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Timing with the Galileo Open Service

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Abstract

The article addresses UTC dissemination through Galileo Open Service and describes the Galileo Open Service Key Performance Indicators related to timing.

Keywords: Galileo; Time; UTC.

1. Signals in Space from IOV Constellation

Galileois an initiative conducted jointly by the European Union and the European Space Agency. Galileo is a global satellite navigation system whose aim is to provide positioning, navigation and timing services all over the world. The path to the Full Operational Capability (FOC) has been constructed as a successions of steps; Figure 1 shows the updated plan (as presented in [1]).

Figure 1 Galileo Deployment and Exploitation Plan

After having successfully deployed the first four satellites the Galileo programme has completed the IOV phase and it is now entering into the FOC one. This will happen gradually and in well-organized steps. Anyway, as of today, the so-called IOV satellites (In Orbit Validation), are already providing timing and positioning information to the community of Galileo users (see [2] for an overview of the IOV test result).

In line with the recommendations of the International Telecommunications Union (ITU), Galileo disseminates the information required to calculate the international reference timescale UTC (Universal Time Coordinated). For the system needs the Galileo System Time (GST) has been established;the GSTis the internal time reference of the system. The GST is a continuous time scale not subjected to the introduction of leap seconds. The GST is closely steered to UTC (modulo 1 second), i.e. the fractional GST-UTC offset is maintained at the nanosecond level and the integer GST-UTC offset is increasing with each new leap second. Both the fractional and the integer GST-UTC offsets are broadcast in the Galileo Signal-In-Space as part of the GST-UTC conversion parameters, (see Figure 2). Thus, the reception of the Galileo Signal-In-Space allows users to measure the difference in terms of time and frequency of their receiver clocks with respect to UTC.

The Galileo system is interoperablewith GPS. As a contribution to the interoperability, Galileo calculates, in coordination with US naval Observatory (USNO), the Galileo GPS Time Offset (GGTO) and then broadcasts it (see [4]). The specification of the timing characteristics are described in the Open Service Signal in Space Interface Control Document (SISICD); this document can be found at [5]. Figure 2summarizes the main characteristics related to the timing capability as published in the Open Service ICD.

Parameter	Definition	Bits	Scale factor	Unit
A_0	Constant term of polynomial	32*	2^{-30}	s
A_1	1st order term of polynomial	24*	2^{-50}	s/s
Δt_{LS}	Leap Second count before leap second adjustment	8*	1	s
t_{ot}	UTC data reference Time of Week	8	3600	s
WN_{ot}	UTC data reference Week Number	8	1	week
WN_{LSF}	Week Number of leap second adjustment	8	1	week
DN	Day Number at the end of which a leap second adjustment becomes effective	3	1	day
Δt_{LSF}	Leap Second count after leap second adjustment	8*	1	s

Figure 2 GST-UTC Conversion Parameters (broadcast since 16 April 2013)

Parameter	Definition	Bits	Scale factor	Unit
A_{0G}	Constant term of the polynomial describing the offset $\Delta t_{systems}$	16*	2^{-35}	s
A_{1G}	Rate of change of the offset $\Delta t_{systems}$	12*	2^{-51}	s/s
t_{0G}	Reference time for GGTO data	8	3600	s
WN_{0G}	Week Number of GGTO reference	6	1	week

Figure 3GPS Galileo Time Offset Parameters (broadcast since 22 April 2013)

Timing as a Service

Galileo Open Service will provide to users access to both precise positioning and timing. The timing capability enables access to UTC through the GST-UTC conversion parameters (see Figure 2) in the Galileo navigation message.

In the first step, the user will be able to estimate the offset of the receiver clock with respect to GST, the internal Galileo system reference. Further, users should apply the GST-UTC conversion parameters.

For the most demanding timing users, like UTC laboratories, the Galileo Open Service definition considers a specific application scenario:

1. A fixed user;
2. At a precisely known (pre-surveyed) position;
3. Equipped with a high-performance dedicated timing laboratory receiver;
4. Precisely calibrated for all signal delays.

For such users, only the clock offset needs to be estimated since the position is precisely known; therefore the access to precise timing is achieved even with only one healthy Galileo satellite in view.

Galileo is entering the phase of Service Validation and (later) provision. A roadmap for the introduction of Initial Services is shown inFigure 4.

