The Time Validation Facility (TVF): An All-New Key Element of the Galileo Operational Phase

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***Abstract*— In the Galileo FOC phase (Full Operational Capability), GMV is the prime contractor for the Time and Geodetic Validation Facility (TGVF), a contract of the European Space Agency (ESA). Within the TGVF, the Time Validation Facility (TVF) is the subsystem in charge of steering Galileo System Time (GST) to UTC, among other duties. The new TVF is operated at GMV headquarters in Madrid, Spain. TVF operations rely on the contribution of five European timing laboratories, located at INRiM, OP, PTB, ROA, and SP. This paper provides a general description of the TVF element and its related activities for the FOC phase, and presents the main results and findings of the TVF operation until now.**

Keywords—Galileo, GNSS, system time, UTC steering, validation, ground infrastructure, GGTO, satellite clocks.

I. Introduction

The Time Validation Facility (TVF) is the TGVF sub-system in charge of driving and assessing all timing-related performances of the Galileo system. In particular the TVF supports the validation of the FOC Galileo timing infrastructure, acts as a preliminary Galileo Time Service Provider (TSP) steering Galileo System Time (GST) to UTC, and coordinates the national timing laboratories participating in the operations. For the FOC phase, the TVF has been fully migrated to a new hardware and software infrastructure hosted and operated at GMV headquarters in Tres Cantos near Madrid, Spain. The new TVF started operations in March 2014.

The TVF makes use of data coming from different external sources, not part of the TGVF, such as the *Bureau International des Poids et Mesures* (BIPM), the *International Earth Rotation Service* (IERS), the *International GNSS Service* (IGS), and the United States Naval Observatory (USNO). The TVF needs data also from other TGVF elements: in particular the Orbit Validation Facility (OVF) provides products for satellite clock validation. Fig. 1 shows the TVF interfaces with the external world.

The TVF software has been developed entirely from scratch in C/C++ language, reusing the software, experience and results from the previous IOV phase [1].

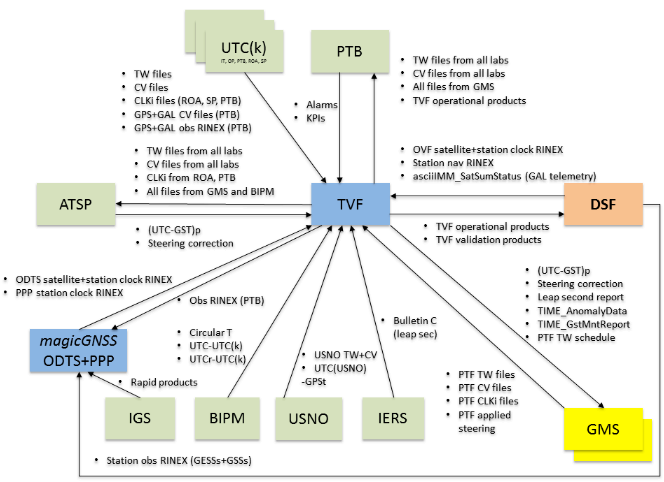

Fig. 1. TVF interfaces with the external world.

II. GST Realization and Steering

GST is the underlying time scale to which the Galileo satellite clocks disseminated in the navigation message are referred to. The broadcast clock parameters represent actually the satellite clock offset versus GST. In order to do this, the Orbit and Synchronization Processing Facility (OSPF) in charge of the Galileo message generation at the Galileo Mission System (GMS), processes measurements from a calibrated Galileo Sensor Station (GSS) connected to GST; this receiver is used as clock reference for all clock estimations in OSPF. Although a free-running GST scale would work perfectly for positioning purposes, for inter-operability with other GNSS systems, and also for timing applications, it is required that GST runs close to UTC. The formal requirement is that GST does not deviate by more than 50 ns from UTC.

GST is physically generated at the Galileo Precise Timing Facilities (PTFs), also part of the GMS. Two Galileo PTFs exist: the master PTF is located in Fucino, Italy (FUC or PTF1), and the backup PTF is located in Oberpfaffenhofen, Germany (OBE, or PTF2). In essence, each PTF is a clock ensemble consisting of two Active Hydrogen Masers (AHMs) and four Caesium clocks. In nominal operations, only the prime AHM plays a role in GST generation, its frequency output being tuned according to steering corrections received from the TVF. When the PTF runs in autonomy mode (i.e., without TVF intervention) the short-term and long-term stability properties of the PTF clock ensemble allow to maintain GST autonomously for several days. The two PTFs are steered independently and in parallel by the TVF. In this sense the two GST scales operated at FUC and OBE are not directly linked to each other, but each of them is kept as close as possible to UTC.

