GGTO and UTC Dissemination results in the GIOVE-Mission

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INTRODUCTION

The assessment of the broadcast GIOVE navigation message performance is one of the primary monitoring activities carried out at the GIOVE Processing Center (GPC) in the frame of the GIOVE Mission (GIOVE-M) experimentations and operations.
An important experimentation objective is to validate GIOVE-A and GIOVE-B end-to-end navigation message chain, from its generation by the Experimental Orbitography and Synchronization Processing Facility (E-OSPF), through its transfer from the GPC to the satellite uplink and the final acquisition by the worldwide network of sensor stations (GESS).
Besides the operational timeliness and robustness of the entire navigation message process, it is important to evaluate the accuracy of the data broadcast to the end user. The navigation message conveys essential parameters which allow the user to determine precise satellite orbits, the calculation of the on-board atomic clock corrections and GGTO and UTC time scale corrections, the latter being the main subject of this paper.
In this context, as part of the GIOVE-M operations, a Key Performance Indicator (KPI) toolset has been implemented on a dedicated GPC facility covering, among others, the mentioned critical areas of the navigation message performance [1-3].
Specific KPI routines have been developed to deal with the dissemination accuracy of GGTO and UTC time scale corrections, based on a continuous navigation message data acquisition through the sensor stations network and the comparison of the broadcast corrections with the a posteriori estimation generated by the E-OSPF at the GPC.
The paper is structured into two parts, a first one covering the GGTO determination and broadcast performance, followed by a second part focused on the UTC dissemination. Both of the sections outline the general objectives of the analyses and describe the methodologies employed to validate the broadcast time scale corrections. The most significant results are presented through a selection of plots which cover different periods, along with the overall statistical trends.

GGTO ACCURACY AS BROADCAST THROUGH GIOVE NAVIGATION MESSAGE

Both GPS and Galileo will have independent internal reference timescales, the Galileo System Time (GST) and the GPSTime (GPSt) respectively. These timescales will be both steered (modulo 1 second) to the international time reference Universal Coordinate (UTC). However, the residual offset between GPSTime and GST may achieve some tens of nanoseconds. If not properly taken into account, this offset will bias the positioning of users of combined GPS/Galileo equipment. As contribution to GPS-Galileo interoperability, both system will determine and broadcast the GPS to Galileo Time Offset (GGTO) through the navigation message [4-5]. This is especially important in the initial phase of Galileo when the satellite installation is not yet completed. Alternatively, the user might treat the GGTO as an additional unknown in the classical positioning algorithm along with the receiver bias.

Early realizations of the GST and GGTO have been implemented within the GIOVE-M, often referred to as EGST and EGGTO for their Experimental purposes. The EGST is driven by the free-running Active Hydrogen Maser connected to the GIEN station at INRiM in Turin, Italy.

The GGTO determination is performed at the GPC by the E-OSPF, which estimates the GGTO in two different ways, one based on ground stations clock information (EGGTO1) and the second based on satellite clock information (EGGTO2), the latter being the only one currently broadcast by the navigation message and therefore the main object of the following analysis. The main difficulty for the GGTO computation is the correct estimation of the GPSTime (GPSt), which is not directly provided to the GIOVE-M.
Nevertheless, the GGTO (EGGTO2) can be determined from the ODTS estimations of the GPS satellite clocks and the clock correction broadcast in the GPS navigation message itself.
Since the satellite clock in the GPS navigation message is referred to GPSt and the ODTS solution is referred to EGST, it is possible to estimate GGTO by comparing the two GPS solutions as follows [6-7]

$$\text{GGTO (EGGTO2)} = \text{MEAN}\left([\text{SATCLK - EGST}]_{odts} - [\text{SATCLK - GPSt}]_{nav}\right) = \text{MEAN}\left(\text{GPSt}_{nav} - \text{EGST}_{odts}\right) \quad (1)$$

where MEAN refers to the average of the chosen GPS satellites at every epoch. Although each individual GPS satellite provides a separate estimation of GGTO, it is understood that averaging for all satellites (actually the best satellites according to their clock stability) will provide a better estimation of GGTO.
Based on the algorithm described, the routine E-OSPF generates estimation and prediction arcs, in the format of .SP3 clock files stored into the Data Server Facility (DSF) at the GPC. These files belong to the core products generated by the ODTS processing. The prediction arcs contain the information assembled into the navigation message.

