GALILEO SYSTEM TIME PHYSICAL GENERATION

Xavier Stehlin, Qinghua Wang, Florent Jeanneret, Pascal Rochat
Temex Time
Vauseyon 29, 2000 Neuchâtel, Switzerland
E-mail: ***stehlin@temextime.com***

Edoardo Detoma
SEPA
Via Andrea Pozzo 8, 10151 Torino, Italy

Abstract

The Precise Timing Facility (PTF) is one of the key facilities of the Galileo ground segment. Its major task is to generate and maintain an accurate, stable, and precise Galileo System Time (GST). Physical representation of GST should be connected to at least one observation station within the network. The PTF is designed with a structure similar to a Timing Laboratory, but with the necessary redundancies in order to be able to work autonomously.

The current paper gives a deeper view on equipment necessary to generate physical GST signals. It covers in particular the atomic clock ensemble, internal redundancies management, and the phase stepper performance in order not to degrade the active Hydrogen Maser (HM) performance. Moreover, to guarantee the continuous GST generation, the backup HM steering algorithm allows a seamless switchover between the backup and primary HMs in case of failure of the latter.

I. GALILEO PRECISE TIMING FACILITY

The Precise Timing Facility (PTF) is the most stable and accurate clock used in the Galileo system. Being part of the Galileo Control Center (GCC), the PTF aim is twofold:

- provide short-term stability for the navigation functions;
- provide medium-to-long term stability and accuracy for the timing function of the system.

The Orbit Determination and Timing Synchronization (OD&TS) function of the system, which estimates the satellites' orbits and the space and ground clocks' relative parameters (time and frequency offsets), requires a very high short-term stability to minimize the clocks noise contribution to the system state estimation. The short-term stability is required from 1 s (where it affects the carrier-phase measurements at the Galileo Sensor Stations, GSS) to a few hours, which is the maximum update time for the system state parameters (orbits and clocks).

As with GPS, Galileo can be used also to disseminate timing information with respect to UTC/TAI; the required accuracy implies that the Galileo System Time (GST), an independent continuous time scale, is steered continuously to UTC/TAI. The correction update, obtained via Common View and Two-Way measurements with major European timing labs and provided by an external entity called Time Service Provider (TSP), is supplied every day, but requires a very high GST medium and long-term stability for the correction to be precisely estimated.

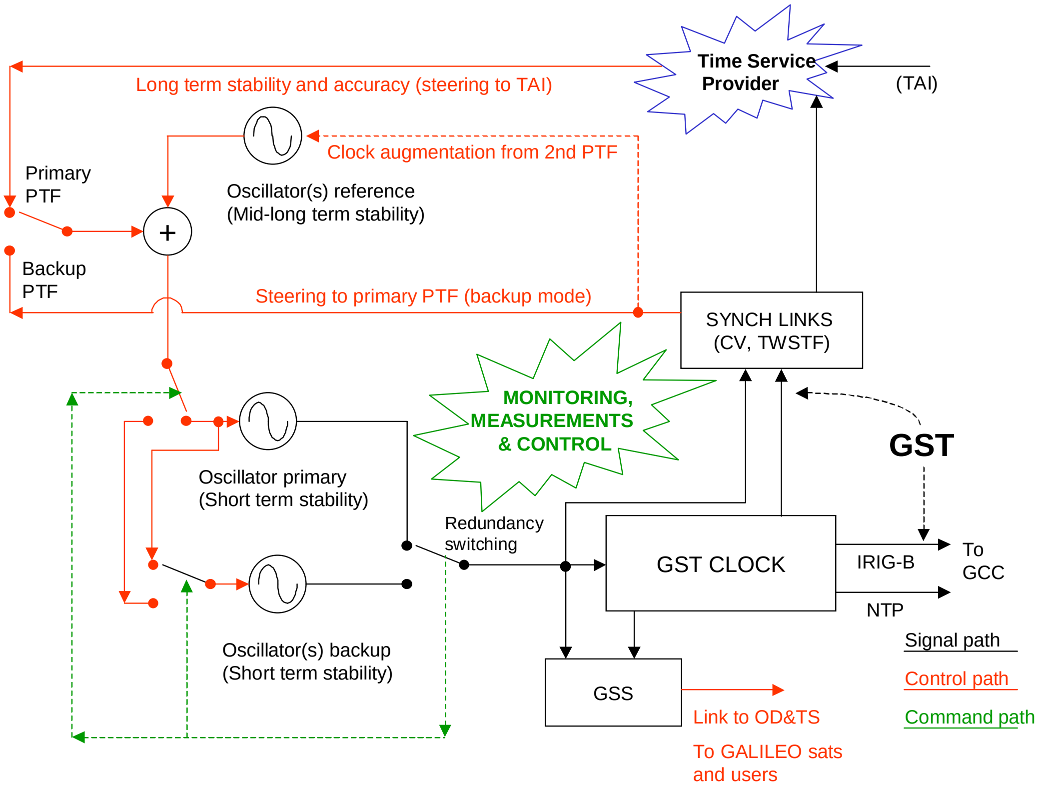

Figure 1. Functional operation of the PTF.