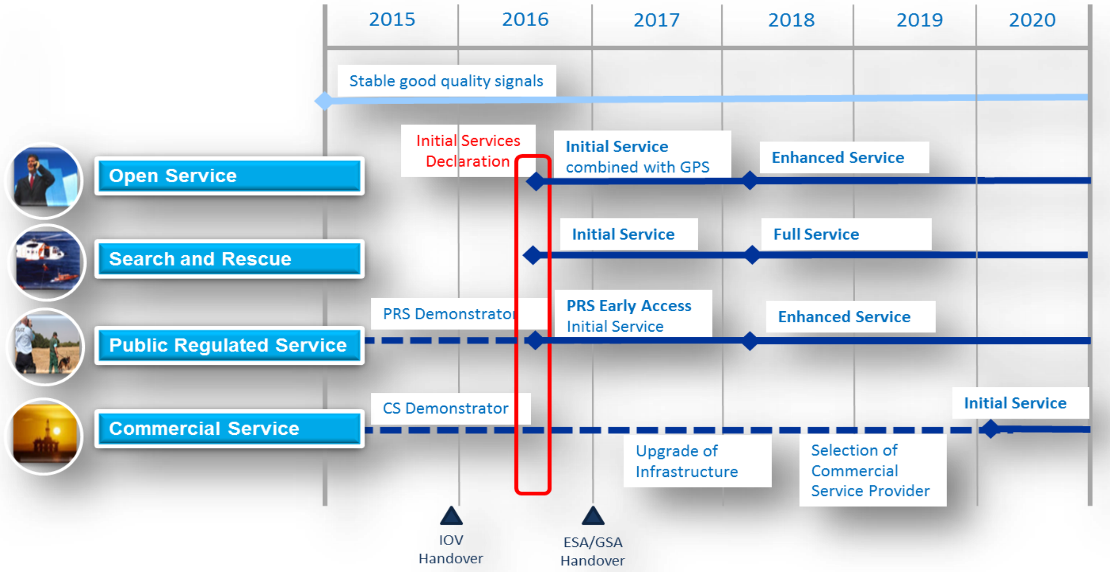

Figure 4 Roadmap to Galileo Services

Anyway, the described capabilities are in place since the end of the IOV phase, therefore available, also today, to the users. The status of this service can be always consulted on the dedicated website of the Galileo Service Center at http://www.gsc-europa.eu/system-status.

This website regularly publishes NAGUs (Notice Advisory to Galileo Users) providing detailed information concerning the status of the Galileo services. Figure 5shows a realistic example of the NAGU text that the users can download from the aforementioned web site.

NOTICE ADVISORY TO GALILEO USERS (NAGU) 2014003

DATE GENERATED (UTC):2014-02-11 17:23
NAGU TYPE: UNP_UNUFN
NAGU NUMBER: 2014003
NAGU SUBJECT: UNAVAILABLE FROM 2014-02-09 UNTIL FURTHER NOTICE
NAGU REFERENCED TO: N/A
START DATE EVENT (UTC): 2014-02-09 04:37
END DATE EVENT (UTC): N/A
SATELLITE AFFECTED: GSAT0101
SPACE VEHICLE ID: 11
SIGNAL(S) AFFECTED: ALL
EVENT DESCRIPTION: GALILEO SATELLITE GSAT0101 (ALL SIGNALS) IS UNAVAILABLE SINCE 2014-02-09 BEGINNING 04:37 UTC UNTIL FURTHER NOTICE.

Figure 5 Notice Advisory to Galileo Users (NAGU)

2. Timing User Algorithm

The Galileo project has implemented the Test User Receiver (TUR) as a tool for validation and monitoring of the system performance. TUR includes the following definition of timing user algorithm.

Step1: Computation of the satellite clock correction, relativistic correction and Sagnac correction.

Sagnac correction ΔS can be computed using the following formula:

$$\Delta S = \frac{\omega_E}{c}(x_u \cdot y_i - y_u \cdot x_i) \qquad (1)$$

where $\omega_E = 7.2921151467 \cdot 10^{-5}$ rad/s – mean rotation rate of the Earth.

