GPS/GALILEO INTEROPERABILITY: GGTO, TIMING BIASES, AND GIOVE-A EXPERIENCE

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Abstract

The future European radio navigation system Galileo will use its own timescale for the synchronization and dissemination of the predicted satellite clocks. Broadcast satellite clock predictions must be referred to a common and stable time reference in order for the user to be able to obtain an accurate positioning solution. The new Galileo timescale is called Galileo System Time (GST) and is the equivalent of the GPS Time (GPST) scale used in the Global Positioning System. For timing applications, both the GPS and Galileo systems broadcast as well the difference between their respective system times (GPST and GST) and the universal timescale (UTC), with a maximum deviation requirement of the order of 1 microsecond for GPS (although in practice the deviation is currently below 10 nanoseconds) and 50 nanoseconds for Galileo. Furthermore, for GPS/Galileo interoperability the Galileo and GPS systems are planning to transmit within their navigation messages the so-called GPS to Galileo Time Offset (GGTO), i.e. the predicted difference between the GPST and GST system times. This paper analyzes the different issues involved in GPS/Galileo interoperability for positioning and timing, including GGTO and timing biases, and presents practical experience and solutions from the data processing of GIOVE-A, the first experimental Galileo satellite.

I. INTRODUCTION

For GPS/Galileo interoperability, the GPS and Galileo systems are planning to transmit within their navigation messages the so-called GPS to Galileo Time Offset (GGTO), i.e. the predicted difference between GPS Time and Galileo System Time. This predicted offset will allow the user of a dual GPS/Galileo receiver to obtain a combined navigation solution from pseudorange measurements to the GPS and Galileo satellites. In practice, the knowledge of GGTO must be combined with a good understanding of the different hardware-induced timing biases involved in the two systems, both in-orbit and on-ground. Common biases cancel out in the navigation solution (in fact, they go into the estimated user clock) and appear as a fixed bias for timing solutions. However, some biases are different for GPS and Galileo and they must be carefully considered in a combined solution. The following sections of this paper show practical evidence of these timing biases using experimental results from the Galileo System

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Test Bed Version 2 project and the processing of signals transmitted by the GIOVE-A satellite.

II. GPS TO GALILEO TIME OFFSET (GGTO)

The GPS Joint Program Office and the Galileo Project Office signed an agreement **[1]** on the interoperability of the two navigation satellite systems asking, among other things, the determination and diffusion of the GGTO by both systems.

GGTO specification asks for both an accuracy less than 5 ns (2σ) and a frequency stability better than 8×10^{-14} over 1 day, even if improved figures are expected by the time Galileo becomes operational **[1,2]**.

Different measurement techniques are envisaged for the evaluation of GGTO. In the initial Galileo phase, the GGTO calculation will be based on calibrated TWSTFT (Two Way Satellite Time and Frequency Transfer) and GPS-CV (Common View) time transfer links between GPS Time as obtained at the US Naval Observatory and the Galileo time as realized at the ground Precise Time Facility (PTF).

In the future, the use of combined GPS/Galileo timing receivers is envisaged to determine GGTO from the Signal In Space (SIS) of both systems. This would be a preferred situation, because corresponding to the actual GGTO experienced by the users.

First GGTO evaluations and transmissions are expected during the Galileo In Orbit Validation phase (after 2008), but the current experimental activity called Galileo System Test Bed V2 can nevertheless give significant insights on the feasibility of the GGTO determination and dissemination, as well on the other timing biases in combined GPS/Galileo receivers that are to be carefully estimated and taken into account as reported in the next sections.

III. THE GALILEO SYSTEM TEST BED VERSION 2

In preparation for the development of the Galileo system, the European Space Agency launched in 2002 the development of an experimental ground segment (Galileo System Test Bed Version 1). Within the GSTB-V1 project, tests of Galileo orbit determination, integrity and time synchronization algorithms were conducted with the GPS satellites and an experimental ground segment consisting of a worldwide network of sensor stations collecting high-quality GPS observables at 1 Hz, an Experimental Precision Timing Station providing the reference time scale steered to UTC/TAI, and a Processing Center located at the European Space Agency (ESA-ESTEC) in The Netherlands. The latter was used for the generation of navigation and integrity core products based on Galileo-like algorithms. In the GSTB-V1 context, preliminary experiments were carried out for the evaluation of GGTO, with particular care to the determination of the accuracy of the GGTO calculation **[3]**.

Within the Galileo System Test Bed Version 2 project (GSTB-V2), two experimental satellites called GIOVE-A and GIOVE-B are being launched. They will mark the first step in the validation of the Galileo system, to be completed with the deployment of the In-Orbit Validation satellites. The GIOVE-A satellite has been developed by Surrey Satellite Technology Ltd (UK). GIOVE-A was launched from the Baikonur cosmodrome by a Soyuz rocket on 28 December 2005. GIOVE-A flies two Rubidium Atomic Frequency Standard (RAFS) clocks and can transmit in two separate frequencies (L1 and either E5 or E6). GIOVE-B flies one Passive Hydrogen Maser (PHM) in addition to two RAFS clocks, and is capable of simultaneously transmitting in three frequencies (L1, E5, and E6). Both satellites carry a Laser Retro-

Reflector (LRR) on board in order to help improving their precise orbit determination. Figure 1 depicts GIOVE-A in stowed configuration. The LRR is shown in the upper left corner.

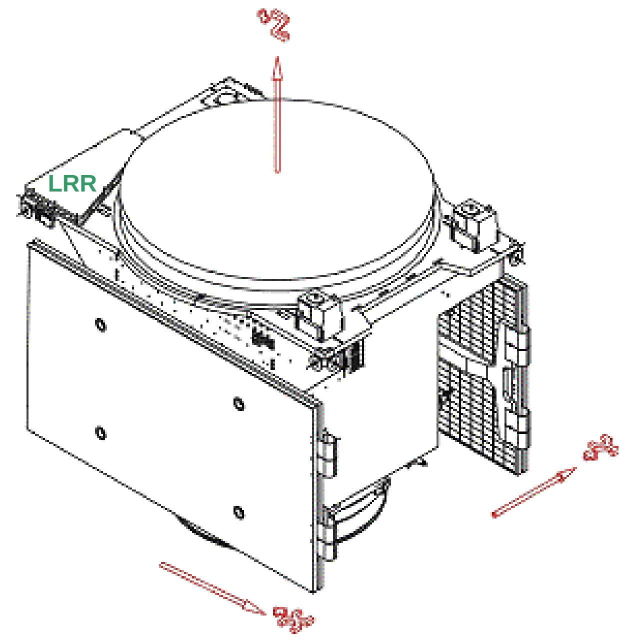


Figure 1. GIOVE-A in stowed configuration.

The GSTB-V2 Mission Experimentation project is intended to mitigate the Galileo project risks by an early assessment of technical aspects like early demonstration and performance assessment of the navigation service (including navigation message generation, uplink, and broadcast), validation of critical in-orbit technology (clocks), end-to-end analysis of the Galileo Signal-In-Space, assessment of Galileo Test Receiver performance, validation of existing ground algorithm prototypes (from GSTB-V1) and testing of new ones (e.g. ionosphere and Broadcast Group Delay), and overall testing of timeliness and operational aspects.

The GSTB-V2 ground infrastructure for experimentation consists mainly of a network of Galileo Experimental Sensor Stations (GESSs) worldwide distributed that acquire and collect the GSTB-V2 satellite signals and send pseudorange and carrier phase measurements to a Ground Processing Center (GPC) located at ESTEC (upgraded from GSTB-V1). One station is to be installed at the Time Laboratory located at INRiM, Turin, connected to an Active Hydrogen Maser, located in a controlled environment. The INRiM time reference will be used as the basis for the Experimental Galileo System Time (EGST) in GSTB-V2. Satellite Laser Ranging (SLR) stations from the International Laser Ranging Service (ILRS) network send measurements to the GPC as well.