In order to keep GST close to UTC, time-transfer equipment is operated at the PTFs, allowing to compare GST with UTC(k) as realized by five European timing laboratories: INRiM in Italy, OP in France, PTB in Germany, ROA in Spain, and SP in Sweden. Common-Views of Global Positioning System (GPS) satellites (GPSCV) and Two-Way Satellite Time and Frequency Transfer (TWSTFT) are the implemented techniques. For TWSTFT, the well-known TimeTech SATRE modem and ancillary equipment is used. Regarding GPSCV, the two PTFs have been recently upgraded with Septentrio PolaRx4 receivers. All TWSTFT and GPS equipment have been calibrated through dedicated campaigns in 2014, [2] and [3], respectively. Time-transfer measurements from the PTFs and from the timing laboratories are sent to the TVF and processed daily. Internal clock-comparison daily data files from the PTF are also processed by the TVF.

Each laboratory maintains its own UTC(k) time scale, which is an independent physical realization of UTC. The TVF computes a weighted average of the GST-UTC(k) differences, and uses it as an approximation of GST-UTC, called GST-UTCapprox. Once the GST-UTCapprox has been obtained, the PTF steering correction is computed as two different terms. The first term is the frequency correction needed to compensate the frequency offset and drift of the PTF primary hydrogen maser. It is computed from historical data of the clock (typically 10 days before the date of computation). By applying this first term the frequency offset of the GST scale is removed, but the GST phase offset could still be far from UTCapprox. A second term is then used to slowly reduce the GST-UTCapprox offset. As the correction is always a small frequency correction (no phase corrections are allowed, for continuity), the second term tries to bring the offset to zero after a certain number of days (typically 30). Fig. 2 shows an example of the steering outcome, with GST-UTCapprox reducing gradually from -6 ns to around zero after one month, and staying around zero afterwards. Only GPSCV was enabled in the TVF during the period reported.

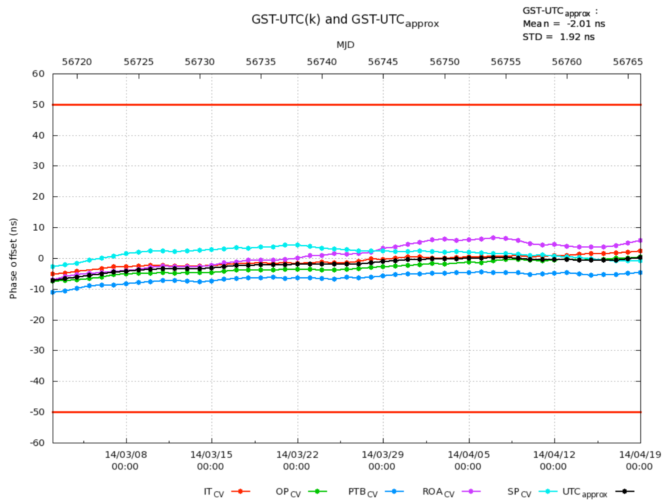

Fig. 2. GST-UTCapprox evolution over one and a half months.

The goal of the TVF steering is to keep GST close to UTC, but at the same time to ensure that GST is stable enough for navigation purposes (satellite clock predictions). To achieve this goal, the frequency corrections computed by the TVF are limited to a maximum of 1E-14 units per day, and the Allan deviation of these corrections is daily monitored. Fig. 3. shows that a steering correction stability better than 3E-15 (ADEV at a 1-day averaging period) is possible, depending on the stability of the steered clock (an AHM in this case).

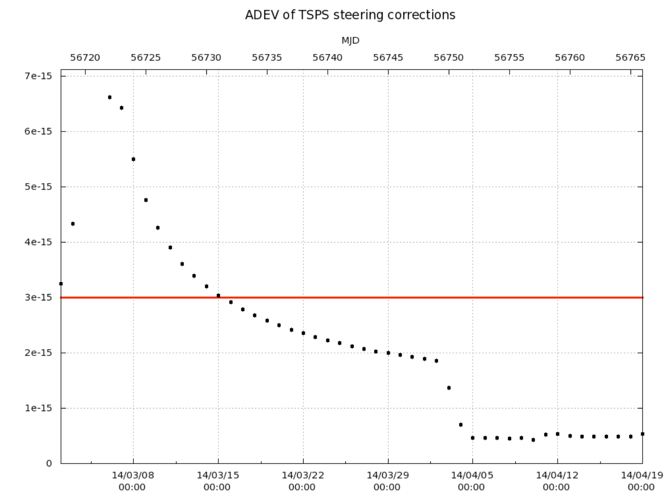

Fig. 3. ADEV of the steering corrections provided by the TVF (at a 1-day averaging period over a 30-day moving window).

