A Report on GPS and Galileo Time Offset Coordination Efforts

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Abstract *- Precise timing is an inherent part of Radio Navigation Systems like GPS and Galileo. This paper will update progress on cooperative efforts between the GPS system and the Galileo system to harmonize the underlying Navigation time scales of both systems to better facilitate a combined GPS/Galileo Navigation solution. This paper will also outline cooperative experimentation and demonstration that will be conducted during the Galileo development phase.*

I. Introduction

Radio Navigation Systems (RNS) like Loran, Global Positioning System (GPS), Glonass and the planned Galileo are based on providing precise time and frequency synchronized ranging signals. Because of the exploitation of very precise timing signals these RNS are used to provide both navigation and time distribution services. Typically the navigation mission only requires relative timing but by providing an absolute timing reference a RNS system may also act as a time distribution system. Interoperability between RNS systems can be enhanced by coordinating the timing references of radio navigation systems.

Since 2002 a joint US/EC technical working group 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. This GPS to Galileo Time Offset (GGTO) 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 Canyons or under deep foliage where availability of a fifth GNSS satellite can not be guaranteed.

II. Basics of UTC, GPS and Galileo Time Scales

The International Bureau of Weights and Measures, "Bureau International des Poids et Mesures" (BIPM) is charged with coordinating the standard UTC time scale for the world. The BIPM receives data contributed from more than 200 atomic clocks and a few primary ("absolute") frequency standards, from over 50 institutions around the world. Once a month these data are used to produce a report which defines the standard international references for frequency and time, International Atomic Time (TAI) and UTC. UTC is equal in rate to TAI, but adjusted by an integer number of leap seconds to account for variations in the rotation of the Earth. The real-time realization of UTC is produced at most of the contributing laboratories.

The GPS is not only a high-accuracy navigation system, but it also delivers time globally with unprecedented accuracy. GPS is presently the world's most accurate globally available one-way source of time and frequency. The GPS system was declared fully operational in 1995 and has revolutionized both navigation and timing. In addition to navigation, the GPS system has also had a huge impact on the use of precise time.

Each GPS satellite contains several atomic clocks and continually broadcasts its position in orbit above the Earth and timing corrections relative to a common time scale (GPS Time). A GPS receiver tracking at least four GPS satellites can solve for the receiver's unknown position (x, y, z) and time (t) at virtually any location on the globe with a precision of a few meters and a time error of a few tens of nanoseconds (excluding receiver calibration errors). A timing user operating from a known fixed location can derive time from GPS using as few as one satellite and with local averaging of GPS errors, a timing accuracy of a few nanoseconds are possible. Time from GPS is now used for many civilian purposes, including synchronization of communications systems, cell phones, and power grids, and also for many commercial applications where accurate time tagging is becoming increasingly important.

The U.S. Naval Observatory (USNO) has been designated [1] to provide the external coordinating time scale for all navigation systems operated by the United States and produces a real time realization of UTC and TAI as a contributing laboratory to the BIPM. This time scale is identified as UTC(USNO). UTC(USNO) is the external UTC timing reference for GPS, and consequently the UTC time

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derived from GPS is considered fully traceable to all international standards for civil and legal time, subject to user equipment errors.

A GPS timing user can obtain UTC time directly from GPS by using the UTC timing corrections broadcast in the navigation message of the GPS satellites (Subframe 4, page 18). The largest uncontrolled error for an L1-only C/A code user is the remaining ionosphere propagation error that cannot be completely removed using the simple Klobuchar Model. Currently only military users and a small group of civilian codeless users make use of the second GPS frequency at L2 (1227 MHz), which allows for the direct estimation of the user ionosphere error. This ionosphere error limits timing accuracy to a few tens of nanoseconds and positioning accuracies to around ten meters.

In December 2005 GPS launched its first IIR-M (modernized) GPS satellite, introducing a new civil L2 service which will not be encrypted and is available to all users free of charge. Presently there are three IIR-M GPS satellites in orbit and broadcasting this new signal. A fourth satellite is scheduled to be launched later in 2007. In 2008, with the first GPS IIF satellite launch, a third civil signal called L5 will be added. This new L5 signal has higher power and will provide a third redundant signal. Since a timing user at a fixed location only needs a single GPS satellite to obtain time, the benefits of these new signals will be immediate.

