The Galileo Precise Timing Facility

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***Abstract* — Consorzio Torino Time (CTT) is conducting the C/D/E1 phase for the implementation of the Precise Timing Facility (PTF) Element, part of the Galileo Mission Segment. The PTF is in charge to generate the Galileo System Time, the physical time reference of Galileo. The PTF detailed design phase is on-going, based on the experience acquired by CTT in the Galileo System Test Bed – V1 (GSTB-V1). The paper presents the PTF overview, its architecture and the design status of the software, algorithms and hardware.**

I. INTRODUCTION

The "Consorzio Torino Time", in charge of the implementation of the Precise Timing Facility (PTF), is constituted by the industrial and academic partners directly involved in the project, as well as by the institutional partners Fondazione TorinoWireless and Finpiemonte, all located in Torino, Piedmont Region, Italy.

The CTT PTF is being developed by the following parts: CTT/ThalesAleniaSpace Italia, responsible for Management / Technical coordination and overall Design, CTT/INRIM (former Istituto Elettrotecnico Nazionale Galileo Ferraris) and CTT/Politecnico di Torino for the GST Generation Algorithm, CTT/Sistemi Elettronici Per l'Automazione (SEPA) for Electrical Design and AI&T, CTT/Alenia SIA for Control & Algo Software implementation and Product Assurance, CTT/Altec for Project Control and Logistics, Astrogeodynamic Observatory (AOS, Poland) for Time Transfer SW implementation, and TEMEX Time (CH) for Backup AHM Steering Algorithm and Picostepper development.

The PTF is a C/D/E1 program of Galileo of worth 4.3 M€.

This key aspect of this program is the challenge of passing from the Research level activities conducted at the Time & Frequency Labs into a real industrial product with a high degree of dependability.

In this effort CTT is taking advantage of its experience acquired in GSTB-V1 phase on the Experimental Precise Timing Station at INRIM.

Currently the PTF is in the Detailed Design Phase. The delivery is foreseen for mid next year to the "On-Site" Galileo Control Centre, i.e. GCC/GMS (Telespazio /Fucino) or GCC/GCS (DLR /Oberpfaffenhofen). Here the Galileo Segment and System level testing will take place, including also the interface with GPS for interoperability purposes. Afterwards, the Initial Operations Verification phase (IOV) will take place with 4 Satellites in orbit, and then the Final Operational Configuration Phase (FOC) with 30 Satellites. The PTF foresees already specific upgrade capabilities for the internal and external resources required for the FOC.

II. OVERVIEW

The PTF can be considered the modern version of the clock invented by John Harrison in the 18^{th} century to solve the Longitude determination problem of maritime navigation. The PTF is actually in charge to generate the physical time scale of Galileo, the Galileo System Time (MasterClock), with two main purposes:

- Metrological Timekeeping :

  This function is implemented by the PTF with the support of the Time Service Provider (TSP), UTC(k)

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Labs and BIPM. The main performance requirements are :
GST(MC) to UTC(mod 1s) offset < 50 ns (2σ) with an uncertainty < 28 ns.
In case of TSP loss : GST(MC) to TAI_p *uncertainty < 20 ns (2σ) for 10 days (where* TAI_p *is TAI predicted)*

- Navigation Timekeeping :

This is a critical task for Navigation, needed for orbit determination and prediction, to be ensured even in lack of TSP. Its main performance requirement is :

GST(MC) to TAI Freq. stability < $4.3\ x10^{-15}$ *ADEV in 24 hours, including contribution due to steering corrections.*

The operational scenario of the PTF is shown in Figure 1.