III. ALTERNATIVE GST STEERING BY SP

ATSP, alternative Time Service Provider, is an independent entity in support of the TVF. The design of the ATSP has been chosen to be different from the main TSP, while maintaining functional and performance compatibility and providing redundancy in the estimation of the GST steering and monitoring signals.

The ATSP is based on a clock ensemble filter that is deployed at SP for the estimation of UTC(SP) [4]. The clock combiner is a classical Kalman filter that uses clock difference measurements as input. A clock is modeled using three states: phase, frequency and possibly frequency drift representing a clock's absolute estimate relative to UTC. The states are connected in a set by a sequence of integrated noise processes, creating a simplified clock model. The clock states are parameterized by a standard set of parameters that were derived for typical clock behavior, distinguishing H-masers and Cs clocks. The parameters are time invariant representing an equal weighting scheme, which can be considered a robust filter approach. The filter is only run in the forward direction, but can dynamically reprocess data several times in order to include delayed information. This is especially true for reference data, which is a clock's true phase to UTC and/or UTCr. Initial state information is usually derived from reference data.

Clocks within a site, UTC(k)'s and PTFs, are related to its local time scale using time interval measurements. Time scales are in turn compared using a combined TWSTFT and GPSCV time link. At any given epoch with available clock data the ATSP creates a minimal matrix of clock differences that covers all clocks of the involved sites. The filter then consumes the measurements and in turn estimates updated clock states and uncertainties. The time scale at each site, such as GST, is estimated using its master clock estimate and the local TIC measurements. ATSP applies the same rules as the main TSP in order to calculate the steering suggestion that minimizes phase and frequency offset of GST. The ATSP usually combines more than 50 clocks at any epoch providing daily GST-UTC phase and frequency estimates to the TVF.

IV. UTC-GST AND GGTO DISSEMINATION

The UTC-GST offset and GGTO (GPS-to-Galileo Time Offset) are calculated by the GMS and disseminated in the Galileo navigation message through the Galileo Signal-In-Space (GALSIS). UTC-GST is needed by the Galileo timing user in order to convert the receiver clock offset obtained from the Galileo PVT (Position/Velocity/Time) solution from GST to UTC. GGTO is needed to align GPS and Galileo satellite clock offsets in a combined GPS+Galileo PVT solution. Both offsets are calculated operationally by the GMS and validated independently by the TVF. The operational values of the two broadcast offsets are obtained by the TVF through navigation messages from the Galileo Experimental Sensor Station (GESS) network. A GTR51 calibrated GPS+Galileo receiver at PTB is also used, named PT10 station. PTB sends GPS and Galileo CGGTTS files daily to the TVF.

For UTC-GST offset validation, Galileo CGGTTS files from PTB give the station clock offset with respect to GST for each Galileo satellite. The satellite average at each epoch provides the station clock offset versus GST. Since the station has been calibrated [5], the station clock being UTC(PTB), we obtain UTC(PTB)-GST. We then apply the UTC-GST offset from the GESS navigation messages in order to obtain UTC(GALSIS)-UTC(PTB). An example is shown in Fig. 4.

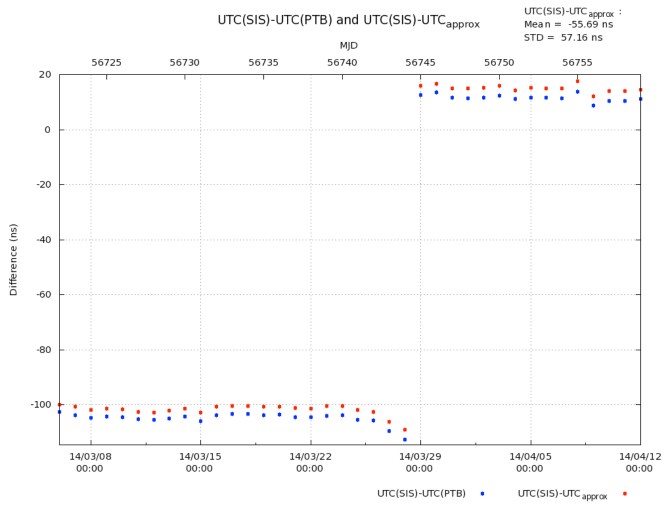

Fig. 4. Validation of the operational UTC-GST offset from the Galileo navigation message using a calibrated receiver at PTB.

