

# GIOVE Navigation Message Validation through Keys Performance Indicators

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## BIOGRAPHY

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## INTRODUCTION

The primary purpose of the GIOVE Mission Segment is to mitigate the Galileo project risks. This is in accordance with an incremental development approach which, contrarily to a traditional “V-shaped” life-cycle, is based on the pre-development of ground and space critical components allowing the verification of the system design well before the critical design of the operational system is completed [Ref.1].

In this framework, most of the critical on-board technology has been already validated through extensive and continuous experimentations over the last three years. Promising results have been obtained for the on-board atomic clocks, the navigation signal generator units, the signal design and the impact of the MEO radiation environment. These activities are supporting the design of the Galileo In Orbit Validation (IOV) satellites which, scheduled to be launched in 2010, are envisaged to be part of the fully operational final constellation. Obviously, at the moment, the GIOVE Mission does not provide any real positioning service, being the space segment composed only of two experimental satellites. Excluding a complete Position, Velocity

and Time (PVT) solution at user level, it is nevertheless possible to test and demonstrate essential navigation capabilities both in terms of the broadcast ephemeris and clock performance as well as in terms of the operational aspects of the end-to-end navigation message processing chain.

Therefore, in light of this context, the present paper intends to discuss the accuracy of the clock and ephemeris corrections conveyed by the broadcast navigation message. After illustrating the system overall architecture, we will describe how the data from the worldwide network of stations is collected and processed by the GPC and how the navigation message is generated.

The broadcast corrections are then compared with the *a posteriori* estimations provided by the experimental Orbit and Synchronisation Processing Facility (E-OSPF), as a result of the batch least square algorithm.

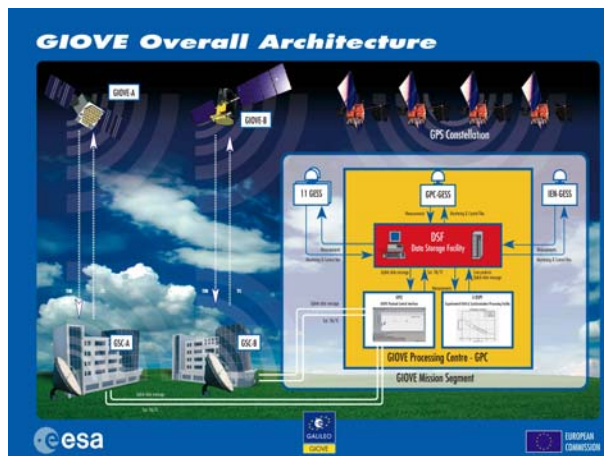
A set of so-called Key Performance Indicators (KPI) are generated at the GPC to continuously measure the quality of the processing. The KPI cover the areas of the navigation message performances including the Orbit Determination and Time Synchronization (OD&TS) processing performances, the Orbits and Clock prediction accuracy, the Experimental Galileo to GPS Time Offset (EGGTO) determination and prediction accuracy, the Broadcasted Group Delay (BGD) stability and the input data latency and completeness for the OD&TS processing. The KPI will also cover the Experimental GIOVE System Time (EGST) stability, the Intersystem Bias and the delay and validity of the generated and received navigation messages.

### **GIOVE Overall Architecture**

As illustrated in Fig.1, the GIOVE Mission Segment comprises three segments:

- The space segment
  - The GIOVE-A Satellite built by Surrey Space Technology Limited (SSTL, UK) and launched in December 2005
  - The GIOVE-B Satellite built by AST-D and its partner, launched in April 2008
- The ground control segment
  - The GIOVE-A Control Centre operated by SSTL in Guilford (UK)
  - The GIOVE-A TTC stations located at Oxford (UK), Santiago (Chile) and Kuala Lumpur (Malaysia)
  - The GIOVE-B Control Centre operated by Telespazio in Fucino (I)

- The GIOVE-B TTC stations located at Fucino (I) and Kiruna (SE)
- The ground mission segment
  - The GIOVE Processing Centre (GPC) operated by VEGA SELEX Systems Integration Plc in Noordwijk (NL)
  - The global network of Galileo Experimental Sensor Stations



