Fidelity – Progress Report on Delivering the Prototype Galileo Time Service Provider

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Abstract— **The Fidelity consortium is currently implementing and will operate the Galileo Time Service Prototype Facility (GTSPF) in order to deliver Coordinated Universal Time (UTC) services to the Galileo satellite system during its In-Orbit Validation phase (due to begin in 2008). A key element of this plan is to integrate the Galileo timing activities into the wider time and frequency community, including the Bureau International des Poids et Mesures (BIPM). The main function of the GTSPF is to provide parameters for steering Galileo System Time (GST), as realized at the Galileo Precise Timing Facility (PTF), to UTC (modulo 1 s). This will be achieved in a three step process. First, the GST (as realized in the Galileo PTF from an ensemble of atomic clocks (active H-masers, high performance Caesium standards) with dedicated measurement equipment and clock ensemble algorithm) is compared against the participating UTC(k) time scales by Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GPS P3 techniques. These raw data are sent to the GTSPF for processing. The Fidelity consortium is responsible for the calibration of the time transfer equipment. Second, the GTSPF generates a prediction of the difference UTC - GST (modulo 1 s) by means of an intermediate composite clock obtained from an ensemble of atomic standards maintained in the PTFs and in the participating European National Metrology Institutes (NMIs), and using the data of UTC - UTC(k) as computed by the BIPM. The benefits of the composite clock include enhanced stability and integrated integrity monitoring. Third, the GTSPF sends daily steering parameters to the PTF to be used to align the physical realization of GST against UTC (modulo 1 s) as required by the Galileo system specifications.**

The specification and design phase of the implementation of the GTSPF was concluded in August 2006 with the successful completion of the Critical Design Review (CDR). This included the functional and physical design of the GTSPF and the verification of the uncertainty budget by means of extensive simulations. The design and functions of the GTSPF currently being implemented are detailed in this paper. The algorithm to be used for the prediction of UTC – GST is described. The time transfer link calibration activities under the responsibility of Fidelity are detailed. The PTF interactions with the GTSPF are described. A possible relationship between the GTSPF and EGNOS, the first step of European navigation satellite systems, is proposed. Finally, this paper gives a summary of the current status of the GTSPF implementation and the planned future activities of the Fidelity consortium.

I. INTRODUCTION

The realization of the European satellite navigation system Galileo is currently managed by the European GNSS Supervisory Authority (GSA), which replaced the former Galileo Joint Undertaking (GJU) in January 2007. The Fidelity consortium has been under contract since June 2005 for the specification, design, implementation, testing, and operation of a Galileo Time Service Prototype Facility (GTSPF). The members of Fidelity are listed in Section II. The role of the GTSPF is described in Section III. It has to deliver time metrology activities to support the In-Orbit Validation (IOV) phase of Galileo, currently scheduled for

2008. Specifically, it must provide the parameters to steer the Galileo System Time (GST) time scale to Coordinated Universal Time UTC, in order to keep the difference UTC - GST in compliance with requirements listed in this paper. The Fidelity consortium must also manage the relationship with the Bureau International des Poids et Mesures (BIPM). Further, Fidelity has to plan for a smooth transition from the GTSPF at IOV towards the future Full Operational Capability (FOC) of Galileo, together with the potential wider use and role of Galileo timing services.

To fulfill its role, the GTSPF prototype has been designed as an automated facility. Its architecture and functions are detailed in Section IV. Section V describes the algorithm to be used for the prediction of UTC - GST, a major issue with respect to the requirements of the GTSPF prototype. This algorithm is based on clock comparisons between the Galileo Precise Timing Facilities (PTF) and the European National Metrology Institute (NMI) core members of the Fidelity consortium, called "UTC(k) laboratories" in many documents. Of course, time transfer requires calibrations, as discussed in Section VI. The PTF functions and design are also described together with the PTF interactions with the GTSPF in Section VII, followed by a proposal for the interaction between the GTSPF and the first step of European navigation satellite systems, EGNOS. The paper is concluded by the current status and future planning of the project.

II. THE FIDELITY CONSORTIUM

The Fidelity consortium comprises a balance of leading industrial companies in the field of navigation and the scientific and technical capabilities of European NMIs. The consortium was specifically established to exploit the strengths of each member in delivering the prototype GTSPF.