As specified in the Galileo OS SIS ICD [5], the satellite clock correction is computed as follows

$$\Delta t_i(X) = a_{f0}(X) + a_{f1}(X) \cdot [t - t_{oc}(X)] + a_{f2}(X) \cdot [t - t_{oc}(X)]^2 + \Delta t_r \quad (2)$$

X:the selected signal combination (either E1/E5a or E1/E5b for Galileo OS).

$\Delta t_r = F \cdot e \cdot \sqrt{A} \cdot \sin E$ is the relativistic correction term with the orbital parameters

e: the orbit eccentricity,

$\sqrt{A}$: the square root of the semi-major orbit axis,

E:the mean anomaly, and

$F = -2 \cdot \sqrt{\mu}/c^2 = -4.442807309 \cdot 10^{-10}\ s/m^{1/2}$.

Step2: Computation the user clock offset versus GST

The user clock offset with respect to GST, t_u, is computed as follows:

$$t_u = \frac{1}{c} \cdot \frac{\sum_{i=1}^{N} \frac{\rho_i - r_i}{\sigma_i^2}}{\sum_{i=1}^{N} \frac{1}{\sigma_i^2}} \quad (3)$$

here

c: speed of light,

N: number of valid pseudorange measurements

σ_i : the expected RMS of the pseudorange measurement to i-th satellite

ρ_i: the pseudorange measured with i-th satellite and corrected with the satellite clock correction, relativistic correction and Sagnac correction computed as described above,

$r_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2}$

Where (x_i, y_i, z_i) are the coordinates of i-th satellite in GTRF, derived from the satellite ephemeris data using the algorithm specified in the OS SIS ICD [5], and (x_u, y_u, z_u)arethe coordinates of the user antenna phase center in GTRF.

The instantaneous estimate of GST, t_E,is finallycomputed as

$$t_E = TOR - t_u - t_{cal} \quad (4)$$

TOR - is the reading of user clock at the time of reception of satellite signals,

t_{cal} : calibrated group delay of TUR.

Step3: Computation of the user clock offset versus UTC

t_E shall be corrected with the broadcast GST-UTC conversion parameters (see Fig. 2) according to the algorithm described in the OS SIS ICD [5].

Galileo timing performance is defined for the averaging period of 24 hours. Therefore, the instantaneous estimates of the user clock offset versus UTC should be averaged over this period.

3. Timing Infrastructure

Galileo has put in place a dedicated infrastructure in order to provide a stable metric time scale continuously steered to UTC (see e.g. [3]). We will mention here the Precise Timing Facility (PTF) and the Time Validation Facility (TVF), which is part of the Time and Geodesy Validation Facility (TGVF). The PTF generates the Galileo System Time (GST) which is provided to all elements for time synchronization purposes. Each Galileo Control Center (Galileo has two Control Centers; one based in Fucino (Italy), the other in Oberpfaffenhofen (Germany)) has a PTF. At the time of writing the PTF providing the reference time scale is the one located in Fucino while the one in Oberpfaffenhofen is deployed and undergoing tests.