Functionally, the PTF is schematically depicted in Figure 1. Two extremely stable oscillators (a primary and backup), each one externally steered via a precision phase picostepper, provide the physical realization of GST, insuring the extremely high short-term stability required. Two active H-masers are employed in this function. Both the H-masers and the precision picosteppers are supplied by two Swiss companies, T4Science and Temex Time respectively. A doubly redundant switching matrix insures that, if the primary oscillator fails, the backup comes on-line with a minimum phase and frequency discontinuity. A doubly redundant clock follows to generate GST and its physical realization in the form of 1 pps, IRIG-B, and NTP signals that are distributed to the users. 10 MHz and 1 pps signals are fed to the local GSS station, which constitutes the mean to transfer GST to the OD&TS process.

The seamless switchover of the two primary oscillators, the two active H-masers, implies that the backup is continuously steered to the primary to avoid a frequency offset and an integrated time offset. To this end, a closed loop is implemented using high-resolution phase measurements on the 10 MHz signals of the two H-masers, measurements provided by a Multi-Channel Phase Comparator (MCPC) with sub-ps resolution.

The primary H-maser is steered by the corrections provided by the TSP. However, to provide a medium-term stability to the GST in the event the TSP corrections are temporarily missing, a second group of clocks, based on Cs-beam frequency standards, is used to steer the primary H-maser to the average frequency and time of the ensemble.

Clearly the backup H-maser is always steered to the primary H-maser; however, in case of failure of the latter, the backup becomes primary and the steering corrections must be switched to this unit; moreover, the current Galileo system configuration envisages the presence of two PTFs, a primary and a backup, where the backup is continuously steered to the primary until the primary fails and the backup is used as primary instead. This explains the switching arrangement on the control path of the two oscillators in Figure 1.

Satellite synchronization links (common-view and two-way) are used for hourly and daily inter-comparisons between GST and the major European labs, the second PTF, and the U.S. Naval Observatory, to provide an estimate of the GPS-to-Galileo Time Offset (GGTO). While the synchronization data with the second PTF is used to steer the backup PTF to the primary, the inter-comparisons between GST and the major European labs are used by the TSP to estimate the periodical correction to GST to steer the latter to UTC/TAI using the published BIPM information.

The architectural implementation is shown in Figure 2, where the functional blocks are translated into real equipment; expansion to a third H-maser is foreseen in the future and the current design (including the switching matrix) allows up to 4 H-masers and an expansion of the Cs-beam clocks ensemble to cope with future needs.