In order to assess the broadcast GGTO correction as transmitted by the GIOVE navigation message, we need to compare the broadcast GGTO values with the correspondent E-OSPF *a posteriori* estimations, as illustrated in Fig. 1.
The input files required for this analysis are:

- the navigation message received by the GESS and
- the RGGTO core products generated by the E-OSPF

The processing consists basically of 2 steps:

1. **Broadcast GGTO computation**, this is done using the correction parameters broadcast by the navigation message.
2. **Broadcast GGTO accuracy estimation**, the GGTO based on the broadcast data from the GIOVE message is compared with the a posteriori E-OSPF estimation

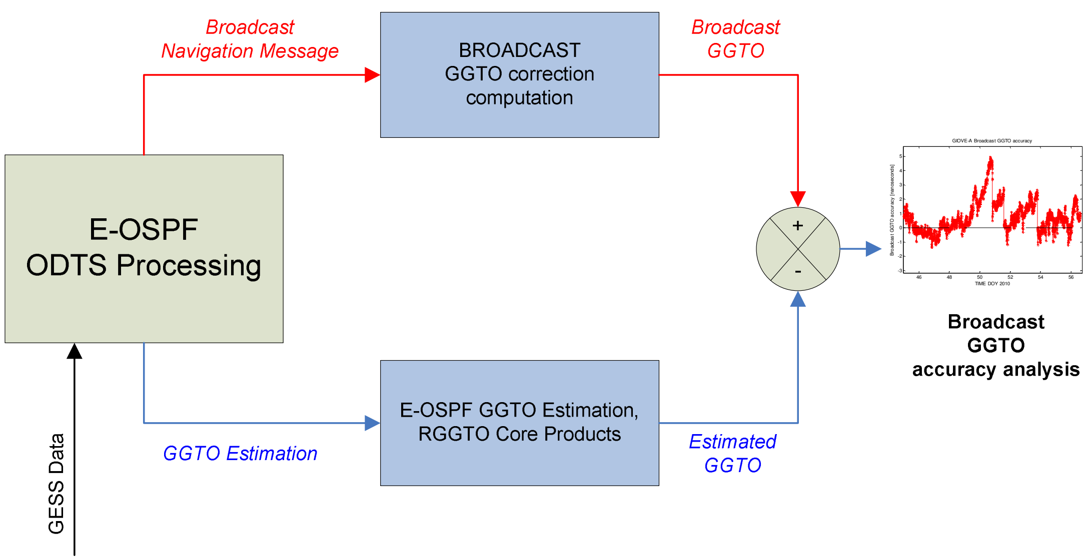

Fig. 1 – Diagram of the GGTO accuracy evaluation

Two separate data flow originated by E-OSPF ODTS processing can be identified in Fig.1, one corresponding to the data conveyed by the broadcast navigation message, and the other to the offline GGTO estimation. The received navigation message are parsed for the broadcast GGTO computation and then compared with the offline estimation. The main results of this process are provided in the next paragraph.

Following the GIOVE A+B SIS-ICD [8], the GIOVE-A navigation message includes a set of parameters for the correct estimation of the GGTO.

Parameter	Definition	Bits	Scale factor	Units
GGTOval	Validity flag, '1' indicates valid GGTO	1	n/a	n/a
A_{0G}	Constant term of the offset $\Delta t_{systems}$	20 (*)	2^{-32}	s
A_{1G}	Rate of change of the offset $\Delta t_{systems}$	12 (*)	2^{-51}	s/s
t_{0G}	GGTO data reference Time of Week	8	3600	s
WN_{0G}	GGTO data reference Week Number	6	1	week
	GPS Time to GST Offset Parameters	**47**		

* Parameters so indicated are two's complement, with the sign bit occupying the MSB

Tab. 1 – Parameters for the GPS time to GST offset computation

The user evaluates the difference between the GIOVE-A/B Galileo and the GPS time scales by the expression

$$GGTO_{BROADCAST} = A_{0G} + A_{1G}(TOW - t_{0G} + 604800 \cdot ((WN - WN_{0G}) \bmod 64)) \tag{2}$$

where

TOW GIOVE-A/B GST TOW (seconds)
WN GIOVE-A/B GST Week Number corresponding to GST TOW

and $A0G$, $A1G$, $t0G$ and $WN0G$ according to Tab. 1 .

