EXPERIMENTAL GALILEO SYSTEM TIME (E-GST): ONE YEAR OF REAL-TIME EXPERIMENT

Franco Cordara, Roberto Costa, Luca Lorini,
Diego Orgiazzi, Valerio Pettiti, Ilaria Sesia, and Patrizia Tavella
Time, Frequency, and Electromagnetic Department
Istituto Elettrotecnico Nazionale (IEN) "G. Ferraris"
Torino, Italy

Paola Elia, Marco Mascarello
Alenia Spazio S.p.A.
Torino, Italy

Marco Falcone and Joerg Hahn
European Space Agency (ESA/ESTEC)
Nordwijk, The Netherlands

Abstract

The Galileo System Test Bed (GSTB) V1 is the first experimental phase in the Galileo project supported by the European Space Agency (ESA). The aim is testing the Galileo algorithms in a mixed configuration where the space segment is given by the existing GPS constellation, while the ground segment is an experimental setup as close as possible to the Galileo architecture. In the framework of the GSTB V1, Alenia Spazio, in collaboration with the Istituto Elettrotecnico Nazionale (IEN), had the responsibility to design and realize an infrastructure able to generate the Experimental Galileo System Time (E-GST), which is the reference time for all the GSTB V1. The infrastructure that allows the realization of E-GST is the Experimental Precise Timing Station (E-PTS), which is implemented at the IEN facilities, Turin, Italy. The paper reports the main results of the E-PTS experimentation carried out during the whole of 2004, addressing the E-GST overall performance with respect to the demanding GSTB V1 goals. The lessons learned from the experiment are also pointed out in the paper, together with some recommendations to be taken into account in the design of the Precise Timing Facilities (PTFs) of the Galileo ground segment.

I. TIMEKEEPING INSIDE THE GSTB V1

During the GalileoSat Definition Phase an early experimental stage, named Galileo System Test Bed (GSTB), has been defined as an integral part of the Galileo Design Development and Validation Phase in order to mitigate program risks **[1-3]**.

The main goal for the GSTB first stage (GSTB V1) is to conduct a set of experiments to verify, in a real context, the Galileo concepts defined in the Galileo B2 phase **[4]**. These major objectives have been pursued relying on the existing GPS constellation and realizing a ground infrastructure close to the final Galileo setup where the critical algorithms (system time generation, orbit determination, time synchronisation, and integrity) could be implemented and tested continuously for a significant period (12 months).

In this scenario, an Experimental Precise Timing Station (E-PTS) has been designed and implemented by Alenia Spazio, Italy, and Istituto Elettrotecnico Nazionale (IEN), Turin, Italy, to test the Galileo system time algorithms in a real environmental condition. The E-PTS is an infrastructure able to generate a real-time Experimental Galileo System Time (E-GST), which was the reference time for the whole GSTB V1, allowing the realization of a large set of experiments in the timing domain.

II. THE EXPERIMENTAL PRECISE TIMING STATION (E-PTS)

The E-PTS infrastructure (Figure 1) that provides the E-GST was installed and has been continuously operated since 2003 at the IEN premises in Turin, Italy, using the facilities and personnel of the IEN Time and Frequency laboratory in collaboration with Alenia Spazio people.

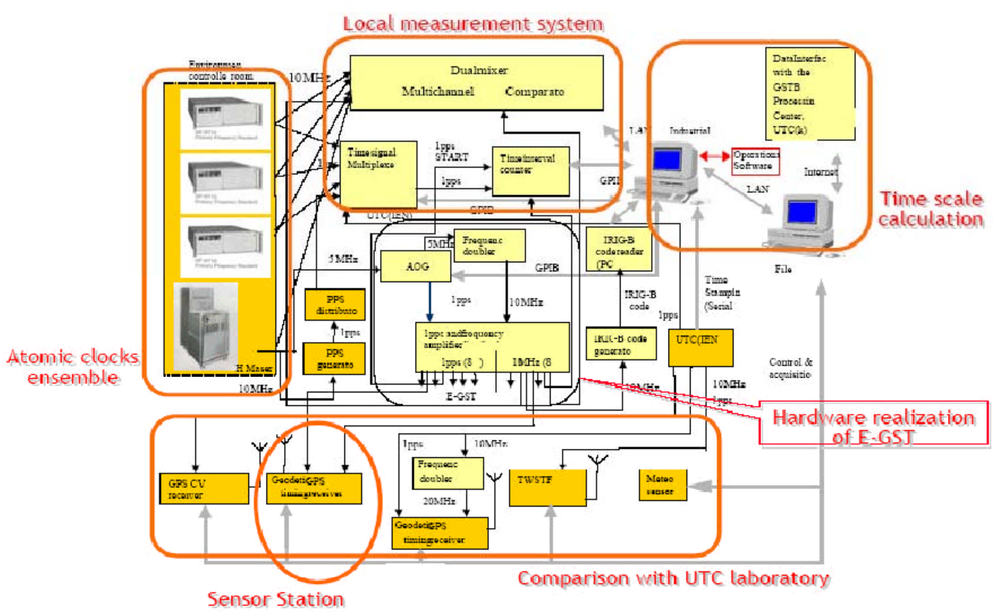

Figure 1. The E-PTS architecture and its major functions.

In particular, the E-PTS architecture partially reuses the IEN atomic clock ensemble, that is, a hydrogen maser (H-maser) and three commercial cesium (Cs) clocks (Figure 2) **[5,6]**. Moreover, the remote time transfer equipment (TWSTFT station and GPS Common View receivers) for comparison with external UTC laboratories, namely PTB (Germany) and NPL (UK), are also shared with IEN institutional duties. Because both systems are driven by the local UTC (IEN) time scale, their measures are then related to E-GST by means of supplementary internal measurements.

Figure 2. Hydrogen maser and commercial cesium clocks at the E-PTS.

All the other new hardware equipment especially procured for E-PTS is located in a dedicated rack hosted in the IEN laboratory (Figure 3). Here, two independent local measurement systems perform the measurements of the time difference between couples of clocks readings, as required by the time scale generation algorithm.

