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A novel Robust and Precise Timing Facility for Galileo

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Abstract:
A fundamental component in each Global Navigation Satellite System is the timing facility, which is responsible for the synchronization of all elements within the ground segment as well as for the satellites in space. Different concepts exist to provide a time scale that fulfils all requirements, e.g. master clock principle, weighted clocks or composite clock algorithm. In the European Global Navigation Satellite System Galileo, the so-called Precise Timing Facility (PTF), located in Oberpfaffenhofen, Germany, and Fucino, Italy, has the task to provide the Galileo System Time (GST). The actual published design of the PTF depends on a master clock principle and is therefore sensitive to failures of individual units within the GST generation [1].

At DLR Galileo Competence Center we propose an alternative design for such a timing facility, which is called Robust Precise Timing Facility (RPTF). The focus of the concept is on mitigating technical vulnerabilities and increasing the tolerance to the failure of any of the components of the existing PTF.

In this paper we present the concept, current status and future plans for such a RPTF to generate robust system timescales for the next generation of the European satellite navigation systems. The aim is to build, test and characterize the RPTF under the aspect of a 24/7 operational service. The key element is the combination of all the individual atomic clocks in the facility via the composite clock approach to generate a weighted average, the so-called Implicit Ensemble Mean (IEM), and to provide redundancy and test opportunities in case of hardware and software failures.

Key words: Galileo, Robust Precise Timing Facility, active hydrogen maser, short- and long-term stability, composite clock

Introduction

The task of the Precise Timing Facility (PTF) is to generate, maintain and distribute the Galileo System Time (GST) with the aim of providing a very stable time reference for navigation purposes and of disseminating timing information synchronized to UTC/TAI to the Galileo users. Therefore, it is very important that the PTF provides both short- and long-term stability.

The setup of the PTF is shown in Fig. 1. The so-called master clock principle, employing a high-precision clock with very good short-term stability, an active hydrogen maser (AHM), is used as basis for the GST generation. The derived timing signals are subsequently distributed to all Galileo segments. A second AHM is used as backup source and its output signals are steered to the signals of the master AHM in order to avoid a frequency offset and an integrated time offset. The medium- and long-term stability is guaranteed by cesium clocks and by using the measurement data provided by the Time Service Provider (TSP) for UTC/TAI. If the master clock or one PTF component shows an error or fails while generating the system time, no correct time scale will be provided and the end customer will not able to use the Galileo system for position determination. Therefore, in order to avoid “single points of failure”, two PTFs are operated in the Galileo system. They are located in Oberpfaffenhofen (Germany) and in Fucino (Italy) and are synchronized to a certain degree of accuracy via satellite connections: Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GPS All-in-View (AV). However, in the case of regular maintenance of one of the PTFs, there is no further redundancy in the system. This led to the failures of the Galileo system in autumn 2018 and summer 2019, with the last incident lasting more than five days. As upgrades and replacements of system components are to be expected in the ongoing and future operations of Galileo, it is foreseeable that during their occurrence, due to the consequent lack of further delocalized and redundant PTFs in the Galileo system, any disturbance or fault may result in reduced availability, degradation, or failure of the PTF, the GST, and potentially of the entire Galileo system.

Examples of such disturbances and faults include but are not limited to:

- frequency and phase jumps of the clocks and of other PTF elements
- errors in the measurement instruments
- wrong GST time distribution to other elements of Galileo Ground Segment
- loss of TWSTFT or AV, e.g. due to jamming and/or spoofing of the received satellite signals
- non-availability of backup PTF in case of maintenance
- software failures, especially when abnormal situations occur that are often not considered or tested
- missing monitoring capabilities/parameters to assess the operational status of the PTF

In order to mitigate these technical vulnerabilities and to increase the tolerance to the failure of any PTF component, we propose the concept of the RPTF. Its design is based on the introduction and integration of the features described in the following section. Its architectural implementation is presented in Fig. 2, along with the connection to external partners.