Each GPS satellite includes in its navigation message a prediction of its position, an estimate of the difference between its internal clock and GPS system time, and an estimate of the difference between GPS system time and UTC(USNO). The GPS Master Control Station updates these predictions approximately once a day. GPS Time is the internal GPS navigation time scale, which is not adjusted for leap seconds, and which is very gently steered to UTC(USNO) modulo 1 second. GPS Time is specified to be maintained to within one microsecond modulo integral seconds; and for the past ten years it has been maintained to within (+/-25 ns) of this goal. A GPS timing user obtains precise time by first computing the user position and time offset relative to GPS Time, and then applying the UTC correction terms including the leap seconds offset.

GPS is now completing a planned expansion of it's network of ground monitor stations and improvements to the GPS Operational and Control Segment's (OCS) orbit and clock determination software. And early in the next decade a new GPS OCS will be completed, which will have the capability to more rapidly update the GPS navigation message which will further improve both timing and navigation accuracy. As part of this upgrade improvements to UTC(USNO) are also planned with RMS accuracies expected to be much less than 5 nanoseconds. In fact for the last six years GPS delivery of UTC(USNO) has already achieved an RMS stability of around 5 nanoseconds.

In partnership the European Commission (EC) and European Space Agency (ESA) are now in the Development and In-Orbit Validation Phase of a new radio navigation and timing system called Galileo. Galileo is specified as a high-accuracy navigation system providing integrity to Safety-of-Life critical users and accurate time information on a global scale. Together with GPS and GLONASS it will become another source of accurate time.

Each Galileo satellite will contain several atomic clocks (two Rubidium, two passive Hydrogen masers) and will continually broadcast its position in orbit above the Earth and timing corrections relative to the internal Galileo System Time (GST). The principle application of Galileo's navigation signals is to calculate a position and accurate time identical to the one used with GPS described above.

Two fundamental system functions are concerned with timing. The "Navigation Timing" is critical for the entire navigation mission. It will be needed for orbit determination/ prediction and internal satellite clock synchronization. This function is not directly intended for timing applications.

The "Metrological Timekeeping" may not be critical for navigation, but is required to provide UTC timing services (time dissemination) in support of communication systems, banking, power grid management, etc.

Galileo System Time (GST) as realized in the global core infrastructure will be steered to a prediction of UTC, modulo one second, obtained through an external Time Service Provider (TSP). Galileo System Time will be kept to within 50 ns (95%) of UTC, modulo one second, over any one-year time interval. The offset between UTC and GST (respectively modulo one second) will be known with a maximum uncertainty of at least 28 ns (2-sigma).

ESA recently decided on the start epoch of GST. The GST start epoch is defined as 00:00 UT on Sunday August 22nd 1999 (midnight between August 21st and 22nd). At the start epoch, GST is ahead of UTC by thirteen (13) leap seconds. Note: Since the next leap second was inserted at 01.01.2006, this implies that as of 01.01.2006 GST is ahead of UTC by fourteen (14) leap seconds.

Users equipped with a Galileo timing receiver will be able to predict UTC to 30 ns for 95% of any 24 hours of operation.

The key timing element in the Galileo system architecture will be the Precision Timing facility (PTF). This element is in charge of the navigation timekeeping and will:

- Maintain a stable ensemble of clocks in a well controlled environment;
- Measure the time offsets of all the clocks compared to the master clock through the local measurement system;
- Compute Galileo System Time;
- Steer GST towards UTC, modulo one second, through the steering correction provided by the external Time Service Provider (capability of being autonomous from TSP for 10 days);

- Provide GST to the orbit determination and time synchronization process.

The metrological function and associated performance will be provided by the external TSP and will:

- Operate the daily links to UTC(k) laboratories required for the estimation of UTC, the periodic calibration of the equipment and remote control facilities, etc.;
- Perform the data analysis of all the measurements GST-UTC(k);
- Develop and operate the required prediction algorithm for UTCp;
- Provide Galileo with the daily predicted value of (UTCp-GST) time and frequency offset and the daily steering correction;
- Interface with the BIPM by sending the internal clock data and GST-UTC(k) and receive from BIPM the Circular T (GST-UTC(k)old);
- Provide data exchange under request from Galileo Control Segment (Two-Way Satellite Time Transfer (TWSTT) and GPS / Galileo Common View);
- Provide an extended scientific activity, in collaboration with the leading European laboratories, to improve accuracy of GST (which is expected to exceed present specifications) and match the present and future accuracy of the USNO time scale.

An experimental version of the PTF called E-PTS was established through ESA's Galileo System Test Bed V1. Results are reported for example in [2].

To summarize:

Galileo Time (GST), modulo one second, will be steered to a prediction of UTC taken from a number of UTC(k) via an external Time Service Provider (TSP). GST will not be adjusted for leap seconds.