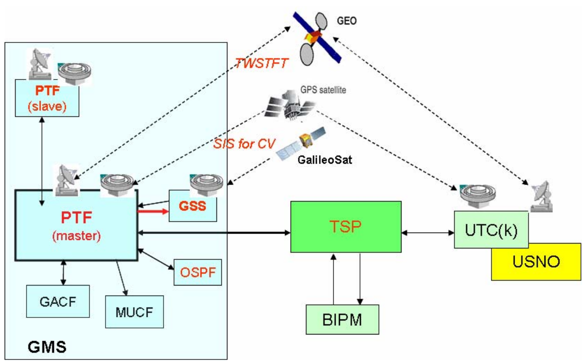

Figure 1. PTF operational scenario

The key functional and design requirements of the PTF are :

- Unmanned Operations with Error & Anomaly management, under Remote Control & Monitor by GMS Control Elements,
- Cooperation with Time Service Provider (TSP), i.e. acceptance of Steering corrections and supply of GST(MC) to TAI offset measurement data
- Master /Slave Operational Modes (with respect to the second PTF), Autonomy Mode in case of TSP loss
- Supply of the GST(MC) signals to the co-located Galileo Sensor Station (GSS) for measurement of the Galileo Satellites clock
- Reliability (including redundancy handling), Availability, Maintainability and Safety to ensure the coverage of the entire Galileo operational life
- SW Quality in front of the Galileo SW Standards to satisfy the needs of safety critical applications.

III. PTF ARCHITECTURE

The main functions to be implemented by the PTF are the GST Generation chain and the Time Transfer.

These functions operate under the PTF monitor & control functions.

The GST Generation chain is based on the Active Hydrogen Masers (AHM) that constitutes the source of the GST signals characterised by a very good short term stability.

The stability on medium and long terms is ensured by a dedicated function mainly based on the local Caesium ensemble and on the TSP data.

A second AHM is present as a backup unit, which output signal is steered to the master one.

The Time Transfer function executes time offset measurements of GST(MC) with respect to the UTC(k) labs, the second PTF and with GPS/USNO. In addition, the GPS-Galileo Time Offset (GGTO) and the PTF1-PTF2 Time Offset products are evaluated.

The GST(MC) signals are provided as physical reference to the co-located Galileo Sensor Station (not part of the PTF), to provide pseudo-ranging measurements to the GMS Orbit Determination & Time Synchronisation functions.

GST(MC) time codes are also provided to the Galileo Control Centre Elements.

The functional block diagram of the PTF is shown in Figure 2.

The main external control functions are the GMS Galileo Asset Control Facility (GACF) for configuration aspects and, for performance aspects, by the Time Service Provider (TSP) and by the Monitoring and Uplink Control Facility (MUCF).