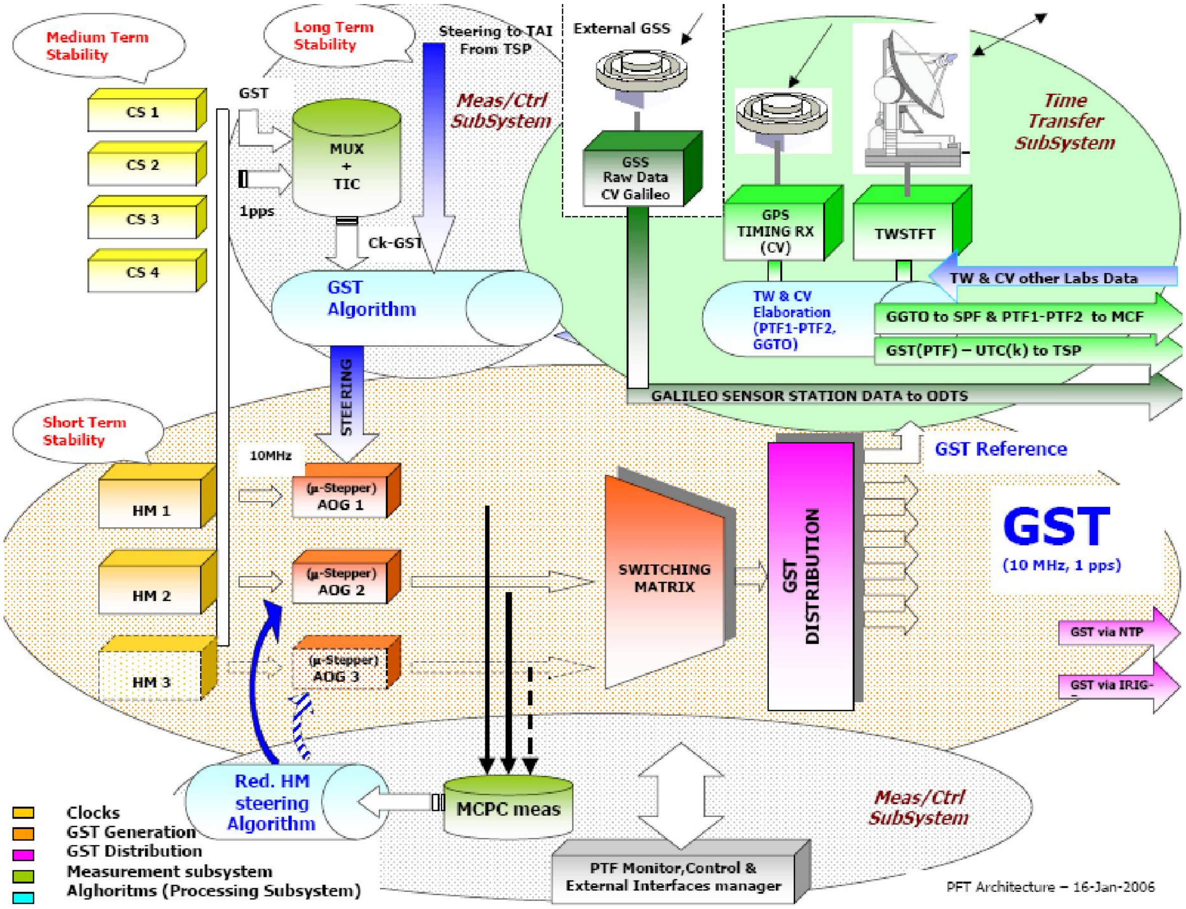

Figure 2. PTF architecture.

II. PHASE STEPPER

The phase stepper is an upgrade of the existing Temex Time PicoStepper™ (Figure 3) in terms of performance in order to satisfy the PTF requirements. The major improvements are the phase-stepping resolution and the phase noise characteristics by keeping the existing architecture, firmware, and software. The goal of the improved phase stepper is to obtain a minimum phase step of +/- 0.1 ps without degrading the Active H-Maser performance in terms of phase noise and short-term stability.

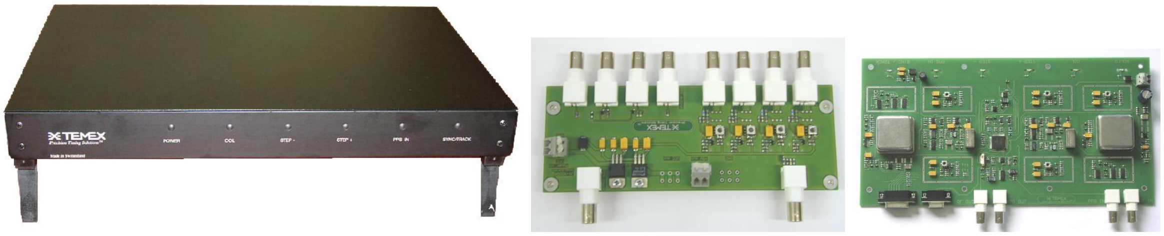

Figure 3. Temex Time PicoStepper™.

Table 1 lists the main specifications of existing PicoStepper™ and the phase stepper developed for the PTF.

Table 1. Main specifications.

	PicoStepper™	PTF Phase Stepper
Input Frequency	10MHz	
Number of Outputs	4 x 10MHz	
Outputs Amplitude / Impedance	1VRMS ±20% / 50Ω	
Minimum Phase step on 10MHz	± 10ps	± 0.1ps
Output jitter without stepping	< 1ps	< 0.15ps
Output jitter while stepping	< 10ps	< 0.15ps
Out of Lock Alarm	Bit alarm / Front panel Indicator	
Phase / Frequency Command	RS232 commands	

The design is based on a double heterodyne architecture, where a first structure is used for positive phase/ frequency adjustment and the second structure for negative adjustment.

As shown in the high level block diagram (Figure 4), each positive/negative loop contains a VCXO (Voltage-Controlled Xtal Oscillator), a phase detector, a frequency mixer, a frequency multiplier, a pulse removing circuit, a frequency divider, and a loop filter. A micro-controller is in charge to manage the stepping commands sent by RS232. It has also the capability to execute a self test of the unit.