GPS Time is steered to be within one microsecond of UTC(USNO), modulo whole seconds. GPS time is not adjusted for leap seconds.

Both GST and GPS-Time are real-time realizations of UTC/UTC(k) laboratories they reflect, modulo whole seconds.

If the offset between GST and GPS Time is made available to the user, interoperability is enhanced.

III. GGTO Sub-group to WGA

Between the US and the EC a so called Working Group A (WGA) has been setup to ensure and enhance interoperability and compatibility of both systems.

The purpose of a specific sub-group of the WGA on GPS to Galileo Time Offset (GGTO) is to implement the EU-US agreement ARTICLE 4.3 "to transmit the time offsets between Galileo and GPS system times in the navigation messages of their respective services".

A kickoff meeting was held 31 May and 1 June 2005 hosted by the USNO, Washington DC. This meeting produced objectives of GGTO WGA-subgroup, proposed a GGTO membership, produced a documentation tree, preliminary joint development plan, preliminary joint verification plan and identified core technical issues and prioritized the tasks for the next meetings to come.

The objectives can be listed such:

- Ensure GGTO core implementation;
- Coordinate jointly the implementation activities towards GGTO on both GPS and Galileo sides;
- Agree on the GGTO interface work logic and ensure its implementation;
- Define and coordinate the GGTO interface calibration and validation;
- Agree and maintain under configuration control the documents listed in the preliminary joint documentation tree;
- Coordinate the schedule and development plan;
- Establish interface definition milestones and objectives;
- Establish interface verification & validation milestones and objectives;
- Organize regular meetings to report on the progress on both sides;
- Identify GGTO related technical topics to be treated on both sides.

The group is composed by experts from both the US and EU side, from institutions and industry.

Both authors of this paper are the points of contact respectively.

IV. GGTO Interface Performance Requirements

Here we summarize the driving performance requirements associated to GGTO:

- GGTO validity

The validity period of the GGTO shall be 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 2-sigma confidence level over any 24 hours.

- GGTO Stability

The stability of the GGTO, expressed as an Allan deviation, shall be better than 8x10e-14 over any one day.

V. PROPOSED METHODS

The following options to produce the GPS to Galileo 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 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 to implement a solution 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 start up or under conditions of limited satellite availability and the estimated GGTO value produced with the receiver.

VI. IMPLEMENTATION PROPOSAL FOR PHASE 1

It was discussed to split the GGTO implementation into two phases. 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 set-up based on a Two-Way Time and Frequency Transfer sketched in Fig. 1.

The working principle is as follows:

- USNO estimates the GPS time offset measured through a GPS timing receiver (GPS_{SIS}) traceable to UTC(USNO):

$$\Delta_1 = GPS_{SIS} - \mathrm{UTC(USNO)} + b_1 \qquad (1)$$

with b designating a remaining (unwanted) associated bias.

- The Galileo PTF estimates the Galileo time offset measured through Galileo timing receiver (GST_{SIS}) traceable to the local Galileo PTF Master Clock;

$$\Delta_2 = GST_{SIS} - GST(PTF) + b_2 \qquad (2)$$

- A Two-Way Satellite Time and Frequency Transfer via a geostationary transponder is used to estimate the time difference between UTC(USNO) and the Galileo Master Clock at PTF;

$$\Delta_3 = GST_{PTF} - \mathrm{UTC(USNO)} + b_3 \qquad (3)$$

- Differencing these three measurements will cancel the local clocks at USNO and Galileo PTF leaving the GGTO at Signal-in-Space (user) level.

$$\begin{aligned}\Delta_1 - \Delta_2 - \Delta_3 &= GPS_{SIS} - GST_{SIS} + b \\ &= \mathrm{GGTO} + b\end{aligned} \qquad (4)$$

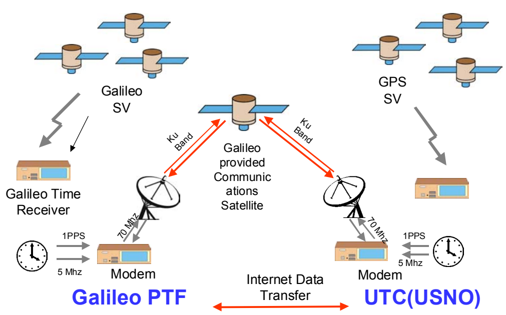

Figure 1. Proposed Setup for GGTO Implementation Phase 1

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…).

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.

The implementation of this approach is subject to confirmation by the WGA.