The command & control hierarchy is shown in Figure 3

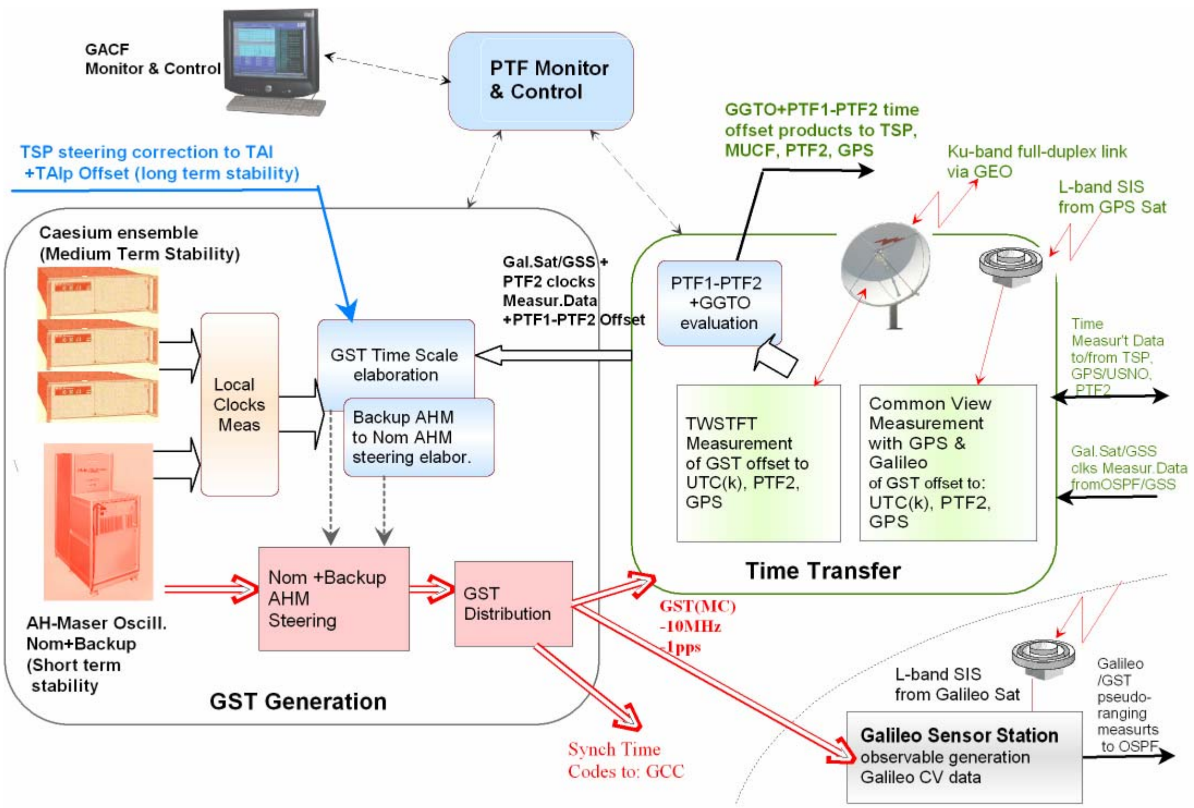

Figure 2. PTF functional block diagram

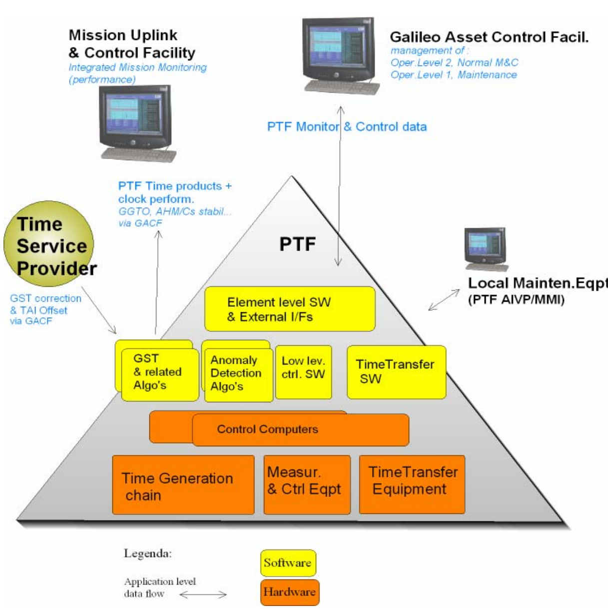

Figure 3. PTF Command & Control Hierarchy

The PTF Architecture is organized on the following Sub-Systems (S/S):

- Time Generation S/S, including Intruments to generate and distribute GST(MC), i.e. 10 MHz and 1pps, with high dependability, namely the local oscillators i.e. 2 Active Hydrogen Masers and 4 Caesium clocks.
- Time Transfer S/S, including TWSTFT Station, CV Rx, OSPF/GSS I/F (to acquire the Galileo on-board and ground "remote" clocks) and the Time Transfer SW to control the such high-accuracy synchronization links.
- Measurement and Control S/S, including Control Computers, Data Network and Measurement Instrumentation, namely Time Interval Counter (TIC) and Multi-Channel Phase Comparator (MCPC). The SW includes the Algorithms to control the other S/S's and to monitor the GST performance.

The PTF Architecture is shown in Figure 4.

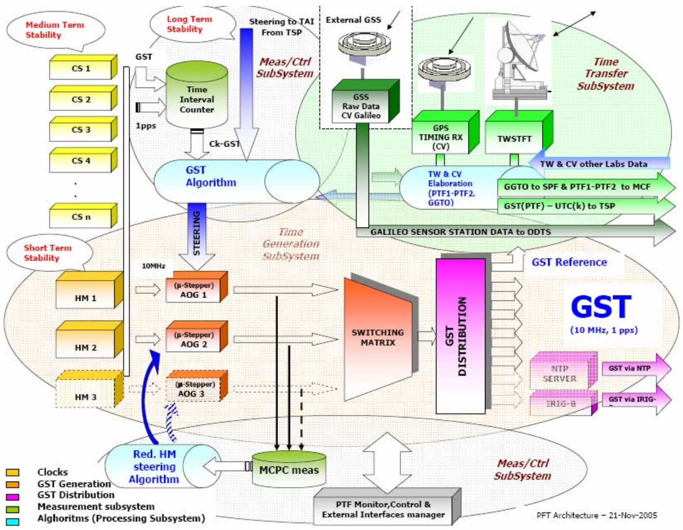

Figure 4. PTF Architecture (with upgrade capability)

