Abstract—Timekeeping is crucial in Global Navigation Satellite Systems (GNSS), being the positioning accuracy directly related to a time measurement. As a consequence, the typical expertise of time metrology laboratories is necessary in many different aspects of a navigation system. This paper presents the experience of INRiM in the development of the Galileo navigation system from the earlier studies till the very recent In Orbit Validation phase showing how the time metrology practice has been useful in the understanding of time aspects of navigation and showing as well how the navigation service perspective has stimulated new ideas and better understanding of time measures.

Keywords—time metrology; atomic clocks; steering; time scales; GNSS timing; timekeeping; space clocks; system noise

I. INTRODUCTION

The European Union (EU) and the European Space Agency (ESA) are building the European satellite navigation system, Galileo. In addition to the positioning service, Galileo will be able to disseminate globally accurate time.

Currently there are 4 Galileo satellites already in orbit, launched in 2011 and 2012 for the In Orbit Validation (IOV) phase. Two experimental satellites were launched in 2005 and 2008 and operated in the GIOVE Mission phase. The remaining satellites of the system will be launched between 2014 and 2018, in order to complete the constellation for the Initial Operational Capability (IOC) and the Full Operational Capability (FOC) phases [1].

During these years, the role of European metrological institutions, which cooperated and worked together with space industries and the ESA, has been significant and fruitful.

National Metrology Institutes (NMI) have the instruments, expertise, and competencies required to ensure the high performances of time measurements as necessary in navigation systems. In fact, NMI time laboratories realize their national time scales, called UTC(k), and are hence used to face the issues related to the accuracy, reliability, and robustness of the timing systems. The international reference time is the Universal Time Coordinated (UTC), and UTC(k) are local real time approximation as realized by the k laboratory.

Time metrology is implicated in several aspects of a navigation system: from the reference time scale definition to the design of specific algorithms for clock characterization and anomaly detection, as well as in the evaluation of the measurement system, the research on new clock technologies, calibrations, evaluation of uncertainty, and dissemination of accurate time.

This paper presents the experience of the Italian National Institute of Metrological Research (INRiM) time laboratory in the Galileo experimental and validation phases.

II. THE GALILEO EXPERIENCE

INRiM has been involved in the Galileo system since 1999 and participated to different phases of the project.

The first experimental phase was the Galileo System Test Bed Version 1 (GSTB V1) in 2002 in which INRiM participated, together with the British NPL and the German PTB laboratories, to generate the experimental Galileo System Time, the reference time scale of the system, obtained from the Experimental Precise Timing Station located in INRiM. GSTB V1 supported the validation of the on-ground algorithms for orbit determination and time synchronization. In that phase the main learned lesson was the difficulty of generating a reference time scale, synchronized to UTC, in a complete automatic and unmanned way, as Galileo requested. It appeared clear that not only optimal algorithms and devices are necessary, but that robustness was the issue and different monitoring and control checks had to be devised [2]. This project constituted an essential contribution to the understanding of the Galileo mission segment development.

The next phase, from 2005 to 2011, was the Galileo System Test Bed Version 2 (GSTB-V2), then named GIOVE Mission [3–4], in which INRiM role consisted in the realization of the experimental Galileo System Time, driven by the free running Active Hydrogen Maser connected to an experimental Galileo receiver, named GIEN, located at INRiM, and the characterization of the clocks of two experimental satellites GIOVE-A and GIOVE-B, in addition to the ground station clocks.

Ground and space clocks performances were evaluated through systematic monitoring and campaign activities. Both short term and long term clock behaviors were characterized [5–7].

Particular care was given to the detection and identification of feared events in satellite clocks, as for example the frequency jumps that sometimes could be observed over long data periods, as well as to the correlation of clocks’ behavior and clock internal telemetries [8–9]. Moreover, specific analysis were performed on clock prediction strategies [10].
The results of this phase have been used for the risk mitigation for the IOV subsequent phase [5].

From 2011 to 2013, within the In Orbit Validation Phase (IOV), INRIM role consisted in the support to the In Orbit Test (IOT) after the launch of the first 4 IOV Galileo satellites and in the design and development of the Time Validation Facility, to assess and characterize all the timing aspects of the Galileo system [11]. The In Orbit Validation satellites were launched on October 2011 and October 2012 from the Guiana Space Centre, and their design was already representative of that of the final Galileo constellation.

The fundamental time metrology aspects in the support to the Galileo experimental phases will be discussed in the next sections.

III. TIME METROLOGY ACTIVITIES

A. Timing Infrastructure

The most recent project in which INRIM has been involved from 2010 to 2013 is the design and development of the Time Validation Facility (TVF), in the frame of the Time and Geodetic Validation Facility (TGVF) project. The TVF had two main tasks [11]:

- the operation as a preliminary Galileo Time Service Provider (TSP) during IOV phase, computing the steering corrections needed to align the Galileo System Time to the international reference time UTC
- the validation of the whole timing infrastructure of the IOV phase, including space and ground clocks and Galileo System Time (GST) performances.

To accomplish these objectives, the TVF has worked in cooperation with some European laboratories: NPL (UK), OP (F), ORB (Belgium), PTB (Germany), ROA (Spain), and, recently, SP (Sweden), contributing with their UTC(k) national time scales.

