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THE GENERATION OF THE EXPERIMENTAL GALILEO SYSTEM TIME IN THE GALILEO SYSTEM TEST BED V1

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Abstract - **This paper provides an overview of the infrastructure required to generate a real time Experimental Galileo System Time and a description of the concerned algorithms and experiments that will be examined and carried out in the framework of GSTB V1.**
***Keywords* - Satellite Navigation, Time scale algorithms**

I. INTRODUCTION

The Galileo System Test Bed (GSTB) V1 is the first experimental phase in the Galileo project supported by the European Space Agency (ESA). In the framework of the GSTB V1, the realization of a reference time scale, the Experimental Galileo System Time (E-GST), plays an important role since it provides the time reference inside the GSTB V1. In addition, since E-GST is steered to the International Atomic Time (TAI), also the possibility to disseminate accurate time is tested. Different clocks ensembles, measurement systems, remote synchronization techniques, and algorithms are foreseen to test the stability and accuracy performances of the resulting time scale.

The realization of such an experimental time scale requires a time and frequency laboratory with the state of the art instrumentation and human expertise. The infrastructure that allows the realization of E-GST is the Experimental Precise Timing Station (E-PTS), that is being implemented at the Istituto Elettrotecnico Nazionale (IEN), Turin, Italy using the facilities and personnel of the Time & Frequency laboratory, under the responsibility of Alenia Spazio.

The E-PTS main task is the realization of a real time E-GST. Moreover the E-PTS will allow the development of interesting experiments, aimed to verify the results of the system synchronization achieved by the Orbit Determination and Time Synchronization (OD&TS) algorithms, the clock stability analysis, the steering of the E-GST to TAI, and the peculiarities of the different time scale algorithms.

The work will be carried on with the direct participation of other two major European national metrological institutes , the PTB (Germany) and the NPL (UK).

II. THE GALILEO SYSTEM TEST BED (GSTB)

A. GSTB Purpose

During the GalileoSat Definition Phase, an early experimental stage, the GSTB, has been defined as an integral part of the Galileo Design Development and Validation Phase in order to mitigate program risks [1,2,3].

The GSTB has a twofold purpose:

- conduct early experimentation in order to provide feedback to the definition of critical system algorithms (OD&TS, integrity, etc.) in the Galileo Design and Development Phase. In this frame a collaboration with several scientific communities is established.
- set up an experimental infrastructure that will represent a provisional version of the Galileo System infrastructure.

The GSTB is subdivided in two main development steps, Version 1 (V1) and Version 2 (V2), with the following characteristics:

- GSTB V1**:**

The main purpose of the GSTB V1 is to verify the Galileo concepts for the algorithms. For this purpose the GPS constellation is used as space segment while the ground one integrates present infrastructure (provided by ESA, CNES and others) with new elements designed for the GSTB.

During GSTB V1 development, collaboration with the International GPS Service (IGS) community and UTC time community is established. Furthermore, interfaces with the EGNOS System Test Bed (ESTB) and other GPS related national infrastructures are foreseen.

- GSTB V2:

It will consist of an experimental Galileo satellite to be launched at the beginning of 2005 and an extension of GSTB V1 including Galileo receivers and real-time processing algorithms.

B. The GSTB V1

The GSTB V1 experimentation phase will last for about 12 months, starting at the end of 2003. The fulfillment of the experimentation objectives requires the set-up of the core infrastructure, which is in progress during this year. The European Space Agency has specified a list of experiments (the so called Test Cases, Fig. 1) to be performed in GSTB V1:

- Orbit Determination and Time Synchronization (OD&TS) algorithms performance assessment and comparison of alternative methods.
- E-GST generation algorithm.
- E-GST steering to the TAI.
- User Equivalent Range Error (UERE) budget characterization.
- Signal In Space Accuracy (SISA) computation algorithm and Integrity Flag (IF) computation performance assessment.