The GSTB-V2 system consists of the following two elements, apart from the GIOVE satellites:

- The Ground Control Segment
- The Ground Mission Segment

The elements within the Ground Control Segment are:

- The GIOVE-A Control Center operated by SSTL in Guilford (UK)
- The GIOVE-A Telemetry Tracking and Control (TTC) stations located at Oxford (UK), Santiago (Chile), and Kuala Lumpur (Malaysia)
- The GIOVE-B Control Center in Fucino (Italy)
- The GIOVE-B TTC stations located at Fucino and Kiruna (Sweden)

The Ground Mission Segment consists of:

- The GIOVE Processing Centre (GPC) in Noordwijk (The Netherlands)
- The global network of 13 Galileo Experimental Sensor Stations (GESS), containing Septentrio combined GPS/Galileo receivers, for time synchronization of the two systems

The satellites are monitored and controlled by the Satellite Control Centers through a network of TTC stations at various locations in the world using S-Band communication.

The GPC computes precise orbits and clocks of the GIOVE satellites based on the measurements collected by a global network of stations that collect Galileo and GPS observables at 1 Hz sampling rate. Navigation messages are generated by the GPC and uplinked to the satellites through the respective Satellite Control Center.

The GPC collaborates with and uses as input information from different institutions:

- Satellite Laser Ranging data from the International Laser Ranging Service (ILRS)
- Precise GPS orbits and clocks from the International GNSS Service (IGS)
- Precise earth rotation parameters from the International Earth rotation and Reference systems Service (IERS)

The GPC generates several core products of interest to external registered users in the fields of:

- Precise orbits and clocks
- Satellite clocks characterization
- Navigation message demonstration
- Station error budget characterization
- Ionosphere and Broadcast Group Delay modeling
- Other satellite models calibration and validation.
-

IV. THE SENSOR STATION NETWORK

The Galileo Experimental Sensor Station (GESS) consists mainly of the following elements, depicted in Figure 2:

- A wide-band antenna tracking L1 signals and also L2 signals (GPS) and E5/E6 signals (Galileo)
- A dual GPS/Galileo receiver called Galileo Experimental Test Receiver (GETR) developed by Septentrio
- A UPS unit and a Monitoring & Control core computer
- A commercial rubidium clock (iTest^{+TM} PFRS by TEMEX) for most of the stations in the network
- For the master clock stations (located at INRiM and USNO), connectivity to an external clock through an interface based on a 10 MHz frequency signal and a 1 PPS signal.

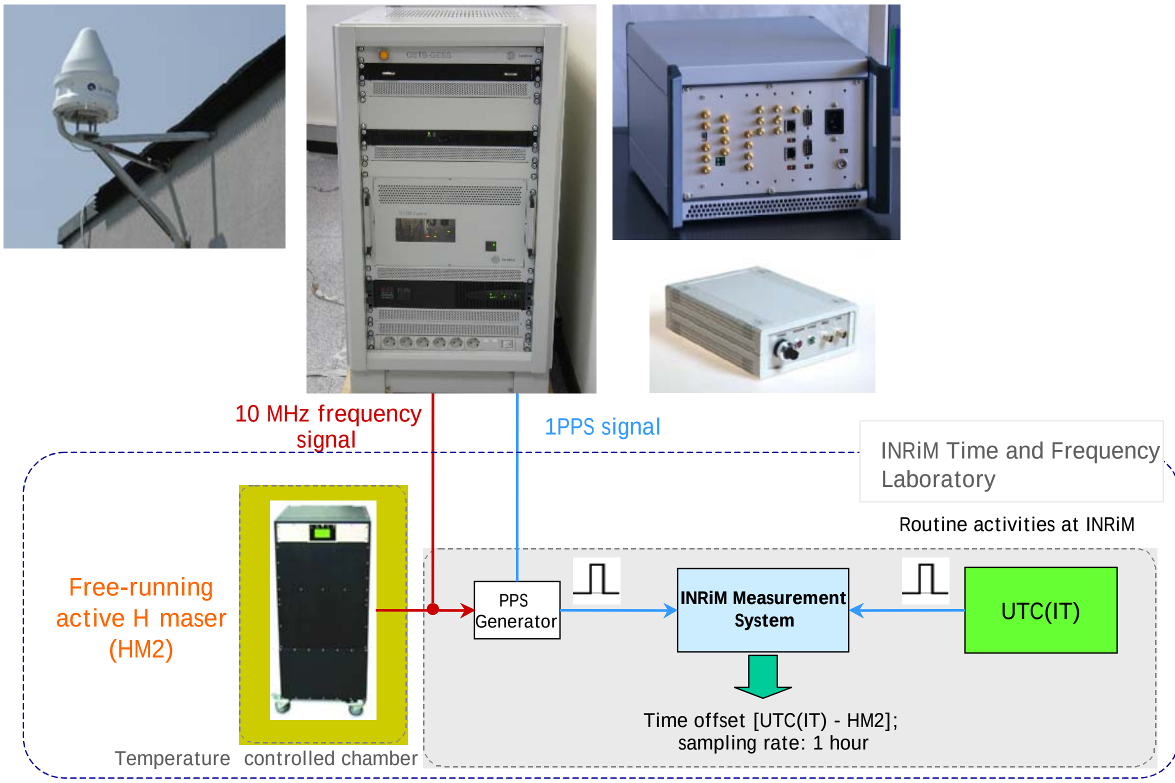


Figure 2. Elements of the Galileo Experimental Sensor Station (GESS).

Table 1 shows the list of GESS stations belonging to the GSTB-V2 network. Only the stations highlighted in green are available during Early Experimentation. The GTHT station is also available, but normally generates GPS data only. The GIEN station, located at INRiM, Turin, Italy, is connected to a free-running Active Hydrogen Maser clock. This is the reference clock in all GSTB-V2 experiments. The H-maser signal, both 10 MHz and 1 Pulse Per Second (PPS), is fed to the INRiM station as an external reference time scale. The maser is continuously monitored versus the ensemble of atomic clocks of INRiM and also compared versus external reference time scales as the Universal Coordinated Time (UTC) realized by the BIPM.

Figure 3 shows the geographical coverage provided by the nine stations available during the Early Experimentation phase. The colors indicate the number of stations in view of the GIOVE satellite, when the satellite is flying over a particular area. The figure can be also interpreted as the so-called Depth-of-Coverage (DOC). A DOC-1 means that the satellite is in view of at least one station over a particular area (orange color or above). A DOC-2 means that the satellite is in view of at least two stations over a particular area (yellow color or above).

Table 1. List of available stations during Early Experimentation (in green).