TABLE I. FIDELITY TEAM STRENGTHS AND ROLES

	Main activity	**Role in project**
Helios, UK	Technical and management consultancy	Project Manager Lead definition and design
NPL, UK	UK NMI	Lead for GTSP Operational. Contributing to definition and design, GST-TAI prediction and steering algorithms
Kayser-Threde, DE	Design, development & manufacturing in space, scientific and industrial sector	Systems engineering. Contributing to definition and design
CNES, FR	French space agency	GTSP operations.
INRiM, IT	Italian NMI	Standardization, support on algorithms, relation with BIPM
PTB, DE	German NMI.	TWSTFT: operations and link calibration
LNE-SYRTE, FR	French NMI	GPS: operation and receiver calibration
Thales, UK	Global electronics company	Composite clock software
AOS, PL	Polish research institute	Performance assessment

Table 1 provides the identity and country of origin for each of the nine Fidelity partners. It also provides a short summary of the main activities for each partner organization and a mapping onto their main roles within the Fidelity project.

III. ROLE OF GTSPF PROTOTYPE

The main role of the GTSPF prototype is to provide parameters for steering GST as realized at the Galileo PTF to UTC (modulo 1 s). This is achieved in a three step process. First, the GST, as realized in the PTF from an ensemble of atomic clocks (active H-masers, high performance Caesium standards) with dedicated measurement equipment and clock ensemble algorithm, is compared to UTC(k) time scales by Two-Way Satellite Time and Frequency Transfer (TWSTFT) [1] and GPS P3 [2] techniques. Clock and time transfer raw data are sent to the GTSPF for further processing on a daily basis. The Fidelity consortium is responsible for the calibration of the time transfer links (see Section VI). Second, the GTSPF generates a prediction of the difference UTC - GST (modulo 1 s) by means of an intermediate composite clock obtained from the ensemble of H-masers and Caesium clocks maintained in the PTFs and in the European NMIs, and using the data of UTC - UTC(k) as computed by the BIPM. The benefits of the composite clock include enhanced stability and integrated integrity monitoring (see Section V). Third, the GTSPF sends daily steering parameters to the PTF to be used to align the physical realization of GST against UTC (modulo 1 s) as required by the Galileo system specifications.

The performance requirements on GST steering which must be met by the GTSPF are: UTC – GST (modulo 1 s) time offset less than 50 ns (coverage factor k = 2); uncertainty of the UTC – GST time offset less than 26 ns (k = 2); contribution to GST stability due to the GST to UTC steering as computed by GTSPF less than 3×10^{-15} in terms of Allan deviation at an averaging time of one day; uncertainty of the UTC – GST normalized frequency offset less than $5{,}4 \times 10^{-14}$ (k = 2) at an averaging time of one day.

The design phase, including the uncertainty budget, has been successfully completed in August 2006 during the Critical Design Review. The next chapter describes the design and functions of the GTSPF automated facility needed to perform these activities. The work in progress concerns the implementation, verification and validation phase and preliminary operations of the GTSPF, together with the planning for the relationship with EGNOS and the future wider use and role of the Galileo timing services.

IV. GTSPF DESIGN

A. *GTSPF Architecture*

The GTSPF is the facility to be implemented to support Galileo IOV activities. The initial stage of the design phase concerned the production and review of the GTSPF system level requirements and the GTSPF external Interface Control Document (ICD). This led to the development of the GTSPF element level requirements and the GTSPF design.

B. *Context and Scope of the GTSPF*

Figure 1. graphically presents the context and scope of the GTSPF for Galileo IOV assumed here. In the figure, the central solid rectangle represents the GTSPF specified and

designed by Fidelity. This is currently under implementation and testing and will be delivered in time to support Galileo IOV activities. The external entities with which the GTSPF must interface are represented by the other boxes, and are described below. The broad arrows then represent the information flows across the GTSPF external interfaces.

