TECHNICAL STATUS OF THE GALILEO SYSTEM DEVELOPMENT

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Abstract

The development of the Galileo System continues under the partnership of the European Commission and the European Space Agency. ESA is charged with the development of the elements of the "Global Component," which will be comprised of the complete constellation of satellites together with the ground segment. The ESA development will culminate in the establishment of an In Orbit Validation (IOV) milestone, which will contain a minimum number of each element of the Full Operational Configuration (FOC).

An overview of the Galileo services and requirements is provided. We briefly outline the architecture of the Galileo Global Component. We also introduce the overall development approach and risk mitigation activities such as GSTB-V1/V2 and GIOVE-A/B/M. The interoperability aspects (i.e. GGTO) are highlighted as well. The present master working schedule is presented.

1 INTRODUCTION

1.1 GALILEO SYSTEM HIGH-LEVEL OVERVIEW

Galileo will be an independent, global European-controlled satellite-based navigation system. It will have a constellation of satellites complemented with a ground segment providing system and satellite monitoring and control, including an integrity function to broadcast real-time warnings of satellite or system malfunctions.

Galileo will provide navigation services of the following types:

- Open Services providing global positioning and timing services, free of charge, by means of navigation signals, separated in frequency to allow user autonomous correction of ionospheric delay error.
- Safety-of-Life Services providing integrity services with a defined time-to-alert limit, by means of supplementary data signals, which will be either encrypted or authenticated, within the Open Service signals.
- Commercial Services providing data dissemination services, by means of supplementary data signals, which may be encrypted, within the Open Service signals, and a third navigation signal

on a separate frequency, to which access may be controlled, to allow users to use three-carrier phase-ambiguity resolution (TCAR) techniques.

- Public Regulated Services providing global positioning and timing services by means of two navigation signals, to which access will be controlled, separated in frequency to allow user autonomous correction of ionospheric delay error.

Table 1. Galileo Service (source: European Commission).

Service			Receiver	Benefits	Target user groups	Availability
Open Service	OS		**Single frequency**	• **Additional satellites for better multi-system coverage (e.g., deep urban)** • **Coding and modulation advances for increased sensitivity and multi-path mitigation** • **Pilot signal for fast acquisition**	• **Low end mass market (e.g., LBS, outdoor)**	**Open**
			**Double frequency**	• **As above + increased accuracy with 2nd frequency**	• **High end mass market (e.g., car navigation, maritime)**	**Open**
Commercial Service	CS		**Double frequency**	• **Increased accuracy using additional frequencies and signals** • **Additional features under investigation (e.g., data rate capacity)**	• **Professional markets (e.g., surveying, precision agriculture)**	**Commercial basis**
Safety of Life Service	SoL		**Single frequency (Level B)**	• **As OS +** • **Integrity and authentication of signal** • **Continuity and service guaranty**	• **Aviation (en route)**	**Certified receivers**
			**Double frequency (Level A and C)**	• **As above at higher performance levels suitable for stringent dynamic conditions**	• **Aviation (A)** • **Maritime (C)** • **Road, Train (A)**	**Certified receivers**
Public Regulated Service	PRS		**Dual frequency**	• **As OS +** • **High Continuity (in times of crisis)** • **Improved Robustness (vs jamming, spoofing)**	• **Law enforcement** • **Strategic infrastructure**	**Regulated**
Search and rescue	SAR		**Single frequency**	• **Almost instantaneous reception of emergency calls** • **Exact positioning of emergency beacon**	• **Emergencies**	**Certified & registered beacons**

Galileo will provide navigation services using satellites only and also using satellites augmented with local, ground-based systems providing supplementary navigation signals or data dissemination services, by means of local transmissions using either special-purpose equipment or existing navigation or communications systems.

The Galileo ground segment will provide integrity, monitoring the quality of the signals of all the Galileo satellites and broadcasting integrity messages to safety-of-life users via Galileo satellites, with global coverage. However, it shall be possible to implement integrity in a gradual manner, either with reduced initial performance or with reduced initial coverage.

Galileo will be able to provide dissemination by Galileo satellites of integrity data generated by External Region Integrity Systems (ERIS). Currently, it is foreseen that such data may be uplinked to the satellites either by Galileo or by the external region systems, as may be requested by the external region operator.

Galileo will provide satellite-based augmentation services in support of GPS and GLONASS, using EGNOS, the European contribution to the First Generation Global Navigation-Satellite System (GNSS-1).