GIEN	INRiM, Turin	Italy
GKIR	Kiruna	Sweden
GKOU	Kourou	French Guyana
GLPG	La Plata	Argentina
GMAL	Malindi	Kenya
GMIZ	Mizusawa	Japan
GNNO	New Norcia	Australia
GNOR	ESA, Noordwijk	The Netherlands
GOUS	Dunedin	New Zealand
GTHT	Tahiti	French Polynesia
GUSN	USNO, Washington	USA
GVES	Vesleskarvet	Antarctica
GWUH	Wuhan	China

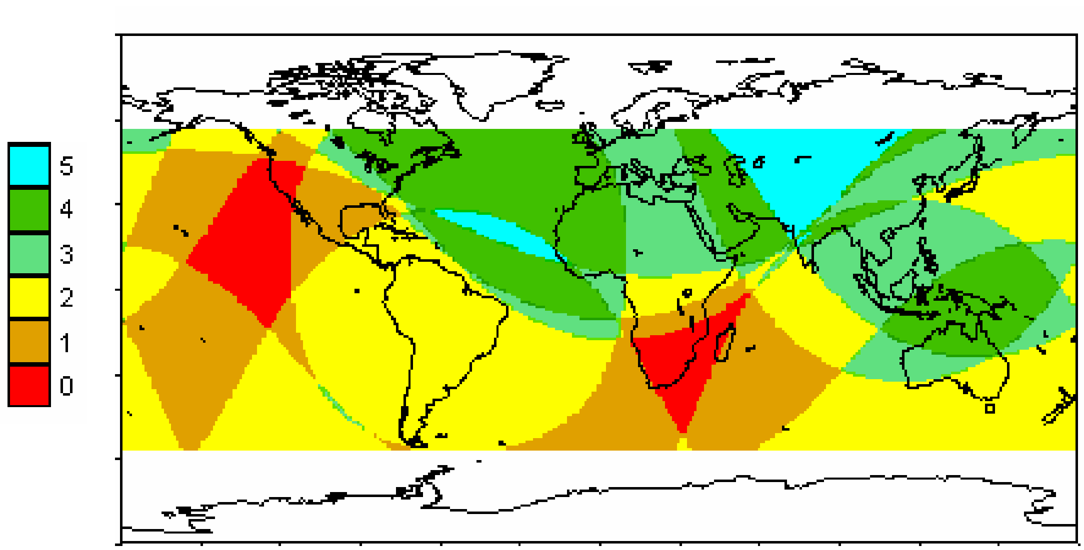
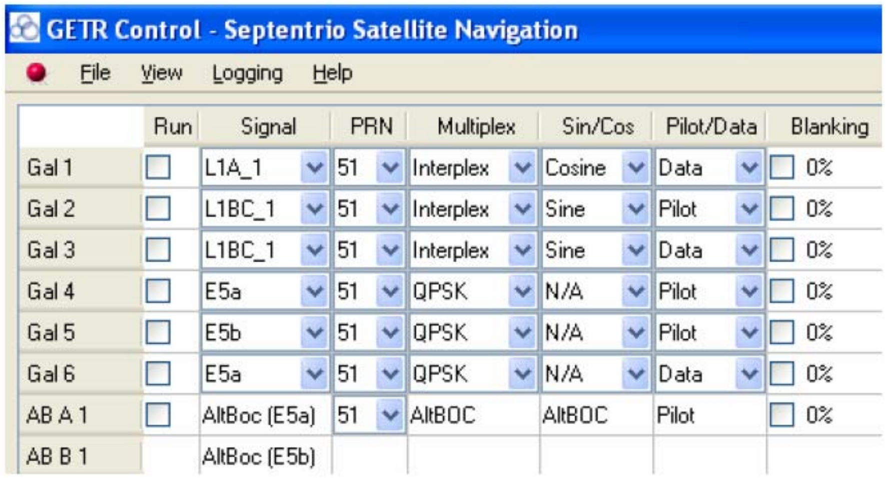


Figure 3. Nine-station coverage during early experimentation.

It must be emphasized that not all stations provide data continuously during the analyzed period, during to different limitations of the V2M ground system at these early stages of the experimentation. Data gaps exist for most stations at different times.

The Galileo Experimental Test Receiver (GETR) within the GESS station has seven Galileo channels, configured during the analyzed period as shown in Figure 4. All receivers within the V2M station network are configured in the same way.



	Run	Signal	PRN	Multiplex	Sin/Cos	Pilot/Data	Blanking
Gal 1		L1A_1	51	Interplex	Cosine	Data	0%
Gal 2		L1BC_1	51	Interplex	Sine	Pilot	0%
Gal 3		L1BC_1	51	Interplex	Sine	Data	0%
Gal 4		E5a	51	QPSK	N/A	Pilot	0%
Gal 5		E5b	51	QPSK	N/A	Pilot	0%
Gal 6		E5a	51	QPSK	N/A	Data	0%
AB A 1		AltBoc (E5a)	51	AltBOC	AltBOC	Pilot	0%
AB B 1		AltBoc (E5b)					

Figure 4. The GETR receiver configuration.

According to this GETR configuration, Table 2 shows the code (pseudorange) and phase observables available from the receiver. In the analyzed period, GIOVE-A was transmitting the L1 and E5 signals. The three-character observable names follow the new RINEX 3.00 convention. Any L1 code/phase observable can be in principle combined with any E5 code/phase observable in order to build an iono-free code/phase observation or a geometry-free code/phase observation.

Table 2. Observables available from the GETR.

Frequency Band	Frequency (MHz)	Pilot/ Data	Pseudo Range	Carrier phase
L1	**1575.420**	Data	C1A	L1A
		Data	C1B	L1B
		Pilot	**C1C**	**L1C**
E5a	1176.450	Data	C5I	L5I
		Pilot	C5Q	L5Q
E5b	**1207.140**	Pilot	**C7Q**	**L7Q**
E5a+b (AltBOC)	1191.795	Pilot	C8Q	L8Q

The C1C-C7Q iono-free code observable and the L1C-L7Q iono-free phase observable have been used, together with the P1-P2 iono-free code observable and the L1-L2 iono-free phase observable from GPS. The equivalent geometry-free observables have also been used in our experimentation.

V. TIMING BIASES IN GSTB-V2

In a dual GPS/Galileo system like GSTB-V2, a good understanding of the different hardware-induced timing biases involved in the two systems, both in-orbit and on-ground, is essential. Common biases cancel out in the navigation solution (in fact, they go into the estimated user clock) and appear as a fixed bias for timing solutions. However, some biases are different for GPS and Galileo and they must be carefully considered in a combined solution. One such non-common bias is the so-called inter-system bias, i.e. the differential delay undergone by the GPS and Galileo signals inside the user receiver. Another source of non-common bias comes from the fact that broadcast satellite group delays (for single-frequency users) might not be calibrated in an absolute way. Figure 5 shows a synthetic overview of the different hardware-induced timing biases involved in GSTB-V2. A discussion about the origin of timing biases at signal and receiver level can be found in **[4]**.