IV. PTF SOFTWARE

The Operational SW is split into the following components :

- PTF Control & Algorithms SW
- Time Transfer SW
- AIV support SW, including local Man Machine I/F

The SW implementation, in C language, is subject to a rigid process specified by the Galileo SW Standard. The design constraints depend on the criticality of each module, classified in Development Assurance Levels (DAL).

The Algorithms are passing a prototype phase with MATLAB coding, also subject to Galileo SW Standards.

The architecture of the PTF Control & Algorithms SW, shown in Fig. 5, foresees partitions where the modules are contained according to their DAL, and is based on the certifiable Operating System LynxOS 178.

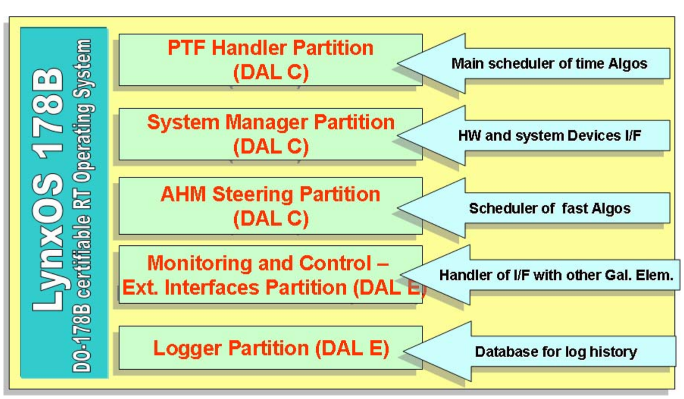

Figure 5. PTF SW Architecture

The following Algorithms are present in the PTF SW:

- GST Generation and Slave PTF Steering Algo, generating GST(MC) while in Master Nominal Mode (with TSP support as shown in Figure 6) and in Master Autonomy, as well as to steer the GST(MC) to the PTF 2 while in Slave Mode. In Master Nominal mode the strategy foresees the steer to TAI the weighted average of the Caesium clocks ensemble, then to validate the correction received from the TSP and to apply it to the picostepper. In Autonomy Mode the correction is calculated internally.
- GGTO and PTF1-PTF2 Evaluation Algo, calculating the Time Offset of the Galileo System Time (GST) to the GPS/USNO and to the PTF-2.
- Back up AHM Steering Algo, to steer the Backup AHM for a smooth switch-over in case of master AHM malfunction.
- Anomaly Detection Algos, to identify Phase /Frequency jumps and instability anomalies in GST(MC) and clocks. Figure 7 shows the detection of a phase jump introduced in the divider chain by cross-checking MCPC and TIC respective acquisitions of 10 MHz and 1pps.