Galileo will also provide support to the international Search and Rescue (SAR) satellite services by relaying distress signals from Search and Rescue (SAR) beacons operating to COSPAS-SARSAT standards and relaying responses to these distress signals back to those SAR beacons equipped with Galileo receivers.

The overall Galileo System is illustrated in Figure 1.

Figure 1. Overall Galileo System overview.

1.2 Design Choices

During the development of Galileo the following design choices have been made at the architecture level:

- SCALABLE architecture: evolution from one mission phase to the next should be done by deployment/removal of elements, but not by redesign of concepts/parts of the system
- ADAPTABLE architecture: in case the final design solutions evolve and also to allow later decisions in the program for mission and system aspects which cannot be frozen at this stage
- STEPWISE DEPLOYABLE architecture: adapted to the programmatic constraints of the Galileo program (cost, verification, schedule, etc) without major design impacts.

Design choices have been made at a lower level as follows:

- Mission data (Navigation/Integrity/Search & Rescue) are uplinked separately from TTC data
- Robust TTC uplink provided through 13-m S-band antennas
- Mission data uplink provided through dedicated C-band antennas
- Co-location proposed for satellite control/navigation control/integrity control common functions:

  - Common navigation/integrity network of sensors stations
  - Common navigation/integrity monitoring & control facilities
  - Uplink elements in common sites
  - TTC global coverage is retained for special operations
  - Independent Search & Rescue payload (incl. forward antenna) onboard the satellite.

The Galileo space segment will be comprised of a constellation of 27 operational satellites in medium-Earth orbit (MEO, Walker 27/3/1), so that at least 10 satellites will normally be visible from any point on the Earth's surface, plus nominally three nonoperational in-orbit spare satellites, one in each orbit plane. The orbit altitude will be approximately 29600.318 km with an inclination of 56 degrees and an orbital period of 14 hours 4 min and 42 sec. The ground-track repeat cycle will be 10 days or 17 orbits. Each satellite will broadcast precise ranging and time signals on four carriers, together with clock synchronization, orbit ephemeris, and other data. A user equipped with a suitable receiver will be able to determine his position to within a few meters when receiving signals from just four Galileo satellites.

1.3 GALILEO SATELLITES

The Galileo satellites will contain the following main subsystems:

- The timing subsystem has two pairs of redundant clocks, each pair consisting of two different technologies (rubidium clock and passive H-maser)
- The signal generation subsystem provides formatting, encoding, & modulation of carrier frequencies, controlled by the navigation processor
- The RF subsystem amplifies the modulated carriers, the baseline being use of solid-state power amplifier technology
- The antenna subsystem transmits the navigation signals to users
- The C-band receiver subsystem receives navigation and integrity (mission) data uplinks from ground (up to six channels simultaneously).

1. 4 GROUND SEGMENT

The Galileo ground segment will control the whole Galileo constellation, monitoring satellite health and uploading data for subsequent broadcast to users. The key elements of these data, clock synchronization and orbit ephemeris, will be calculated from measurements made by a worldwide network of stations. Galileo will provide an interface to Service Providers. These Service Providers will give users a point-of-contact to the Galileo system, will provide a variety of value-added services and will play a role in collecting fees. This interface may also include provision of specialist data, such as clock and ephemeris history and predictions to specialist scientific users.

The overall architecture building blocks (see Figure 2) can be listed as follows:

- Galileo Sensor Stations (GSS): forty stations for orbit determination/time synchronization (ODTS) and integrity purposes. Each station hosts two receiver chains (navigation/integrity and integrity only).
- Galileo TTC stations (S-band) (TTC): five stations each hosting one 13-m antenna dish
- Galileo Mission Uplink Stations (C-band) (ULS): nine stations each hosting 5 or 6 3-m antenna dishes
- Worldwide communications network