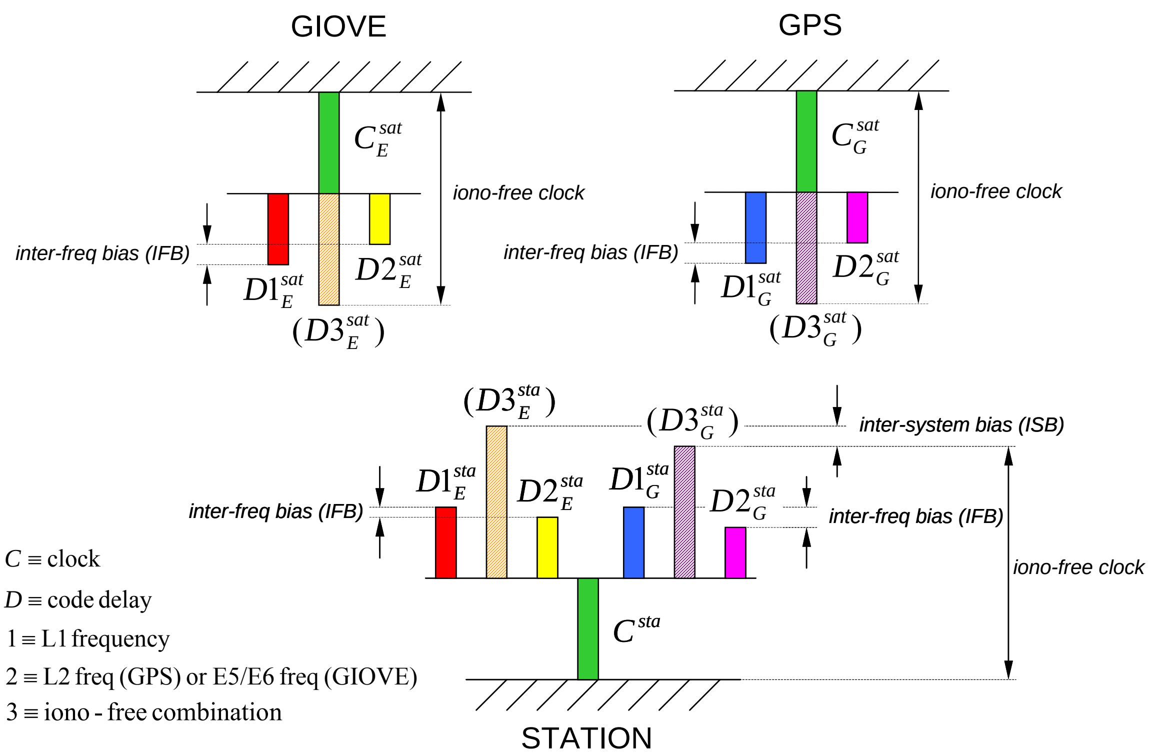


Figure 5. Timing biases in GSTB-V2.

On the space side, each GPS or GIOVE satellite flies an atomic clock, but the clock observed from the data contains the signal delays all the way from the physical clock to the satellite navigation antenna. This delay depends on the actual signal frequency (actually it can be different for each code within the same frequency). In Figure 5, the delays are called *D1* and *D2*, assuming that the satellites always transmit on two separate frequencies. These delays are assumed to be nearly constant, with only small variation at the nanosecond level, mainly due to temperature changes. When doing iono-free combinations, the *D1* and *D2* are combined into a virtual iono-free delay called *D3* in Figure 5. Therefore, the *observed* GPS and Galileo clocks are not the pure clocks, but they contain the combined dual-frequency delay *D3* (iono-free) up to the satellite. The broadcast GPS and Galileo clock are based on such *observed* iono-free clocks. The differential delay between the two frequencies (*D1-D2*) is useful for the single-frequency user in order to convert the broadcast dual-frequency clock to single frequency (normally L1). This differential delay is also called *inter-frequency bias* (IFB) and is transmitted in the navigation message.

On the ground side (GESS stations), the situation is slightly more complicated. The station is driven by a single clock that is common to the GPS and the Galileo channels. The station antenna is also common for GPS and Galileo, but the hardware delay between the clock and the antenna is different for the GPS and the Galileo channels. Therefore, within the station there is a dual-frequency delay *D3* (iono-free) for GPS and a different one for Galileo. The difference between these two iono-free delays is called *inter-system bias*. Because of this bias, the station *observed* clock through GPS is slightly different than the one through Galileo, with a nearly constant difference between them. The station *observed* clock is normally referred to the GPS part of the station, since this is much more observable due to the many flying GPS satellites (as opposed to only one flying GIOVE satellite at present).

VI. PSEUDORANGE COMBINATIONS

The basic observables coming from the stations are pseudorange (code) and carrier-phase measurements. The code observations have normally a much larger error that the phase observations (typical error levels are 1 meter and 1 centimeter, respectively). However, phase observations contain an ambiguity and normally cannot be processed alone. A typical approach is to extract the relevant information from code using the phase observables to smooth the code. According to this, the parameters to be analyzed in GSTB-V2 are obtained from dual-frequency code combinations, as depicted in Figure 6 (phase observations are not shown, but they are used to reduce the code noise).

- GPS raw pseudoranges:

$$P1_G = R_G + T + I1_G + C^{sta} - C_G^{sat} + D1_G^{sta} - D1_G^{sat}$$

$$P2_G = R_G + T + I2_G + C^{sta} - C_G^{sat} + D2_G^{sta} - D2_G^{sat}$$

$$I1_G = \frac{TEC}{F1_G^2} \qquad I2_G = \frac{TEC}{F2_G^2} \qquad \gamma_G \equiv \frac{F1_G^2}{F2_G^2}$$

- GIOVE raw pseudoranges:

$$P1_E = R_E + T + I1_E + C^{sta} - C_E^{sat} + D1_E^{sta} - D1_E^{sat}$$

$$P2_E = R_E + T + I2_E + C^{sta} - C_E^{sat} + D2_E^{sta} - D2_E^{sat}$$

$$I1_E = \frac{TEC}{F1_E^2} \qquad I2_E = \frac{TEC}{F2_E^2} \qquad \gamma_E \equiv \frac{F1_E^2}{F2_E^2}$$

- Iono-free pseudoranges:

$$P3_G \equiv \frac{P1_G \cdot F1_G^2 - P2_G \cdot F2_G^2}{F1_G^2 - F2_G^2} \qquad P3_E \equiv \frac{P1_E \cdot F1_E^2 - P2_E \cdot F2_E^2}{F1_E^2 - F2_E^2}$$

$$P3_G = R_G + T + \overbrace{\left(C^{sta} + D3_G^{sta}\right)}^{ionofree\_station\_clk} - \overbrace{\left(C_G^{sat} + D3_G^{sat}\right)}^{ionofree\_GPS\_clk}$$

$$P3_E = R_E + T + \overbrace{\left(C^{sta} + D3_G^{sta}\right)}^{ionofree\_station\_clk} + \overbrace{\left(D3_E^{sta} - D3_G^{sta}\right)}^{ISB} - \overbrace{\left(C_E^{sat} + D3_E^{sat}\right)}^{ionofree\_GIOVE\_clk}$$

- Iono-free delays:

$$D3_G^{sta} \equiv \frac{D1_G^{sta} \cdot F1_G^2 - D2_G^{sta} \cdot F2_G^2}{F1_G^2 - F2_G^2} = D1_G^{sta} + \left(D1_G^{sta} - D2_G^{sta}\right) \cdot \frac{1}{\gamma_G - 1}$$

$$D3_G^{sat} \equiv \frac{D1_G^{sat} \cdot F1_G^2 - D2_G^{sat} \cdot F2_G^2}{F1_G^2 - F2_G^2} = D1_G^{sat} + \left(D1_G^{sat} - D2_G^{sat}\right) \cdot \frac{1}{\gamma_G - 1}$$

$$D3_E^{sta} \equiv \frac{D1_E^{sta} \cdot F1_E^2 - D2_E^{sta} \cdot F2_E^2}{F1_E^2 - F2_E^2} = D1_E^{sta} + \left(D1_E^{sta} - D2_E^{sta}\right) \cdot \frac{1}{\gamma_E - 1}$$

$$D3_E^{sat} \equiv \frac{D1_E^{sat} \cdot F1_E^2 - D2_E^{sat} \cdot F2_E^2}{F1_E^2 - F2_E^2} = D1_E^{sat} + \left(D1_E^{sat} - D2_E^{sat}\right) \cdot \frac{1}{\gamma_E - 1}$$

- Geometry-free pseudoranges:

$$P4_G \equiv P1_G - P2_G$$

$$P4_E \equiv P1_E - P2_E$$

$$P4_G = TEC \cdot \left(\frac{\gamma_G - 1}{F1_G^2}\right) + \overbrace{\left(D1_G^{sta} - D2_G^{sta}\right)}^{station\_GPS\_IFB} - \overbrace{\left(D1_G^{sat} - D2_G^{sat}\right)}^{GPS\_IFB}$$

$$P4_E = TEC \cdot \left(\frac{\gamma_E - 1}{F1_E^2}\right) + \overbrace{\left(D1_E^{sta} - D2_E^{sta}\right)}^{station\_GIOVE\_IFB} - \overbrace{\left(D1_E^{sat} - D2_E^{sat}\right)}^{GIOVE\_IFB}$$

Figure 6. Pseudorange (code) combinations used in GSTB-V2.