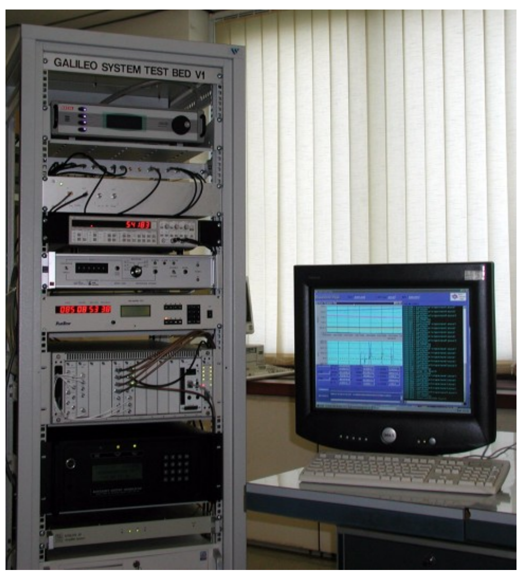

Figure 3. The E-PTS rack and the MMI interface at the Italian timing laboratory (IEN, Turin).

The primary measurement system is based on a 1PPS (one pulse-per-second) signal multiplexer followed by a high-resolution time interval counter (TIC), providing hourly measures to the E-GST generation algorithm. In addition, a multi-channel phase comparator (MCPC) acts as an auxiliary system that performs simultaneous high rate (down to 1 Hz) measurements of all the E-PTS clocks, aiming at effective real-time monitoring and analysis of the behavior of each oscillator.

The timely processing of the data provided by both measurement systems is allocated to the E-PTS operational software (Figure 4), which is also in charge of the following main functions:

- automated schedule and overall management of the E-PTS operation;
- *real-time* generation, steering, and physical realization of the E-GST time scale;
- algorithm testing in different scenarios (*off-line* experimentation);
- experimental results (core products) generation, formatting, archiving, and transfer to the GSTB Processing Center (GPC) at ESA/ESTEC premises, Nordwijk, The Netherlands.

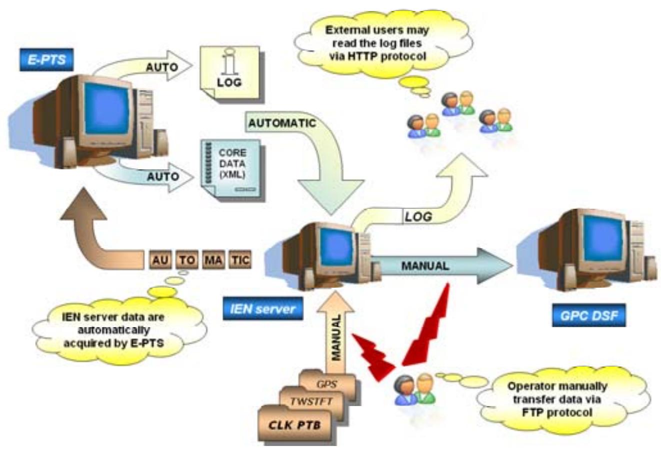

Figure 4. Major operations at the E-PTS in the current configuration.

The frequency output of the H-maser is fed to a high-accuracy phase micro-stepper (namely an Auxiliary Output Generator, AOG), which is able to avoid degrading the intrinsic short-term stability of the H-maser. A frequency correction is then imposed to the AOG according to the E-GST algorithm: the output of the AOG (5 MHz and 1PPS signals) is the physical realization of E-GST, a real-time hardware time scale.

A dual-frequency GPS receiver (a Javad Legacy receiver) is also operated by the E-PTS as an element of the GSTB V1 sensor station network. This receiver is directly connected to the physical realization of E-GST (10 MHz and 1PPS signals), allowing the orbitography algorithms to be referenced to E-GST within the Orbit Determination and Time Synchronization (OD&TS) experimentation activities.

EARLY E-PTS VERSIONS

During the deployment phase of the overall GSTB V1 core infrastructure, a reduced functionality E-PTS has been established to support the early operations of the GSTB V1 (integration and verification activities).

In particular, since April 2003, a first version called E-PTS V1.1 has been operated, providing raw data from an IEN-property dual-frequency geodetic GPS receiver (an Ashtech Z-12T) directly referenced by the local UTC (IEN) time scale.

Once the installation and verification of the E-PTS sensor station was completed (July 2003), an additional provisional version was delivered to provide 1 Hz raw data referred to a free-running active H-maser of the IEN Time and Frequency laboratory. This version, called E-PTS V1.2, was used as a very stable reference during the OD&TS preliminary experimentation.

III. THE EXPERIMENTAL GALILEO SYSTEM TIME (E-GST)

As a prototype of the final Galileo System Time (GST), the E-GST needs to have optimal characteristics for both navigation and time dissemination purposes. Moreover, as mentioned before, E-GST is realized in real time and with a hardware representation.

In addition, to fulfill the time dissemination purposes of a global navigation satellite system such as Galileo, its reference time has also to be strictly synchronized (modulo 1 second) to the international reference time, called Universal Time Coordinated (UTC). To this aim, E-GST is then steered versus the International Atomic Time, TAI (which differs from UTC by an integral number of seconds), by the use of continuous comparison measurements versus several local national time scales UTC (k). It's worth mentioning that, in the final Galileo architecture, the steering function to TAI will be accomplished by the use of an external Time Service Provider (TSP) **[7]**.

The real-time E-GST (referred as the *on-line* version) is realized following a basic scenario involving only the E-PTS clocks and a baseline algorithm based on the Galileo Phase B2 algorithm **[8]**, with additional features suitably devised for the GSTB V1 purposes. With the aim of meeting Galileo navigation and time dissemination requirements, the real-time E-GST generation algorithm is given by the three-step process below, also following the recommendations in **[9]**:

- at first, an ensemble time scale, called GSTR', is computed every day as a weighted average of the E-PTS cesium clocks;

- the ensemble time scale GSTR' is in turn compared to TAI every month, as soon as the BIPM Circular T data are available, and then corrected in frequency, with the aim of being in agreement with TAI in the long term. The resulting steered time scale, called GSTR, is then kept in agreement with TAI;

- the frequency drift of the E-PTS master clock (the IEN active H-maser) is daily estimated versus the steered time scale GSTR. The frequency correction is then applied to the H-maser through the AOG, providing the real-time physical realization of E-GST.

It follows that the resulting E-GST should provide:

- the good short-term stability of the E-PTS H-maser to support the navigation tasks of Galileo (mainly orbit determination and time synchronization), being that the AOG doesn't degrade the intrinsic short-term stability of the H-maser itself;

- the medium-term stability of the cesium clocks ensemble, allowing the estimation of the E-PTS clocks parameters (in particular, the frequency drift of the H-maser);

- the long-term stability (and the accuracy as well) of TAI and, hence, UTC to fulfill the time dissemination purposes.

IV. E-PTS PERFORMANCE ASSESSMENT

Table 1 reports the E-PTS performance targets as required **[4]** in the frame of GSTB V1, together with the goals expected for the final Galileo.