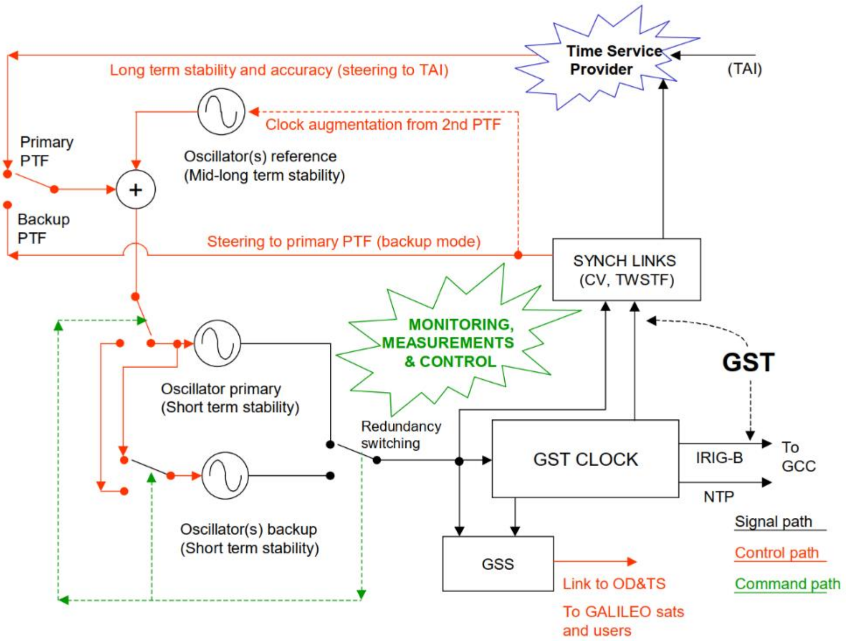

Fig. 1. Functional operation of the Galileo PTF, actual published scheme from [1]. The master clock principle, with primary and backup oscillators, and the two PTFs are depicted.

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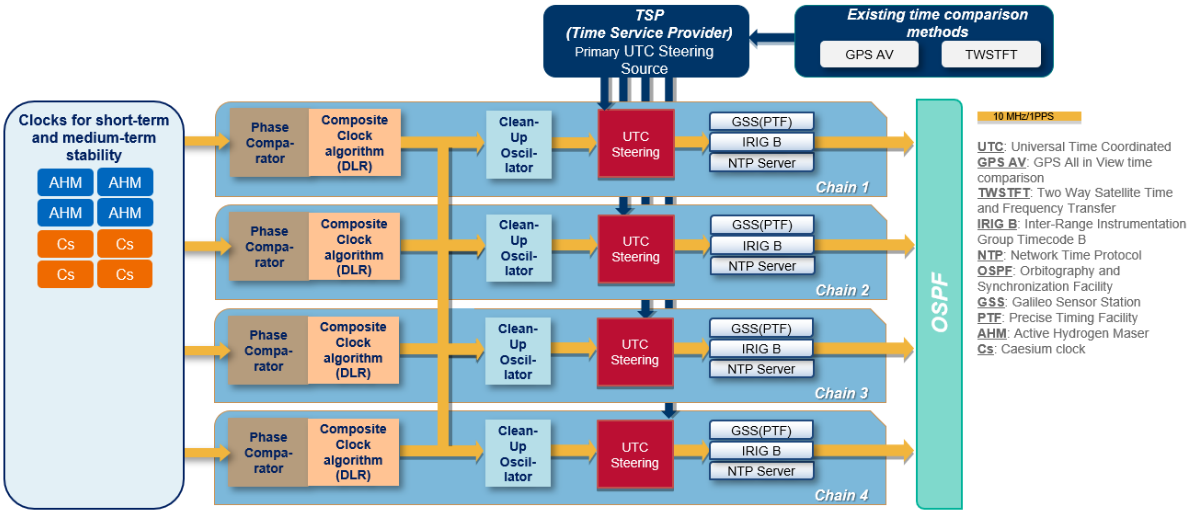