B. Reference Time Scale Validation

In order to validate the Galileo reference time scale, the TVF collected the data from the different European time laboratories involved in the project, as well as from external entities as the BIPM. The difference between each laboratory time scale and GST, namely UTC(k)-GST, was measured using time transfer data obtained at the time laboratories and at the Galileo Precise Time Facility (PTF) realizing GST, using the Two Way Satellite Time and Frequency Transfer (TWSTFT) stations and the GPS timing receiver techniques. Starting from these offsets, a real time approximation of UTC−GST, named UTC\text{approx}−GST, was obtained. Finally, such offset was used to compute the steering corrections required to align the GST to UTC. These corrections were regularly sent to the Galileo PTF since February 2013, in order to maintain the time offset |UTC−GST|\text{(mod 1s)} within the specified limits, as asked by Galileo requirements. The TVF verified the fulfillment of such requirement on a monthly basis, after the publication of the BIPM Circular T containing the final UTC data. Fig 1 shows the |UTC-GST|\text{(mod 1s)} offset in the period May-Oct 2013, which remained less than 10 ns.

A second product of the TVF was the daily prediction of the offset UTC−GST to be transmitted in the Galileo navigation message to disseminate UTC to the user. The true offset UTC−GST is known only a posteriori, after BIPM Circular T publication, one month a posteriori.

During the test period, as showed in Fig 2, the prediction error remained below ±8 ns [11, 19].

C. System Clocks Characterization

An additional task of the TVF was the characterization and monitoring of the satellite and ground station clocks of the system. Similar task had already been performed during the GIOVE Mission phase of the Galileo project [5].

System clocks were analyzed by means of proper mathematical algorithms, exploiting the methods and software regularly used by INRIM for institutional purposes [12-19, 20]. These activities were particularly important during the In Orbit Test phases performed after the launch of the Galileo IOV satellites. By evaluating the frequency offset of the clock on board with respect to ground clock, in particular for the high performance space Passive Hydrogen Maser, it has been
possible to verify the effect of general relativity shifting the frequency of the on board clocks [5]. Additionally the clock on board showed sometimes behavior not typically observed on ground, for example the frequency values could suddenly “jump” to another value. This atypical behavior called for the development of additional clock analysis tools, also studied for INRIM institutional activities, that could be integrated in a real time monitoring of GNSS satellite clocks [16–18].

D. Time Dissemination
Galileo started in April 2013 to broadcast the conversion parameters required to obtain the offset between GST and UTC, as well as the GST to GPS Time Offset (GGTO) [21]. The Time Validation Facility verified the Galileo time dissemination service, analyzing the broadcast navigation message. To this purpose, the $UTC - GST$ (mod 1s) offset predicted and commanded by TVF was routinely compared with the value reconstructed at user level through the conversion parameters broadcast in the navigation message.

Fig 3 shows the comparison between the broadcast and reference value computed by TVF during the period June - August 2013. The differences between the two values are due to the rounding of the parameters reported in the navigation message, and the delay in the upload of the computed parameters.

The analysis of UTC Time and Frequency accuracy dissemination at user level was the result of the collaboration with the Royal Observatory of Belgium (ORB).

A GPS/Galileo receiver hosted, operated, and calibrated by ORB was connected to the Belgian time scale UTC(ORB), and allowed to obtain the \( \frac{\{GST(SIS)−UTCr\}}{UTC(ORB)} \) from the Signal In Space (SIS) that is broadcast navigation message, and the difference between the local clock and the Galileo System Time $GST(SIS)−UTC(ORB)$ obtained by processing the pseudo range measurements of the ORB receiver [22].

From the difference between the two previous quantities, it is possible to compute $UTC(SIS)−UTC(ORB)$ which can be compared with the reference value of $UTC−UTC(ORB)$ published in the BIPM Circular T, as well as with the BIPM rapid data for $UTCr−UTC(ORB)$, available with a shorter latency. Fig 4 shows the preliminary results of UTC dissemination, where the accuracy level of Galileo broadcast values was 10 ns.

Galileo Navigation message is broadcasting also the GPS to Galileo time offset (GGTO), which is fundamental for GPS-Galileo interoperability [23]. The TVF validated the broadcast GGTO comparing it with the same quantity evaluated at TVF using the measures of the PTF GPS receiver directly connected to GST, and with the GGTO computed by processing the measures of the ORB receiver pseudo-range measurements, as illustrated in Fig 5.

E. System Noise Evaluation
A typical metrologist job is to evaluate the noise of the measurement system. Generally, in satellite navigation systems, the orbit and clock estimates are generated by a least
squares algorithms, named Orbit Determination and Time Synchronization [3,24], which process pseudorange measures to estimate satellite and ground station position and clock offsets.

The clock estimates represent the offset between each system clock and the ground reference clock. Such offset estimates have to be considered “apparent” clock estimates since they include also the contribution of other instabilities besides the true clock behavior. The estimate of the system noise introduced by this complex network algorithms to provide the clock estimates was carried out [24] showing that the measurement system, based at the epoch on a limited number of ground stations, is barely capable to estimate the true quality of the on board passive H maser, being the noise of the measurement system at the same level of the maser instability. In addition to the satellite clocks, we evaluated also the system noise level when assessing ground clock behavior, both in Galileo and other GNSS systems. To this purpose, we evaluated the system noise as the instability added to the estimate of the offset between two Active Hydrogen Masers (AHM) clocks connected to ground stations of the network: for example one in INRIM, Turin, Italy and one in USNO, Washington, USA. Such H masers have an intrinsic stability which cannot be appreciated by the current state of the art time transfer systems, at least in the short term, as the measurement noise exceeds the H maser stability. The comparison of two remote Active H masers allows setting a lower limit to the noise of the time transfer methods.

IV. CONCLUSIONS

The INRIM time laboratory has been involved in Galileo activities since about 15 years. Time metrology algorithms and expertise have been a support for the GNSS system development, from the design to the validation phase. During the IOV phase of the Galileo project INRIM hosted and operated the Time Validation Facility. The fruitful cooperation and support of different European laboratories have been key element for the success of the project. The paper aimed to show the timing results achieved in Galileo as well as the cross fertilisation that may arise between timekeeping and navigation systems.

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