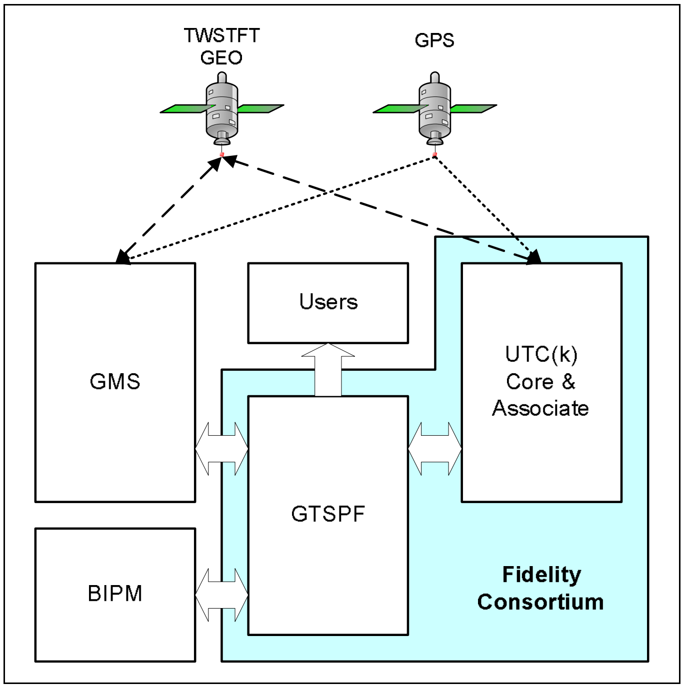

Figure 1. GTSPF Context and Scope

The external entities shown in Figure 1. are:

GMS: The Galileo Ground Mission Segment (GMS) provides the GTSPF with PTF clock and time transfer data on a daily basis, together with the steers actually applied to GST(MC), where MC means "Master clock". GST(MC) is the physical signal representing GST to which all measurements inside a PTF are referred (see Section VII).

BIPM: provides the GTSPF with its Circular T on a monthly basis, which, among other information, contains in the header of its Section 1 the information regarding the offset between TAI and UTC (integer number of seconds) and scheduled changes of this difference whenever the introduction of a leap second is announced. TAI is the Temps Atomique International, computed by the BIPM from about 240 clocks located in about 55 worldwide institutions, from which UTC is built. The GTSPF may also provide the BIPM with the PTF clock and time transfer data to be used for the TAI computation and for possible inclusion of the time difference UTC – GST(MC) in the Circular T as per the current practice for GPS and GLONASS time scales. This is currently under discussion.

UTC(k): The core and associate UTC(k) laboratories provide the GTSPF with individual clock data referenced to UTC(k) and time transfer data on a daily basis. The GTSPF also communicates processing results to individual UTC(k) laboratories.

Users: The GTSPF provides a web site including performance reports on GST to TAI steering among other information for authorized parties (eg, ESA, GSA, Fidelity consortium members, etc).

C. System Functions

The top level functional grouping of the main functions comprising the GTSPF is identified in Figure 2. and a summary of the functionality is provided below.

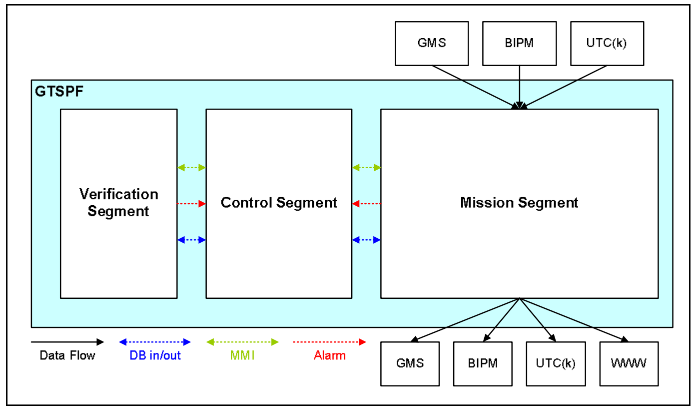

Figure 2. GTSPF Top Level Functional Grouping

1) Verification Segment (VS)

The VS monitors the performance of the whole mission, and provides analysis reports of the performance trends, and configuration and calibration parameters: Verify Daily Parameters (VDP), which include the current UTC − TAI offset and planned changes, the predicted offset TAI – GST(MC) and its uncertainty, and GST(MC) steering parameters; Verify Monthly Parameters (VMP), which include a monthly summary of the GTSPF clocks and time transfer status, the current UTC − TAI offset and planned changes, the maximum daily TAI − GST(MC) offset, and the maximum daily TAI − GST(MC) offset based on a 10-day rolling window; Verify Annual Parameters (VAP), which include an annual summary of the GTSPF clocks and time transfer status, an annual summary of the maintenance activities including calibration, the maximum daily TAI − GST(MC) offset over the reporting year, and a summary of the maximum uncertainty of the TAI − GST(MC) offset based on a 10-day rolling window; Verify System Parameters (VSP), which include the daily, monthly and annual disseminated UTC − GST(MC) performance, based on the predicted offset; and finally Verify Configuration & Calibration Parameters (VCCP), which include configuration of the clocks and time transfer links used by the GTSPF, status of the clocks used by the GTSPF highlighting potential integrity issues, status of the time transfer links used by the GTSPF, schedule of planned and ongoing maintenance activities including calibration.