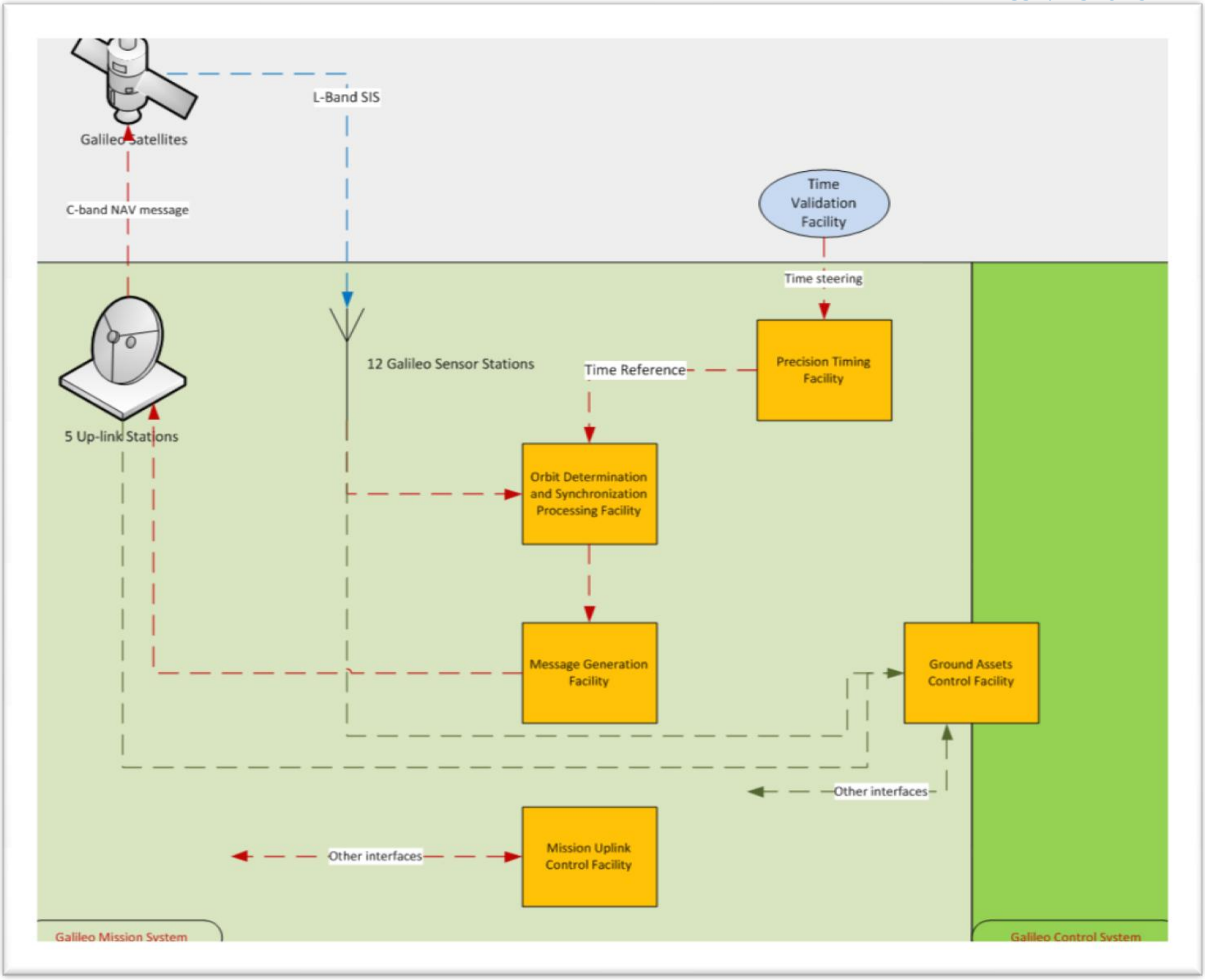

Figure 6 Galileo Timing Infrastructure

The TVF is responsible to link GST to UTC by teaming up European UTC laboratories. This facility, external to the Galileo Mission Segment (seeFigure 6), supports the validation of the Full Operation Capability (FOC) Galileo timing infrastructure (i.e., PTF clocks, ground station clocks, Galileo satellite clocks in orbit), acts as a preliminary Galileo Time Service Provider (GTSP) steering the GST to UTC, and coordinates the national timing laboratories participating in the TVF.

The PTF is built on two fully redundant chains capable of generating the GST; the clocks are two active H-masers (T4Science) and four high-performance Cesiums (Microsemi).

The TVF for FOC is now based in Tres Cantos (Madrid).

4. Galileo Services KPIs

The entrance into the validation and the provision phase of the timing service has the main characteristics that KPIs will be introduced to monitor the quality of the service. KPIs (Key Performance Indicators) are well known in any Service oriented environment. KPIs are metrics used to measure the progress or the fulfillment of critical success factors or objectives within an organization.

KPIs are, therefore, a way to handle complex services in a quantitative way. The Capability Maturity Model Initiative (CMMI) sets at the forth level the achieved capability of providing a service using a quantitative methodology. As a consequence of this, KPIs, concerning both technical metrics and processes, have been defined and will undergo a validation campaign. Once the validation phase is concluded the timing performance KPIs will be published into the Service Definition Document defined by the European Commission.

At the time of writing the KPI defined to measure the Timing performances are:

1. GST-UTC offset;
2. Open Service Dual Frequency UTC Time Determination Accuracy;
3. OS DF UTC Frequency Determination Accuracy;
4. Availability of UTC dissemination;
5. GST-GPS Time Offset Uncertainty;
6. Availability of GGTO.
7. The KPIs will be measured making use of dedicated facilities developed with the purpose to control a wide range of Signal in Space performances.