Fig. 2. The proposed RPTF architecture, including all four chains

Realization of the Robust and Precise Timing Facility

One of the main objectives of the RPTF is to increase the reliability of the system. Instead of the master clock principle, with its intrinsic weaknesses, a Composite Clock Algorithm (CCA) based on Kalman filters as proposed in [2] will be implemented. This generates an Implicit Ensemble Mean (IEM) of all available clocks located at the RPTF, i.e., a weighted average of the contributions of each clock, and it generally outperforms each clock in the ensemble in terms of stability. Currently, four (4) AHMs (T4Science iMaser 3000 and MicroChip MHM 2020) and four (4) cesium high-performance frequency standards (MicroChip 5071A HP) are used to realize the RPTF (see Fig. 2), but the algorithm can be expanded so that any number of clocks can also be added, e.g., from the ground and the space segments. Besides the improved stability another advantage of the IEM is the robustness of the output against phase and frequency jumps, failures or replacement of clocks. In extreme cases, up to seven of the eight existing clocks in the RPTF can fail without any major restrictions on the generation of the system time. Of course, depending on the failed clocks, the accuracy of the generated time scale may be reduced, but it is still available for the Galileo system and no general system failure can occur. These arguments make the use of the IEM for the generation of system time a straightforward choice.

To elaborate further on this point, the clocks are measured with respect to each other in a multi-channel phase comparator. The measured signals are then fed into a Kalman filter which estimates the future states of each clock and implicitly provides the system time of the ensemble in terms of the IEM, a so-called paper clock. As mentioned, the IEM generally exhibits a better stability for all sample intervals than every single clock in the ensemble. However, this quantity is not directly available in hardware, since it requires knowing the exact state of each clock at each time step, which is not directly measurable. Nonetheless, it can be realized by steering a clock signal towards the IEM with a dedicated control loop containing a second Kalman filter and a regulator which computes the control action to be applied. This way, the output of the steered clock provides a physical realization of the IEM. This CCA implementation is based on more than ten years of both theoretical and applied experience gathered at the Institute of Communications and Navigation at the German Aerospace Center (DLR) [3].

Another important aspect of the RPTF design is that not only the clocks, but also the measuring instruments (e.g., phase comparators) will be acquired from at least two different manufactures for the same functionality and similar quality (dual source), so that a direct comparison of the measuring instruments under the same conditions can be performed. This applies not only to the hardware but also to the software. For example, the same CCA could be implemented in two different programming languages.

Furthermore, the RPTF elements will be arranged in four chains, each running an independent comparison of all the clocks and generating an independent IEM. The physical representation of the IEM for each chain is then fed as input to a clean-up oscillator that acts as a failover clock switch: it tracks all selected input channels and switches automatically between them in case of failure of the selected main input channel while maintaining phase coherence. Assuming all IEMs are identical when suddenly a chain is faulty or an IEM input at the clean-up oscillator goes missing, no change at the output of the clean-up oscillators will be seen, as the device automatically switches between the four IEM chains. Afterwards, the output of each clean-up oscillator is steered to UTC. The primary source for steering is the product of the Galileo Time Service Provider (TSP) whose results are based on TWSTFT and GPS AV measurements for the GST. In our case, we have no access to the results of a TSP and no TWSTFT station at Oberpfaffenhofen. Therefore, we steer the IEM/clean-up oscillator output to UTC only by GNSS All-in-View. This steered output is provided to a GNSS receiver, which measures the clock offset of each individual GNSS satellite to the system time, and to a Network Time Protocol (NTP) server for distributing the resulting system time to all system elements where date and time is needed. In addition, the timing signal is also distributed with IRIG-B. Besides, there are further developments that should be taken into consideration while implementing the RPTF: Precise Time Protocol (PTP) and White Rabbit. Both modern protocols can improve the robustness of Galileo.