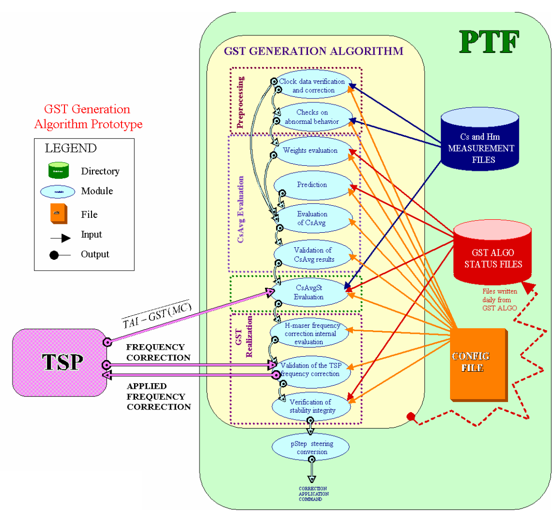

Figure 6. GST Generation Algorithm

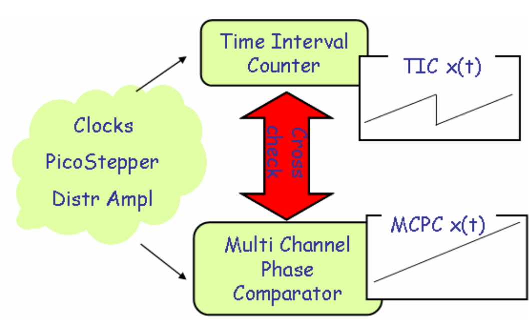

Figure 7. Phase jump Detection Algorithm

V. PTF HARDWARE

This section presents the key equipment under development for the PTF.

A. *Active Hydrogen MASER*

The Active Hydrogen MASER (AHM) is the source of the time generation chain, ensuring the short term stability to GST(MC). The PTF utilizes the European iMASER™ developed by T4Science (CH), that acquired the technology developed at Observatoire de Neauchatel through a joint-venture of French, German and Swiss expert companies. Table I shows its stability characteristics in a +/- 0.1°C controlled environment.

TABLE I. PTF AHM STABILITY

τ	*ADEV*
1s	$1.5 .10^{-13}$
10 s	$2 \ . 10^{-14}$
100 s	$4.7 .10^{-15}$
1,000 s	$2 \ . 10^{-15}$
10,000 s	$2 \ .10^{-15}$
1 day	$2.8 .10^{-15}$ (*)

(*) including the drift

B. *Automatic Switching Matrix*

An Automatic Switching Matrix (see Figure 8) is under development by CTT/SEPA with the aim to ensure GST(MC) continuity by switching to Backup AHM in case of Nom. AHM signal loss, with the following characteristics:

- Simultaneous switching of 10 MHz & 1 pps signals
- Adjusting of 10 MHz signal delays down to few ps
- Input from up to 4 AHMs for upgrade capability and double redundancy
- Automatic or on-command switching

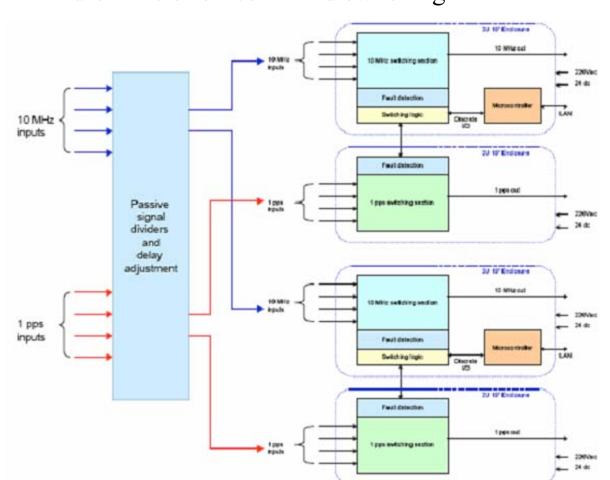

Figure 8. Automatic Switching Matrix

C. *Picostepper*

A high resolution PTF *PicoStepper* is under development to apply frequency corrections to the AHM signals based on the existing PicoStepper™ by Temex Time Neauchatel.

The following is foreseen to meet the PTF requirements :

- Resolution increase by a factor of 100 to obtain a minimum phase step of ± 0.1 picosecond
- Output jitter reduction to get negligible degradation of the AHM signal phase noise and short term stability.

D. *GNSS Time Receiver*

For GPS Common View measurement it is foreseen to use the *TTS-3 Time Receiver* made by AOS, that presents the following features (see Figure 10):

- Multi-channel reconstructed GPS P-code mode
- Compatibility with all available navigation satellites: GPS, GLONASS, WAAS, EGNOS and in future Galileo
- Down to 1 ns accuracy for intercontinental time links and < 1 ns for continental ones (post-processing Ionosphere and precise Ephemerides measurements).

Figure 9. TTS-3 Time Receiver

VI. CONCLUSION

CTT is confident that the PTF, the modern “Harrison clock”, will satisfy the needs of Galileo being based on a consolidated design and algorithms and on state-of-the-art instrumentation.

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