Backup Hydrogen Maser Steering Algorithm for Galileo Precise Timing Facility

Qinghua Wang, Pascal Rochat
Temex Time
Neuchâtel, Switzerland
qinghua@temextime.com

***Abstract*—Two Hydrogen Masers (HM, a primary and a backup) are used in the Precise Timing Facility (PTF) to provide the physical realization of Galileo System Time (GST), insuring the extremely high short-term stability required for the navigation functions, in particular to perform a reliable satellite clock modeling.**

In order to allow a smooth switch-over between backup and primary HMs in case of failure of the latter, without introducing the phase jump exceeding 30ps in the value of GST, the 'backup HM steering algorithm' is developed, which acquires the phase difference between two HMs measured by a phase comparator and elaborates the steering correction applied to the backup HM via a Picostepper with a 0.1ps resolution, to keep the backup HM in phase with the primary one.

The algorithm is designed based on two functions: the Outlier Remover and the Proportional-Integral Filtering Controller. The overall backup HM steering system contributed by the phase comparator, the Picostepper and the algorithm is simulated using real HM to HM measurements, to verify the steering operability and the loop performance under various test cases including the nominal and degraded conditions with simulated anomalies or feared events (phase/frequency spikes, jumps and drift).

I. Introduction

The Precise Timing Facility (PTF) of the Galileo ground segment is to generate and maintain an accurate, stable and precise Galileo System Time (GST). 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 [1], 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).

Two active Hydrogen Masers (HM, a primary and a backup), each one externally steered via a precision Picostepper, provide the physical realization of GST, insuring the extremely high short-term stability required for the navigation functions, in particular to perform a reliable satellite clock modeling. The Picostepper [2] manufactured by Temex Time is providing a minimum phase step of +/- 0.1ps. Such resolution is small enough to perform smooth phase & frequency corrections without degrading the active HM performances in terms of phase noise and short term stability.

The 'backup HM steering algorithm' is implemented in order to allow a smooth switch-over between backup and primary HM in case of failure of the latter, without producing any significant effect in the GST continuity, uniformity and short term frequency stability. The algorithm will acquire the phase difference between HM2 and HM1 by means of a Multi-Channel Phase Comparator (MCPC) with sub-ps resolution, and elaborate a steering correction to be applied to the backup HM via the Picostepper to keep it in phase with the primary one.

II. Architecture

Fig. 1 shows the architecture of the Backup HM Steering Model consisting of MCPC, Picosteppers (one per HM) and the algorithm.

In the nominal situation, Picostepper1 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 Picosteppers are compared by MCPC, whose output is manipulated at the 'Backup HM Steering Algorithm' obtaining the steering command to Picostepper2 which

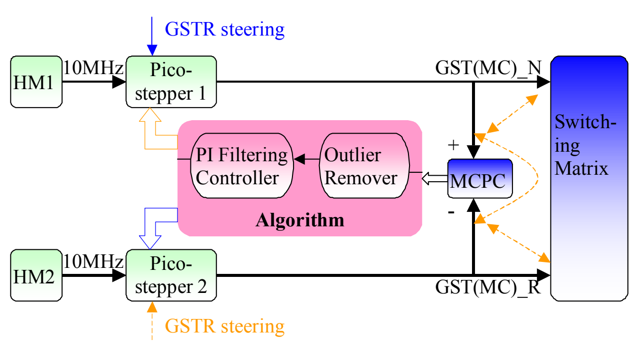

Figure 1. Architecture of the Backup HM Steering Model

connects with the backup HM2. Thus the output of HM2 is kept in phase with HM1.

In case of the HM1 failure, the hot back-up HM2 becomes the primary one by the PTF Switching Matrix. The previous phase offset 'HM2(steered)-HM1' provides the seamless switch-over signal via Picostepper2 which is now applied by the GSTR correction for GST.

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

III. APPROACH

The Backup HM Steering Algorithm together with the MCPC and Picostepper can be modelised like a basic Phase-Locked Loop (PLL) to lock the phase of the backup HM to the primary one. Fig. 2 shows the block diagram of the backup HM steering model.

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 Picostepper.

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

A. *Phase-Locked Loop and PI filter*

Fig. 3 illustrates the PLL control system block diagram in the continuous (Laplace) domain.

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

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

where τ is the loop time constant [sec]: 1000s, which is selected as the tradeoff of the time offset and the frequency stability [2]; ξ is the damping factor: 1; K_c is MCPC gain: 10^{13} step/s; and K_m is the Picostepper gain: 10^{-13}/step.