Iono-free code observations (actually pseudoranges smoothed with carrier phase) contain orbit, clock, inter-system bias, and tropospheric information. *Geometry-free* observations contain differential group delay (also called *inter-frequency bias* or IFB) and ionospheric information. Orbit, clock and tropospheric contributions cancel out when building the geometry-free pseudoranges.

VII. EXPERIMENTAL GALILEO SYSTEM TIME AND OFFSET TO GPS TIME

The experimental version of Galileo System Time in GSTB-V2 is called EGST. The experimental version of the GPS to Galileo Time Offset is called EGGTO. EGST is driven by the free-running Active Hydrogen Maser connected to the GIEN station at INRiM in Turin. Actually EGST is defined as the *observed* clock of GIEN relative to the GPS part of the station, including the group delays up to the antenna. In particular EGST is defined based on the iono-free P1-P2 GPS pseudorange combination. This is depicted as EGST(GIEN) in Figure 7. The GIEN inter-system bias has to be accounted for in order to refer the GIOVE observed clock to EGST. In Figure 7, EGST(MC) means the GIEN clock "in the lab" without the station delays, i.e. the clock at the output of the hydrogen maser Master Clock (MC) or at the input of the station.

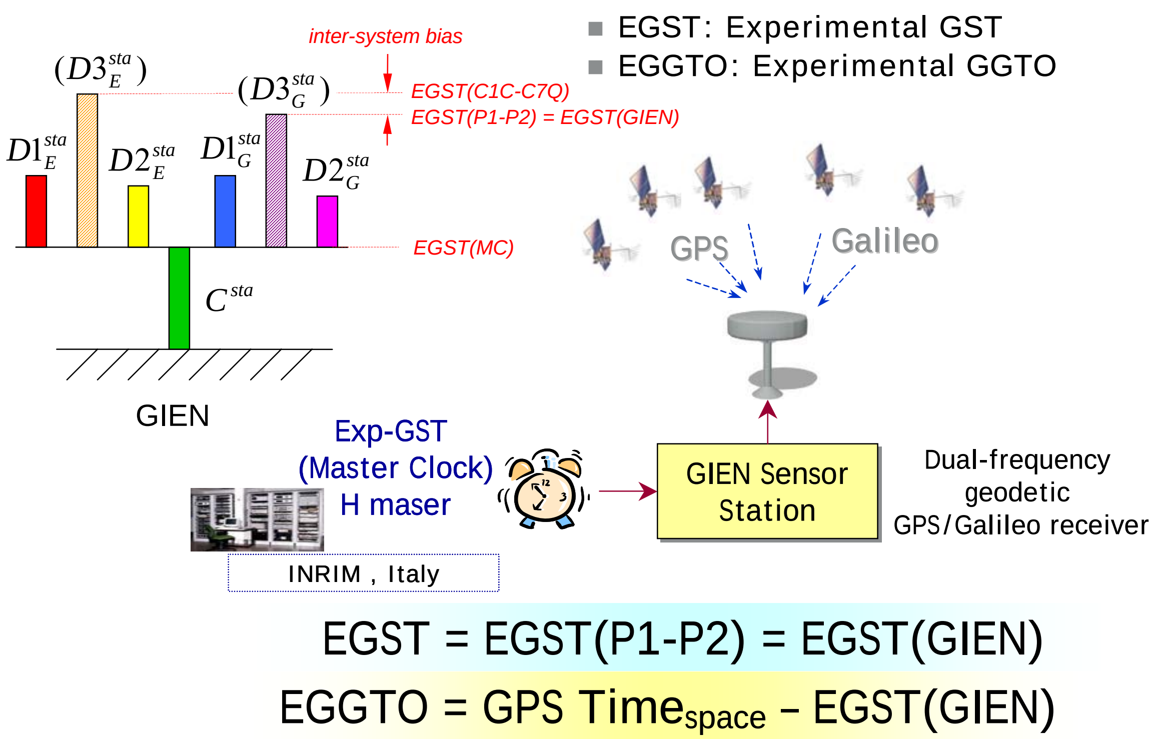


Figure 7. The EGST and EGGTO concepts in GSTB-V2.

EGGTO (the Experimental GPS to Galileo Time Offset) is the difference between GPS Time and EGST as defined above. The definition of EGST is quite clear, but GPS Time can be calculated (actually evaluated) in different ways.

One possibility to evaluate GPS Time is by comparing the GPS clocks broadcast in the navigation message (obviously referred to GPS Time) with the GPS satellite clock estimation done within GSTB-V2 (since the GIOVE and GPS satellites are processed together by the on-ground GSTB-V2 software). Another possibility could be using the GUSN station installed at USNO (assumed to be calibrated to the USNO Master Clock that is continuously monitored versus GPS Time) and evaluating EGGTO as the difference between the GIEN and the GUSN observed clocks. Finally, two-way time transfer techniques between INRiM and USNO can also be envisaged, although this requires dedicated hardware and implies more technical complexity. The final definition and calculation method of EGGTO is not yet decided at this early stage of the GSTB-V2 project.

VIII. THE GIOVE-A NAVIGATION MESSAGE

At a later stage of the GSTB-V2 project, the calculation, uplinking, and broadcast of a GIOVE-A navigation message is foreseen. This message is to be calculated by the processing center at ESA/ESTEC and then sent to the GIOVE-A control center at Surrey (UK) to be uplinked to the satellite using one of the TTC ground stations.

The navigation message is computed by a dedicated software tool called E-OSPF (Experimental Orbit and Synchronization Processing Facility). The E-OSPF consists mainly of two different algorithmic software modules: ODTS (Orbit Determination and Time Synchronization) in charge of orbit and clock estimation and prediction, and IONO, in charge of inter-frequency bias (IFB) and NeQuick ionospheric model parameters for single-frequency users. Figure 8 depicts how the GIOVE-A navigation message is built with information coming from the ODTS and IONO modules. The inclusion of EGGTO in the navigation message is yet to be decided.

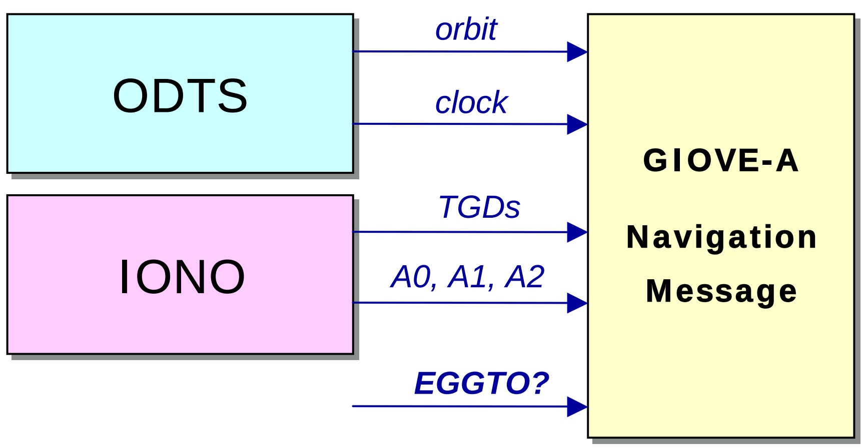


Figure 8. The GIOVE-A Navigation Message computation.

The ODTS module is a batch least-squares estimator that uses iono-free code and phase observables from the stations. It estimates and predicts the orbit and clocks of GIOVE and all the GPS satellites. As indicated above, a single clock is estimated for each station (except for GIEN that is the reference clock and is fixed in ODTS), referred to the GPS part of the station, including hardware delays. An *inter-system bias* is also estimated for each station (again except for GIEN that by convention is used as the reference inter-system bias). Actually, the ODTS cannot separate between a mean offset in the GIOVE clock and a mean offset in the ensemble of on-ground inter-system biases. This is why some reference must be defined for the inter-system bias. This issue is further analyzed in the next section.