Fig. 4 shows also how the use of a calibrated receiver reflects the disseminated UTC as would actually be perceived by an end user from the PVT solution. Starting on February 26, 2014, the broadcast satellite clocks were affected by a spurious bias of around 110 ns caused by a GSS PTF calibration change due to maintenance. The situation went back to normal on March 29.

GGTO is defined as GST-GPSt, where GPSt is GPS Time. For validation purposes, the TVF calculates GGTO alternatively using up to five different methods, described in the next paragraphs.

$GGTO_{PTB}$ is GGTO as seen from a calibrated GPS+Galileo receiver located at PTB. CGGTTS files from PTB give the UTC(PTB) clock offset versus GPSt for each GPS satellite, and versus GST for each Galileo satellite. Subtracting the satellite averages for each epoch, the UTC(PTB) clock offset cancels out and we obtain GST-GPSt (GGTO). $GGTO_{PTB}$ is the main and nominal method for the validation of the broadcast GGTO.

$GGTO_{PTFCV}$ is the daily average of all GPS satellite records contained in the daily GPS CGGTTS file received from a PTF. The PTF CGGTTS file gives the receiver clock offset (GST by definition) versus GPSt for each GPS satellite, then by averaging we get GST-GPSt in a quite straightforward way.

$GGTO_{USNO(AV)}$ is the difference GST-UTC(USNO) as seen from GPS All-in-View time transfer between the PTF and USNO. $GGTO_{USNO(TW)}$ is the difference GST-UTC(USNO) as seen from indirect TWSTFT between the PTF and USNO, using PTB as pivot. UTC(USNO) is used as an approximation of GPSt in these two methods.

$GGTO_{ODTS}$ is GGTO as seen from an Orbit Determination and Time Synchronization (ODTS) process, using the PTF

GSS station (S52M) as reference so that estimated GPS satellite clocks are referred to GST. By then comparing with the GPS satellite clocks contained in the navigation message (referred to GPSt) and averaging for all satellites, we can have an estimation of GST-GPSt. Fig. 5 shows a comparison of the operational GGTO from the navigation message against the five GGTO methods provided by the TVF.

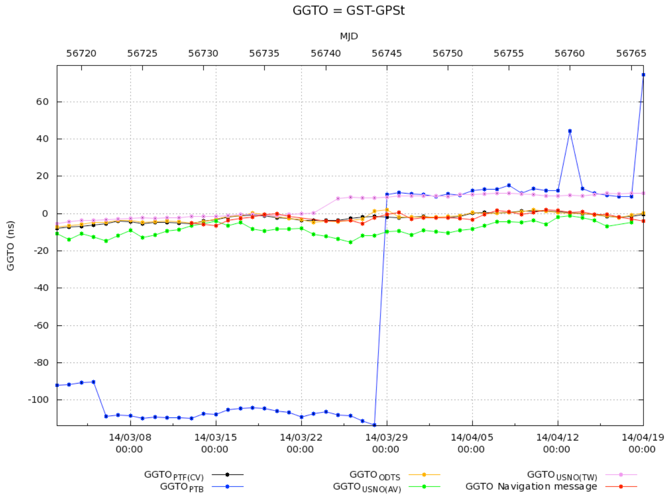

Fig. 5. Validation of the operational GGTO from the navigation message against five alternative GGTO calculations by the TVF.

As in the case of UTC, Fig. 5 shows how the usage of a Galileo receiver ($GGTO_{PTB}$) reflects the disseminated GGTO as would actually be perceived by an end user from PVT.

V. Service Level Agreement

An important feature in the new TVF for the FOC phase is the provision of operations under a Service Level Agreement (SLA) between the prime contractor (GMV) and ESA. The SLA is based on the fulfilment of a number of so-called Key Performance Indicators (KPIs) related to the quality and availability of the operational products delivered by the TVF to the PTFs. During the first four quarters of FOC operations with the TVF system running at GMV, the average level of fulfilment of the SLA with ESA was of 99.5%. The calculation of the TVF KPIs is done independently by PTB based on the raw product files from TVF.