These parameters are available in the header section of the RINEX 3.0 Navigation files. Fig. 2 shows an example of RINEX 3.0 Navigation file with GGTO parameters.

```
     3.00           N                   E                   RINEX VERSION / TYPE
S2R                 INDRA               20100301 011034  UTCPGM / RUN BY / DATE
 GAL    4.5250E+01 -1.2109E-01  1.3306E-02  0.0000E+00       IONOSPHERIC CORR
GAUT  3.7446618080E-05 9.112710586E-13  45056 1573 GSTB   0 TIME SYSTEM CORR
GPGA  3.7293881178E-05 9.090506126E-13  43200 1573 GSTB   0 TIME SYSTEM CORR
                                                            END OF HEADER
E01 2010 03 01 00 00 00 5.033914931118E-04 4.386038199300E-10 0.000000000000E+00
     5.200000000000E+01-1.280937500000E+02 2.311524855717E-09-1.746444432821E+00
    -5.833804607391E-06 9.075895650312E-04 1.691468060017E-05 5.451307552338E+03
     8.640000000000E+04 2.980232238770E-08-1.222113468674E-01-1.471489667892E-07
     9.795714029437E-01-1.518750000000E+01-3.586066009472E-02-5.176287041704E-09
    -3.935878230841E-10 4.000000000000E+00 1.573000000000E+03 0.000000000000E+00
     0.000000000000E+00 7.300000000000E+01 0.000000000000E+00 0.000000000000E+00
     8.697100000000E+04 0.000000000000E+00 0.000000000000E+00 0.000000000000E+00
```

Fig. 2 – RINEX 3.0 Navigation file with GGTO parameters

Broadcast GGTO Analysis results

In this paragraph we present the results on the GGTO broadcast performance within the GIOVE-M. Fig. 3.a shows a typical trend over a period of seven days, specifically from DOY 48 to 55 (17^{th} – 24^{th} February) 2010. It can be observed that the GGTO is for this specific period in the order of 36-37 microseconds, with a drift of about 11.21ns per day or equivalently about 78.5ns per week.

The GGTO has been computed using a *composite navigation message*, involving information combined from different messages received at different GESS stations to achieve the continuity of the reception of the navigation data, as the satellite visibility would be limited and discontinuous for a single station.