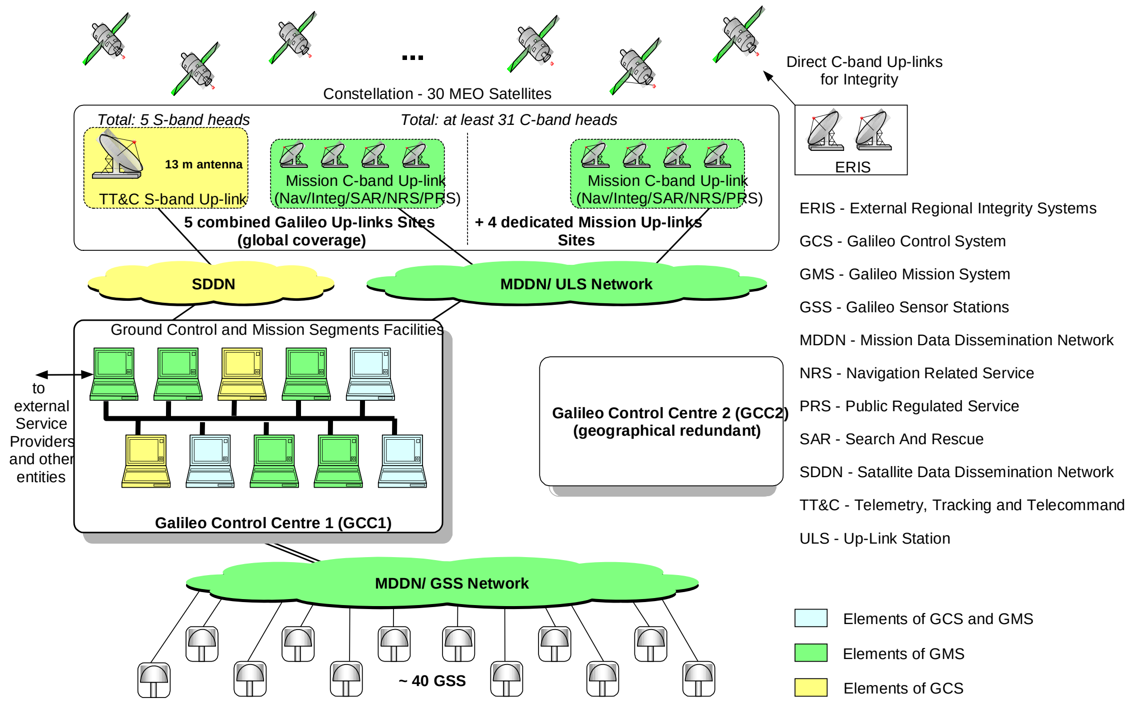

Figure 2. Galileo building blocks.

External components, such as GPS, GLONASS, and LORAN-C, may be interfaced to Galileo receivers to provide combined navigation services. Galileo will thus provide a range of guaranteed services to users equipped with receivers meeting Galileo specifications.

2 GALILEO MISSION PHASES AND DEVELOPMENT APPROACH

The mission phases address all the steps required to reach the mission objectives. This is a logical decomposition and covers the engineering processes of the Galileo Segments.

The implementation of Galileo is characterized by an incremental approach for the buildup of the segments. The following list provides a brief definition of the main phases (see Figure 3):

- In-Orbit validation (IOV) Phase – Its scope is to early validate/verify Galileo (segments, operations, and service provision) before the deployment of the overall system. The IOV concept is based on the definition of an architecture that has to be reduced (with respect to Galileo). The IOV results will finalize the definition and development of the segments and operations.
- Full Deployment Phase: Its scope is to complete the deployment of Galileo till FOC.

- Long-Term Operations Phase: Its scope is to provide guaranteed services to end users. Starting at FOC, it is the final but the longest mission phase dealing with the provision of mission full services and the maintenance/replenishment of the constellation and ground segment. The current baseline design considers a minimum phase of 20 years.