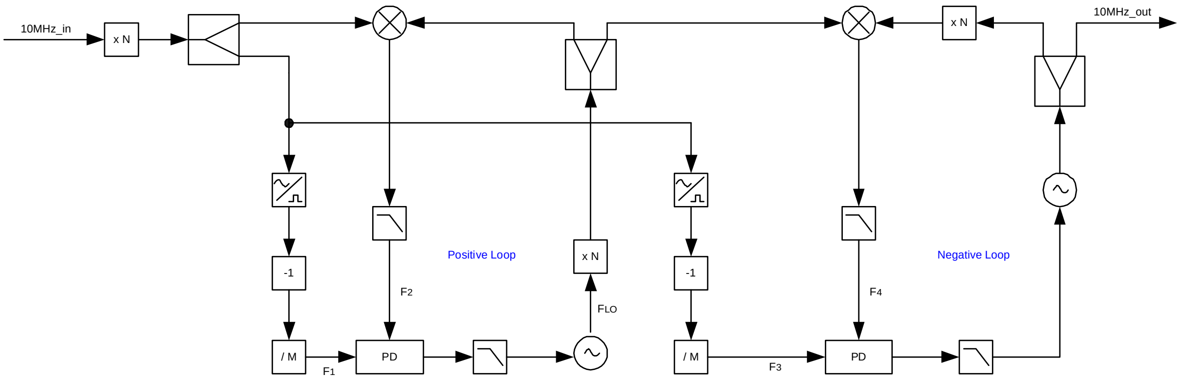

Figure 4. Block diagram of PTF Phase Stepper.

The 0.1 ps resolution of the system is obtained by using an appropriate VCXO frequency multiplication factor and divider ratio. Taking N=10 and M=10^5, the frequency resolution is $\Delta f / f_{IN} = \pm 10^{-13}$, which corresponds in terms of phase to 0.1 ps.

The frequency beats (F1, F2, F3, and F4) in both loops while not stepping is equal to 1 KHz, which is the comparison frequency of the phase detectors. These frequency beats are an important parameter to be able to produce the appropriate cut-off frequency of the system in order to not degrade the performance of the Maser.

Thus, the nominal frequency of the local oscillator is equal to 10 MHz – 1 KHz/N = 9.999900 MHz.

In order to not degrade the Maser performance, a phase noise figure analysis has to be performed. The comparison between the Active Maser specification and the best-performance OCXO available on the market in terms of phase noise close to the carrier gives the required cut-off frequency to be implemented.

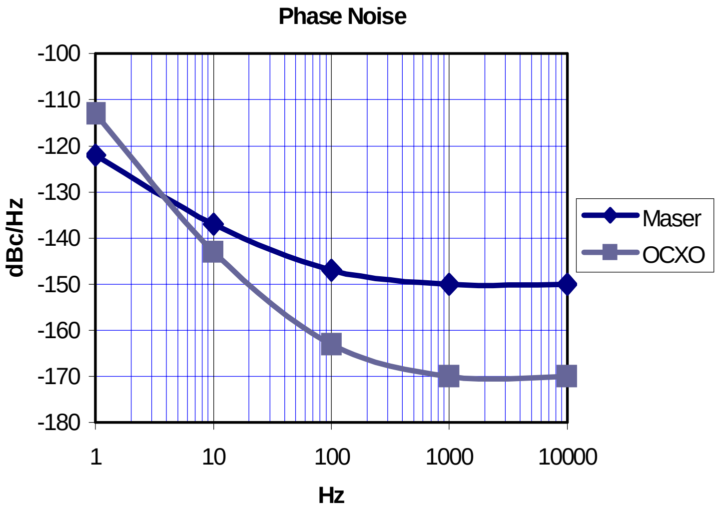

Figure 5. Phase noise figure.

The graphic shows that the optimum cut-off frequency should be around 4 Hz. Taking into account the 1 KHz frequency beats used as comparison signal, there is not too difficult to implement the desired 4 Hz cut-off frequency.

III. BACKUP H-MASER STEERING ALGORITHM

In order to allow a smooth switch-over between backup and primary H-Masers (HM) in case of failure of the latter, without producing any significant effect in the GST continuity, uniformity, and short term frequency stability, this algorithm will acquire the difference between HM2 and HM1 by means of the MCPC, and elaborate a steering correction to be applied to the backup HM by means of the Phase Stepper to keep it in phase with the primary one.

3.1 ARCHITECTURE

Figure 6 shows the architecture of the Backup HM Steering Model consisting of MCPC, phase steppers (one per HM), and the algorithm.