The choice to use four chains is based on the following arguments:

- two chains already offer higher redundancy compared to one only. However, as soon as one element in one of the two chains shows faults, fails and needs to be replaced, or undergoes standard maintenance, or the software of the CCA is updated, the redundancy of this approach is removed.
- the addition of a third chain increases the redundancy and enables the self-indication of the best system time representation in the RPTF via the three-cornered hat method. Therefore, in order to detect anomalies in the chains one can check if the generation of the IEM in the different chains is identical. This way an error in the chains, e.g., a phase jump after the clean-up oscillator can be detected immediately. These three chains represent the operational chains.
- the setup of a fourth chain has the advantage that it can serve as test bed for new algorithms or hardware components. It acts as a backup-chain for troubleshooting activities and in case one of the other three chains is in maintenance.

Fig. 3 shows the detailed structure of a single chain, whereas Fig. 5 shows pictures of two of the four AHMs, the cesium clocks, and one of the four RPTF chains, being arranged in a single rack. Besides the elements already mentioned above Fig. 3 displays various frequency and pulse per second (PPS) distribution units that amplify and distribute the signals within the RPTF, and measurement equipment that compares the states of the four chains. Not only the 10 MHz frequency signals but also the 1 PPS timing signals will be compared to each other, the latter via time interval counters (TIC). Multiple comparisons occur: after generating the four IEMs, the clean-up oscillator, the UTC steering, the time distribution (NTP), and the GNSS receivers. These “check elements” combined in orange shade in Fig. 3 represent the necessary measuring instruments needed for the investigation of availability and accuracy of the system time of the RPTF after different steps of generation. They are part of an agent-based health manager with the task of checking the output of the RPTF versus expected values and ensure that error states are not transferred to further elements, for example the Galileo system. The health manager has capabilities in continuous monitoring, anomaly detection, diagnostics and prognostics so that element failures can be promptly detected and compensated for during operational use. The health manager also allows a detailed view of all processes in the past and supports the analysis in case of troubleshooting. Additionally, combining the results of the health manager and the information of the behavior of the used equipment (e.g., aging processes) one can predict the behavior of the RPTF system time generation.

This, together with the dual source concept, will ensure that supplier-specific weaknesses or errors will not be able to affect the availability of the system. Even a replacement of equipment, e.g., within a necessary calibration cycle, is made possible with this approach and the multiple redundant setup, without the risk of a complete failure of the system time generated by the RPTF.

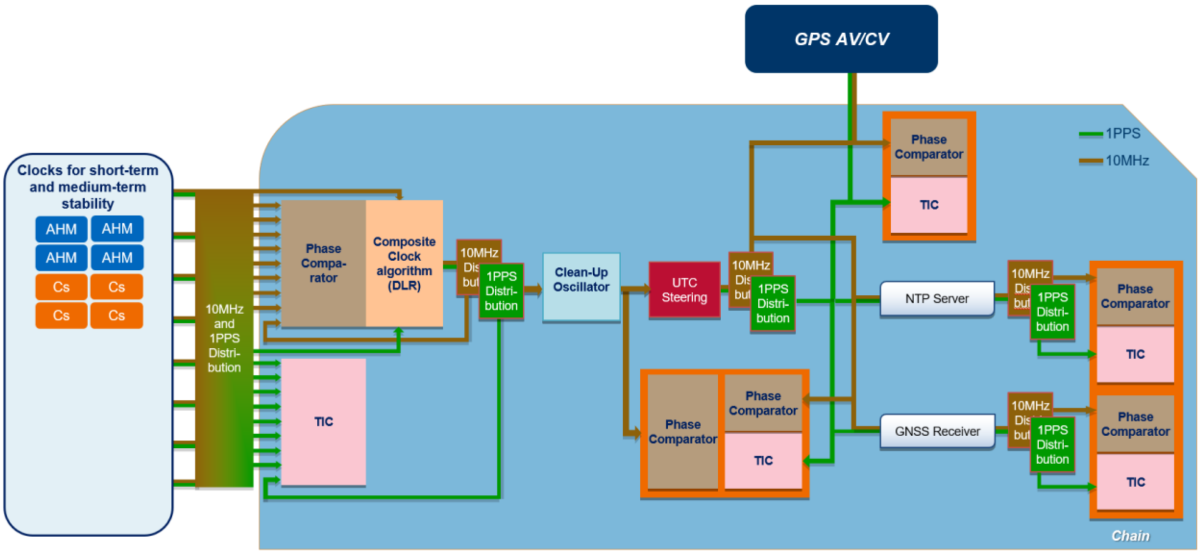

Fig. 3. Detailed structure of a single chain.