In order to ensure the provision of a high-quality service by the TVF, a reliable contribution of the UTC(k) laboratories with their time-transfer data is essential. To this effect, a lower-tier SLA has also been put into place between GMV and the five UTC(k) acting as GMV contractors. The SLA guarantees the timeliness and integrity of the GPSCV and TWSTFT time-transfer files arriving daily at the TVF ftp server. For GPSCV, data from two receivers is required (prime and backup). All time-transfer daily files must arrive at the TVF before 01:00 hours UTC of the next day. All data files must comply with certain rules to ensure their completeness and quality. The SLA between GMV and the laboratories is evaluated daily and also reviewed every quarter, if needed. The daily evaluation is based on the TVF Daily Report which is automatically generated and which summarizes the time-transfer results between the PTFs and the UTC(k) realizations. An example is shown in Fig. 6.

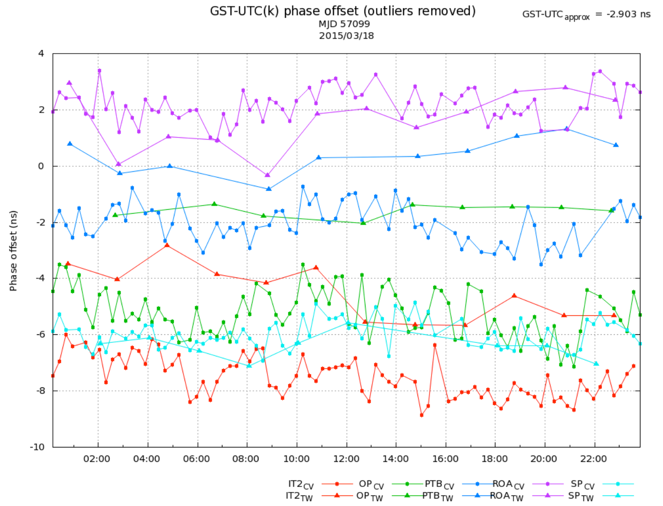

Fig. 6. Daily time-transfer results between a PTF and the five UTC(k) providers (from the TVF Daily Report).

In general, the performance of the UTC(k) service provision by the laboratories is outstanding, and with a similar level of reliability from all of them. In a typical quarter, the average fulfilment of the UTC(k) SLA terms is around 99% for the ensemble of institutes. The UTC-UTC(k) deviation for each laboratory, although not formally subject to SLA, is also monitored using the results published in BIPM's Circular T. An example is shown in Fig. 7. As can be seen UTC-UTCapprox is very close to zero, therefore UTCapprox as realized from averaging the five UTC(k)'s can be used as a very good real-time approximation of UTC.

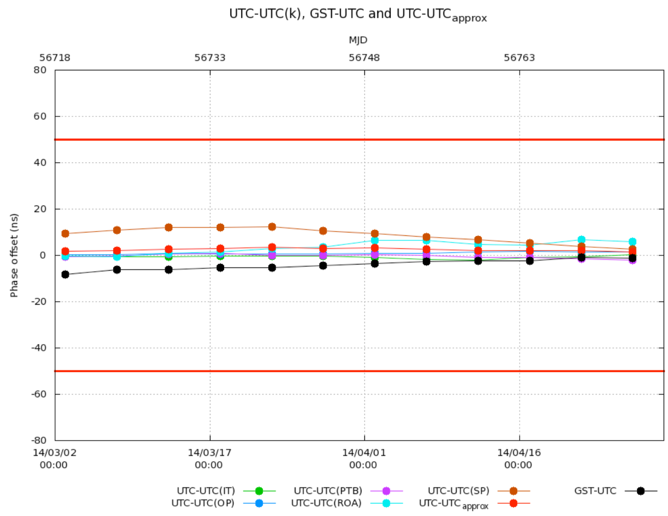

Fig. 7. Performance of UTC-UTC(k) from Circular T for the five laboratories contibuting to the TVF. The evolution of UTC-UTCapprox and GST-UTC is also shown.

