German Timing Expertise to Support Galileo

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Abstract — **This paper describes the potential transfer of competence from national German projects in the field of navigation and precise timing into the Galileo program.**

I. Introduction

Synchronization and monitoring of satellite clocks is crucial for the provision of precise and reliable positioning and timing services through Galileo. For this purposes, Galileo will maintain a reference timescale – Galileo System Time (GST). This timescale will become the heart-beat of Galileo. GST will be produced by the Precise Time Facility (PTF) as an output of an active hydrogen maser steered to the International Atomic Time (TAI). In addition, the PTF will be equipped with four Caesium clocks the excellent long-term stability of which will help to estimate and to mitigate the frequency drift of the maser in case if the link to TAI (established with the help of European timing institutes coordinated by the Galileo Time Service Provider) fails. Offsets between the clocks onboard the Galileo satellites and GST will be calculated by the Galileo Orbitography and Synchronization Facility (OSPF) using the observations collected by the Galileo receiver at the PTF which will be fed with the physical representation of GST.

The major challenge in the PTF development is to meet the demanding requirements to the reliability of this facility and to automate its operations. Experience collected by national industry and research in Europe, and in particular Germany, can assist in achieving this goal. Thus, the requirements and the design of the PTF were harmonized and consolidated in the frame of Galileo Phase C0 studies (accomplished in 2004) by a team under lead of the Munich-based company Kayser-Threde (see also [1]). The main focus of these studies has been set on checking the operational feasibility of the PTF design and operational concepts and on incorporating robustness and reliability into the PTF design. Reliability and robustness issues are of vital importance since GST will be used also for the provision of Galileo Safety-Of-Life services. The corresponding responsibilities and the specifics of Galileo operations, where a high level of automation will be required, set qualitatively new requirements to the GST generation approach and the PTF design.

The core solutions proposed within the C0 studies are being tested in the frame of development and operation of the Galileo Test Environment (GATE) (see [2]) where DLR is responsible for the GATE Time Facility. GATE is a national German project. The goal is to build a ground-based system which provides navigation and timing capabilities in a dedicated terrestrial test area by transmitting Galileo-compatible signals. The primary objectives of the GATE project are to support

- Galileo signal design and validation prior to the launch of the first Galileo test satellite,
- development of Galileo user receiver and positioning algorithms by providing a realistic test environment and Galileo-compatible signals,
- development and test of Galileo applications and studies of Galileo/GPS interoperability.

Started in early 2002, the GATE project has successfully finished the design and definition phases. The development phase started in summer 2004 and will result in the physical implementation of the Test Environment in Southern Germany. Initial Operational Capability is planned to be reached in Autumn 2006.

As for any system providing positioning and timing capabilities on the base of one-way range measurements, synchronization of the GATE signal transmitters will be vital to meet the specified accuracy requirements. Considering that GATE transmitter locations are fixed, synchronization errors are likely to be the main factor limiting the GATE positioning accuracy. During the design and definition phase of GATE a robust synchronization concept has been elaborated and tested with simulated data. This concept has been developed through "scaling" of Galileo solutions to the specific requirements and constraints of GATE. Additionally, a possibility to test those solutions in representative scenarios has been considered in the GATE baseline.

Following the approach adopted in Galileo, GATE will establish and maintain a system timescale (GAST) which will serve as reference for the overall GATE operations. Generated at the GATE Time Facility (GTF) from a high-performance atomic clock, GAST will have a physical representation and will be able to support navigation and metrological functions being both stable and accurate through its steering to UTC. To meet relevant availability and continuity requirements, a redundancy concept and redundancy switching approach for GTF has been elaborated.

The offset between GAST and GPS time will be precisely measured and broadcast to users to support GATE interoperability with GPS.

II. GALILEO TEST ENVIRONMENT (GATE)

A. GATE objectives and architecture

The Galileo Test Environment (GATE) is a national German project aimed at supporting the Galileo definition developing its applications and promoting its use. GATE will include terrestrial signal transmitters (to be installed in southern Germany) and monitoring and control facilities. Its goal is to emulate Galileo as close as possible and to allow test of Galileo signals, receivers, and applications in an "outdoor" environment providing both positioning and timing capabilities. GATE is being developed by a consortium of German companies. Initial operations shall start in 2006.