The IONO module is a Kalman filter that uses geometry-free code and phase observables from the stations. It estimates inter-frequency biases (IFBs) for selected GIOVE code pairs and for the P1-P2 code pair for all GPS satellites. The IONO module also estimates three so-called "Az" ionospheric parameters, by fitting the observed slant Total Electron Content (TEC) values to the NeQuick ionospheric model. The broadcast ionospheric parameters are needed by the single-frequency user in order to correct for the ionospheric delay using the receiver NeQuick model implementation. The IFBs are needed by the single-frequency user in order to convert the broadcast (iono-free) clock to the single-frequency clock that the satellite is actually transmitting on L1. The IFBs are also called Timing Group Delays (TGDs) in the GPS terminology. GPS TGDs and their importance for the user are described in **[5-7]**. Actually, a TGD is a IFB multiplied by a scale factor that takes into account the relationship between the two signal frequencies. The broadcast clocks are converted to single-frequency using the following formulae:

$$C_G^{sat} + D1_G^{sat} = \overbrace{\left(C_G^{sat} + D3_G^{sat}\right)}^{broadcast\_GPS\_clk} + \overbrace{\overbrace{\left(D1_G^{sat} - D2_G^{sat}\right)}^{GPS\_IFB} \cdot \frac{1}{\gamma_G - 1}}^{GPS\_TGD}$$

$$C_E^{sat} + D1_E^{sat} = \overbrace{\left(C_E^{sat} + D3_E^{sat}\right)}^{broadcast\_GIOVE\_clk} + \overbrace{\overbrace{\left(D1_E^{sat} - D2_E^{sat}\right)}^{GIOVE\_IFB} \cdot \frac{1}{\gamma_E - 1}}^{GIOVE\_TGD}$$

The IONO module cannot resolve the mean value of satellite and station IFBs. It is necessary to calibrate somehow one satellite or station IFB in order to refer to it the rest of estimated values. This issue is further analyzed in the next section.

IX. INTER-SYSTEM CALIBRATION

As indicated in the previous section, the ODTS software cannot distinguish between an offset in the GIOVE clock and an offset in the mean inter-system bias of all stations. Two options are possible to tackle this fact. One is to define a zero-average condition for the mean inter-system bias. This option has two disadvantages: first, that the mean inter-system bias actually depends on the set of stations used in the data processing and, second, that the inter-system bias average is not necessarily zero. The second option is to choose one of the stations as reference for the inter-system bias (and by definition fix a zero value for it in ODTS), and then calibrate that inter-system bias *a posteriori* in order to remove the *actual* inter-system bias from the GIOVE clock estimations from ODTS.

The GIEN station has been selected as reference for inter-system bias, since this station is also the reference for all clock estimations. However, how can we calibrate the actual inter-system bias of GIEN?

From Figures 5 and 6, the inter-system bias can be expressed as:

$$D3_E^{sta} - D3_G^{sta} = \left[D1_E^{sta} + \left(D1_E^{sta} - D2_E^{sta} \right) \cdot \frac{1}{\gamma_E - 1} \right] - \left[D1_G^{sta} + \left(D1_G^{sta} - D2_G^{sta} \right) \cdot \frac{1}{\gamma_G - 1} \right]$$

If the station group delay in L1 is approximately the same for the GPS and Galileo paths[3], i.e., if $D1_G^{sta} \approx D1_E^{sta}$, then we have the following expression to calculate the inter-system bias from the station inter-frequency biases (IFBs) calculated by the IONO module:

$$D3_E^{sta} - D3_G^{sta} = \overbrace{\left(D1_E^{sta} - D2_E^{sta} \right)}^{station\_Galileo\_IFB} \cdot \frac{1}{\gamma_E - 1} - \overbrace{\left(D1_G^{sta} - D2_G^{sta} \right)}^{station\_GPS\_IFB} \cdot \frac{1}{\gamma_G - 1}$$

This expression is only useful if the Galileo and GPS station IFBs calculated by the IONO module have been adequately calibrated. In order to do this, the average of the estimated P1-P2 IFB of GPS satellites has been aligned with the mean of IFB values contained in the navigation message, as calculated by JPL. The mean GPS TGD is around +8 ns corresponding to a mean IFB of around +5 ns (after multiplying by a L1/L2 frequency factor). The C1C-C7Q IFB of the GIOVE satellite has been fixed in the IONO module to the L1-E5 hardware delay calibrated by the satellite manufacturer. This value is +888.4 ns (sic).

X. EARLY EXPERIMENTATION RESULTS

This section presents the station IFBs (and the inter-system biases derived from them) obtained from GSTB-V2 data processing during the early experimentation phase. Fourteen days of data were processed by the IONO module, between 1 and 14 November 2006. The data were processed in separate IONO *arcs* of 2-day duration, with a total of seven arcs covering 14 days. IFBs are estimated as constant values within each IONO arc. There is no constraint imposed for continuity between IFBs estimated in consecutive arcs.

As explained in the previous section, the GPS average satellite IFB (P1-P2) was constrained to be +5.4 ns (the mean value from the navigation message during the processing interval) in each IONO arc. However, the IFB of each separate GPS satellite was freely estimated; only the average IFB was constrained, but not the individual satellite values. The C1C-C7Q IFB of the GIOVE satellite was fixed to +888.4 ns in every IONO arc, as indicated in the previous section. The station inter-system bias were calculated from the station GPS and Galileo IFBs, according to the formula presented in the previous section and assuming the same delay for the GPS P1 code and for the Galileo C1C code within the station (this is an approximation).

The resulting IFB and inter-system bias values for the analyzed period are shown in Figure 9 for the different stations available. The values correspond to the average of all (7) IONO arcs. As can be seen from Figure 9, all inter-system biases are relatively small but not negligible, with a maximum value of around +11 ns (actually this value corresponds to the reference station GIEN).

[3] According to Septentrio (the receiver manufacturer), the difference between the GPS C1 code delay and the Galileo C1C code delay within the GETR should be below the nanosecond level, because both codes are processed by the same receiver board. However, the difference between the GPS P1 code delay and the Galileo C1C code delay could reach a few ns, because these codes are processed by different (although synchronized) receiver boards.

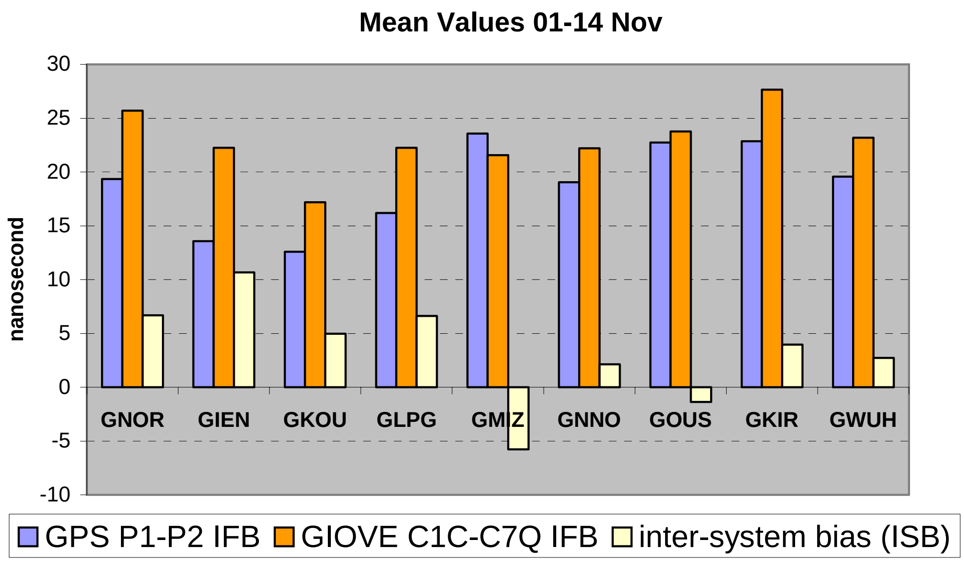


Figure 9. Station IFBs and inter-system biases (mean values).