Table 1. E-PTS performance targets (from **[4]**).

	GSTB V1 Target	**Galileo Target**
Accuracy of E-GST versus TAI	< 1 μs	< 50 ns (95%)
Stability @ 1 day of E-GST versus TAI	$< 5.5 \cdot 10^{-14}$ (2σ)	$< 5.5 \cdot 10^{-14}$ (2σ)
Uncertainty of the prediction of E-GST versus TAI	33 ns (2σ)	28 ns (2σ)

As stated in Table 2, starting from 5 March 2004, the E-PTS has been in the final configuration. The hardware E-GST time scale is continuously generated in real time, according with the computation performed by the algorithm, and it is then fed to the sensor station, obtaining the GPS pseudo-ranges referenced to E-GST.

Table 2. E-PTS major milestones.

27 March 2003	Start of E-PTS V1.1 early version of E-PTS, based on UTC (IEN).
1 July 2003	Start of 6-month initialization period for the E-GST algorithm (till 31 December 2003). Only GSTR' exists.
4 July 2003	Start of E-PTS V1.2 early version of E-PTS, based on a free-running H-maser.
27 September 2003	Start of E-GST to TAI steering. GSTR also exists.
22 January 2004	Start of E-GST day-by-day computation (software version only).
5 March 2004	Start of physical real-time generation of E-GST (AOG on line).
23 March 2004	Start of pre-operational phase of the E-PTS. Sensor Station based on E-GST (for internal evaluation only).
1 April 2004	Switch-on of the E-PTS Sensor Station.
22 December 2004	Stop of E-PTS operation.

It's worth mentioning that the initial value (about –30 ns) is the time offset of the E-PTS free-running H-maser versus TAI at the time when the AOG was enabled. Such an offset has been maintained to avoid phase jumps on the E-GST time scale over the software-to-hardware transition, accepting then a non-zero but known initial bias between the two time scales.

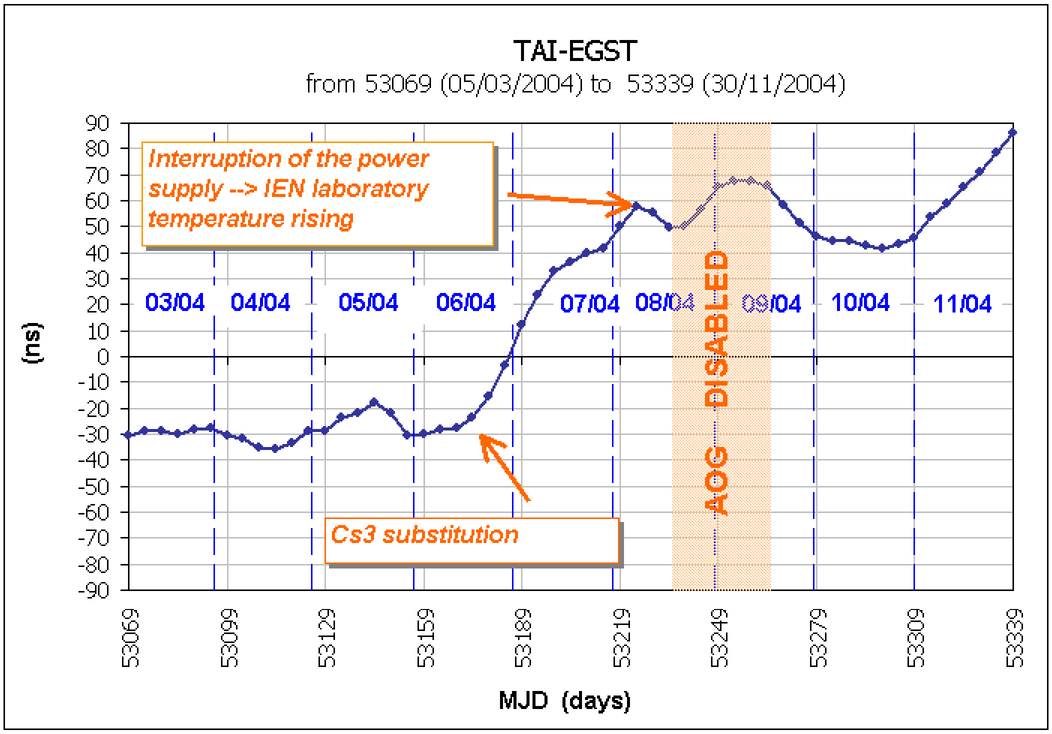

Figure 5. Time offset between E-GST and TAI from March 2004 to November 2004 (9 months). Maximum: 85.8 ns; minimum: -35.7 ns; mean: 17.5 ns. Major events occurred in the E-PTS are also marked.

Figure 5 shows that the initial offset of E-GST with respect to TAI was quite well maintained in the first 3-4 months of the E-PTS operation. However, because several events occurred in the E-PTS during the experiment (such as operational software troubles, Cs clock substitution and uncontrolled rising of the laboratory temperature), the E-GST versus TAI accuracy slightly degraded in the following months.

Despite these problems and the limited set of clocks in the E-PTS ensemble, a good accuracy performance has been achieved, quite promising for designing the final Galileo algorithm and its Precise Timing Facility (PTF). As reported in Figure 7, the absolute value of the E-GST to TAI offset was below 71 ns for 95% of the time (< 50 ns for 70% of time). Even if the GSTB V1 goal has been met, this performance would not fully satisfy the demanding specifications for the final Galileo (50 ns, as reported in Table 1).