Like Galileo, GATE consists of three basic segments (see Figure 1):

- Control Segment;
- Field Segment which has the same function as the space segment of a satellite navigation system;
- User Segment.

Additionally, a Support Segment will assist mission planning and analysis. Elements and functions of GATE segments are listed in Table 1.

GATE will support tests of Galileo interoperability with GPS. It will be also interoperable with GSTB-V2.

Each of the GATE signal transmitters will be equipped with an individual clock. This solution leads to a system design similar to that of Galileo and calls for the implementation of a time synchronization procedure for the transmitter clocks.

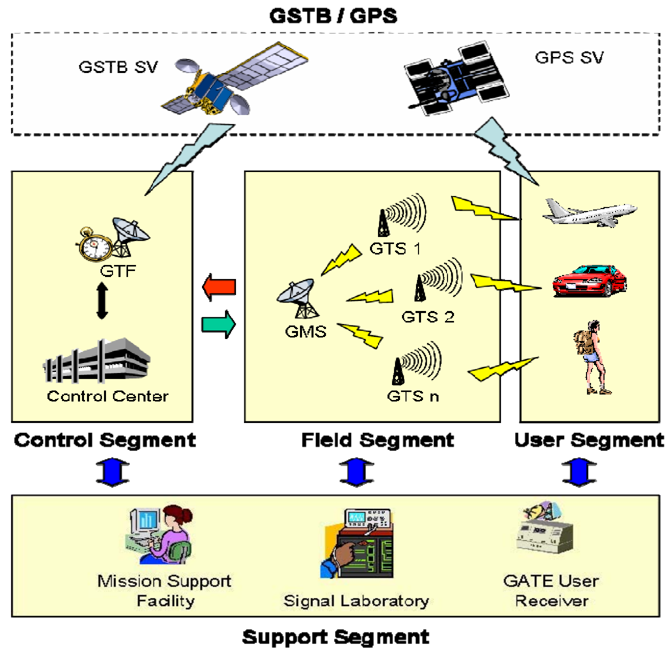

Figure 1 : GATE Architecture

B. Precise timing in GATE: requirements and trade-offs

GATE position and timing services will be based on the same principles as those of Galileo. According to the mission requirements, GATE has to provide positioning based on one-way ranging with a horizontal accuracy better than 10 m (2σ). Thus, transmitter clocks have to be synchronized with respect to a stable time scale which will serve as the GATE System Time (GAST).

Transmitter positions and transmitter clock offsets from GAST will be broadcast in the navigation message. Since GATE transmitters will be static, clock synchronization errors will play the key role in the GATE error budget. Another important error source will be multipath and refraction. Tropospheric errors will be compensated with state-of-the-art models in the user equipment.

Segment	Element	Function
Field Segment	Signal transmitters (GTS)	Transmit signals compatible with Galileo ICD
	Monitoring Station (GMS)	Monitor GTS signals
Control Segment	Control Center	Monitor and control the mission; perform time synchronization; steer signal transmitters; archive mission data
	Time Facility (GTF)	Produce and provide GATE System Time
Support Segment	Mission Support Facility	Plan user tests
	Signal Laboratory	Test signal options; test user receivers in laboratory environment
	GATE User Receiver	Enable user application tests
User Segment	Customer Receivers	Test user receivers

Table 1 : Elements of GATE

A detailed analysis has shown that to meet the GATE performance requirements, the transmitter synchronization error in GATE shall be less than 4.3 ns (1σ). Figure 2 presents the maximal transmitter synchronization error which still allows to reach a given horizontal positioning error (in the range from 4 to 10 m (2σ)) under different multipath conditions.

The next step was to identify requirements to the stability of GAST and the transmitter clocks, and to provide recommendations on the update rate of the transmitter clock parameters in the GATE navigation message. This task represents a kind of multi-parameter optimization exercise where the three parameters — the stability of transmitter clocks, the stability of GAST, and the update rate — have to be optimized with respect to technical constraints, procurement and operational costs and performance. The goal was to achieve a transmitter clock synchronization error of better than 4.3 ns (1σ) with minimal expenses and system complexity.