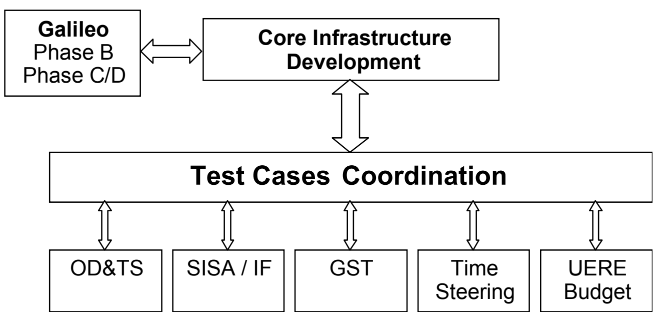

Figure 1 – Test Case Coordination [1]

The GSTB V1 core infrastructure implements the following functions (Fig. 2):

- GPS raw measurements and navigation Data Acquisition in the sensor stations for OD&TS and SISA/IF experimentation.
- Data Communication from the sensor stations to the GSTB V1 Processing Center (GPC).
- Data Formatting, Archiving and Distribution in the GPC, with the objective to achieve a consistent process for OD&TS, GST and Integrity.
- Data Processing in the GPC, generating most of the core products.
- Precision timing including in particular the generation and maintenance of E-GST. This function includes the E-GST steering to TAI.

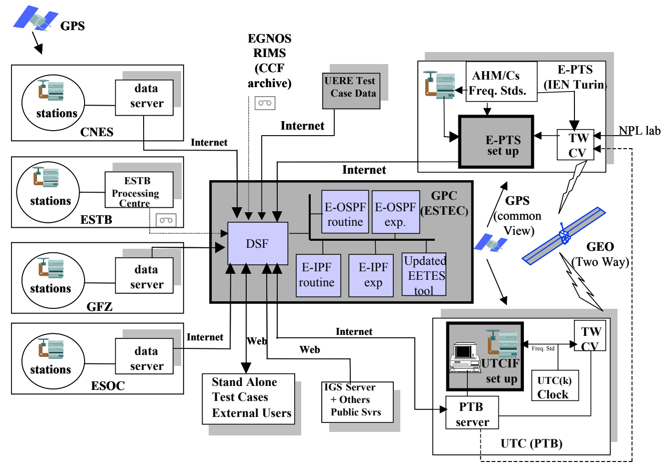

Figure 2 - The GSTB V1 core infrastructure [1]

C. Role of E-GST inside the GSTB V1

As a part of the GSTB V1, the E-GST is intended both as a prototype of the future Galileo System Time (GST) and as the reference time for the whole GSTB V1 experiment. These two scopes define both the infrastructure required to the E-GST generation and the experimental scenarios in which the E-GST algorithms will be tested .
As a prototype of the final GST, the E-GST needs to have optimal characteristics for navigation and time dissemination purposes:

- navigation accuracy requires a state of the art frequency stability at short and medium term
- time dissemination accuracy requires synchronization to TAI and the information on leap seconds to disseminate UTC to users.

The infrastructure dedicated to the E-GST generation and steering is the Experimental Precise Timing Station (E-PTS)
The use of E-GST as a reference time of GSTB V1 requires that E-GST is realized in real time and with an hardware representation. In fact a GPS geodetic receiver, which is part of the GSTB sensor stations network, has to be referenced to a signal representing the E-GST. In this way the E-GST is injected in the OD&TS algorithms.
In addition, the E-GST algorithm has to be robust and flexible to fulfill the GST aims and allow further modifications.
To accomplish to these different scopes the reference time scale will be realized in several versions:

- *a real time version,* giving the time reference to the OD&TS process via the E-PTS sensor station,
- *off line versions,* that are mainly intended to test the various time scale and steering algorithms.