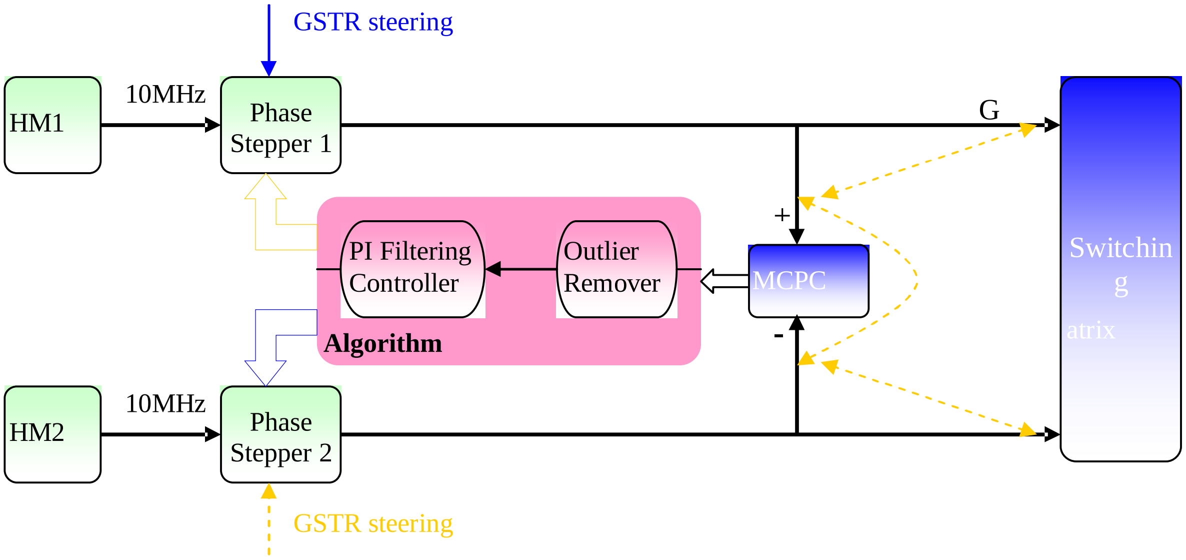

Figure 6. Architecture of the Backup HM Steering Model.

In the nominal situation, Phase Stepper 1 applies the steering correction from PTF GST algorithm to steer the primary HM1, with GSTR obtaining the GST. The phases of two HMs through two Phase Steppers are compared by MCPC, whose output is manipulated at the ‘Backup HM Steering Algorithm’ obtaining the steering command to Phase Stepper 2, which connects with the backup HM2. Thus, the output of HM2 is kept in phase with HM1.

In case of the HM1 failure, the hot backup HM2 becomes the primary one by the PTF Switching Matrix. The previous HM1-steered HM2 provides the seamless switch-over signal via Phase Stepper 2, which is now applied by the GSTR correction for GST.

The Backup HM steering algorithm is contributed to by two functions: the Outlier Remover and the Proportional Integrator (PI) Filtering Controller.

3.2 APPROACH

The Backup HM Steering Algorithm, together with the MCPC and Phase Stepper, construct a Phase-Locked Loop (PLL) to lock the phase of the backup HM to the primary one. Figure 7 shows the block diagram of the backup HM steering model.

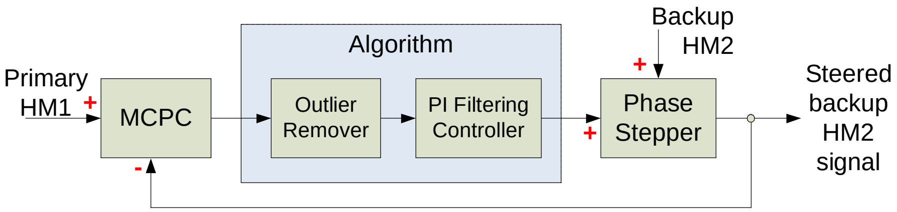

Figure 7. Block diagram of the Backup HM Steering Model PLL.

The algorithm is designed based on a digital PI filtering controller, which contains the PI filter and periodical generation of the steering commands accepted by the Phase Stepper.

To eliminate the impact of the primary HM output signal anomalies (e.g. phase spikes) on the steered backup HM, the algorithm firstly removes the phase outliers by the Least-Squares Linear Fit (LSLF) to eliminate the impact of anomalies of primary HM.

3.2.1 Phase-Locked Loop and PI Filter

Figure 8 illustrates the PLL control system block diagram in the continuous (Laplace) domain.