Extensive simulations of transmitter synchronization errors and its dependence on the update rate of transmitter clock parameters have been performed. DLR's GNSS simulation tool NavSim was used to simulate the measurement and the clock data. An analysis was made

- for transmitter clocks: on different types of Quartz oscillators and Rubidium clocks
- for the source of GAST: on different types of clocks (Rb, Cs, H-masers)
- for the update interval: from 12 seconds to 2 hours .

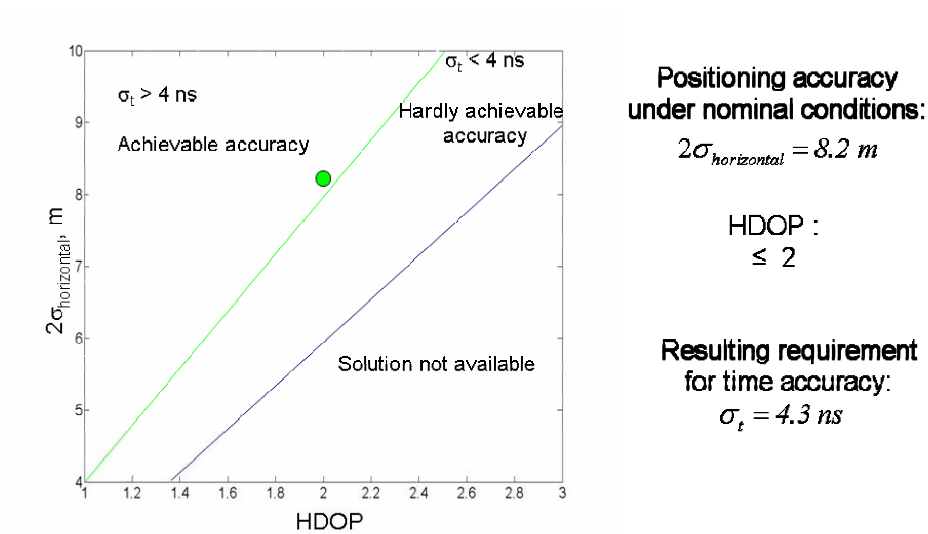

Figure 2 : Transmitter synchronization error vs. HDOP and horizontal positioning error

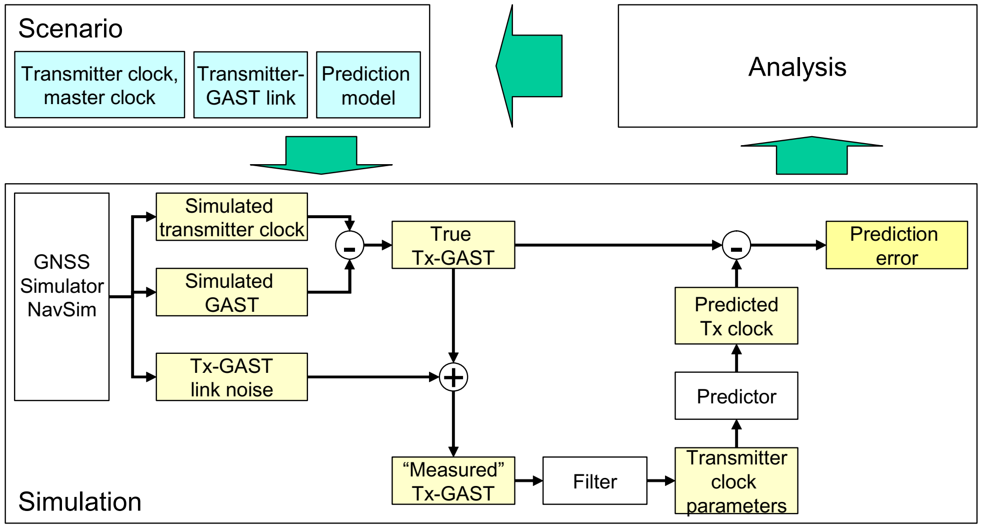

Figure 3 : Simulation of transmitter synchronization error

An overview of the simulation logic is presented in Figure 3. In the simulation process, first we studied the error of transmitter clock modeling, σ_t , for zero noise of the link between transmitter clocks and GAST. The outcome of this analysis is shown in Figure 4. Based on these results, the following set of assumptions was selected for further studies:

- the stability of GAST to correspond to the stability of a commercial Cs clock
- transmitter clocks to be commercial Rubidiums (e.g. LPRO type)
- transmitter clock model to be linear
- update rate between 12 s and 20 min .