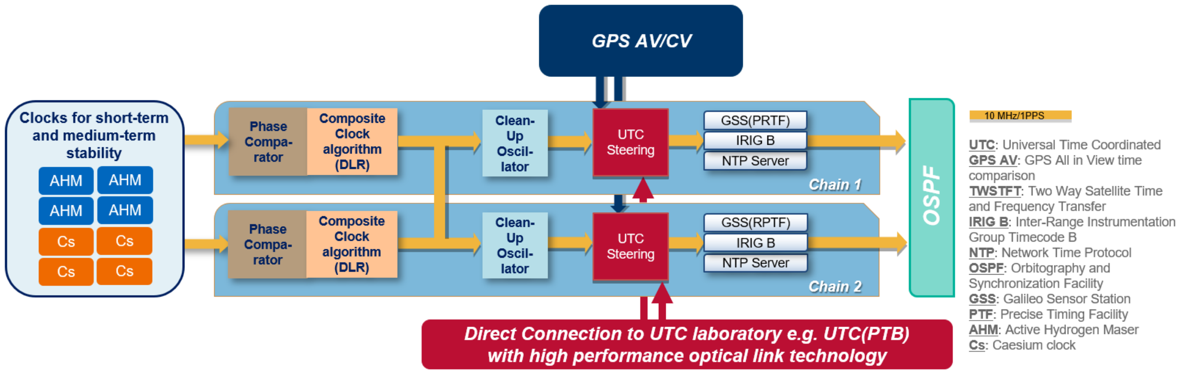

Fig. 4. Fiber link implementation demonstrated on 2 chains.

Fig.5. From left to right: two of the four AHMs; the cesium clocks; one of the RPTF chains, arranged in a rack.

In recent years it was shown that the current spatial diversity in Galileo given by the two locations of the PTFs in Oberpfaffenhofen and Fucino alone cannot guarantee the desired reliability of Galileo. Therefore, alternative connections to external time laboratories are presently being researched to achieve higher availability, redundancy and increased robustness of the GST. To this end, the proposed RPTF foresees a fiber link connection of the RPTF to the Physikalisch-Technische Bundesanstalt (PTB) which is responsible for the legal time in Germany (Fig. 4). This way, the system time generated in the RPTF can be compared directly with the German time and the UTC world time. The fiber link connection promises an accuracy below 100 ps in the long-term behavior which represents an improvement by at least a factor of 10 compared to actual standards used in the Galileo system; not to mention the much higher data rate exchange (e.g., every second) if compared to other standard methods such as GPS AV or TWSTFT.

Outlook

In conclusion, with our suggested approach of the RPTF, we assume that the currently published Galileo PTF will be significantly improved in terms of robustness.

The hardware and software implementation of the RPTF is currently under realization. A detailed evaluation of the RPTF elements with regard to reliability, availability, maintainability, and safety (RAMS analysis) is forthcoming. This analysis will classify the RPTF elements according to failure conditions and will clearly ensure that a failure of one or more elements only reaches a certain risk status of the RPTF and thus of the Galileo Systems.

Future developments include, but are not limited to:

- testing of advanced methods for distributing the RPTF-generated system time to all elements of the Galileo ground segment, e.g., PTP and White Rabbit
- testing against non-nominal satellite signals by using GNSS signal simulators
- and finally, the integration of atomic clocks in the time laboratories of other well-established European metrological institutions (in addition to PTB), to generate an even more robust, accurate, and geographically diverse GST by means of fibre optical connections and the composite clock approach

The start of operations of the proposed Robust and Precise Timing Facility is planned for the beginning of 2023.

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