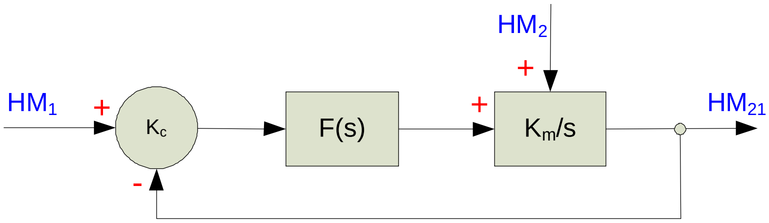

Figure 8. Block diagram of the Phase-Locked Loop.

The s-transfer function of 2nd-order closed loop:

$$C(s) = \frac{2\xi\tau s + 1}{\tau^2 s^2 + 2\xi\tau s + 1} \tag{1}$$

Where τ is the loop time constant [sec]: 1000 s; ξ is the damping factor: 1; K_c is MCPC gain: 10^{13} step/s; and K_m is the phase stepper gain: 10^{-13}/step.

The z-transfer function of the discrete PI filter:

$$D(z) = K_p + K_i \frac{z}{z-1} \tag{2}$$

where, K_i and K_p are coefficients of the discrete integrator and proportional regulator.

As shown in Figure 9, comparing the loop time constant of 1000 s with 5000 s, the phase deviation between the primary HM1 and steered backup HM2 is apparently smaller, and the Allan deviation of the steered HM2 degrades negligibly at shorter averaging times. Therefore, 1000 s is selected as the tradeoff of the time offset and the frequency stability.

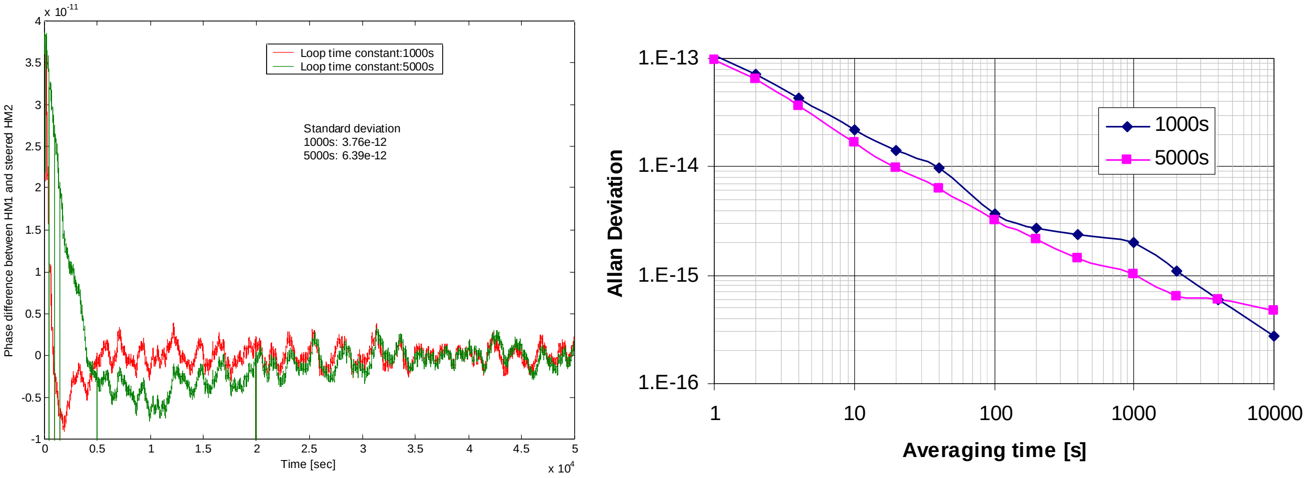

Figure 9. Steered phase deviation from HM1 [sec] and Frequency stability of steered HM2 for loop time constants of 1000 s and 5000 s.

3.2.2 Dynamic Least-Squares Linear Fitting and Outlier Removal

Figure 10 illustrates the block diagram of the Outlier Remover. The input datum from MCPC, e0, is checked by the least-squares fitting to the previous data over 100 s. If the absolute value of the deviation from the fitting line exceeds the outlier criterion C, the datum is removed and replaced by the previous value. Therefore, the phase outliers of the primary HM are ruled out before the steering.

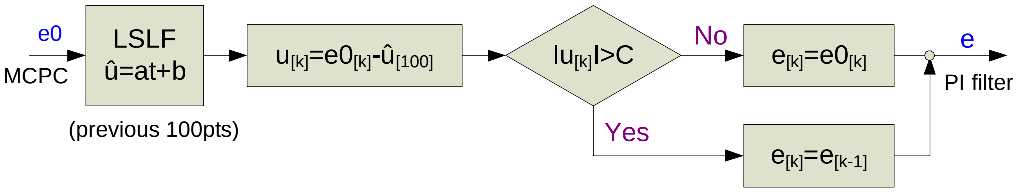

Figure 10. Block diagram of the Outlier Remover.