In discrete domain, basic digital filtering functions can be used. Therefore, the z-transfer function of the discrete PI filter:

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

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

B. *Dynamic least-square linear fitting and outlier removing*

Fig. 4 illustrates the block diagram of the Outlier Remover. The input data from MCPC, e0 is checked by the least-square fitting for the previous data over 100s. If the absolute value of the deviation from the fitting line exceeds the outlier criterion C of 30ps, the data is removed and replaced by the previous value. Therefore the phase outliers of the primary HM are ruled out before the steering.

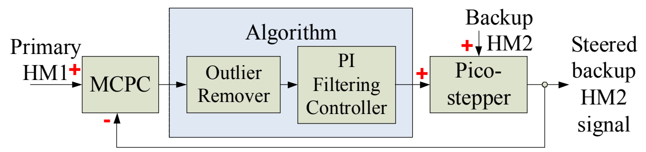

Figure 2. Block diagram of the Backup HM Steering Model

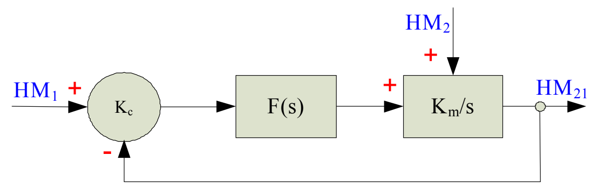

Figure 3. Block diagram of the Phase-Locked Loop

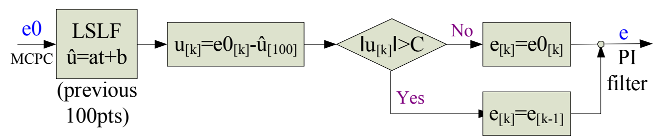

Figure 4. Block diagram of the Outlier Remover

IV. BACKUP HM STEERING SYSTEM SIMULATION AND PERFORMANCE VERIFICATION

A simulation model is created to analyze and verify the steering operability and the loop performance under various test cases including the nominal and degraded conditions with simulated anomalies or feared events (phase/frequency spikes, jumps and drift) occurred in both HMs.

It's required that to switch the maser and slave HM, the phase jump shall not exceed 30ps in the value of the GST.

Fig. 5 to 8 demonstrate the simulation results on various test cases. The backup HM2 is steered properly to the primary HM1 in all test cases:

- With phase spikes at the primary HM1, the algorithm eliminates properly the anomalies. The peak value of the phase offset 'HM2(steered) - HM1(outliers removed)' is 4.0ps which depends on the initial phase difference, and the standard deviation is 1.03ps after the loop is settled down.
- In the presence of the phase step of 30ps (GST(MC) max phase jump) either at the primary HM1 or the backup HM2, the max impacted phase offset 'HM2(steered)-HM1' is 8.0ps
- When the HM signal is applied by GST max frequency correction of 1e-14, the impact on the phase offset 'HM2(steered)-HM1' is 6.3ps.