III THE EXPERIMENTAL PRECISE TIMING STATION (E-PTS)

The E-PTS is implemented inside the Istituto Elettrotecnico Nazionale "G. Ferraris" (IEN), Turin, Italy. The E-PTS partially re-uses the infrastructure of the IEN Time and Frequency laboratory, in particular the IEN clock ensemble, limiting the new hardware installation at this experimental stage.

The E-PTS architecture is designed in such a way to give a complete support to the algorithm experimentation phase; at the same time it allows a provisional hardware implementation of the final Precise Time Facility (PTF) for the Galileo System, giving the possibility to recognize problems and criticalities of such an infrastructure. Figure 3 reports an overview of the E-PTS architecture which is described in details in the following paragraphs.

A. Clock ensemble

The E-PTS clock ensemble is composed by 1 Hydrogen maser and 3 Cesium (Cs) clocks from IEN with suitable characteristics for the generation of the E-GST time scale.

B. Local measurement and acquisition system

The role of the local measurement system is to measure the clock differences. It consists of two parallel systems:

Primary System. It is the measurement system which provides clock differences data for the computation of E-GST and for the monitoring of clock behaviour. It is based on a 1 PPS signal multiplexer followed by a high-resolution Time Interval Counter (TIC). Since the measurements are performed on the 1 PPS signals, which are generated by the local clocks, this system allows to compare the clocks in sequence with a measurement resolution of 25 ps.

Secondary System. It is based on a Dual Mixer Multi-channel Phase Comparator, that allows to compare all the clocks simultaneously**,** with a resolution of 100 ps and with a noise floor of around $5 \cdot 10^{-13}$ at 1 second. The simultaneity of the measurements and the continuity of the data acquisition at a relatively high data rate make it an ideal tool for real time monitoring of the clock ensemble, frequency stability computations and anomalies detection.

C. Control and acquisition system

The E-GST generation and clock monitoring functions will be performed by a local computer, an industrial PC, which acquires measurements both from the multiplexed TIC and from the Multi-channel Phase Comparator.

The operational software, developed by Alenia Spazio with the scientific support of IEN, will be in charge of the following main functions:

- automated schedule and management of the E-PTS operations
- instrumentation management
- data acquisition
- generation, steering and physical realization of the E-GST time scale.

The E-PTS raw measurements and status are made available to the GPC via an Internet connection supported by a local server.

D. E-GST generation and distribution hardware

A high resolution phase microstepper (AOG: Auxiliary Output Generator) accepts the maser frequency as an input and provides phase and frequency shifted outputs (1 PPS and 5 MHz) signals that represent the E-GST. Then the 5 MHz signal is frequency doubled and distributed, together with 1 PPS one, inside the E-PTS. An IRIG-B code generator will provide a coded-representation of E-GST to the PC, allowing the time tagging of the data in the E-GST time scale

E. Synchronization links

A link with external UTC laboratories, which is needed for the TAI steering of E-GST, is realized with the GPS Common View (CV) and the Two-Way Satellite Time and Frequency Transfer (TWSTFT) comparison systems. Both systems are driven by the UTC(IEN) time scale and their measures are related to E-GST through a supplementary internal measurement.

The calibration of such time transfer tools is fundamental for an accurate remote time comparison. In fact the instrumentation involved in the GPS CV and TWSTFT systems (receivers, transceivers, modems) introduce some unknown delays that must be calibrated. Calibration of the GPS CV equipment is performed using the periodical circulations between the UTC labs of an absolutely calibrated receiver from BIPM. For the TWSTFT a calibration trip between IEN and PTB of a transportable station is organized as a GSTB V1 activity with the collaboration of the Technical University of Graz (Austria).

F. E-PTS sensor station

The E-PTS provides a complete sensor station, based on GPS geodetic receiver, which is part of the GSTB V1 sensor stations network. The GPS geodetic receiver is directly connected with the physical representation of E-GST (via the 10 MHz and 1 PPS signals) and this allows the OD&TS function to be referenced to E-GST itself.