Based on these results and considering a potential need for expert support on time keeping issues, it was decided to allocate the responsibility of GAST generation to a dedicated facility, the GATE Timing Facility (GTF). Other options under consideration were

- to produce GAST as a Composite Clock (ensemble of all transmitter clocks) — this option was rejected due to complexity of software implementation and maintenance;
- to generate GAST at the GATE Monitoring Station (GMS) which will be equipped with a GATE/GPS receiver and will be responsible for monitoring of GATE performance — this option was rejected since the Monitoring Station will be unmanned.

To reduce the project costs and to benefit from available infrastructure and expert support, it was decided to collocate the GTF with the time laboratory of DLR.

With these assumptions, a second set of simulations was produced where the noise of the link transmitter-to-GAST was included. This link consists of two sub-links:

Transmitter – Monitoring Station. This link will be established through GATE ranging signals that allow to measure the offset between transmitter clock and GMS clock.

Monitoring Station – Timing Facility. The clock of the Monitoring Station will be linked to GAST via GPS Common View (CV).

The outcome of these simulations is presented in Figure 5. These results show that to ensure the transmitter clock synchronization error of less than 4.3 ns (1sigma), the update interval of the broadcast transmitter clock parameters shall be less than 6 min. To leave some accuracy margin, the requirement to the update interval was set to 5 min.

Another important conclusion is that the main accuracy limiting factor will be not the clock prediction error itself, but biases due to calibration of time transfer equipment.

The discussion above referred to the ability of GAST to support GATE navigation services. In addition, GATE will provide also timing services. It shall enable synchronization to UTC with errors of less than 100 ns (2sigma). Therefore, GAST is required to be physically synchronized to TAI within 90 ns 95% of any yearly interval. The residual GAST-to-TAI offset will be estimated and broadcast in the GATE navigation message as well as the TAI-to-UTC offset which will be retrieved from the International Earth Rotation Service (IERS).

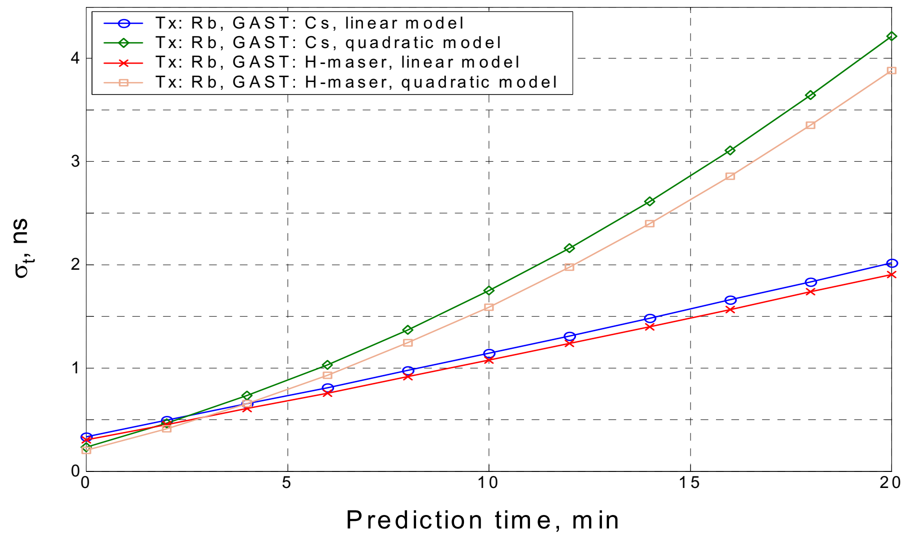

Figure 4 : Error of transmitter clock prediction σ_t (no noise on transmitter-to-GAST link)

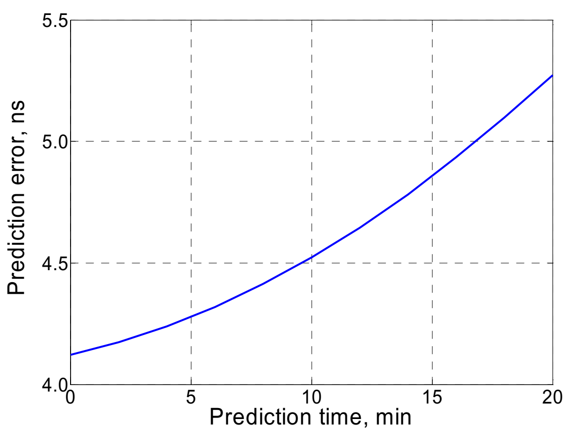

Figure 5 : Error of transmitter clock prediction (including link noise and calibration errors)