VI. Characterization of Satellite Clocks

A key task of the TVF, is the performance evaluation of the Galileo satellite on-board clocks. Each satellite flies a Passive

Hydrogen Maser (PHM) on each side of the platform (thus the clocks are named PHM-A and PHM-B), and also a Rubidium Atomic Frequency Standard (RAFS) on each side (RAFS-A and RAFS-B). The OVF provides GPS and Galileo orbit and clock estimations based on the combination of global network solutions from three Processing Facilities (PFs): GFZ, University of Bern, and ESA/ESOC [6]. The station network used by the PFs is composed of Galileo GSS and GESS stations, and IGS stations. The TVF analyses the satellite clocks in continuous weekly intervals based on "rapid" OVF products, and in continuous quarterly intervals based on "final" products. The OVF processes a number of pre-selected stations that can be used as continuous ground clock reference in the TVF analyses. In particular, PTBB located at PTB and connected to UTC(PTB) is preferred by the TVF and normally used as reference.

The TVF produces satellite-reference clock phase, frequency, and ADEV plots. The clock frequency is calculated in an approximate way as the time-derivative of the raw phase in two consecutive values. The satellite clock characterization is limited by the "system noise" of the OVF estimation and combination process, and by the stability of the ground reference clock, normally UTC(PTB). For the evaluation of the "system noise" the ADEV stability of a stable reference clock is plotted (e.g., USN4). The "system noise" does not include the satellite clock error derived from the orbit/clock correlation in the OVF solution.

A novel activity in the FOC phase is the evaluation of PHM clocks over long periods of time (one quarter). Fig. 8 shows the evolution of the E19 PHM-B clock offset (versus PTBB) over one quarter. The stability of the reference clock (PTBB) and the "system noise" are evaluated by comparison with USN4 clock. Fig. 8 demonstrates that PTBB is stable enough for satellite clock characterization. Fig. 9 shows the corresponding ADEV for the same period, for all active PHM clocks at the time.

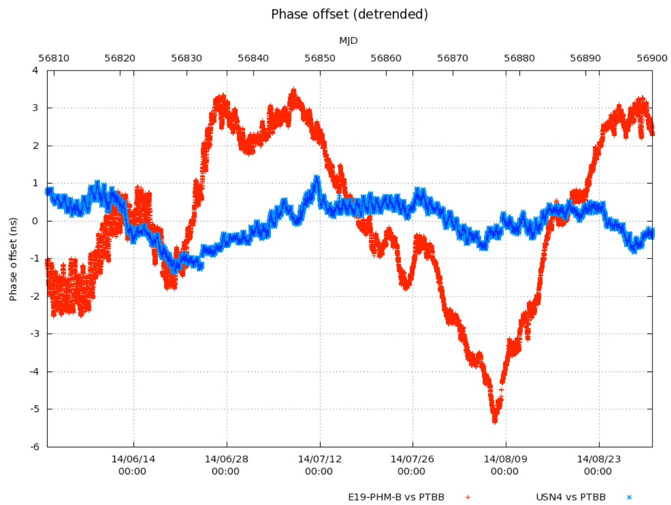

Fig. 8. E19 PHM-B satellite clock offset evolution over one quarter (91 days), versus PTBB. The USN4 clock evolution is also shown.

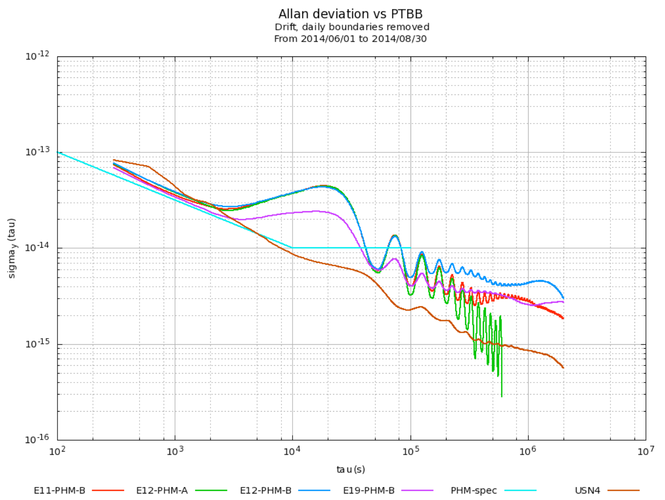

Fig. 9. ADEV stability of the Galileo PHM clocks including "system noise" evaluation (USN4).