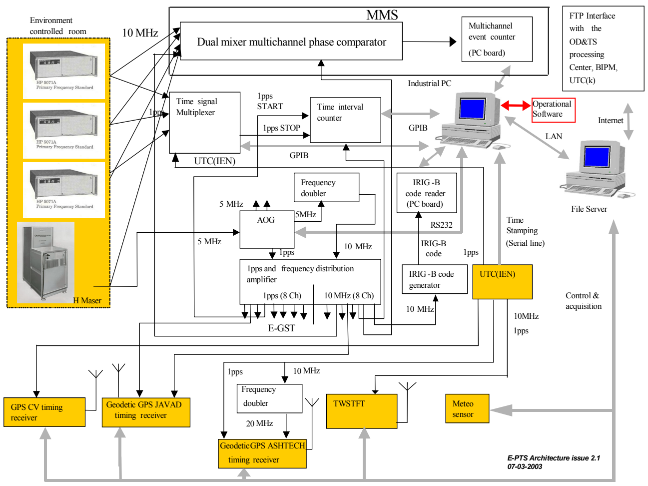

Figure 3 - E-PTS architecture

G. E-PTS schedule

The E-PTS will be available with its definitive configuration at November 2003, but with the aim of support early operations in GSTB V1, provisional versions of E-PTS are provided earlier. Since 2003 March 27, a first version of the E-PTS, named E-PTS V1, is operating, providing raw data from a geodetic GPS receiver referred to the UTC(IEN) time scale (a UTC steered output of a commercial Cs beam standard).
Starting from June 2003, a second provisional version will provide raw data (1 Hz sampling) from an additional geodetic GPS receiver referred to a free running active H maser. Based on different and independent receivers, these two provisional versions are able to run in parallel during the early operations period.

IV. THE TEST CASES

Experimental work inside the GSTB V1 is organized in two Test Cases:

- E-GST generation,
- Steering versus TAI.

Each Test Case experimental work relies on several scenarios involving different configurations and algorithms. The following description distinguishes the scenarios (both from E-GST generation and TAI steering Test Cases) involved in the realization of the real time of E-GST from those that are be tested off-line.

A. Test Case on E-GST generation: real time version

The real time E-GST is realized following a basic scenario involving only the E-PTS clocks and a selected algorithm (the algorithm proposed in the Galileo Phase B2 study [6]). All other scenarios, involving different clock ensembles and algorithms, will be tested off line.
As recommended in [5] the E-GST generation is three step process, according with the scheme reported in Fig. 4:

1. the ensemble time scale obtained from the E-PTS Cs clocks is evaluated according to a stability algorithm [6]. This ensemble time scale, called E-GSTR0, is used as a reference to estimate and correct the frequency drift of the H maser.
2. the ensemble time E-GSTR0 is compared versus a TAI prediction, and then is corrected in frequency to be synchronized with TAI. This activity is part of the TAI steering test case.
3. As a result of the algorithm of the points 1) and 2), a frequency steering is imposed in real time to the H maser through the AOG with the double aim of matching the Cs ensemble time E-GSTR0 in the medium term and the TAI prediction in the long term. The output of the AOG is the physical representation of E-GST.

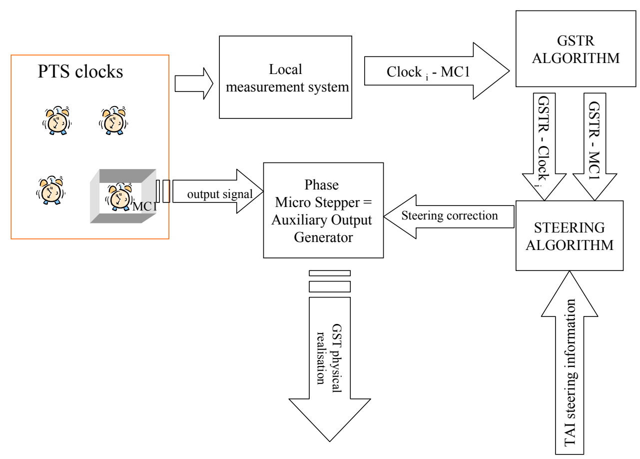

Figure 4 - Scheme of the generation of E-GST

B. Test Case on E-GST generation: off line versions

As a second step, the baseline algorithm is tested on different clock ensembles, using also additional IEN, PTB and NPL clocks (Fig. 5). This test has the aim of evaluating the benefit/drawback of using more clocks, both Cs standards and H masers, made available from external laboratories that could eventually contribute to the operative GST.