C. *Design of the GATE Timing Facility*

As mentioned above, for cost and operational simplicity reasons, the GATE Timing Facility (GTF) will be collocated with the UTC laboratory of DLR. The specific equipment for GTF will be installed at DLR's timing laboratory which will provide a controlled environment and operational support from experienced personnel. Also, the time laboratory will play the role of a UTC provider for GATE, establishing a link between GAST and TAI and retrieving TAI-to-UTC offset information from IERS. Unlike Galileo, only one time facility is to be built for GATE.

GATE will represent an experimental tool that will be operated "on demand", i.e. operations will be scheduled according to user requests. Thus, GATE will need to make certain commitments for its services against user wishes to test their equipment and/or applications. Therefore, GATE requirements comprise also those of availability and continuity for the services (and for the whole system). These requirements were propagated also to GAST and GTF as follows:

- GAST (=GTF as a whole) availability shall be at least 98%
- GAST (=GTF as a whole) continuity risk shall be less than 2% for a mission (the mission duration is two weeks)

One additional design driver was to reduce operational costs and complexity. Considering this driver and the requirements listed above, a preliminary GTF architecture has been defined (see Figure 6). In the next step, GAST stability and availability/continuity requirements were propagated to individual GTF elements and the detailed design of GTF was elaborated. The proposed design baseline optimally combines the equipment already available at the UTC laboratory of DLR and the equipment needed for GTF, including

- Precise atomic clocks (hydrogen masers),
- An automatic switch,
- Phase microsteppers,
- 1PPS and RF distributors,
- GPS receivers.

GAST will be produced as an output of a precise atomic clock. A Caesium clock would meet GAST stability and availability requirements. However, to allow Galileo-relevant test, two active hydrogen masers (in master-back-up configuration) will be used in the initial phase of GATE operations. Potential maser failures like phase and frequency leaps will be automatically detected by the clock switch and if necessary GAST will be switched to the back-up maser.

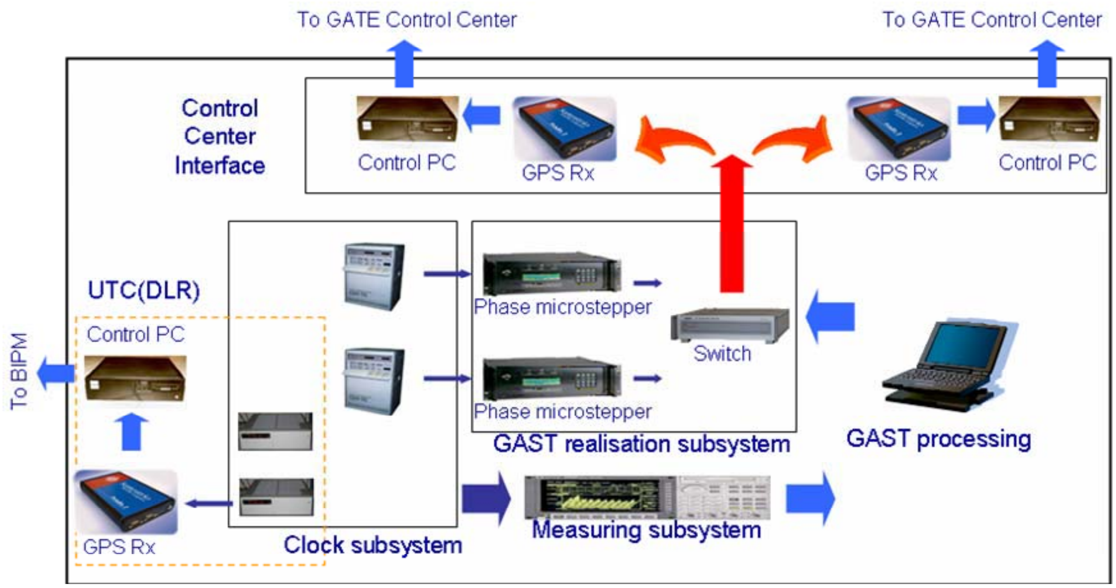

Figure 6 : GTF design baseline

Since the same task shall be solved at the Galileo PTF, the experience collected in GATE will become valuable for the Galileo operations.

