (AV) technique is exploited.

From the measured $\text{UTC}(k) - \text{GST}$ offsets, the TVF estimates $\text{UTC}_{\text{approx}} - \text{GST}$, that is a real time approximation of $\text{UTC} - \text{GST}$. The difference between UTC and GST is defined modulo 1s, the labelling of the seconds in fact is not the same for the two time scales as GST is labelling the seconds in agreement with GPS time scale, therefore currently GST differs from UTC by 16 seconds.

Figure 1 shows the behaviour of $\text{UTC}_{\text{approx}} - \text{GST}$ from May 1st, 2013 to October 20th, 2013, as well as the measured differences $\text{UTC}(k) - \text{GST}$.

The computed offset $\text{UTC}_{\text{approx}} - \text{GST}$ is used by the TVF to evaluate the steering correction needed to maintain GST time and frequency offset with respect to UTC within the specified limits. This correction is evaluated and communicated daily to the Galileo Precise Time Facility (PTF) on a regular base since February 2013.

The magnitude of the frequency correction provided to PTF is estimated in order to fulfil the Galileo System requirement asking for the time offset $\{\text{UTC} - \text{GST}\,\text{mod 1s}\}$ to be less than 50ns (for 95% of the time).

This requirement is verified by TVF each month, a posteriori, when the BIPM Circular T is available. Figure 2 shows that the GST accuracy requirement is fully met during the test period (from February 11 to October 14th, 2013). In particular, the $\{\text{UTC} - \text{GST}\,\text{mod 1s}\}$ offset is less than 10 ns for the whole considered period; the only period outside this value is the period from March 18th to April 8th, 2013, during which the PTF was in autonomy mode (therefore not applying the TVF steering correction) and undergoing GPS and TWSTFT links re-calibration [6].

Since the true $\{\text{UTC} - \text{GST}\,\text{mod 1s}\}$ offset is known only a posteriori via the BIPM circular T, the real-time time dissemination service offered by Galileo is based on a prediction of this value which is reported in the Navigation Message, broadcasting the predicted $\{\text{GST} - \text{UTC(SIS)}\,\text{mod 1s}\}$ (including leap seconds), enabling Galileo to be relied on for precision timing applications.

According to Galileo System requirements, the error between the predicted value $\{\text{UTC} - \text{GST}\,\text{mod 1s}\}$ and the reference value obtained via BIPM Circular T shall not exceed \(\pm 28\text{ns}\) (for 95% of the time). From Figure 3, it can be noticed that the requirement is fully met during the considered period from February 11th to October 14th, 2013. Indeed, during the whole test campaign $\{\text{UTC} - \text{GST}\,\text{mod 1s}\}$ prediction error remains within $\pm 8\text{ns}$. 

![Figure 1 - GST steering: The measures differences $\text{UTC}(k) - \text{GST}$ and the estimated $\text{UTC}_{\text{approx}} - \text{GST}$ (from May 1st to October 20th, 2013)](image1)

![Figure 2 - GST validation: $\text{UTC} - \text{GST}\,\text{mod 1s}$ time offset (from February 11th, 2013 to October 14th, 2013)](image2)

![Figure 3 - GST validation: $\text{UTC} - \text{GST}$ prediction error (Feb 2013/Oct 2013)](image3)
UTC Time Dissemination

Galileo provides both precise positioning and timing capabilities by UTC dissemination. In all its services, Galileo broadcasts conversion parameters between its time scale GST and UTC.

One of the tasks of the Time Validation Facility is to verify the Galileo UTC dissemination service. The TVF is in charge to verify periodically the matching between the $\text{UTC} - \text{GST}$ (mod 1s) time offset predicted and commanded by TVF itself and the value received and reconstructed (through the conversion parameters) at user level.

This is obtained by comparing the GST–UTC values transmitted in the Galileo navigation message and received by the Galileo Experimental Sensor Station (GESS) hosted at INRIM premises, named GIEN versus the TVF daily predicted values.

*Figure 4* is comparing the broadcast value and the reference one computed by TVF during the period June - August 2013. The differences between the two realizations are due to: 1) the rounding of conversion parameters reported in the navigation message, 2) the delay of uploading of GST–UTC parameters between the validity time periods.

![Figure 4](image)

*Figure 4- Signal in Space Validation: Comparison between GST–UTC values broadcast versus reference value computed at TVF level (from June 1, 2013 to September 2nd, 2013)*

The detailed analysis of UTC Time and Frequency accuracy distribution at user level is the result of the collaboration with the Royal Observatory of Belgium (ORB). In fact the role of user receiver is played by a GPS/Galileo receiver hosted, operated, and calibrated by ORB. This Galileo receiver is connected to $\text{UTC(ORB)}$ and it measures the quantities reported in (1) and (2) below:

$$[\text{GST(SIS)} - \text{UTC(SIS)}]_p \quad (1)$$

where (1) is obtained from the broadcast navigation message and (2) is the difference between the local clock and the Galileo System Time obtained by processing the pseudo range measurements of the ORB receiver [1,2].

SIS stands for Signal In Space, meaning the information obtained from the navigation message.

By adding (1) and (2), the following is obtained:

$$\text{UTC(SIS)} - \text{UTC(ORB)} \quad (3)$$

which can then be compared with the reference value of $\text{UTC} - \text{UTC(ORB)}$ published in the BIPM Circular T.

*Figure 5* compares (3) with

$$\text{UTC} - \text{UTC(ORB)} \quad (4)$$

obtained by BIPM Circular T with a sampling rate of 5 days and with

$$\text{UTC}_r - \text{UTC(ORB)} \quad (5)$$

obtained by BIPM UTC rapid data with a sampling rate of 1 day, during the test period from October 29, 2013 to November 13th, 2013.

![Figure 5](image)

*Figure 5- Signal in Space Validation: Comparison among UTC(SIS)–UTC(ORB), UTC–UTC(ORB) and UTCr–UTC(ORB)*

Preliminary results in *Figure 5* show that the UTC time information disseminated by Galileo has an accuracy at the level of 10 ns.
GGTO Validation

The TVF is in charge to verify the GPS to Galileo Time Offset (GGTO) transmitted in the navigation message based on PTF measures [6] with the same quantity estimated at user level [1]. This can be obtained in different steps. First the GGTO values transmitted in the Galileo navigation message are compared versus the GPS Galileo Time Offset estimated through the PTF GPS receiver directly connected to GST. This helps in validating the transmitted values. An example of this comparison is reported in Figure 6.

![Figure 6](image)

Figure 6-Signal in Space Validation: Comparison between the GGTO computed by TVF and the broadcast one [3].

Then, the GGTO is additionally compared to what is obtained by processing the pseudo range measurements of the ORB receiver [1] as illustrated in Figure 7.

![Figure 7](image)

Figure 7-Signal in Space Validation: Comparison among the GGTO computed by TVF, estimated at user level, and the broadcast one.

The updating of the broadcast GGTO is not always performed daily. The broadcast value is mainly in good agreement with the TVF and user estimates.

CONCLUSIONS

For the overall duration of the IOV period, INRIM has been in charge to host and operate the TVF. For the next FOC phase, a new contract has been signed between ESA and GMV which will be the new TVF responsible.

The expertise of time metrology useful in GNSS covers various aspects. In the last 15 years, INRIM and European time laboratories have been deeply involved in the development of the Galileo project. The paper aimed to show recent Galileo timing results but also the important and fruitful cross fertilization that may arise between timekeeping and navigation.

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REFERENCES


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