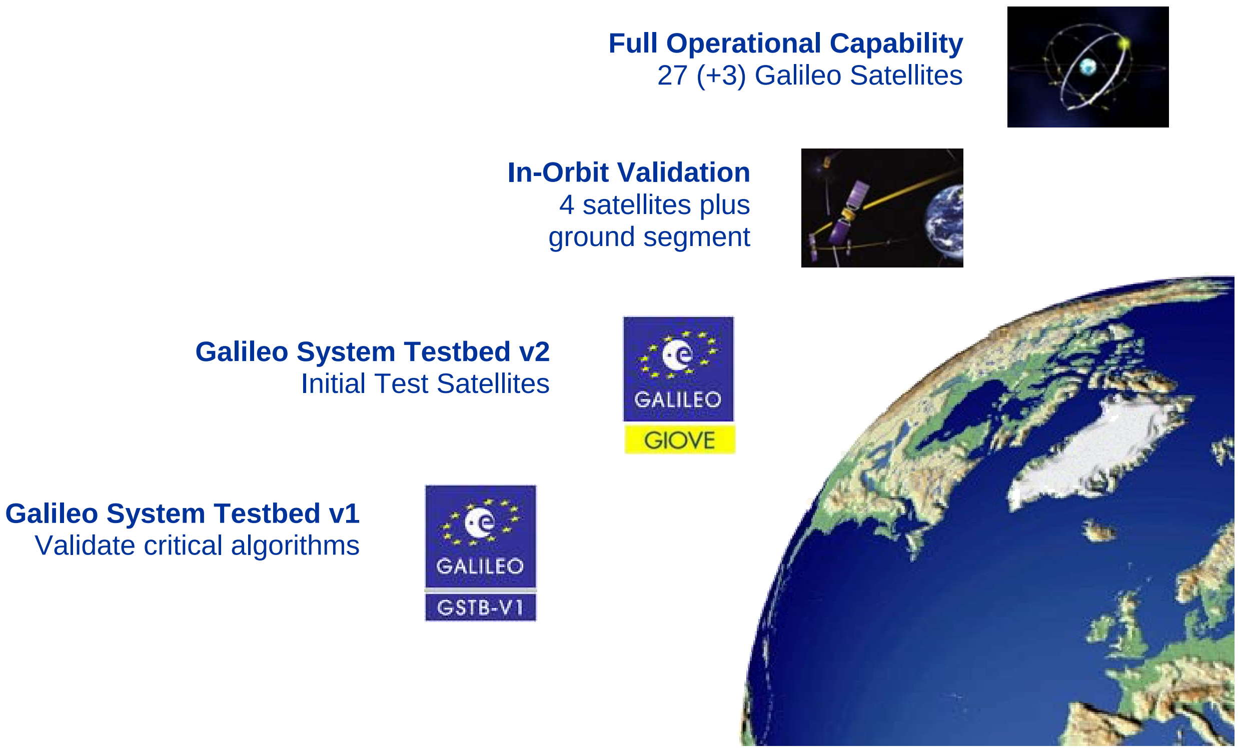

Figure 3. Galileo mission phases.

3 IOV PHASE

The mission objectives of the Galileo IOV Phase can be listed as:

- Verification of all space, ground, and user components, including their interfaces, prior to full system deployment
- Analysis of system performance with the view to refine the FOC system prior to full system deployment
- Verification of the adequacy of the siting requirements
- Verification of navigation processing
- Verification of integrity processing regarding the establishment of confidence levels of critical performance parameters, characterization of feared events and time-to-alert analysis
- UERE budget characterization
- Deployment risk reduction
- Verification of operational procedures

For the Space Segment, the following configuration will be put in place for the IOV Phase:

- up to four satellites constellation will be launched
- Main driver: Synchronization Error, i.e. satellites close to each other so as to be as much as possible visible simultaneously from the Sensor Stations:
  - baseline: four satellites in two planes,
  - alternative: four satellites on the same orbital plane
- The SAR payload is considered part of the baseline for IOV.

The drivers for the TTC stations are:

- Onboard autonomy allows for 12-hr max gap in coverage
- Downlink of high sampled TM required for feared events characterization
- SV Health Status and key TM parameters downlinked via Navigation Message.

Two TTC stations (failure-resistant) equipped with one antenna each will be deployed.

For the IOV sensor station network, one has to consider that navigation & integrity measurements need to be acquired globally. The sensor stations will have a common (Nav/Int) Galileo Receiver Chain at a 1 Hz sampling rate. This is required to verify the clock stability to characterize the Signal in Space Accuracy parameter (SISA) confidence level and perform feared-events characterization. There will be 20 Galileo Sensor Stations globally distributed.

The mission uplink stations for IOV are driven by the need for global navigation (in particular SISA) Data Uplink Rate (clock prediction) every 100 min and the regional (Europe) Integrity Flag dissemination rate of 1 sec.

The IOV configuration will be five ULS stations (5 deg masking), which will be equipped at least with 1 (+ 1 backup) antenna per site.

3.1 PASS/FAIL CRITERIA FOR IOV

All Galileo system requirements will be verified during IOV as much as possible by test. However, end-to-end service performances, due to the limitations of the IOV configuration, cannot be directly verified as such. For this reason, Performance Targets to be used as Pass/Fail Criteria have been derived from the system requirements for acceptance.

One simple example: Positioning Accuracy is derived from DOP*UERE, where the DOP value is given by Constellation Geometry (SVS) and the UERE components are measured individually through test. The ODTS ranging accuracy target value at Worst User Location (100 minutes prediction validity, RMS) is set to 300 cm.

During IOV, GPS observations will be used. The reasoning is twofold:

- Validation using Galileo-only data:
  1. Ensures functional verification, including endurance testing in FOC representative configuration
  2. Guarantees measurement of performance, but in a limited way.