2) Control Segment (CS)

The CS is responsible for providing the means to configure and control the GTSPF as well as the means to communicate information concerning the GTSPF performance to external users. Its comprises the Data Manager (DM), the Asset Control Facility (ACF) and the Website, plus the Data Base Management System (DBMS) which underpins all GTSPF data management and includes the archiving and retrieval functionality, the GTSPF Archive (ARCH) facility, the Man-Machine Interface (MMI) which operators will use to monitor, configure and control the various elements, and the Alarm Manager (AM) which monitors status messages raised by other GTSPF elements and routes them to the appropriate places (MMI and possibly external entities).

3) Mission Segment (MS)

The MS is responsible for providing the mission critical processing of the time transfer data and the production/dissemination of the GST steering parameters. It comprises the Pre-Processor (PP), Processing Facility (PF) and Communications Manager (CM). The pre-processing applies to various data and monitors their integrity: GPS P3 observables; Galileo observables (this functionality will be implemented for FOC only); time differences measured physically between pairs of clocks in the same laboratory or PTF; TWSTFT observables. From there, the Composite Clock (CCLK) forms a close to optimal free running ensemble timescale C_{GTSP}, and the Time Prediction and Steering (TPREDSTEER) produces the steering parameter of GST(MC) to TAI, to be provided to the PTF on a daily basis (see Section V).

Moreover, the External Interface Manager (XINT) manages the interface with all external entities including the communications protocols (Virtual Private Network where necessary) and addressing. The Data Decoder (DD) decodes data from external entities and stores them in the DBMS. The Message Generator (MSG) formats data products into a format suitable for the different external entities. And finally, the restricted access Website (WWW) makes daily, monthly and annual data products available to authorized users only.

D. Physical Architecture

The GTSPF system physical architecture will be the operational system at Galileo IOV to be hosted by CNES. It has been optimized to be robust and secure. The GTSPF data collection, processing and outgoing message generation all take place behind firewall and a Virtual Private Network (VPN) router protection. All data which is to be made available to the outside world (including GMS) will be placed on either a data cache or a web server in the protected zone between two firewalls. The operational processing takes place on a platform with a cold standby to ensure availability even in the case of a hardware failure.

V. Algorithm for the Prediction of UTC-GST

A. Composite Clock algorithm

The Composite Clock algorithm is based on a Kalman filter computation, because when properly adapted it produces a near to optimal time scale for all averaging times. This was preferred to a time scale based on a weighted average of the clock data, which produces an optimal result for one single averaging time only. One of the drawbacks of Kalman algorithms, which was the indefinite growth of the covariance matrix [3] because the physical parameters represented by the state vector are only partly observable from the measurements made between individual clock pairs, was recently overcome for all noise types as demonstrated on simulated and real clock data in [4]. Moreover, the Kalman filter clock algorithm was found to operate well when the component clocks exhibit linear frequency drift, which is the case with H-masers.

From all individual clock pairs, measured either directly or with the use of remote time transfer, the Composite Clock algorithm builds daily the free running ensemble timescale C_{GTSP}, which is realized through each individual clock C_I, one of these being GST(MC), by the product of the computation process $C_{GTSP} - C_I$. Since April 2007, the clock and time transfer data of the participating NMIs are collected daily in order to test the Composite Clock algorithm.

B. Time Steering Prediction

The developed Kalman filter clock predictor was demonstrated to perform significantly better than a simple linear predictor, in the presence of the modulation noise types usually present in the clock data [5]. The Time Steering Prediction is a two stage process. First, the offset between TAI and the free running ensemble timescale C_{GTSP} is both extrapolated from past known data published by the BIPM, and then steered to TAI to form C_{GTSPS}. C_{GTSPS} becomes that way a near real time approximation of TAI that is available on a daily basis. Second, TAI – GST(MC) is estimated on a daily basis, the future values of the TAI – GST(MC) offset are predicted and steering corrections to enable the PTF to align GST(MC) to TAI are provided, together with estimates of the normalized frequency offset between TAI and GST(MC). The GTSPF then delivers daily the steering parameters to the PTF.

On the other hand, the GTSPF will provide as a side product a daily prediction of UTC – UTC(k) based on a large ensemble of clocks, which might be of utmost metrological interest for the participating NMIs.