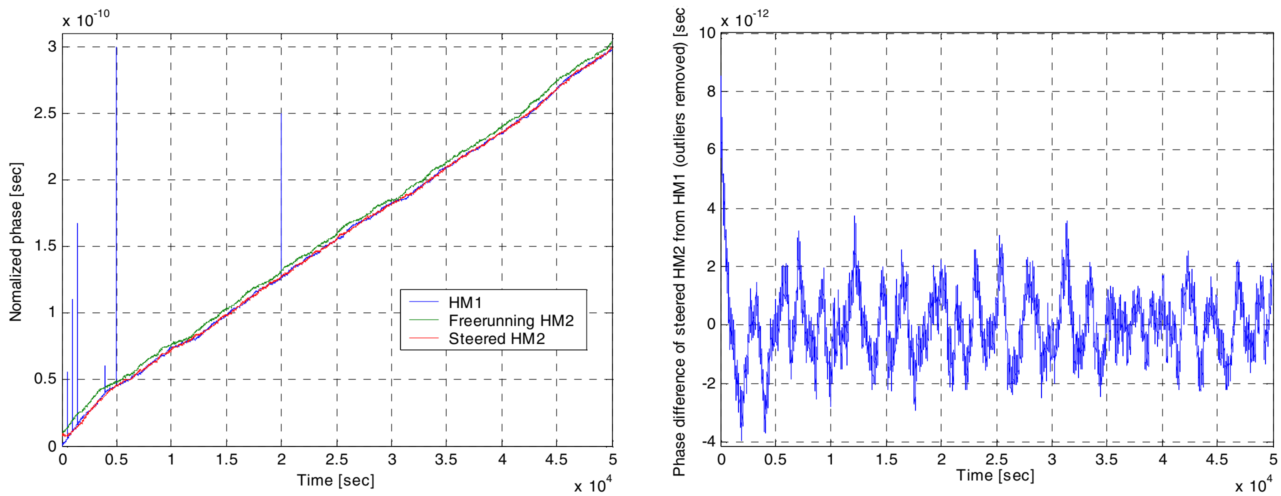

Figure 5. Simulation on phase/frequency spikes at primary HM1

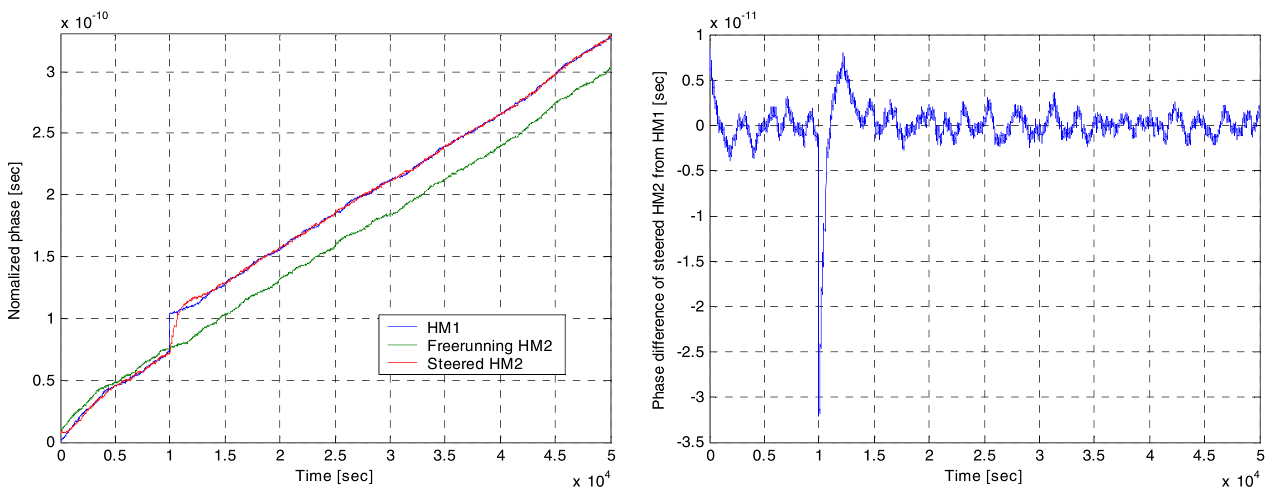

Figure 6. Simulation on phase jump of 30ps in HM1 (similar at HM2)

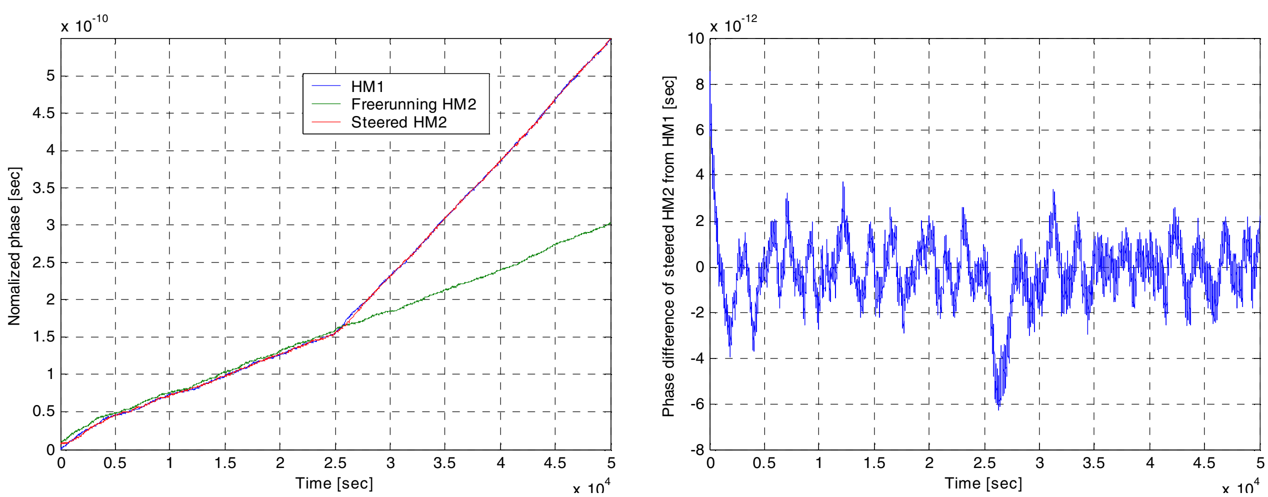

Figure 7. Simulation on frequency jump of 1e-14 at HM1 (similar at HM2)