- Validation using combined GPS and Galileo data:
  1. Provides truth reference for ODTS and integrity processing at ns and cm level
  2. Establishes confidence that FOC performance can be met.

The IOV testing will be performed in both cases with corresponding Pass/Fail Criteria.

3.2 Risk Mitigation Activities As Part of IOV

The Galileo risk analysis identified the following needs for:

- Early verification of Navigation and Integrity processing performance
- Protection of Galileo signal filings
- Early in-orbit verification of payload technology, in particular onboard clocks (RAFS and PHM)
- MEO orbit environment characterization
- Provision of Galileo SIS for early experimentation and demonstration of GALILEO (at receiver level).

This lead towards two essential risk mitigation activities: Galileo System Test Bed V1 and V2.

3.2.1 GSTB-V1

In the GSTB-V1, activity the following objectives have been set:

- Reduce the risk on the Galileo ground segment development through early experimentation with the Orbit Determination & Time Synchronization and Integrity algorithms
- Conduct facility pre-developments based on realistic measurements from the GPS system
- Collaborate with the established International GPS Service community and UTC Time Community.

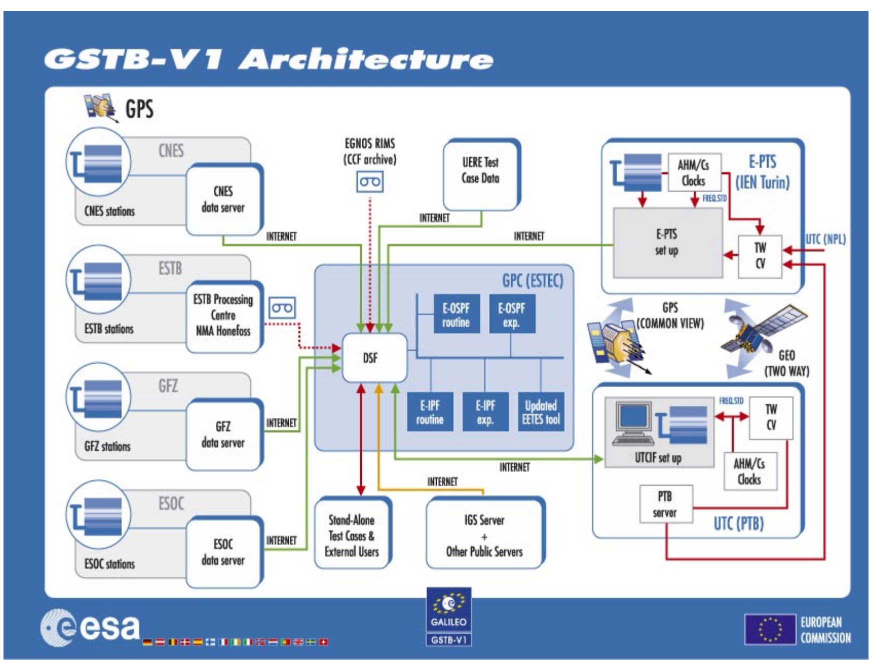

Figure 4. GSTB-V1 architecture overview.

During GSTB-V1, GPS measurements were collected worldwide by a network of stations and processed offline to verify GALILEO timing, navigation, and integrity concepts. The test bed was successfully completed in December 2004 with the provision of validated prototype algorithms and models to the ground mission segment IOV Phase CDE1 contract.

3.2.2 GSTB-V2/GIOVE

The main objectives of the GSTB-V2 arise in the following:

- Secure Galileo Frequencies
- Test Payload technology in-orbit
- Provide experimental Signal-in-Space
- Characterize MEO radiation environment.

Since the schedule is highly critical, a risk mitigation approach was implemented, which led to the launch of two experimental satellite (Galileo In-Orbit Validation Element) developments:

- GIOVE-A by Surrey Satellite Technology Ltd
- GIOVE-B by Galileo Industries SA (now replaced by Astrium GmbH).

This test bed is an experimental GALILEO satellite program. It can be considered as a precursor of the IOV Phase.

GIOVE-A was launched 28 December 2005 with a Soyuz-Fregat upper stage into the correct Galileo orbit. GIOVE-B is expected to be launched in the first quarter of 2008. More information can be obtained via **[3]**.

The associated GSTB-V2 mission segment (GIOVE-M) segment drivers are:

- Acquire and store 1 Hz raw observables from GIOVE-A and -B signal in space to support experimentation
- Process raw data to generate core products
- Make core products available to the experimentation community inside and outside ESA
- Collect payload and platform TM from GIOVE-A and –B to support investigation of onboard phenomena
- Support navigation message generation for user receiver demonstration and validation purpose.