VII. Performance Budget

The performance budget for the above described setup will be built on contributions related to:

- Contributions of the GPS-SIS (related to the GPS User Equivalent Range Error, UERE);
- Calibration of the GPS receiver relative to UTC(USNO), which is the accuracy of determining b_1;
- Calibration of the Two-way link UTC(USNO) – PTF, which is the accuracy of determining b_3;
- Contributions of the Galileo-SIS (related to the Galileo UERE-budget);
- Calibration of the Galileo receiver relative to the PTF, which is the accuracy of determining b_2;
- Other internal contributions of both systems (switching etc.);
- Uncertainty of the GGTO prediction over 24 hours (influenced by the stabilities of both time scales);
- Contributions due to the truncation of the navigation messages.

Recent estimates indicate that it is challenging to meet the specified requirement of 5 ns, 2 sigma over 24 hours. Further discussions with highest priority are ongoing to tackle these issues in more detail. Experimentation results have been published in [3].

It has to be noted here that proper calibration of a combined GPS/Galileo user receiver has to be ensured in order to benefit from the accuracy provided with the broadcast GGTO.

VIII. E-GGTO Activities

In the framework of ESA's GIOVE Mission segment (GIOVE-M) activities [4] the USNO agreed to host a Galileo Experimental Sensor Station (GESS). This is one GESS out of 13 in the present observation network. Such 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 centre which confirms its excellent performance. GUSN offers the possibility for GGTO experimentation.

The GIOVE infrastructure allows for GGTO Experimentation. Both the European and US teams discussed several methods for such product:

- use of Orbit Determination and Time Synchronization (ODTS) process
- use of ODTS process + GPS navigation message
- use of TWSTFT and GPS Common View

The overall goal is to verify the GGTO performance budget for the IOV Phase (detailed budget have been made available by ESA to USNO).

The experimentation details remain still to be agreed.

The GIOVE-A SIS-ICD was released 2 March 2007 (available for download at the GIOVE Webside, [4]).

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 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.

A E-GGTO closed-loop test via GIOVE-A was performed in April 2007.

IX. Planning

GPS is planned to implement the GGTO message in the L2C and L5 navigation messages presently scheduled as part of GPS OCS upgrades scheduled for 2011 +/- one 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 with 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. ESA undertook to arrange for a proper solution. 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 stepwise solution to ensure the budget for transponder lease on the European side through the end of 2011. This will cover for 12 individual sessions per day.

For the combined receiver development the following scheme will be followed:

- GESS (GIOVE) reference stations will be used for early GGTO demonstrations
  - Joint studies, conference papers expected
  - Common antenna, common clock, but different receiver architecture
- GPS would like to procure a combined GPS/Galileo receiver to support US GGTO (late 2007)
  - Several companies have express interest in building this receiver and have demonstrated a combined receiver
- Galileo is developing specifications supporting procurement of a GPS/Galileo GGTO reference receiver

X. Conclusions

Today GPS serves the world as both the most widely available and the most accurate source of UTC time. It is anticipated that by the year 2010 when Galileo becomes operational Galileo will provide a UTC timing service similar in performance as that of GPS.

Once Galileo is operational it is envisaged by many that most users will use a combined GPS and Galileo positioning, navigation and timing service. Interoperability between Galileo and GPS is enhanced by providing the user information about the navigation time scale offset between GPS and Galileo. Thus the US and EU have agreed to provide this information through each system's navigation signals.

This paper demonstrates the ongoing GGTO development status. The GGTO is a joint product resulting from coordinated technical activities within both GPS and Galileo. In the coming months all activities related to GGTO will be coordinated jointly through a dedicated sub-group to the US/EU WGA. Implementation details will be tackled in the very near future. The (E-)GGTO should be first in place through the Galileo (GIOVE) SIS starting as of 2009 (2007).

The opinions discussed in this paper are those of the authors and do not necessarily represent those of the USNO and ESA and other agencies in charge of the GPS and Galileo programs.

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XI. Biography

Jörg H. Hahn received his M.Sc. in Physics and Mathematics from the Belorussian State University, Minsk in 1993 and his Ph.D. in Engineering Sciences from the University FAF, Munich in 1999. After being with DLR's Oberpfaffenhofen navigation group for almost 8 years in year 2000 he joined ESA's Galileo Project Office in Noordwijk as a system engineer. He is now primarily in charge of all Galileo End-to-end Performances.

Edward D. Powers received his B.S. and M.S in Electronic Engineering and Instrumental Science from the University of Arkansas in 1984 and 1987 respectively. In 1987 he joined the Naval Research Laboratory as an engineer working on GPS clock development program. In 1997 he joined the USNO and now works as the GPS operations division chief responsible for development of improved precise time synchronization and GPS timing.

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