A critical activity phase for the TVF is the so-called satellite In-Orbit-Tests (IOT), a period of several weeks after the satellite launch where the satellite basic navigation functionality is evaluated. In this phase it is important to evaluate in a rapid way the performance of the on-board clocks. The first IOT supported by the TVF in the FOC phase is the one of the fifth Galileo satellite (E18), launched on August 22, 2014. During the IOT two "hot" clock swaps were performed, from PHM-B to RAFS-B, and back to PHM-B. It is the first time that such procedure is executed by a GNSS satellite without signal interruption. As analyzed by the TVF, the clock transitions went smoothly with phase steps of the order of few cm only. An example is shown in Fig. 10.

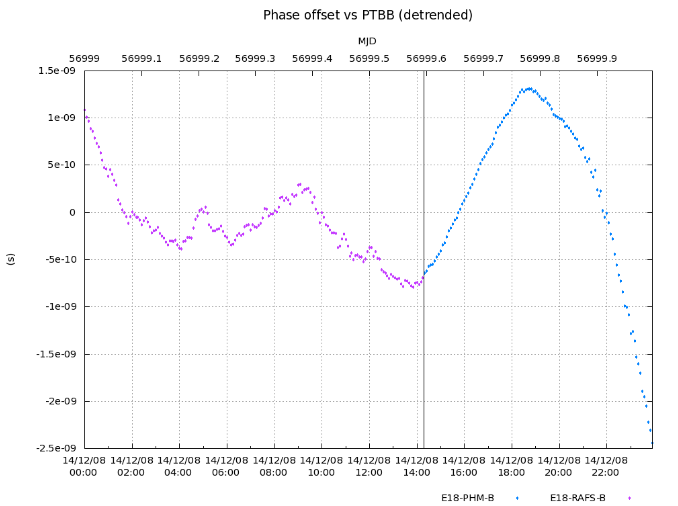

Fig. 10. "Hot" clock swap from RAFS-B to PHM-B during the E18 satellite In-Orbit-Tests (IOT).

VII. SENSOR STATION UPGRADE

The GESS network is managed under the TGVF contract. The network consists of fourteen GPS+Galileo receivers worldwide distributed. During the FOC phase all the GESS stations have been upgraded with new Septentrio PolaRx4 receivers for improved measurement quality. Some of the GESS are located at UTC(k) laboratories. Such "timing" stations are GIEN, GNOR, GPTB, and GUSN, located at INRiM (Italy), ESTEC (The Netherlands), PTB (Germany), and USNO (Washington DC, USA), respectively. GIEN is connected to a free-running Active Hydrogen Maser (AHM), and GNOR, GPTB, and GUSN are connected to UTC(ESTC), UTC(PTB), and UTC(USNO), respectively. These receivers are PolaRx4 timing versions accepting as input 10 MHz frequency and 1PPS timing signals. GESS timing receivers are essential for the TVF because they provide a reliable and traceable clock reference for satellite clock characterization from OVF products, with direct support from the hosting laboratories if necessary.

The GPTB station at PTB is new in the FOC phase. Its installation was completed at the end of 2014. Fig. 11 shows the GPTB antenna and the rack hosting the receiver and ancillary equipment.

Fig. 11. The new GPTB station at PTB.

GPTB is the only station in the GESS network that has been fully calibrated for GPS and Galileo signals. The GPS calibration has been done relative to the co-located PTBB reference station. This is possible since both GPTB and PTBB are connected to UTC(PTB). The calibration is done by processing and comparing GPS P1 and P2 pseudoranges from both stations in RINEX format. Once the GPS receiver delays have been calibrated, it is possible to calibrate the Galileo delays in E5a and E5b relative to GPS P1/P2 using the method developed by ORB [7]. The key feature of the ORB method is the cancellation of the GPS and Galileo ionospheric delays when combining pseudoranges from two satellites with a close position in the sky. The Galileo calibration is done by processing GPS and Galileo pseudoranges from GPTB in RINEX format, using a dedicated TVF software tool. Satellite positions are read from a SP3 orbit file. Details on the GPTB calibration process can be found in [5].

VIII. CONCLUSIONS

The new TVF for the Galileo FOC phase started operations in March 2014 and has been running for one year now. Its main role is the daily steering of GST to UTC, which is achieved thanks to the participation of a group of European timing laboratories providing time-transfer measurements between the Galileo PTFs and their UTC(k) realizations. The GST-UTC offset is normally maintained at a few-ns level. The TVF paves the way towards the future Galileo Time Service Provider (TSP) and Galileo Reference Center (GRC).

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