GAST will be measured against UTC(DLR) (the latter being steered to UTC according to the data published by the BIPM and thus representing a real-time realization of UTC). According to the measurement results, GAST will be steered to UTC(DLR). The residual offset GAST-UTC(DLR) will be broadcast in the GATE navigation message.

In case of a failure in the UTC(DLR) generation chain, GAST will temporarily loose the link to UTC. However, performance of the GATE navigation service will not be affected, and degradation of GATE timing service accuracy will be relatively small due to high stability of the GATE reference clocks.

III. Composite Clock for Galileo

The major drawback of the master clock concept selected for GATE and for the Galileo PTF is the reliance on a single clock as a physical source of the system time. Even if backed by local hot spares, the system time in principle is vulnerable to any clock event (like phase and frequency steps) and to hazards involving the PTF itself (like natural catastrophes and terrorist attacks).

This problem can be solved by computing the system as a weighted average from the ensemble of system clocks, a so-called Composite Clock. For Galileo it would be clocks at the ground tracking stations and onboard the satellites which sums up the ensemble to at least 58 Rubidium clocks (30 satellites plus 28 tracking stations). Such an ensembling algorithm also might be applied to GATE. GATE may utilize clocks at its terrestrial transmitters (6 Rubidium clocks, 1 per transmitter) and monitoring stations (2 Rubidium clocks).

GPS adapted this approach to generation of the system time in 1990. This technology is also highly relevant for precise timekeeping allowing to produce national and local reference timescales from a distributed clock ensemble making the timescale more robust and less vulnerable to various natural and human-caused hazards. In addition, the Composite Clock allows to reliably characterize the performance of each individual clock in the ensemble.

A test-bed presently being designed by a consortium of German industry and research institutes under the lead of Kayser-Threde (see Fig. 7) will allow to gain operational experience with this technology and to adapt it for Galileo and also metrological applications.

The test-bed foresees to track GPS satellites at the following three monitoring stations equipped with active hydrogen masers:

- Physikalisch-Technische Bundesanstalt (the national time institute of Germany) in Braunschweig,
- DLR in Oberpfaffenhofen, and
- Bundesamt für Geodäsie und Kartographie in Wettzell.

The test-bed will enable a detailed study of performance and failure modes of the GPS onboard clocks from which a Composite Clock has to be computed.

Another major goal of the test-bed is to elaborate a method to combine the Rubidium clocks onboard the satellites with considerably more stable active hydrogen masers on ground into a common timescale. Studying performance of the algorithm on one hand and gaining operational experience with this novel algorithm (especially, handling of clock extractions and introductions and detection of clock failures) on the other hand would be highly relevant for further improvements of the Galileo system.

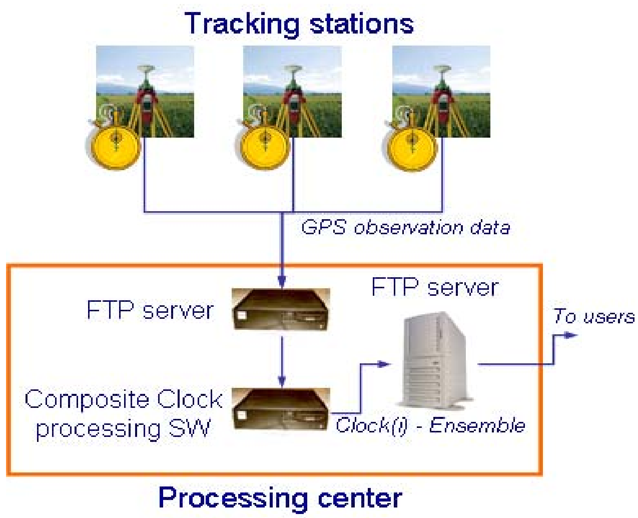

Figure 7 : Composite clock test-bed

ACKNOWLEDGEMENTS

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