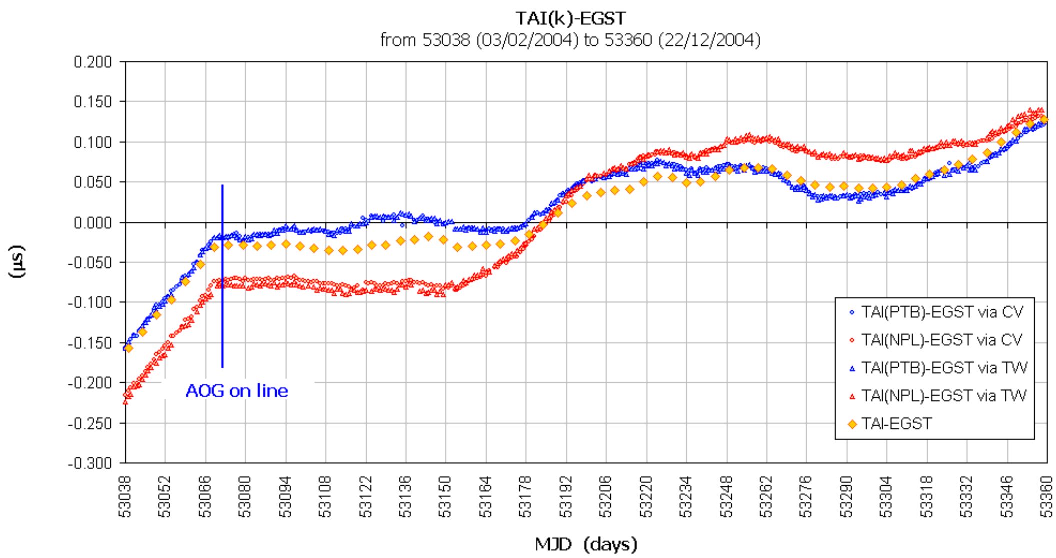

Figure 6. E-GST comparison versus TAI (yellow diamonds), PTB (blue), and NPL (red) time scales, both by GPS CV (circles) and TWSTFT (triangles), up to 21 December 2004. Steering of E-GST started on 5 March 2004 (MJD 53069).

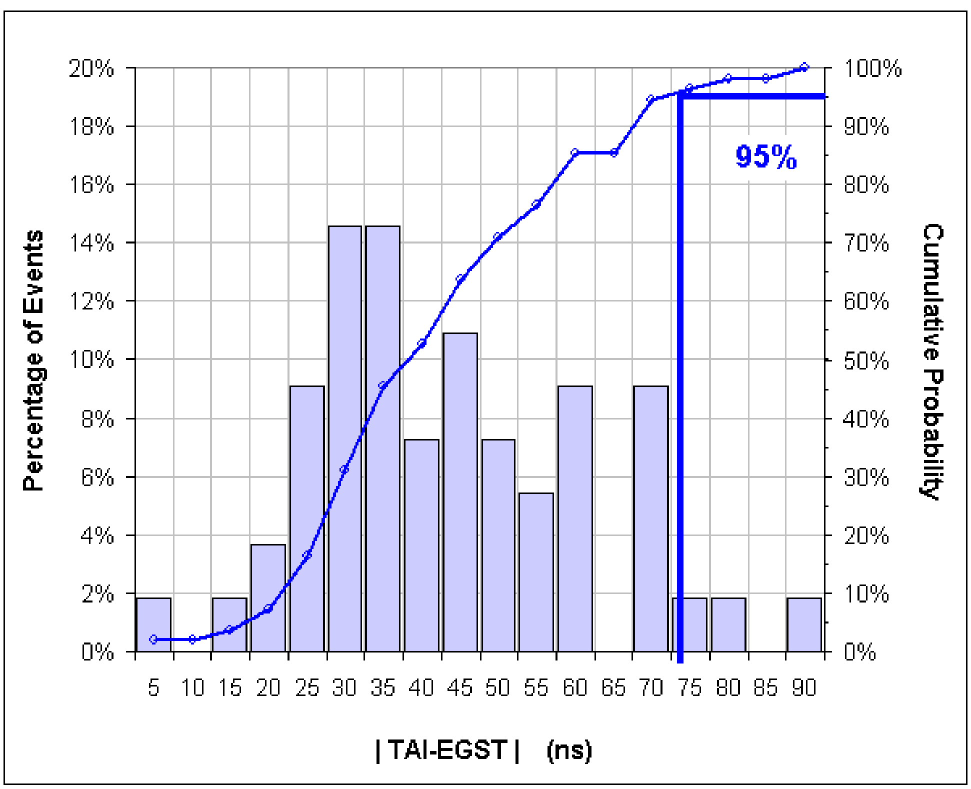

Figure 7. Time distribution of the offset between E-GST and TAI (histogram) and associated cumulative probability.

IV.B. E-GST STABILITY (SHORT-TERM AND LONG-TERM)

The long-term stability of E-GST versus TAI has been estimated through the computation of the Allan deviation (ADEV) **[10]** of the time difference between E-GST and TAI. Table 3 reports the ADEV values at different observation times τ, up to 50 days, over the 9-month period of interest.

Table 3. E-GST stability versus TAI in term of Allan deviation (ADEV). ★ = extrapolated value.

τ, days	**ADEV (1σ)**
1	$1.45 \cdot 10^{-14}$ (★)
5	$6.5 \cdot 10^{-15}$
10	$8.0 \cdot 10^{-15}$
20	$8.6 \cdot 10^{-15}$
50	$7.8 \cdot 10^{-15}$

Since the BIPM data are spaced by 5 days, the stability at τ = 1 day (as requested by GSTB V1 specification **[4]**) has been extrapolated starting from the value obtained for 5 days. Assuming that E-GST is mostly affected by a white frequency noise, the extrapolation expression is:

$$\sigma_y(1\,day) = \sigma_y(5\,days) \cdot \sqrt{\frac{(5\,days)}{(1\,day)}} = \sigma_y(5\,days) \cdot \sqrt{5}$$

Even if this expression seems to be pejorative (especially considering the findings below concerning the E-GST short-term stability analysis), the resulting stability of $2.90 \cdot 10^{-14}$ (2σ) is fully compliant with the dissemination requirements reported in Table 1.

Moreover, for observation intervals up to one day, the E-GST stability is expected to be the H-maser stability, apart from possible corruption due to the AOG and the signal distribution chain as well as the daily steering procedure.

To evaluate such an impact, the time offset between E-GST and the free-running H-maser has been measured by the MCPC of the E-PTS architecture (1 Hz acquisition rate). Since E-GST is just a frequency steered replica of the same H-maser, the difference provided by MCPC drops out the contribution of the H-maser itself. Only the augmentation of the AOG plus the distribution chain plus the steering procedure is then taken into account, giving a figure of the noise added by this equipment.

Stability results in term of ADEV are given in Figure 8 below (dotted red line) for an observation interval from 1 second up to about 1 day. The nominal stability of the E-PTS H-maser (dashed blue line) and the intrinsic limit of the measurement system (solid blue line) are also reported on the same plot for comparison purposes.