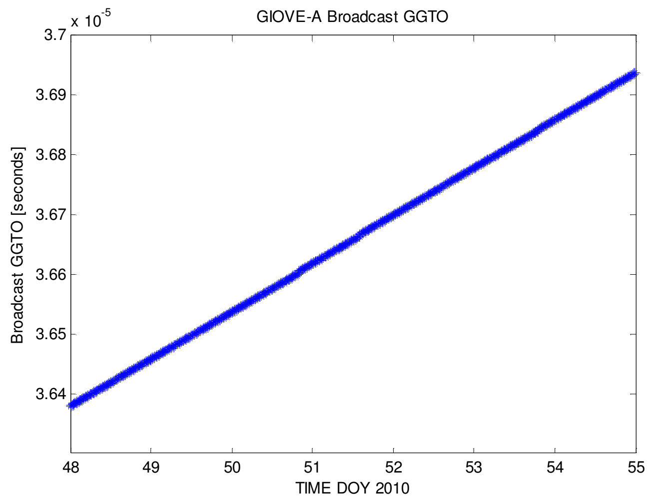

Fig. 3 – GIOVE-A Broadcast GGTO, 17 – 24 February 2010

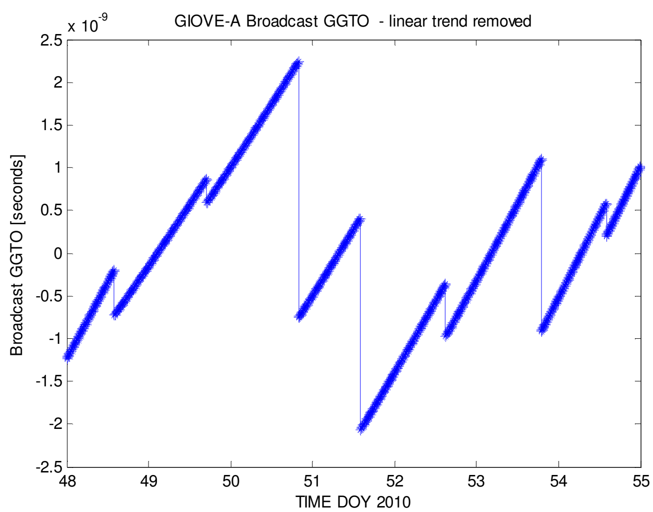

Fig. 4 – GIOVE-A Broadcast GGTO, 17 – 24 February 2010
Linear Trend Removed

The linear trend of the broadcast GGTO is related to the current Experimental-GST realization in the GIOVE-M, being the reference time based on a free running active hydrogen maser installed at GIEN station in Turin, Italy, i.e. the clock frequency is not adjusted to the international time reference. Unlike EGST, the operational GST will be closely steered (modulo 1 second) to UTC both in phase and in frequency with the GST-UTC offset less than 50 ns (modulo 1second). This will limit the GGTO value to a few tens on nanoseconds or less.

Nevertheless, removing the linear trend from the broadcast GGTO it is possible to spot the upload cutovers corresponding to the sequence of the navigation messages, as shown in Fig 4. This pattern is superimposed to the linear trend depicted in Fig. 3. We can identify the relation between the broadcast GGTO discontinuities and the broadcast message sequence. Based on update ODTS estimations, every new message contains updated GGTO corrections. Two consecutive broadcast GGTO dataset appear to differ in the order of a few nanoseconds.

The prediction uncertainty of the broadcast GGTO is computed following the diagram of Fig. 1. The broadcast GGTO prediction error is estimated epoch by epoch as difference between the prediction conveyed by the navigation message and the E-OSPF a posteriori estimation contained in the Restituted GGTO (RGGTO) files.