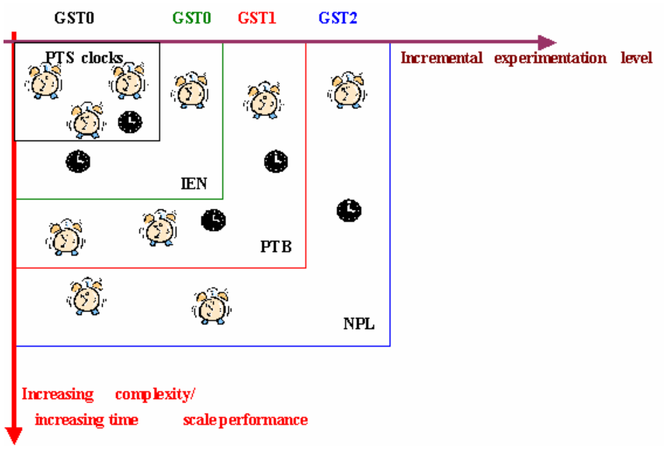

Figure 5 - Addition of external clocks

In addition, to assess the characteristics of the E-GST generation algorithm, two different alternative algorithms will be implemented and tested on the same clock data:

1. the algorithm for the generation of the AT1 time scale of the US National Institute for Standards and Technology (NIST);
2. the GPS-like Composite Clock algorithm.

The different peculiarities of these three algorithms make the test quite interesting because most of the time scale algorithm approaches are here tested. In a general way, it can be said that all the three algorithms are based on a weighted average of clock readings, where each clock reading is firstly corrected by its predicted bias. Therefore, we have two fundamental ingredients that have to be suitably fixed:

1. weight determination;
2. frequency prediction.

The Galileo Phase B2 algorithm [6] fixes the weight and prediction definition by examining the stochastic noises affecting the clock signals and uses optimal estimation procedures.
The NIST AT1 algorithm [7] is based on a similar general approach but weights and predictions are based on exponential filters that tends to forget the past behavior with the aim of dynamically estimate the clock state.
The GPS-like Composite Clock algorithm [8], on the other hand, uses a Kalman filter, for the clock prediction.
The parallel computation of ensemble time scales by the use of these different algorithms will therefore help in getting an insight to the deep nature of time scale algorithms.

C. Test Case on E-GST steering versus TAI

The TAI steering Test Case will test the algorithm which discipline the E-GST to the TAI time scale. To this aim a connection with the UTC community is needed.
The E-GST is locally measured versus UTC(IEN); by using the BIPM Circular T data concerning UTC - UTC(IEN) it is possible to estimate E-GST versus TAI and UTC (taking care of leap seconds) Because of the deferred availability of the TAI results (about 1.5 months) the steering has to be based on a prediction of TAI and it can be checked with real data only a posteriori. Therefore the TAI steering algorithm is based on a linear prediction of E-GST-TAI difference based on the past Circular T data.
Figure 6 reports a pictorial representation of the steering procedures. The Cs clock data are averaged to obtain a “Cesium average” which has a good long term stability. This average is compared to TAI and, with a prediction, corrected with the aim of being in agreement with TAI in the long term. Every day the H maser (in bold line) is compared versus the steered Cs ensemble and its frequency drift is corrected with the aim of maintaining the good short term stability of the H maser, matching the medium term stability of the Cs average, and matching the long term stability and accuracy of TAI.
By means of appropriate statistical treatments, the stability and accuracy of the resulting E-GST will be estimated.