VI. Calibration of Time Links

A. TWSTFT for the GTSPF

The PTFs shall become part of the existing European TWSTFT network which includes, among other institutes, the UTC(k) laboratories that are core members of Fidelity. TWSTFT shall be performed between the two PTFs, the four NMIs INRiM, LNE-SYRTE, NPL and PTB, and USNO. The schedule of measurements has to be agreed by the Working Group on TWSTFT of the Consultative Committee on Time and Frequency (CCTF) and will then be communicated through the GTSPF to the PTFs (GMS). The Fidelity consortium is responsible for the calibration of the time links.

The procedures and measurement quantities detailed in [6] are relevant for calibration with a portable TWSTFT station within Europe. The portable TWSTFT station is installed next to a stationary set-up for two days typically and is included in the TWSTFT measurement schedule. A SATRE code is assigned to the portable station, and time slots are reserved for performing measurements between the two co-located TWSTFT stations connected to the same time reference and linked by the same Ku band transponder. This constitutes a so-called common clock experiment. It allows the determination of the delay difference between the participating stations, in pairs, with about 1 ns uncertainty.

For the transatlantic link between the PTFs and the USNO, which will determine the GPS Galileo Time Offset (GGTO), the calibration requires an independent technique [7] because of the use of two different Ku band transponders for the two signal propagation directions, E-W and W-E respectively.

B. GPS P3 Calibration

GPS P3 will be the backup method for time transfer between the PTFs, the UTC(k) laboratories, and the USNO for GGTO determination. The links will be differentially calibrated in a classical way [8] by using traveling equipment (receiver, cable, antenna) first evaluated against the LNE-SYRTE operational equipment. Two calibration trips are currently scheduled to take place, at the start of operation of the PTFs, and at the end of IOV activities, between the same set of stations.

VII. The Precise Timing Facility

Fidelity has no responsibilities in the Precise Timing Facility (PTF) design, realization or implementation. The PTF is only described here for a complete understanding of the interactions between PTF and GTSPF.

A. General Description

The Galileo System timing architecture comprises among other elements two PTFs which will be physically implemented within the Galileo Control Centers (GCC). The primary purpose of the PTF is to provide to the Galileo satellite navigation system a reliable and stable time reference in the form of GST which shall be available as a physical output signal. The PTF is designed as a basically un-manned Element and thus has to embark on a high level of automation and a sophisticated monitoring and control installation. The major functions of the PTF can be summarized as follows:

1) Maintain a stable ensemble of ground clocks (active H-masers and Caesium standards) in a stable environment. One maser will be assigned the Master Clock (MC) status, and the second maser shall serve as the Backup Clock (BC);
2) Compute GST as a weighted average of all clocks operated in the PTF and provide steering of the MC to this ensemble in case of PTF autonomous operation;
3) Accept steering corrections provided by the GTSPF and steer GST to UTC (modulo 1 s);
4) Provide a physical realization of GST (1 PPS, 10 MHz);
5) Distribute GST(MC) externally and within the GCC; in particular one Galileo Sensor Station (GSS) will be co-located with the PTF and will use GST as its reference time scale, thereby making GST available as time reference in the Orbit Determination and Time Synchronization (ODTS) process;
6) Operate time transfer equipment, comprising of a GPS receiver providing GPS P3 data, at a later stage a mixed GNSS timing receiver, and a TWSTFT ground station. TWSTFT has been defined as the primary method for the mutual synchronization of the two PTFs (see below), for the determination of the GST-GPS time offset during the IOV phase [9], and for the support of the TSP activities;
7) Realize a backup GST based on the BC and steer the second realization of GST tightly to the primary one so that switching between both physical realizations can be done – automatically in case of MC signal loss or intentionally – without disruption of the ODTS process.
8) Measure all individual clock time offsets with respect to GST(MC) through a local measurement system;
9) Monitor and survey PTF clock frequency instability;
10) Provide GST parameters and PTF clock ensemble data to GTSPF;
11) Disseminate GST as analogue time coded signal (IRIG-B) in the GCC and via SNTP in the Galileo Wide Area Network (WAN).

B. Master-Slave Concept

During the IOV phase two PTFs will be available [10], PTFK developed by a team under leadership of Kayser-Threde, Germany and PTFC, developed by Consortio Torino Time [11]. Both are currently being developed based on the same set of requirements and will thus be similar in design. One PTF will be initially assigned 'Master PTF' with the responsibility for the generation of GST. The other will be assigned 'Slave PTF', producing a redundant GST. Should the need arise, switching the MC status within each PTF, or switching the Master PTF status between the two facilities shall be performed. By definition, the final GST is always the Master Clock output from the Master PTF.