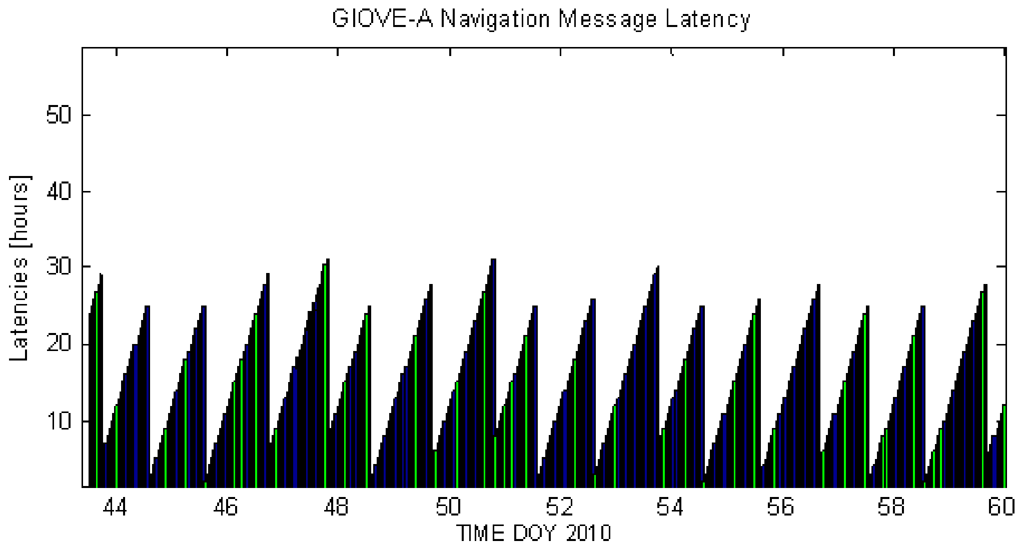

Fig. 5 – GIOVE-A Navigation Message Latency, DOY 44-60 2010

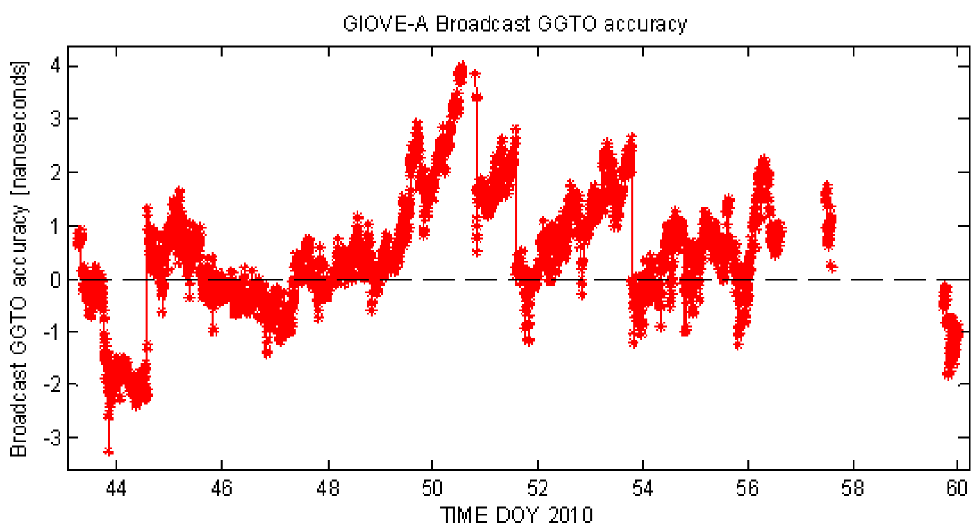

Fig. 6 – GIOVE-A Broadcast GGTO accuracy, DOY 44-60 2010

The resulting broadcast GGTO prediction uncertainty for the analyzed period is reported in Fig. 6. The absolute error fluctuates between -1 and +5ns, reaching the larger values only for navigation message latencies exceeding the 24 hours. The discontinuity patter associated to the sequence of the message uploads (Fig. 5) is visible also in this case.

In Fig. 7 it is shown the histogram representing the broadcast GGTO error distribution, based on the data presented in the previous plot (Fig. 6), corresponding to the period DOY 43-60 2010 with a mean GGTO prediction error around 0.45ns. In Fig. 8 the low correlation between the GIOVE-M navigation message latency ranging from 0 to 30 hours and the broadcast GGTO error confirm that a single navigation message upload per day (as specified in [5]) is sufficient in the operational phase of Galileo. Low GGTO prediction error gives a good prospect for meeting the GGTO accuracy of 5ns (2 sigma) (also see [5]).

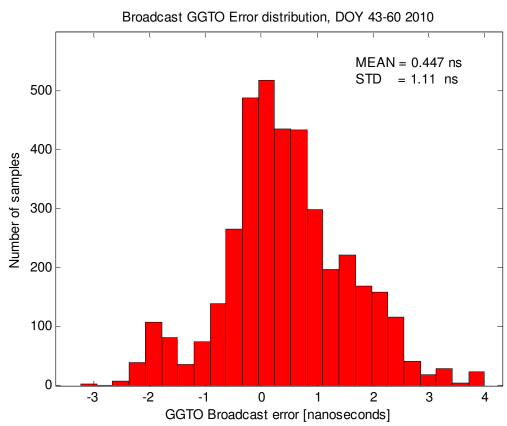

Fig. 7 – Broadcast GGTO Error distribution

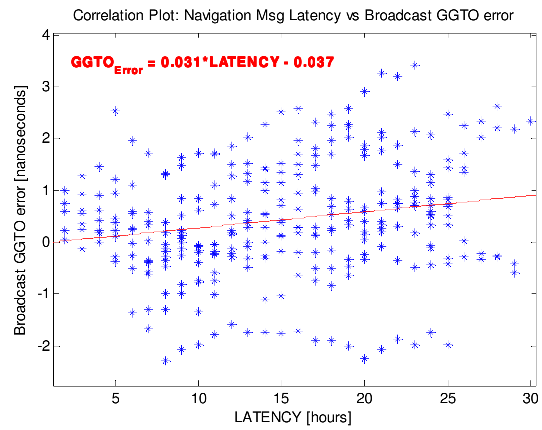

Fig. 8 – Correlation Plot: Navigation Message Latency vs Broadcast GGTO error

We conclude this section reminding that the results presented are based on the experimental GIOVE-M infrastructure, thus not fully representative of the future Galileo performance.