Figure 10 shows the variability of station IFBs and inter-system biases during the period 1-14 Nov. The reported values are actually the standard deviation (of 7 values, one per IONO arc) of the estimated values. As can be seen from Figure 9, the IFB stability is remarkably good, of the order of 0.2 ns for the majority of stations. Some stations show a worse stability, notably GIEN on C1C-C7Q (probably due to a known interference problem in L1), and GKOU both on P1-P2 and C1C-C7Q (probably due to the particular location of the station at the Equator, where ionospheric activity is higher). The long-term stability of IFBs over many months is to be analyzed at a later stage of the GSTB-V2 experimentation.

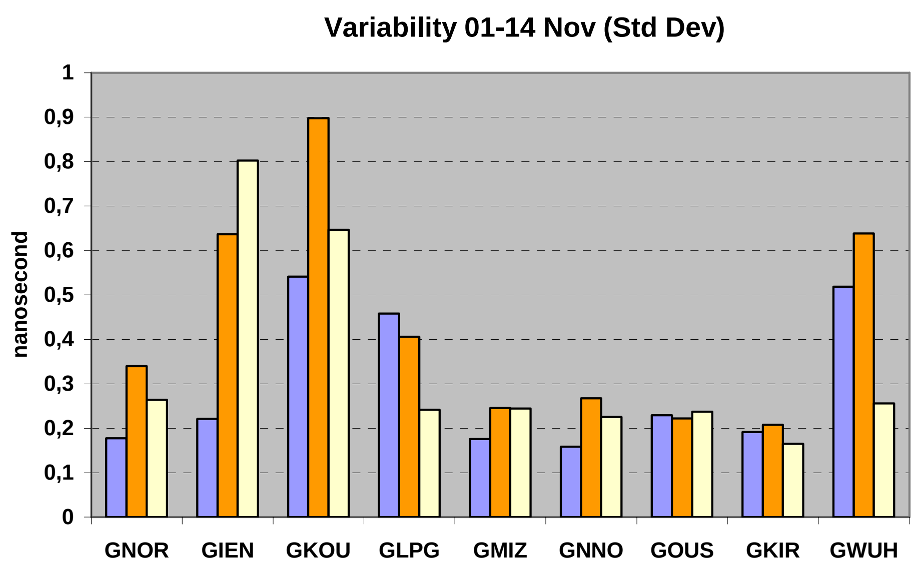


Figure 10. Station IFBs and inter-system biases (variability).

As a quality check for the overall processing, the estimated GPS satellite IFB values were compared against the values from JPL (navigation message) and also against the values contained in IONEX files from IGS[4]. The resulting standard deviations of the comparison are 0.22 ns for JPL and 0.14 ns for IONEX. The agreement with JPL and IONEX values is considered to be remarkably good, considering the reduced network of ground stations involved in the IONO processing.

XI. IMPACT ON SINGLE-FREQUENCY USER

According to the facts and results presented in the previous sections, this section analyzes the impact of on-orbit and on-ground timing biases for a dual GPS/GIOVE user receiver, both for the single-frequency case and for the dual-frequency case. Other interesting discussions about GPS/Galileo interoperability, GGTO, and the effects on the user solution can be found in **[8-10]**.

Figure 11 depicts the situation for a single-frequency user (the frequency is assumed to be L1). The GPS broadcast clocks are given with respect to GPS Time. The GIOVE broadcast clock is given with respect to EGST. It is assumed that GIOVE transmits also EGGTO, i.e. the difference between GPS Time and EGST. The basic (raw) pseudorange equations from Figure 6 are also applicable to the user receiver.

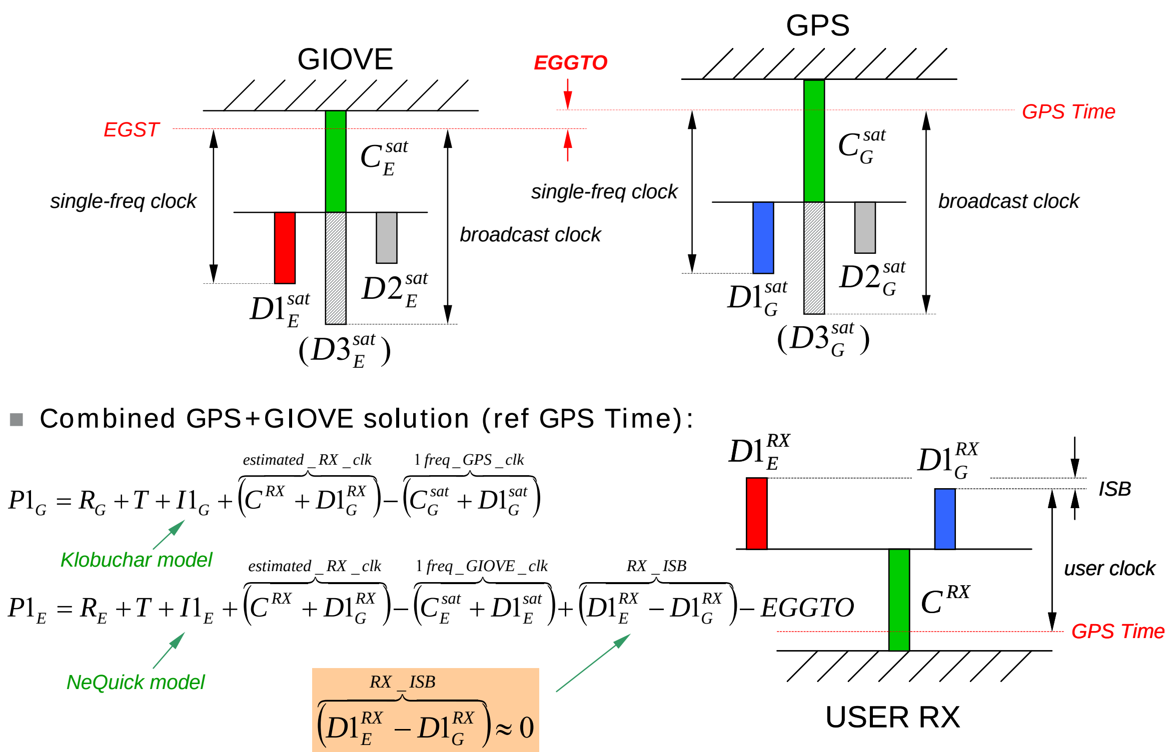


Figure 11. User solution for a single-frequency receiver.

[4] The IFB values contained in IONEX files for GPS satellites have a zero mean, as opposed to the calibrated values from JPL that have a non-zero mean (actually +5.4 ns). This fact has been considered when comparing with the values estimated by IONO.

The satellite broadcast clocks (GPS and GIOVE) are iono-free and must be converted to the L1 frequency by adding the TGDs transmitted in the navigation message, as described previously. The calibration of TGDs is a delicate matter and it is certainly possible that the TGDs of each system contain some kind of miscalibration, normally a constant offset in the mean TGD value. For a single-system user (GPS-only or Galileo-only), this global offset does not affect the position solution, but does affect the user timing solution, since the offset is seen as an offset in the user clock. For a dual-system user (GPS and GIOVE), a global TGD offset would affect both the position and timing solution (assuming that the TGD offset is different for the GPS and GIOVE systems).