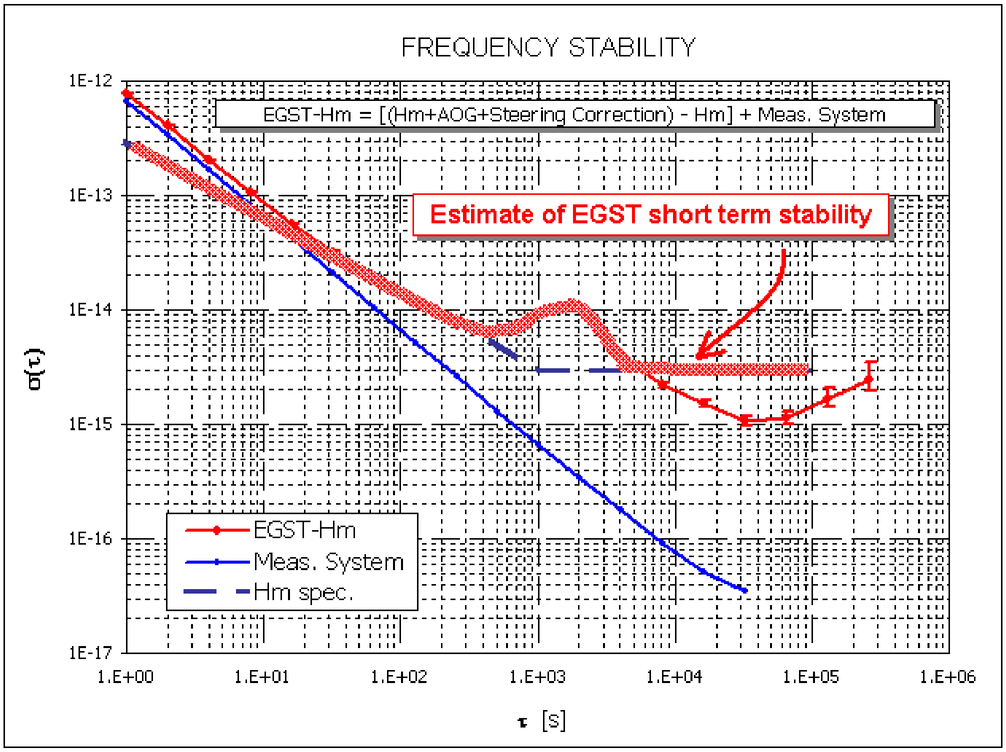

Figure 8. E-GST short-term frequency stability versus the free-running H-maser (dotted red line), together with the stability of the E-PTS H-maser as provided by manufacturer specifications (dashed blue line) and the intrinsic limit of the measurement system (solid blue line).

Looking at the plot, the measurement system acts as a lower bound for the E-GST behavior up to some tens of seconds. The E-GST generation and distribution chain do not degrade the H-maser frequency stability, except for a "bump" around an observation time of 2000 seconds, which may be due to a thermal effect. In addition, the E-GST short-term stability could be estimated as the thick red line plotted in Figure 8. It's worth mentioning that this stability has been clipped with a $3.0 \cdot 10^{-15}$ floor, according to the manufacturer specification of the H-maser **[11]**.

To summarize, the short-term stability estimated above, along with the long-term stability measured versus TAI (Table 3), gives then a complete characterization of the actual E-GST stability (from 1 second to 50 days). As mentioned before, it may be inferred that the E-GST stability over 1 day required by the Galileo specifications ($5.5 \cdot 10^{-14}$) and estimated by an extrapolation ($2.9 \cdot 10^{-14}$) was possibly an over-estimation, because the value from real experimentation seems even better ($< 3.0 \cdot 10^{-15}$).

Besides, the EGST short-term stability as measured inside the E-PTS is still not the last evaluation. Actually, E-GST is visible from outside the E-PTS through the GPS measurement (and the subsequent processing) provided by the dual-frequency GPS receiver acting as the E-PTS sensor station in the frame of the OD&TS experimentation activities.

Aiming to get an estimate of E-GST as seen through external measurement systems, the E-PTS sensor station data have been processed using a Precise Point Positioning (PPP) technique **[12,13]**, referring E-GST to the International GPS Service Time (IGST) scale **[14]**. In addition, the time offset between E-

GST and the UTC (USNO), as estimated by the OD&TS process, has been taken into account **[15]**. Stability results in term of ADEV are given in Figure 9, starting from a 300-second (5-minute) observation interval.

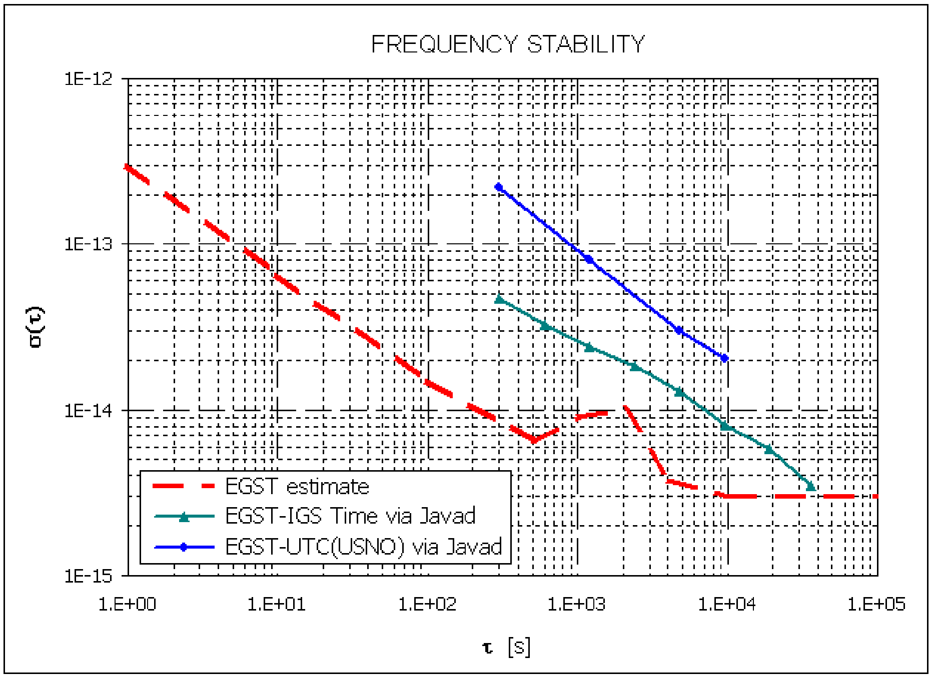

Figure 9. E-GST frequency stability as estimated versus the IGST time scale by a Precise Point Positioning (PPP) technique (green line) and versus UTC (USNO) by OD&TS processing (blue line). The E-GST stability as measured inside the E-PTS is also reported (dashed red line) as a reference.

As expected, the plot shows that the E-GST stability is degraded by the external measurement systems (receiver equipment and data processing algorithms). In addition, also the intrinsic noise of the external time scales used as reference (namely IGST and UTC (USNO)) affects the overall E-GST stability.