As far as KPI evaluation is concerned, it is important to underline that theTGVF has a two-fold role: it provides the services of Time Service Provider (within TVF) and the Geodetic Service Provider (within the Orbitography Validation Facility) to Galileo; it also serves as a tool for the evaluation of the Galileo system performance implementing the preliminary KPI evaluation. KPIs are evaluated monthly and reported to ESA. A realistic example of the KPI evaluation by TGVF for February 2014 is presented in

Figure 7 and Figure 11Preliminary timing KPIs for Feb 2014: UTC frequency dissemination accuracy

. The 95% levels are marked with green or red lines in the plots.

KPI	Value
GST-UTC offset	9.8 ns (95%)
UTC dissemination accuracy (phase)	5.3 ns (95%)
UTC dissemination accuracy (frequency)	7.8E-14 (95%)
GGTO dissemination accuracy	11.7 ns (95%)

Figure 7Preliminary timing KPIs for February 2014

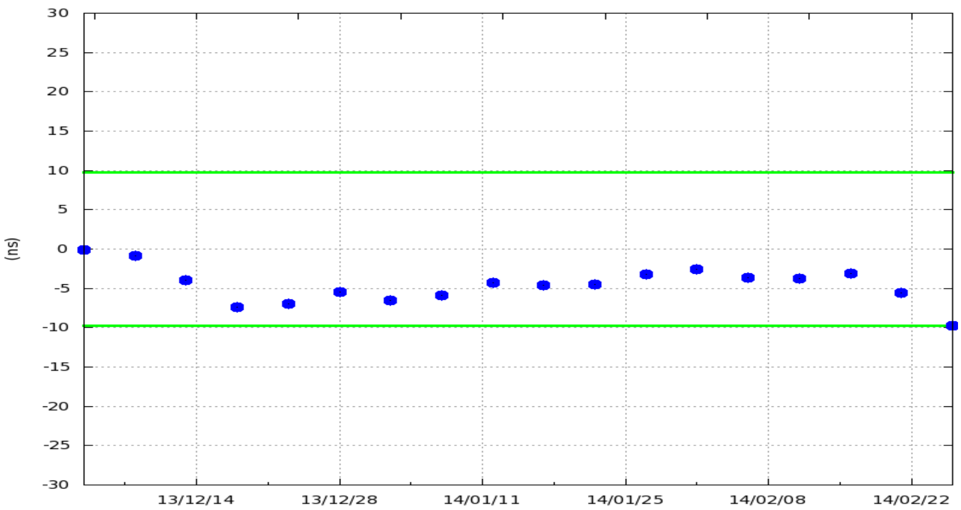

Figure 8Preliminary timing KPIs for Feb 2014: GST-UTC offset