This leads to the architecture summarized in Figure 5.

4 TIMING INTEROPERABILITY

Since 2002, a joint US/EC technical working group (i.e. Working Group A, WGA) has been working to enhance interoperability between GPS and Galileo. It is envisioned that the future navigation users would benefit from a combined GPS/Galileo navigation solution using the 20 or more GPS and Galileo satellites potentially in view. To take advantage of this combined GPS/Galileo constellation, knowledge of GPS/Galileo system time difference is required. Interoperability and Compatibility of GPS and Galileo signals are discussed in **[5]**.

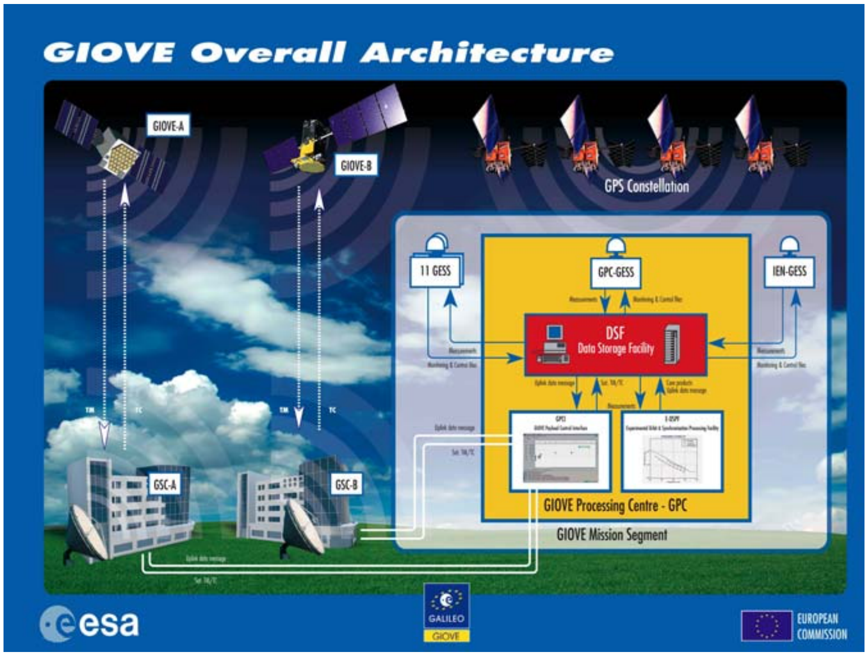

Figure 5. GIOVE architecture overview.

4.1 GGTO

The GPS to Galileo Time Offset (GGTO) (information extracted from **[6]**) can be solved for within each user receiver at the penalty of a fifth satellite being required for a navigation solution and/or the GGTO value could be provided as part of each systems navigation message. The GGTO navigation approach may be important to a user operating in an urban canyon or under deep foliage where availability of a fifth GNSS satellite cannot be guaranteed.

The driving performance requirements associated to GGTO can be summarized as:

- GGTO validity: The validity period of the GGTO shall be a minimum 24 consecutive hours
- GGTO offset accuracy: The accuracy of the offset between GST and GPS Time (modulo 1 s) shall be less than 5 ns with a 2-sigma confidence level over any 24 hours
- GGTO Stability: The stability of the GGTO, expressed as an Allan deviation, shall be better than 8×10^{-14} over any 1 day.

4.1.1 Proposed Methods

The following options to produce the GPS-to-Galileo time offset have been identified:

1. GGTO broadcast as part of the GPS and Galileo navigation message and determined by:
   - Two-way satellite time and frequency transfer (TWSTFT);
   - Common-view time transfer;
   - GPS co-located timing receiver at a Precision Timing Facility (PTF);
   - GPS/Galileo combined monitor station receiver.
2. GGTO not broadcast as part of the GPS and Galileo navigation message:

- GGTO estimated in each GPS-Galileo capable receiver at the cost of one SV tracked.

In coordination with the WGA, it was jointly agreed that a solution would be implemented out of option 1 as the baseline for Galileo's IOV Phase. This does not prevent that receiver manufacturers additionally go for option 2. In fact, we expect that all receiver manufacturers will likely implement a blended solution utilizing both the broadcast GGTO during startup or under conditions of limited satellite availability and the estimated GGTO value produced with the receiver.