IV.C. Uncertainty of the Prediction of E-GST versus TAI

As mentioned before, the E-GST to TAI time offset is known from BIPM data only 1.5 months *a posteriori*. When BIPM data are available, a prediction of the E-GST to TAI offset is evaluated for the subsequent 1.5 months (45 days). When fresh data from BIPM will be available, the difference between predicted versus real measures is evaluated. This difference is the prediction error. As reported in Table 1, the GSTB V1 requirements ask to have a prediction error within 33 ns (95%).

For the 9 months of E-PTS operation, the prediction error as a function of the prediction length has been evaluated, and the results are reported in Figure 10 below.

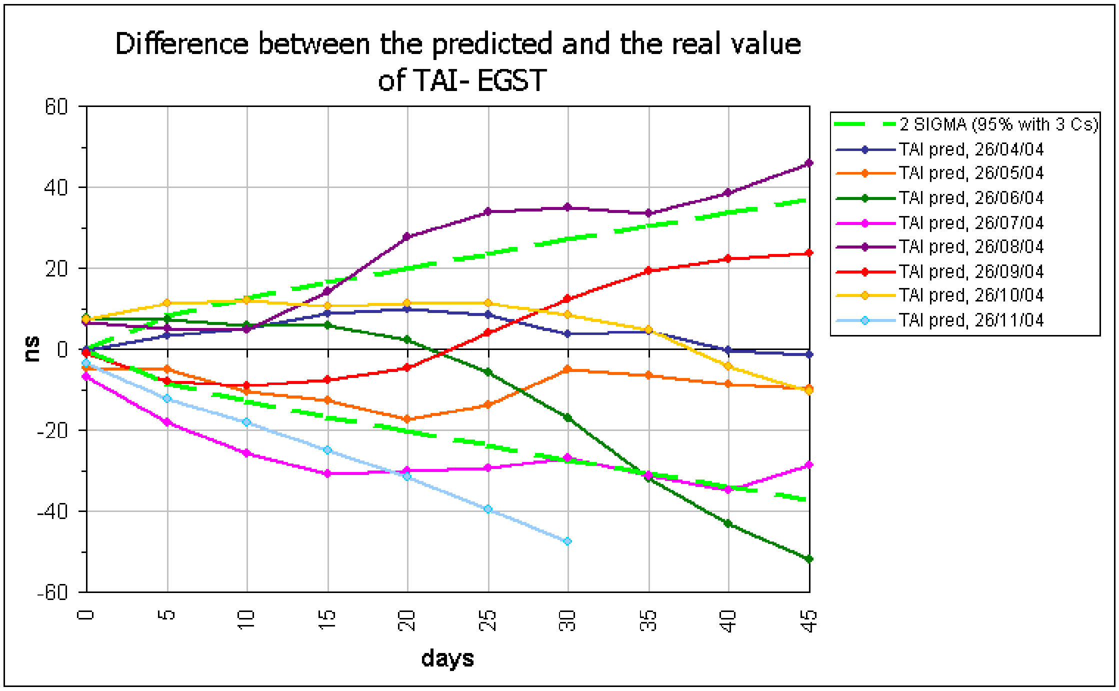

Figure 10. Prediction error on the E-GST versus TAI time offset, evaluated for the 9 months of E-PTS operation. The 95% boundary provided by a theoretical model **[15]** is also reported.

As expected, the prediction for a short period is more accurate than the prediction over a long period. In particular, it can be seen that at 45 days the prediction error covers a region of about ±40 ns, which is outside the specification. Besides, the worst prediction errors are for the months of July and August, where several troubles in the E-PTS operation were experienced.

In addition to these experimental results, the prediction error has been also estimated by means of a theoretical model **[15]**. As mentioned before, in GSTB V1 the E-GST steering versus TAI is obtained through different intermediate steps that firstly steer the Cs clocks ensemble on TAI, then steer E-GST versus the steered Cs ensemble. The evaluation of the uncertainty of the E-GST to TAI offset becomes therefore quite complicated, and an approximate evaluation was performed basing on certain assumptions.

In detail, the TAI prediction is obtained as a linear extrapolation of the past month of BIPM data and it is assumed that the uncertainty on the prediction of E-GST versus TAI is mostly driven by the following reasons:

- the medium-long-term stability of E-GST is completely driven by the cesium ensemble stability (i.e., the H-maser steering algorithm is working very well following the cesium behavior for observation times larger than 1 day);
- the Cs clocks are mostly affected by a white frequency noise (WFN) of about $3 \cdot 10^{-14}$ at 1 day and they have a frequency offset that is estimated versus TAI based on the previous month of BIPM data;
- the steering versus TAI does not corrupt the Cs ensemble stability.

Under these hypotheses, the uncertainty prediction for an interval t is estimated as **[15]**:

$$u^2(t) = u_{linear\_slope} \cdot t^2 + \frac{\sigma^2_{WFN}}{N} \cdot t = \frac{1}{T} \cdot \left(\frac{\sigma^2_{WFN}}{N} + \frac{2}{T}\sigma^2_{meassystem}\right) \cdot t^2 + \frac{\sigma^2_{WFN}}{N} \cdot t$$

where:

- N is the number of Cs clocks;
- T is the previous observation time, that is, 1 month;
- $\sigma^2_{WFN}(\tau) = \sigma^2_y(\tau) \cdot \tau$ is the Cs clock noise due to the white frequency noise. For τ = 86400 s = 1 day, the estimated Allan deviation of a cesium clock is then $3 \cdot 10^{-14}$;
- u_{linear_slope} is the uncertainty of the estimate of the linear slope from the past month of data;
- $\sigma_{meas.system}$ = 1.4 ns for the calibrated TW link and $\sigma_{meas.system}$ = 5.1 ns for the calibrated GPS link.

It follows that, under these assumptions, the uncertainty depends both on the number of Cs clocks and on the uncertainty of the measures linking E-GST to TAI (through TWSTFT or GPS CV). In particular, the uncertainty of the TWSTFT link (used to connect UTC (IEN) to UTC) was estimated to be 1.4 ns (1σ) **[17,18]**; therefore, the prediction uncertainty for a period of 45 days comes out to be about 37 ns (95%, N = 3). In the case of a GPS CV technique being used, the prediction uncertainty would become about 41 ns (95%, N = 3), because of the higher uncertainty (5.1 ns, 1σ).