EVALUATION OF UTC DISSEMINATION PERFORMANCE THROUGH GIOVE NAVIGATION MESSAGE

This section presents an assessment of the quality of the UTC-EGST transmitted in the GIOVE Navigation Message. The objective is to analyze the UTC dissemination by the GIOVE satellites and the performance at user level. The inputs required are the broadcast navigation message containing UTC-EGST correction parameters and the a posteriori UTC-EGST estimation provided by the E-OSPF.

It is important to note that in the GIOVE-M the time scale which is disseminated through the navigation message to the end user is not the international UTC, as the UTC-GST link will be provided only in the operational phase of the Galileo system by the Galileo Time Service Provider (GTSP). Nevertheless, within the current GIOVE-M it is possible to get an approximation of UTC using the UTC(USNO) as observed by the GUSN station located in Washington DC. GUSN is connected to UTC(USNO) but it is not calibrated, the calibration bias is around 155ns (as April 2010). In the operational Galileo the link to UTC will be provided by the Galileo Time Service Provider relying on the effort of the European timing institutes.

Similarly to the GGTO analysis, the processing can be summarized in 2 steps:

1. **Broadcast UTC computation**, this is done using the correction parameters broadcast by the navigation message.

The GIOVE –A/B GST is converted to the UTC using the parameters (Tab. 2) and the formula from the GIOVE Signal In Space ICD [8].

$$t_{UTC} = (t_E - \Delta t_{UTC})$$

$$\Delta t_{UTC} = \Delta t_{LSF} + A_0 + A_1 \cdot (t_E - t_{ot} + 604800 \cdot ((WN - WN_t)) \quad (3)$$

where

t_{UTC} is the UTC time

t_E is the Experimental GST

Δt_{UTC} is the offset between UTC and Experimental GST

WN GIOVE-A/B GST Week Number corresponding to GST TOW

and A_0, A_1, *t*ot and WN_t according to Tab.2**.**

Table 34: Parameters for GST-UTC Conversion

Parameter	Definition	Bits	Scale factor	Unit
A_1	Rate of change (in seconds per second) of the offset Δt_{UTC} between GST and UTC time scales	24 (*)	2^{-50}	Sec/sec
A_0	Constant term (in seconds) of polynomial describing the offset Δt_{UTC} between GIOVE-A/B System and UTC time scales at the time t_E, that is the GIOVE-A/B System Time as estimated by the user on the basis of correcting $t_{S/C}$ for the satellite clock offset and relativity terms as well as for ionospheric effects	32 (*)	2^{-30}	Seconds
Δt_{LS}	Offset due to the integer number of seconds between GST and UTC	8 (*)	1	Seconds
t_{0t}	Time of validity of the UTC offset parameters	8	2^{12}	Seconds
WN_t	UTC reference week number	8	1	Weeks
WN_{LSF}	Week number for the leap second adjustment	8	1	Weeks
DN	Day number for the leap second adjustment (becomes effective at the end of the day)	8	1	Days
Δt_{LSF}	Is the offset due to the introduction of a leap second at WN_{LSF} and DN	8 (*)	1	Seconds
	Total	104 (UL)		**Bits**

(*) Parameters so indicated are two's complement with the sign bit occupying the MSB

Tab. 2 – Parameters for GST-UTC Conversion

2. **Broadcast UTC accuracy estimation**, the UTC based on the broadcast data from the GIOVE message is compared with the a posteriori E-OSPF GIEN-GUSN estimation

Broadcast UTC – GST Analysis results

A typical trend of the broadcast UTC(GUSN) correction along with the GUSN-GIEN station estimation is shown in Fig.9. The absolute EGST-UTC(GUSN) prediction error is within 2ns, with a mean value around 0.2 ns.