4.1.2 Implementation Proposal for Phase 1

Splitting the GGTO implementation into two phases was discussed. The first phase has to deal with implementation constraints resulting from the Galileo In-Orbit Validation (IOV) Phase, namely the availability of only four Galileo satellites by 2008. The second phase would benefit from a full Galileo constellation and associated ground segment. In such a phase, a combined GPS/Galileo monitor station receiver is considered the best performing and efficient implementation solution.

For the first phase, the GGTO sub-group suggested to the WGA the following setup based on a two-way time and frequency transfer sketched in Figure 6.

In this setup, it is proposed that the Galileo program would provide:

- The communications satellite link in Ku-band;
- A two-way infrastructure to support IOV test /operational phase at primary PTF;
- An Internet-based data method (physical link, encryption, firewall standard, etc.).

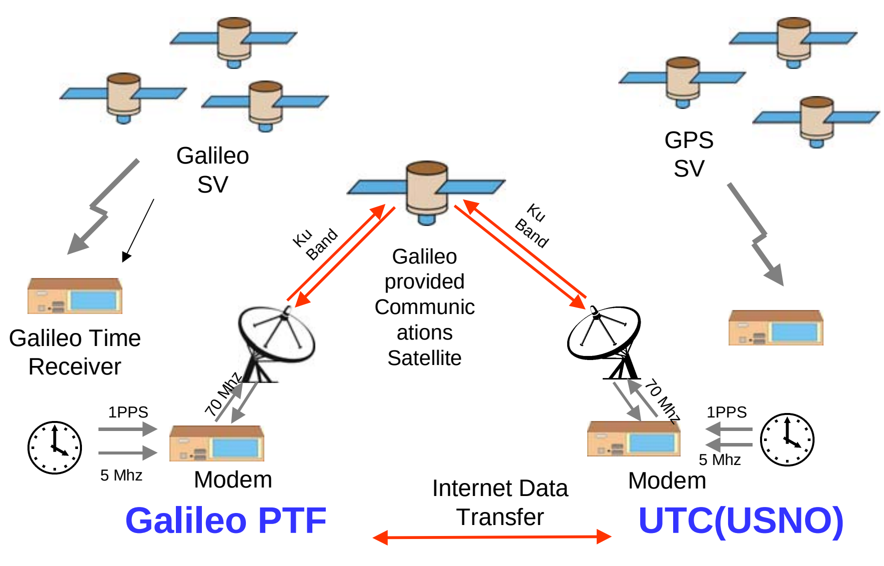

Figure 6. GGTO determination setup during Phase 1.

On the other hand, GPS (USNO) would provide:

- A USNO-owned earth terminal (single dish, no backup in Phase 1);
- A USNO-owned spread-spectrum modem;
- A data server computer to exchange data (automated);
- The remote calibration.

4.1.3 Experimental GGTO Activities

In the framework of ESA's GIOVE Mission segment (GIOVE-M) activities, the USNO agreed to host a Galileo Experimental Sensor Station (GESS). This is one GESS out of 13 in the present observation network. Such a GESS offers the possibility to receive GPS and GIOVE pseudo-ranges simultaneously. This GESS is connected to the USNO Master Clock and is referred to as GUSN. GUSN was characterized by the GIOVE-M processing center, which confirms it excellent performance. GUSN offers the possibility for GGTO experimentation.

The GIOVE-A SIS-ICD was released 2 March 2007 (available for download at GIOVE Website, **[3]**). The SIS-ICD includes GGTO parameters in the navigation message. GIOVE-M will produce an Experimental GGTO (E-GGTO) in the coming weeks and make it available for uplink to GIOVE-A. Once E-GGTO is available at the user level, a GIOVE/GPS receiver could output PVT based on both systems' signals and messages. E-GGTO closed-loop testing via GIOVE-A was performed in April 2007.

4.1.4 GGTO Planning

GPS plans to implement the GGTO message in the L2C and L5 navigation messages presently scheduled as part of GPS OCS upgrades scheduled for 2011 ± 1 year. The L1C GGTO message will be first broadcast with GPS III and its format is described in IS-GPS-200D.

Galileo will broadcast the GGTO in the navigation message of the IOV satellites. To achieve this, a special data interface with GPS and time transfer links to USNO and GPS is being developed.

In addition, as outlined above, the broadcast of E-GGTO is envisaged for the GIOVE satellites.