Figure 11 plots the prediction uncertainty for a different number of Cs clocks, as estimated applying the theoretical model above and assuming to use a TWSTFT link. It can be seen that, with three Cs clocks, the uncertainty is about 37 ns (95%), while a value of about 28 ns (95%), as required in final Galileo, would be ensured by operating at least six Cs clocks.

Besides, comparing the 95% boundary obtained by this approximate theoretical model with the experimental data (as reported in Figure 10), it follows that a good agreement is then achieved.

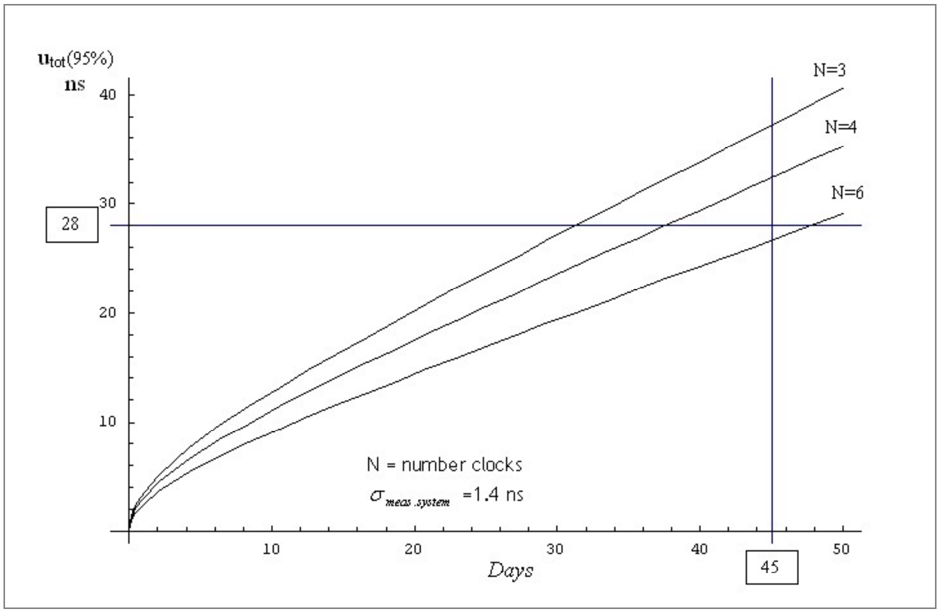

Figure 11. Uncertainty of the E-GST to TAI offset prediction for a different number of Cs clocks, as estimated using the theoretical model described in **[15]**.

V. CONCLUSIONS

According with the experimentation conducted up to now, the results can be summarized in the following:

Table 4. E-PTS performance results with respect to targets (see Table 1).

	GSTB V1 Target	**GSTB V1 Results**	**Galileo Target**
Accuracy of E-GST versus TAI	< 1 μs	71 ns (95%)	< 50 ns (95%)
Stability @ 1 day of E-GST versus TAI	$< 5.5 \cdot 10^{-14}$ (2σ)	$2.9 \cdot 10^{-14}$ (2σ)	$< 5.5 \cdot 10^{-14}$ (2σ)
Uncertainty of the prediction of E-GST versus TAI	33 ns (2σ)	40 ns (2σ)	28 ns (2σ)

It follows that the GSTB V1 targets have been reached, apart the uncertainty on the prediction of E-GST with respect to TAI. Moreover, the comparison respect the Galileo targets gives us confidence that with a dedicated laboratory having, e.g., an higher number of Cs clocks and redundant systems, the targets could be reached even if they are more demanding.

Many lessons have been learned by the E-PTS team from this long, day-by-day operation and experimentation. Generally speaking, the generation of a reliable, stable, and accurate time scale with completely automated procedures asks for large efforts to ensure robustness both on algorithms and on hardware/software.

To summarize, following valuable recommendations on hardware, software, and algorithm can be then issued, in view of the future work for the Galileo ground segment, about the PTFs' design and implementation:

- Apart from redundancy needs, additional Cs clocks in each PTF ensemble are highly advised, mainly aiming to maintain the demanding agreement of Galileo system time versus TAI (50 ns, 95%). As a consequence, the future PTF architecture (in term of both hardware and software) shall be designed in order to be able to process an higher number of clocks (12, for instance) and allow a safe management of the introduction and removal of a clock (e.g., for purposes of maintenance).

- One or even two H-masers are not able to allow the monitoring of its behavior (i.e., performance analysis and anomalies detection). The procurement of three H-masers for each PTF should be then taken into account during the architecture design.

- Since most of H-masers allow a limited range of operating temperature only (e.g., 4°C around 22°C for the equipment used in GSTB V1), the clocks room inside the PTF should be designed to avoid large temperature oscillations even in the case of malfunctions of the thermal control system. This will prevent severe failures from affecting the H-masers and the Cs clocks as well. Moreover, all the hardware equipment involved in the clocks measurement system and in the GST physical realization (namely the AOG and the distribution system) should be placed in the same temperature-controlled room.

- Even if the E-GST baseline algorithm (as defined in Phase B2) meets most of the requirements and is also accepted as the Galileo system time algorithm, some improvements should be addressed by next re-engineering stage. In particular, it is suggested to insert an additional check on clock anomaly (with respect to the expected behavior) at the very beginning of the data preprocessing, to avoid inserting "bad" measures in the GST computation.

- The check on the frequency steering correction to be imposed on the H-maser through the AOG was too weak and did not protect versus large anomalies (as experienced in the last months of the experimentation). It follows that a more robust check should be addressed, maybe taking into account a configurable threshold with respect to the last imposed correction on the H-maser.

- It is possible that, for some intentional or accidental reasons, a clock may suffer a time or frequency jumps. However, such jumps have to be compensated before using those clocks in the GST algorithm, not to inject false instabilities. It follows that the time and frequency jump compensation features should be included and fully managed inside the GST processing algorithm.

- Because of the very strong correlation between a single clock and an average time scale based on a small ensemble of clocks, a single clock may very much influence the average time scale and degrade its stability in the case of clock malfunctioning. To reduce the risk of the so-called "clock ensemble correlation" **[19]**, a corrective factor should be then applied.

- The current baseline algorithm is designed to maintain E-GST in agreement with TAI, but no recovery actions are envisaged to cope with possible degraded situations. In case GST is too far away from TAI, a manual recovery action should be available, providing a configurable time or frequency step to be triggered by the PTF operator.

In addition, it must be noticed that some PTF key activities were not planned in the GSTB V1 experimentation, which was mainly devoted to testing critical algorithms in a real but experimental setup. Nevertheless, hardware matters (such as H-masers, the automatic switching system, architecture redundancy and its impact on the performance, and second PTF switching) should be fully investigated in the early steps of the Galileo program, in order to have a reliable design.