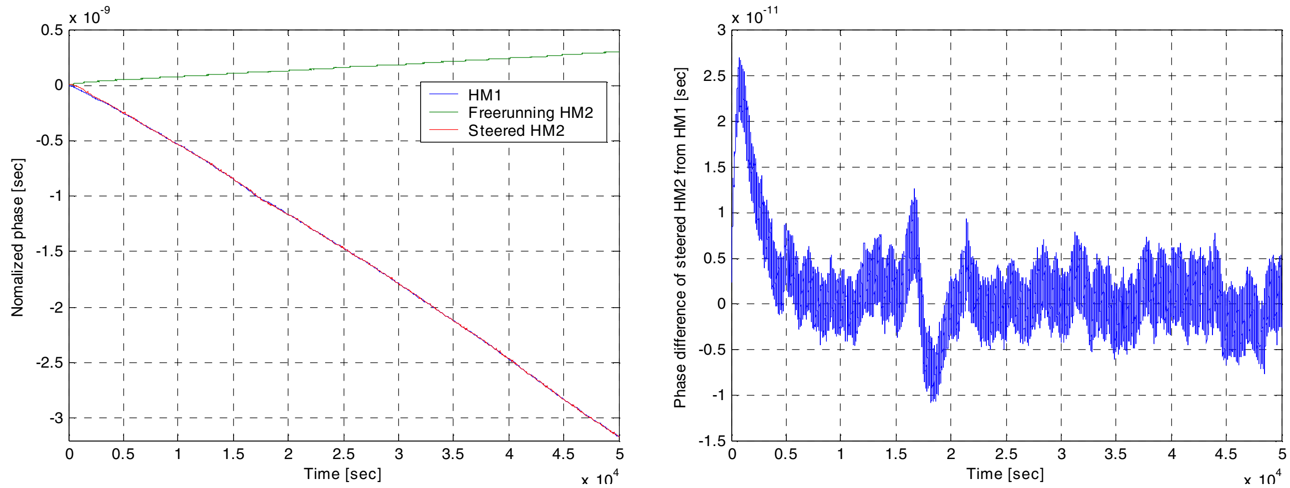

Figure 8. Simulation on frequency drift of 1e-13 at HM1 (similar at HM2)

TABLE I. OVERALL PERFORMANCE BUDGET

Algorithm Simulation	**Test case**	**1**	**2**	**3**	**4**	**5**
	Test event	**Nominal**	**Phase / frequency spikes**	**Phase jump of 30ps** ***(GST(MC) max phase jump)***	**Frequency jump of 1e-14** ***(GST(MC) max frequency correction)***	**Frequency drift of 1e-13/d** ***(10 times worse of AHM spec.)***
	Peak phase offset	4.0ps	4.0ps	8.0ps	6.3ps	27.0ps
Calibration accuracy		5ps				
MCPC resolution		0.1ps				
Picostepper resolution		0.1ps				
Total (phase offset)		6.4ps	6.4ps	9.4ps	8.0ps	27.5ps

- Even If the HM frequency drift is seriously degraded, the phase offset 'HM2(steered)-HM1' is well in spec after the loop settling time, and the peak offset around the loop time constant is 27ps for the frequency drift of 1e-13/d (10 time worse of the specification of T4science AHM, whose typical value is few e-15/d.). (The max phase offset as 12.5ps near to 20000s is due to the accompanying frequency jump of 2.5e-14 in the HM signal.)

Table I 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, the MCPS resolution and the Picostepper resolution. The total performance is within the requirement on the switchover phase jump of 30ps.

In addition, the worst cases are analysed:

- The PLL will beyond the Picostepper max control range (1e+4steps) when the phase jump is bigger than 5ns, or the frequency jump is bigger than 8e-12.
- For above latter case the phase offset 'HM2steered-HM1' is out of the specification of 30ps. To meet this specificaion the frequency jump is allowed to be less than 5e-13.

REFERENCES

[1] R. Zanello, M. Mascarello, P. Tavella, L. Galleani, E. Detoma, A. Bellotti, "The Galileo precise timing facility", in this symposium, unpublished.

[2] X. Stehlin, Q. Wang, F. Jeanneret, P. Rochat, E. Detoma, "Galileo system time physical generation," 38th Annual Precise Time and Time Interval (PTTI) Meeting, 5-7 Dec. 2006, Virginia (USA), in press.