Thus, the overall <u>Joint Development Plan</u> can be summarized as follows:

- <u>GIOVE A and B Experiment Phase (now – 2010)</u>
    - GGTO Development Phase
        - Interface Definition (2006)
        - Test Plans and Procedures development (2007)
        - Development of Interface (Software and Hardware, 2007 – 2008)
        - Testing of GGTO Interface (2008)
        - Deployment prior to IOV test phase
- <u>IOV Test Phase (late 2009)</u>
    - GGTO Connected Clock (method used by Galileo)

    - GGTO Combined Receiver (method used by GPS)
- IOC Deployment Phase (2010 - 2011)
    - Galileo and GPS both deploy GGTO Combined Receiver
- FOC (2012 forward).

For the planned two-way satellite time and frequency transfer, a GEO communication transponder is required. The target GEO-Transponder is through Intelsat Corp., which is used by the international TW community. Galileo will use it during the validation phase for:

- GGTO (PTF(s) – USNO)
- PTF1 – PTF2
- PTF(s) – TSP.

In cooperation with the European GNSS Supervisory Authority, ESA found a solution to ensure the budget for transponder lease on the European side for up to end of 2011. This will cover 12 individual sessions per day.

4.2 Galileo System Time Start Epoch

One outcome of the interoperability discussions is related to the start epoch of Galileo System Time (GST). The GST start epoch will be 00:00 UT on Sunday, 22 August 1999 (midnight between 21 and 22 August). At the start epoch, GST is being ahead of UTC by 13 leap seconds.

Note: Since the next leap second was inserted at 1 January 2006, this implies that, as of 1 January 2006, GST will be ahead of UTC by 14 leap seconds.

5 GALILEO PROGRAM WORKING SCHEDULE

The current overall working schedule for the development, deployment, and operation of Galileo and EGNOS is depicted in Figure 7.

6 CONCLUSIONS

The IOV Phase CDE1 started on 21 December 2004. Up to now, there are more than 1000 persons actively working on the program all over Europe. More than 400 subcontracts have been implemented. The technical baseline is fully consolidated from system down to the element/equipment level (internal and external interfaces, including security). The procurement of sites hosting IOV Galileo remote stations (TTC, ULS, GSS) is well underway. The implementation of the Galileo Control Centre on two sites (on final FOC locations Oberpfaffenhofen, Germany and Fucino, Italy) is ongoing.

The advancement status at elements/equipment level is between Preliminary and Critical Design Review. The deployment of ground segment items, as well as the integration of payload equipment and satellite subsystems, will be carried out in 2008. The first launch of IOV satellites is expected in 2009.

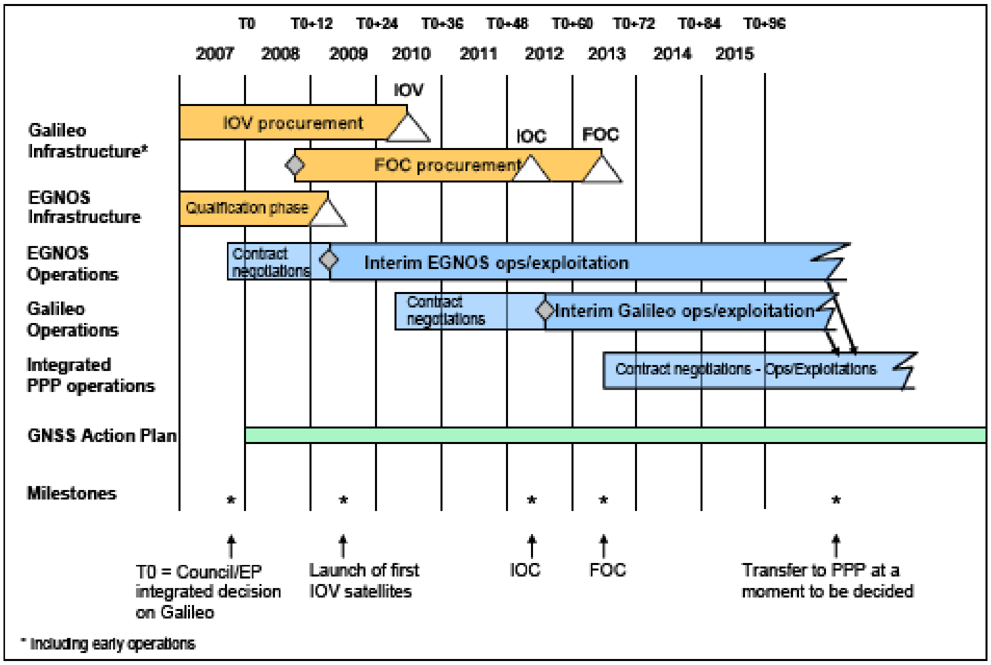

Figure 7. Galileo overall working schedule (source: European Commission).

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