Figure 11 shows the simulation of HM2 steered to HM1 with phase spikes in order to investigate the impact caused by the spike level. Without the 'Outlier remover' function, the anomalies in HM1 lead to the phase jumps on the steered HM2. The outlier criterion C is selected to remove the phase outliers at the Master HM >30ps.

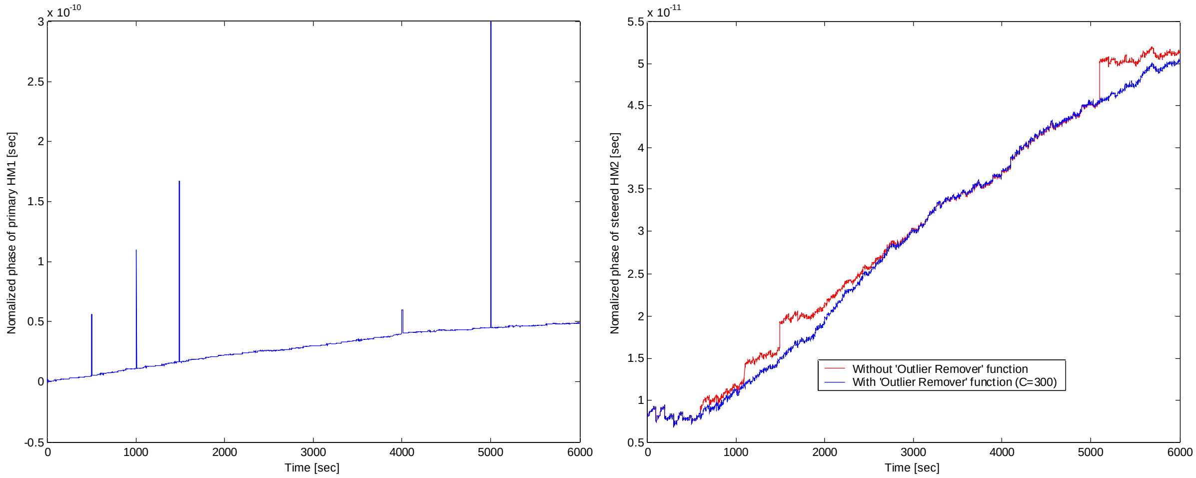

Figure 11. Phases [sec] of the primary HM1 (with phase anomalies) and the simulation results of the steered HM2 without or with the Outlier Remover function.

3.3 BACKUP HM STEERING SYSTEM SIMULATION AND PERFORMANCE VERIFICATION

A model shown in Figure 12 is created to simulate, analyze, and verify the overall Backup HM Steering system implemented with the algorithm.

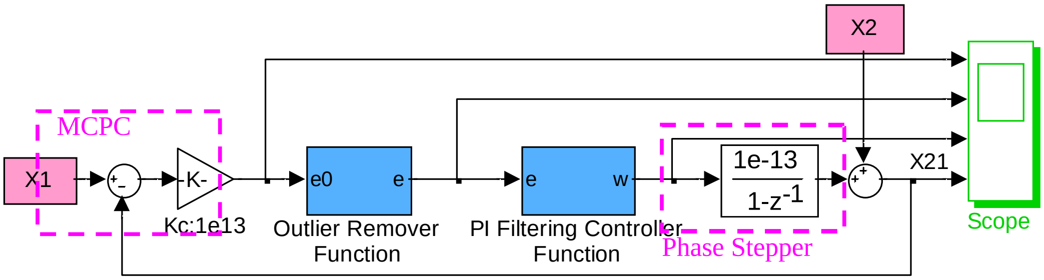

Figure 12. Simulation model for the overall Backup HM Steering system.

The algorithm performance is verified when the Master HM signal X1 is applied by a max frequency correction of 10^{-14}. Figure 13 shows that the backup HM2 keeps in good phase with master HM1, and the impact of the HM1 frequency step of 10^{-14} on the phase difference is 6.3 ps.

Table 2 summarizes the overall performance budget taking into account the calibration errors of the cables between the input of the MCPC and the input of the Switching Matrix, which is within the requirement on the switchover phase jump of 30 ps.