The ionospheric delay can be corrected by the user receiver software by using the broadcast parameters for the Klobuchar model (GPS) and the NeQuick model (Galileo). The receiver differential hardware delay between the GPS and GIOVE channels should in principle not be a problem, since receiver group delay in L1 should be approximately the same for the GPS and Galileo paths ($D1_G^{RX} \approx D1_E^{RX}$). Of course, the estimated user clock will contain this delay between the actual receiver clock and the antenna. If the user wants to analyze the actual receiver clock, some kind of *ad hoc* calibration will be required in order to remove the L1 hardware delay from the user clock estimations.

It is assumed that the user clock is estimated with respect to GPS Time, by using the GPS pseudoranges directly and converting the GIOVE pseudoranges from EGST to GPS Time by subtracting EGGTO. This means that a possible offset or miscalibration in EGGTO would also possibly bias a dual-system solution (both in position and time).

In summary, for a dual-system single-frequency user, the following potential sources of miscalibration could affect the position and timing user solution: GPS mean satellite TGD, GIOVE mean satellite TGD, and EGGTO. From the user point of view, these combined effects are seen as a constant (or nearly constant) offset between the GPS and the Galileo systems. This offset could be estimated at user (receiver) level at the cost of one in-view satellite. However, since the offset is assumed to be constant, there is no need to estimate it continuously; therefore, there is no need to always waste one in-view satellite in its solution. For example, in urban canyons the offset estimation could be switched off using the latest value of the estimated offset.

XII. IMPACT ON DUAL-FREQUENCY USER

Figure 12 depicts the situation for a dual-frequency user. The L1 frequency is common for GPS and Galileo, but the second frequency is not the same in both systems (it is L2 for GPS and E5 or E6 for Galileo). As in the single-frequency case, the GPS broadcast clocks are given with respect to GPS Time and the GIOVE broadcast clock is given with respect to EGST. However, in the dual-frequency case, since the satellite broadcast clocks (GPS and GIOVE) are already dual-frequency (iono-free), they can be processed by the user directly without any transformation required (TGDs are not needed).

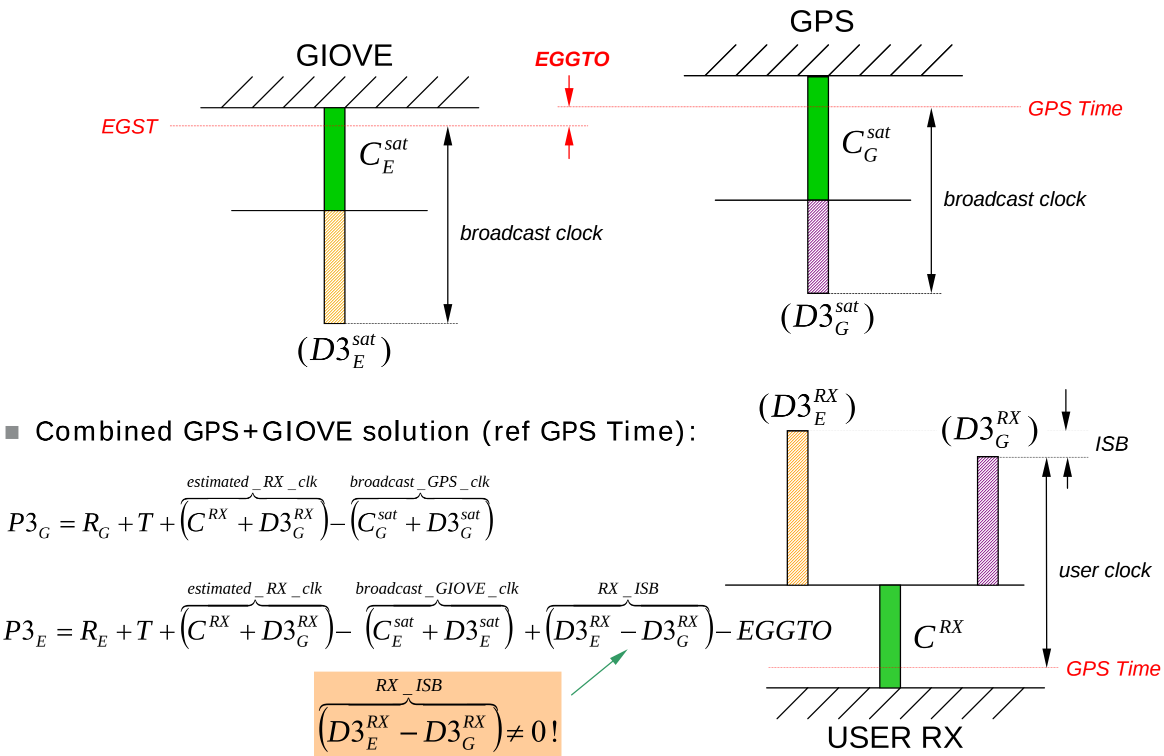


Figure 12. User solution for a dual-frequency receiver.

The iono-free pseudorange equations from Figure 6 are also applicable to the user receiver. As opposed to the single-frequency case, the user does not need to apply any correction for the ionospheric delay, because it is cancelled out when doing the iono-free combination of the two frequencies. The receiver iono-free differential hardware delay between the GPS and GIOVE channels (actually the *inter-system bias* as defined in the previous sections) might be a problem, depending on the receiver construction and properties. Let us recall from previous sections that the $\left(D3_E^{RX} - D3_G^{RX}\right)$ inter-system bias of a station can reach up to 11 ns. As in the single-frequency case, the estimated user clock will contain the hardware delay between the actual receiver clock and the antenna.

As in the single-frequency case, it is assumed that the user clock is estimated with respect to GPS Time, by using the GPS pseudoranges directly and converting the GIOVE pseudoranges from EGST to GPS Time by subtracting EGGTO. This means that a possible offset or miscalibration in EGGTO would also possibly bias a dual-system solution (both in position and time).

In summary, for a dual-system dual-frequency user, the following potential sources of miscalibration could affect the position and timing user solution: receiver inter-system bias and EGGTO. As in the single-frequency case, from the user point of view these combined effects are seen as a constant (or nearly constant) offset between the GPS and the Galileo systems that could be estimated at user (receiver).

XIII. CONCLUSIONS AND FUTURE WORK

This paper has presented the GSTB-V2 project, the Experimental implementations of Galileo System Time (EGST) and GPS to Galileo Time Offset (EGGTO), and the GIOVE navigation message. Some GSTB-V2 preliminary results have been presented showing practical evidence of GPS and GIOVE timing biases, their magnitude, and their relationship. In particular, a method has been proposed for station inter-system bias estimation based on calibrated GPS and GIOVE satellite inter-frequency biases (IFBs), without the need of complex and costly calibration measurements at the station. Such a method assumes that the station hardware delay on L1 is the same for all GPS and Galileo channels. The method also relies on an accurate calibration of the GPS and GIOVE satellite IFBs. Since satellite IFBs (or TGDs) are also important for single-frequency users (especially in the time domain), the need to have reliable IFB values for the GPS and Galileo constellations becomes clear.

Combined GPS+GIOVE position and timing user solutions have been presented, both for single-frequency and dual-frequency users, showing that for true interoperability, in addition to GGTO, a good understanding of in-orbit and on-ground timing biases is important. Combined user solutions could be challenging (depending on the level of accuracy required) due to possible system miscalibrations. A practical approach could be the estimation of a constant inter-system parameter at user level, at the expense of one satellite in view, but not necessarily re-estimated on a regular basis.

Future work in the frame of the GSTB-V2 experimentation includes the processing and analysis of additional code delays (GPS: C1, GIOVE: C1A, C1B, C5Q, C5I…) and long-term stability monitoring of inter-frequency and inter-system biases.

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