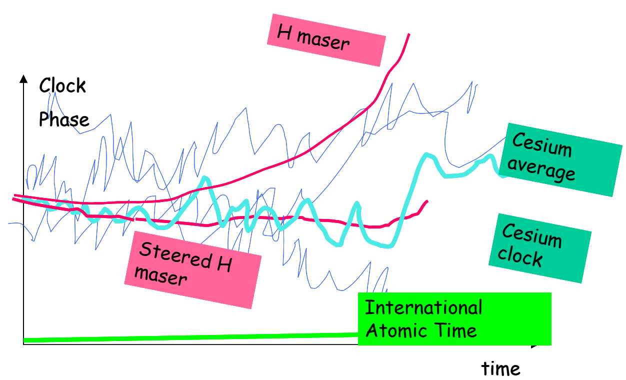

Figure 6: Pictorial representation of clock behaviour: the Cs clocks are in light solid line, while the Cs average is in thick light solid line, the H maser is in bold solid line.

A quasi real time monitor of E-GST steering to TAI is performed by linking E-GST to UTC(PTB) and UTC(NPL); these time scales, available in real time, are good representations of TAI. This is done by means of GPS Common View and TWSTFT measurements.
This test has the double aim of evaluating the capabilities offered by the one-way versus the two-way synchronization links and of verifying the steering to the international TAI of E-GST using real time UTC(k) time scales.
It has been also proposed, as a research activity, to use the IEN Cs fountain to calibrate the E-GST frequency. In fact, TAI is the international reference time scale whose frequency

is adjusted to be in agreement with the best realizations of the SI second. The best realization of the second is provided by the primary frequency standards that are operated in the different national metrological laboratories and that, presently, can reach a relative accuracy of a few units in 10^{-15} with the Cs fountain [9].

D. Detailed subalgorithms

The definition of the complete automatic algorithm for the generation of a real-time time scale asks for several other sub-algorithms because many additional features are to be estimated and controlled. We identified the following list of necessary sub-algorithms, involved in both the E-GST generation and TAI steering tests cases, that have to fulfil different functions:

- smoothing and filtering on raw measurement data;
- check on anomalous clock behaviour;
- average time scale computation including weight and frequency prediction definition according to the choice of the selected main algorithm;
- estimation of clock frequency offset and drift of the master H maser for steering purposes;
- prediction of the TAI.

All these sub algorithms have been designed for the E-GST case and the different steps are now under codification in an appropriate software that is flexible enough to allow the test of different parameter values.

V. THE AGATA ANALISYS TOOL

A software tool devoted to preliminary consolidation of the proposed time scale algorithms and clock behaviour simulation has been developed. This tool, named AGATA (Application for Galileo Timing Analysis), is based on already existent Alenia Spazio proprietary SW modules, integrated with IEN proprietary modules.
AGATA was developed with the scope to provide a powerful tool for the System Engineering in the Galileo frame. AGATA is able to:

- load clock measurement data (both real and simulated)
- calculate the time scale according to the selected algorithm (baseline or alternatives)
- visualize the clock and time scale data in ASCII code or/and plot them
- store clock and time scale data in ASCII and binary code.

VI. CONCLUSION

GSTB V1 is the first experimental test bed in the Galileo program context. The architecture and Test Cases are designed to evaluate the criticalities of the algorithms for the Galileo system.
Concerning time and frequency activities, the GSTB timing test cases are expected to give interesting results on the use of different clocks, primary standards, measurement systems and algorithms for the generation of a reference time scale, adding some value to the entire time and frequency community.
Implementation of the E-PTS at IEN is in progress and the detailed design phase has been completed. Now the work is focused on completing software development, hardware installation, testing and calibration.

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The opinions discussed in this paper are those of the authors and do not necessarily represent those of ESA and other agencies in charge of the Galileo program.

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