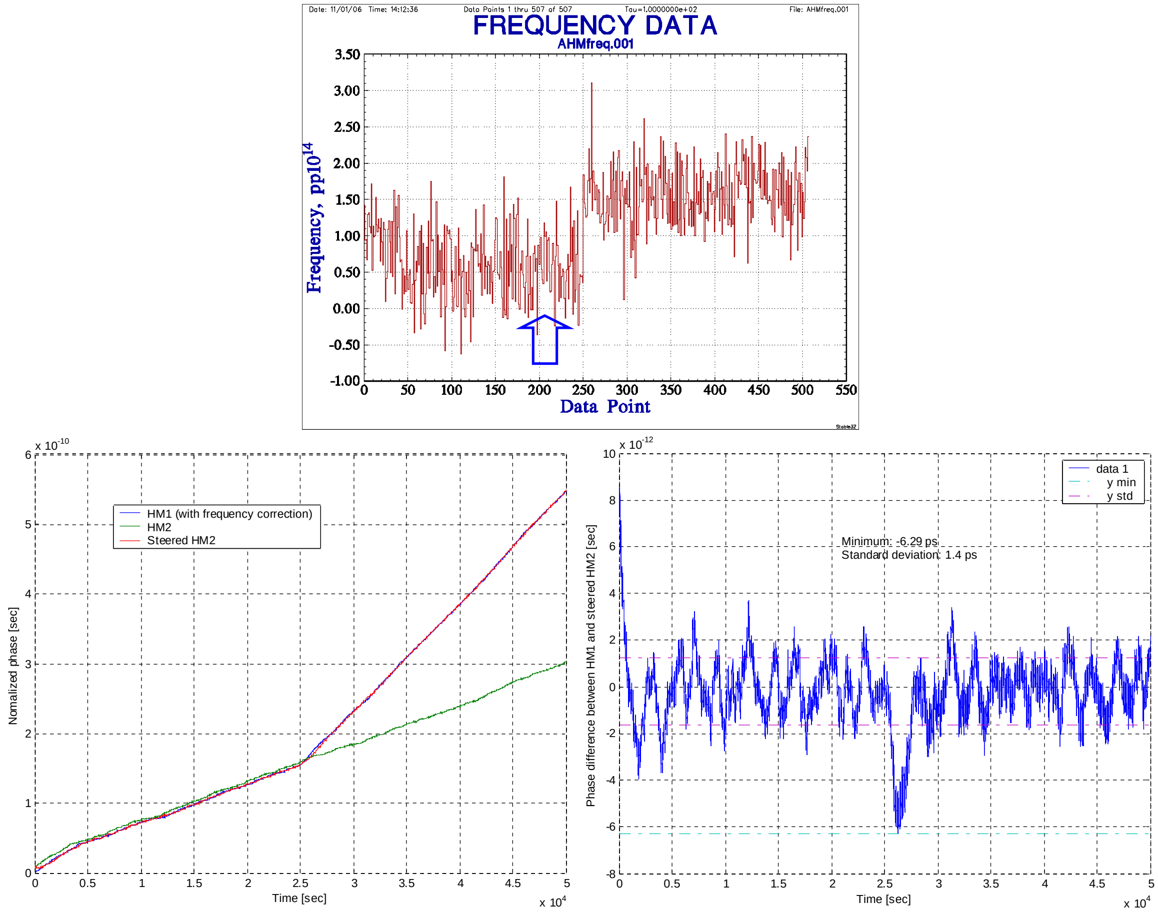

Figure 13. Top: frequency changes of the primary HM1 with the frequency correction of 10^{-14}. Left: Phase [sec] of the primary HM1, free-running backup HM2, and steered HM2. Right: Steered phase deviation between the backup and primary HMs [sec].

Table 2. Overall performance budget.

Algorithm Simulation	Standard deviation	Peak
	1.4 ps	6.3 ps
Calibration accuracy (cable from GST(MC)_R to MCPC)	5 ps	
MCPC resolution (ADEV @1 s = 710^{-14})	0.1 ps	
Phase stepper resolution	0.1 ps	
Total	5.2 ps	8.0 ps

IV. ACKNOWLEDGMENTS

Two PTFs are currently under development by two separate teams in Germany and Italy. The discussion provided in this paper refers to the Italian development, coordinated by the Consorzio Torino Time (CTT) in Torino, with the partnership and support of Temex Time and T4Science in Neuchâtel (Switzerland), and AOS (Poland). The authors are thankful for the contributions to this paper of the following companies and institutions that are engaged in the development of the PTF for Galileo: Alcatel Alenia Space (Italy and France), Temex Time, T4Science, AOS, SEPA, Alenia SIA, ALTEC, INRIM (former IEN), and the Politecnico di Torino.

Communication information:

Qinghua Wang
Temex Time
Vauseyon 29, 2000 Neuchâtel, Switzerland
E-mail: qinghua@temextime.com
Tel: +41 32 732 96 74
Fax: +41 32 732 16 67