Finally, it's worth mentioning that, in the final Galileo architecture, the steering function to TAI will be accomplished by the use of an external Time Service Provider (TSP) **[7]**.

VI. ACKNOWLEDGMENTS

GSTB V1 is an ESA program and the prime contractor is Galileo Industries (GaIn); in turn, GaIn is a joint company consisting of Alenia Spazio, Alcatel Industries, Astrium GmbH, Astrium Ltd., and GSS (Galileo Sistemas y Servicios).

The E-PTS, one of the GSTB V1 elements, is under the responsibility of Alenia Spazio. The companies and institutions involved in the E-PTS development are Alenia Spazio and the Istituto Elettrotecnico Nazionale "Galileo Ferraris" (IEN, Italy); Space Software Italia (SSI) developed the software; and the National Physical Laboratory (NPL, UK) and the Physikalisch Technische Bundesanstalt (PTB, Germany) provided external contributions.

REFERENCES

[1] M. Falcone, R. Lucas Rodriguez, F. Emma, and J. Hahn, 2001, *"The GALILEO System Test Bed (GSTB),"* in Proceedings of the GNSS 2001 Conference, 8-11 May 2001, Seville, Spain.

[2] E. Breeuwer, R. Franco, M. Falcone, J. C. De Mateo, P. Erhard, and N. M. Hollreiser, 2002, *"Simulation and Experimentation in the GALILEO System Design and Verification,"* in Proceedings of the GNSS 2002 Conference, 27-30 May 2002, Copenhagen, Denmark.

[3] M. Falcone, F. Amarillo-Fernandez, J. Hahn, and H. Favin-Leveque, 2002, *"The GALILEO System Test Bed for Early Prototyping and Experimentation of GALILEO Algorithms,"* in Proceedings of the ION GPS 2002 Meeting, 24-27 September 2002, Portland, Oregon, USA (Institute of Navigation, Alexandria, Virginia).

[4] GSTB-V1 Statement of Work (ESA-APPNG-SOW/00114), 5 October 2001.

[5] E. Detoma, S. Facioni, M. Gotta, G. Graglia, F. Cordara, L. Lorini, V. Pettiti, P. Tavella, and J. Hahn, 2003, *"The Experimental Precise Timing Station (E-PTS) for the Galileo System Test Bed (Phase V1): Architectural Design and Experimental Goals,"* in Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 3-5 December 2002, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 127-138.

[6] G. Graglia, E. Detoma, F. Cordara, R. Costa, L. Lorini, D. Orgiazzi, V. Pettiti, P. Tavella, and J. Hahn, 2002, *"The Experimental Precise Timing Station and the Galileo System Time generation in the Galileo System Test Bed Phase V1,"* in Proceedings of the GNSS 2003 Conference, 22-25 April 2003, Graz, Austria.

[7] Galileo Joint Undertaking, *"GALILEO Research and Development Activities, Activity E Galileo Mission Implementation,"* Statement Of Work (GJU/03/103/issue3/OM/ms), pp. 23-25.

[8] F. Cordara, R. Costa, L. Lorini, D. Orgiazzi, V. Pettiti, P. Tavella, G. Graglia, E. Detoma, and J. Hahn, 2003, *"The generation of the Experimental Galileo System Time in the Galileo System Test bed V1,"* in Proceedings of the 2003 IEEE International Frequency Control Symposium (FCS) & PDA Exhibition Jointly with the 17th European Frequency and Time Forum (EFTF), 5-8 May 2003, Tampa, Florida, USA (IEEE 03CH37409C), pp. 306-311.

[9] J. Laverty, P. Tavella, *et al.*, 2001, *"Report and recommendations of the GalileoSat Working Group on the Galileo Time Interface,"* ESA STR-243, ISSN 0379-4067.

[10] D. W. Allan, 1987, *"Time and Frequency (Time-Domain) Characterization, Estimation, and Prediction of Precision Clocks and Oscillators,"* in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, **UFFC-34,** 647-654.

[11] Symmetricom, Inc., Specifications of MHM 2010 Active Hydrogen Maser (*http://www.symmttm.com/products_pfr_ahm_overview.asp*).

[12] J. Kouba and P. Héroux, 2001, *"Precise Point Positioning Using IGS Orbits and Clocks Products,"* in **GPS Solutions, Vol. 5**, No. 2.

[13] P. Tavella, and D. Orgiazzi, 2004, *"'Timing-oriented' processing of geodetic GPS data using a Precise Point Positioning (PPP) approach,"* in Proceedings of the 6th Meeting of Representatives of Laboratories Contributing to TAI, 31 March 2004, BIPM, France (*http://www1.bipm.org/en/committees/cc/cctf/tai_symposium.html*).

[14] J. Ray and K. Senior, 2003, *"IGS/BIPM pilot project: GPS carrier phase for time/frequency transfer and timescale formation,"* **Metrologia, 40,** S270-S288.

[15] *"GSTB-V1 – Clock Reference Station Analysis"* (GT-GAIN-TN-1122, issue 1.0), July 2004.

[16] G. Panfilo and P. Tavella, 2003, *"Preliminary test on the steering algorithm for keeping a time scale synchronized to UTC,"* in Proceedings of the 2003 IEEE International Frequency Control Symposium (FCS) & PDA Exhibition Jointly with the 17th European Frequency and Time Forum (EFTF), 5-8 May 2003, Tampa, USA (IEEE 03CH37409C), pp. 301-305.

[17] F. Cordara, L. Lorini, V. Pettiti, P. Tavella, D. Piester, J. Becker, T. Polewka, G. De Jong, O. Koudelka, H. Ressler, B. Blanzano, and C. Karel, 2004, *"Calibration of the IEN-PTB TWSTFT link with a portable reference station,"* in Proceedings of the 18th European Frequency and Time Forum (EFTF), 5-7 April 2004, Guildford, UK.

[18] W. Lewandowski, F. Cordara, L. Lorini, V. Pettiti, A. Bauch, D. Piester, and O. Koudelka, 2004, *"A simultaneous calibration of the IEN/PTB time link by GPS CV and TWSTFT portable equipment,"* in Proceedings of the 18th European Frequency and Time Forum (EFTF), 5-7 April 2004, Guildford, UK.

[19] P. Tavella, J. Azoubib, and C. Thomas, 1991, *"Study of the clock-ensemble correlation in ALGOS using real data,"* in Proceedings of the 5th European Frequency and Time Forum (EFTF), 12-14 March 1991, Besançon, France, pp. 435-441.