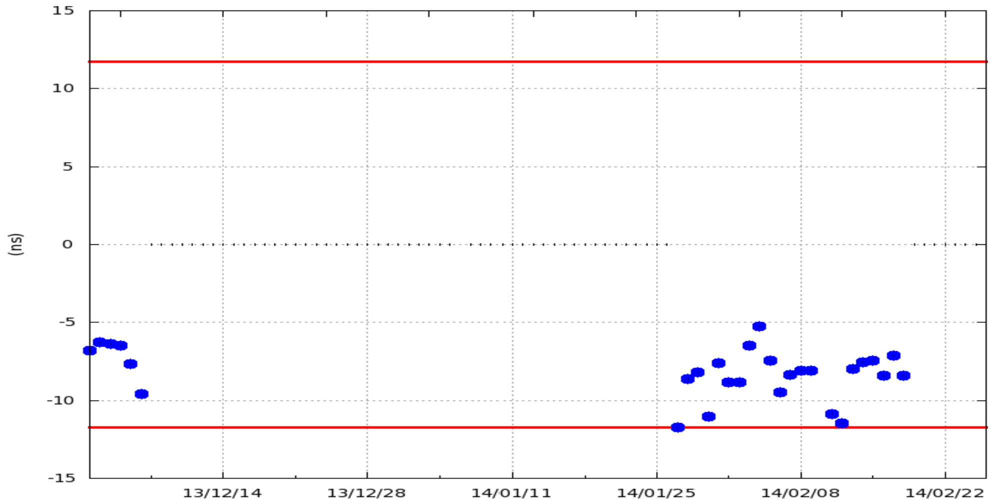

Figure 9Preliminary timing KPIs for Feb 2014: GGTO dissemination accuracy

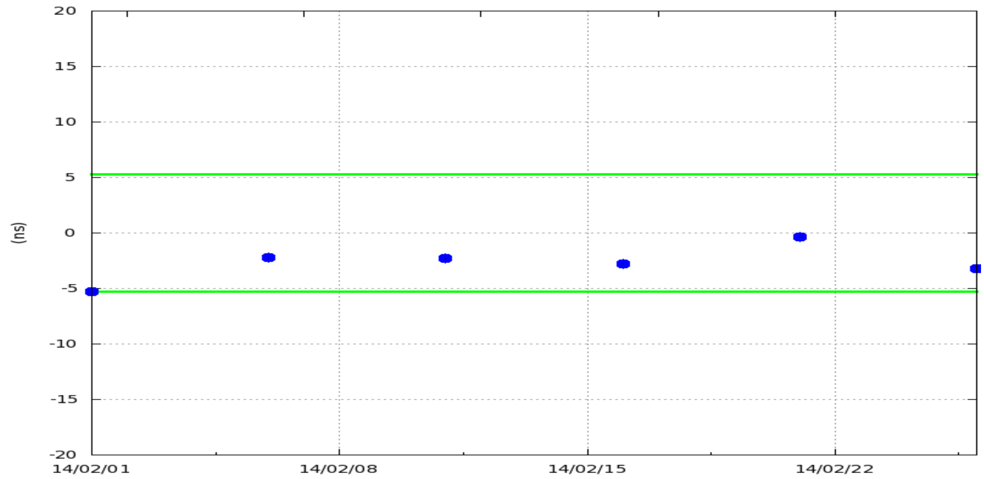

Figure 10Preliminary timing KPIs for Feb 2014: UTC time dissemination accuracy

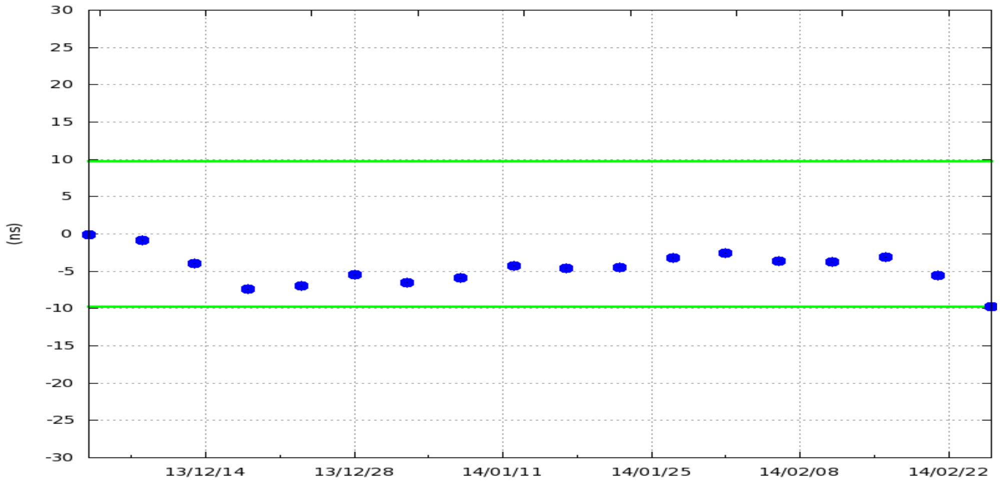

Figure 11Preliminary timing KPIs for Feb 2014: UTC frequency dissemination accuracy

5. Conclusions

Galileo is already providing a reliable and highly accurate signal both for navigation and timing. The full Galileo constellation is starting being deployed and, for what concerns the timing capability, the availability of this service is already relevant. It is sufficient to have a single Galileo satellite in view to access Galileo timing service. Interruption may occur during the deployment but these will be documented by means of NAGU to Galileo users.

Acknowledgment

The Author thanks the ESA System Team and TGVF team for the data provided and support.

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