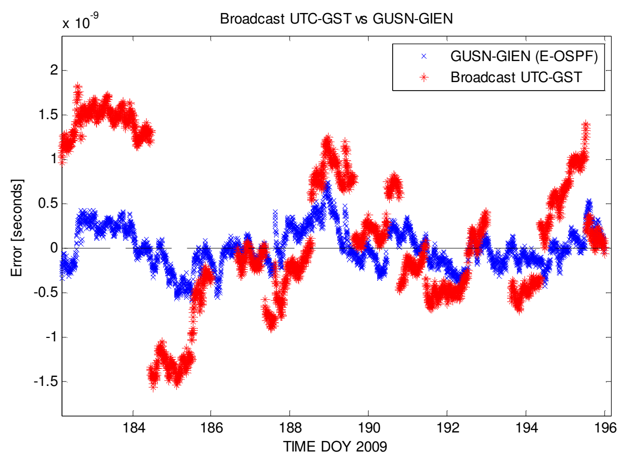

Fig. 9 – Broadcast UTC(GUSN)-EGST vs GUSN-GIEN (E-OSPF estimation), DOY 182-196 2009

A longer period has been considered for statistical analysis, from July to December 2009, leading to the histogram shown in Fig. 10. The distribution is clearly non Gaussian, as observed also for other error based on the broadcast navigation message, such as User Ranging Error and the clock and orbit components [9]. For the period considered, the mean of the UTC error is around **0.47ns**, with a standard deviation around **0.88ns**.

Fig. 11 shows a correlation plot of the navigation message latency against the broadcast UTC(GUSN)-GST correction, based on data from August to October 2009. No significant correlation is observed. Even with low latency values, the broadcast error is quite spread between the minimum and maximum. This is true as far as we limit the latency to the maximum observed in the analyses, i.e. around 50-60 hours. Higher latencies are expected to influence more significantly the UTC dissemination; however this would be the case of very anomalous operations with no fresh message upload in days. This result confirms Galileo baseline to update the UTC parameters once a day.

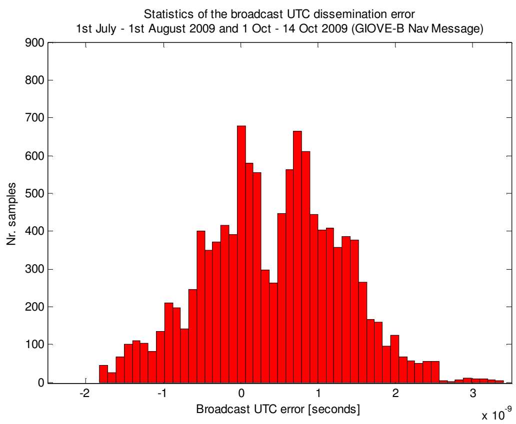

Fig. 9 – Broadcast UTC Error distribution

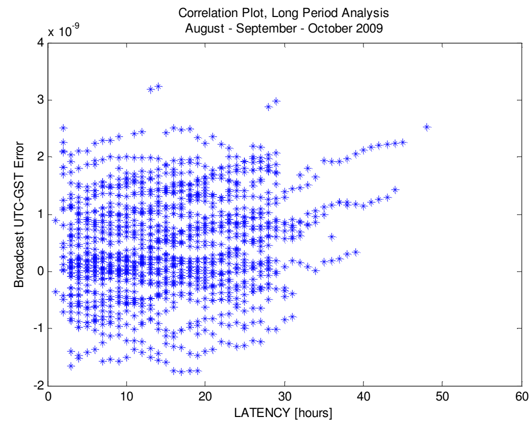

Fig. 10 – Correlation Plot: Navigation Message Latency vs Broadcast UTC-GST error

The conclusion is that the UTC dissemination performance is primarily affected by the GIEN-GST time stability and estimation accuracy, whereas the message latency characterizing the nominal operations period has a minor effect.

CONCLUSIONS

The results presented in this paper provide additional confidence that GGTO determination with 5 ns (2σ) accuracy can be achievable. GGTO validity of 24h is confirmed by these results.

Similarly, also the Galileo budget allocation for the UTC prediction is tested with experimental data, with a very good performance of the UTC prediction within the 24h and no correlation between the message latency and the broadcast corrections that confirms the selected baseline to update UTC parameters daily.

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