C. PTF interaction with the TSP

From a technical point of view, it is most important that time scale comparisons between both PTFs and the UTC(k) laboratories associated with Fidelity will be established. Fidelity also has the task to arrange calibration of the time links. The time comparison data form, among other inputs, the basis for the prediction of GST – UTC by the GTSPF. The PTF will receive the GST to UTC steering command which will be used to steer the MC output. A secondary activity is the provision of PTF internal clock data so that they can be used in the GTSPF algorithm, as well as being relayed to BIPM for use in the calculations of TAI (still under discussion). The PTFs will receive back notification of any malfunctions or anomalies of the clocks and time transfer equipment.

VIII. Relationships between EGNOS and the GTSP

The European Geostationary Navigation Overlay Service (EGNOS) is the first step of European navigation satellite system. It provides integrity assessment and corrective terms on the GPS signal available over Europe. EGNOS Network Time (ENT) is the reference time scale for EGNOS, built from the clocks located in the 34 Earth stations of the system.

EGNOS broadcasts in its Message 12 the time difference ENT – UTC. This offset is computed using an EGNOS station in the Observatoire de Paris, in order to relate ENT to UTC(OP), and a prediction of UTC – UTC(OP). A detailed description is given in [12]. ENT – UTC is then obtained from the equation: [ENT – UTC(OP)] – [UTC – UTC(OP)].

A. *Possible role of the GTSP in the monitoring of the time offset ENT – UTC*

The GTSPF will compute everyday a prediction of UTC – UTC(OP) which may be useful to improve the estimation of ENT − UTC, even if the current issues are more about the ENT – UTC(OP) computation [13]. Such a modification may have impacts on the EGNOS operational procedures and remains under discussion.

B. *Possible role of the GTSP in the monitoring of the time offset ENT – GST*

ENT – GST can be computed with respect either to GST(MC) as generated in the PTF, or to GST_{user}, where GST_{user} is the Galileo System Time as received by the users. The first of these will use the measurements performed by the PTF GNSS receiver which is driven by GST(MC). Applying EGNOS corrections on its GPS measurements provides accurately ENT – GST(MC) if all the PTF calibrated delays are properly considered. On the other hand, the computation of the position of the PTF using Galileo measurements gives access to GST(MC) – GST_{user}. This processing would allow the monitoring of ENT – GST(MC) as well as GST(MC) – GST_{user}, hence ENT – GST_{user}. It may be carried out by the GMS for real-time needs or by the GTSPF for non real-time needs.

A second method would involve the broadcast timing messages. EGNOS broadcasts an estimation of ENT – UTC, while Galileo will also broadcast an estimation of GST – UTC. Collecting these messages and computing a simple difference yields ENT – GST. This method has the advantage of simplicity, however its accuracy directly relies on the quality of the EGNOS and Galileo broadcast timing messages [13]. Today this method is deemed to be more a cross-validation activity that may be carried out by the GTSPF, the role of which could be extended to monitor in addition GPS and GLONASS broadcast timing messages to form a unique center for determining, assessing and disseminating GNSS time differences.

IX. Current Status and Perspective

The specification and design phase of the implementation of the GTSPF was concluded in August 2006 with the successful completion of the Critical Design Review (CDR). This included the functional and physical design of the GTSPF and the verification of the uncertainty budget by means of extensive simulations.

The project has recently completed the Development Key Point 1 (DKP 1) review, by GSA, of the implementation status, and verification and validation planning for the GTSPF. This review also addressed analysis of and planning for the wider use and role of the Galileo timing services, both in terms of the transition from Galileo IOV to FOC and providing timing services to a wider community.

The calibration activities for the GTSPF will start soon with the procurement of some required equipment. The collection of clock and time transfer data produced by the NMIs has already started, to be used for preliminary tests of the software. The GTSPF development is exactly in line with the plan agreed at CDR. The next major milestones, as currently scheduled, are Test Readiness Review in November 2007, Acceptance Testing Review in February 2008, Validation Key Point in May 2008, and a Final Review to be held in October 2008 at the end of the Fidelity contract. Meanwhile, the work on the wider use and role of Galileo is ongoing, together with the planning for the migration to the Galileo FOC phase.

This schedule of course depends on the operational starting date of the PTFs, on the IOV planning, and more generally on the global Galileo development.

Acknowledgment

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