**Figure 1 GIOVE GPC Processing Overview**

The ground mission segment constitutes the infrastructure of the GIOVE Mission Segment (GIOVE-M) which is responsible for the infrastructure maintenance and renovations and the Mission experimentation and operations. The satellites are monitored and controlled by the Satellite Control Centres through a network of Telemetry Tracking and Control (TTC) stations at various locations throughout the world using S-Band communication. Within the ground mission segment, the GPC is characterized by a Core Infrastructure, which includes the following components:

- The DSF (Data Storage Facility) in charge of the data centralisation, formatting, archiving dissemination, and monitoring and control of the system. This facility has been developed and integrated by Indra (Barcelona, Spain).
- The E-OSPF (Experimental Orbit and Synchronisation Processing Facility) in charge of Orbit Determination and Time Synchronization (OD&TS) processing. This is the computational heart of the system, where the OD&TS, clock characterization and message generation calculations (among others) are carried out. It has been entirely developed by the advanced systems division in GMV (Madrid, Spain).

- The GPCI (GSTB Payload Control Interface) in charge of exchanging data with the operational control centres (GSCs) of the A and B satellites. It allows the experimentation team to manually generate payload configurations and payload

## KEY PERFORMANCE INDICATORS

Along with hardware enhancements, such as new sensor stations attached to the worldwide network, the GPC has been upgraded to generate and report on a set of Key Performance Indicators (KPI) in order to continuously measure the quality of the GPC processing [Ref.2].

These KPI are generated by a software tool, namely the KPI Tool, developed on a dedicated GPC facility at ESTEC.

These Key Performance Indicators, are conceived and assessed for two main purposes:

1. provide support to the experimentation activities carried out within the GIOVE-M segment.
2. support the GPC operations, as a monitoring tool

The main experimentation activities of the GIOVE-M segment which are taken into account by the KPI are related to the early demonstration and performance assessment of the navigation service, in particular the navigation message uplink and broadcast. In addition the KPI will provide an assessment of the estimation consistency of the E-OSPF, and therefore of the overall OD&TS processing.

## ODTS ESTIMATION CONSISTENCY AND PREDICTION ACCURACY

### *E-OSPF and routine ODTS Processing*

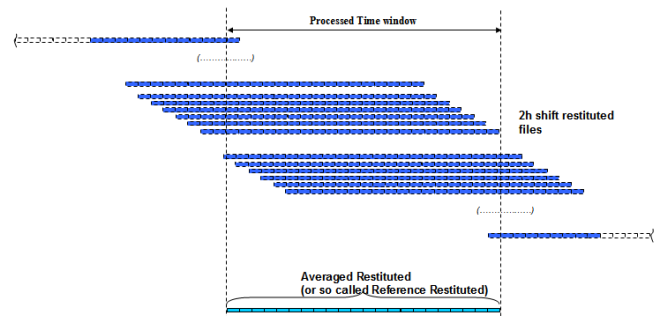
The ODTS performed by the E-OSPF is based on a batch least squares algorithm that processes iono-free GIOVE and GPS code and phase combinations. The data collected at 1Hz are gathered through the worldwide network of sensor stations and stored at the GPC in the DSF. Using these data the ODTS solves for orbits, clocks, troposphere and intersystem bias.

### ***Restituted vs Predicted Clocks***

The KPI Tool will compare the Restituted and Predicted clocks that are routinely generated by the E-OSPF at GPC. The aim of this KPI is to provide an assessment of the accuracy of the prediction over a certain defined time window.

The steps for the KPI computation are:

- Restituted Retrieval block: all the Restituted clocks overlapping, even partially, the Time Window (selected by the KPI Configuration File) are retrieved. The retrieval is commanded to the FTP Download Module.
- Predicted Retrieval block: all the Predicted clocks overlapping, even partially, the Time Window (selected by the KPI Configuration File) are retrieved. The retrieval is commanded to the FTP Download Module.
- Averaged Restituted Computation block: it generates the Average Restituted (or so called Reference Restituted) starting from all the downloaded restituted. Epoch by epoch the reference restituted is the average of all restituted clocks at that epoch (See Fig. 2 ).
- Clock Bias Computation block: it evaluates the Clock Bias Difference between all predicted and averaged restituted.



**Figure 2 – Processing – generation of averaged restituted**

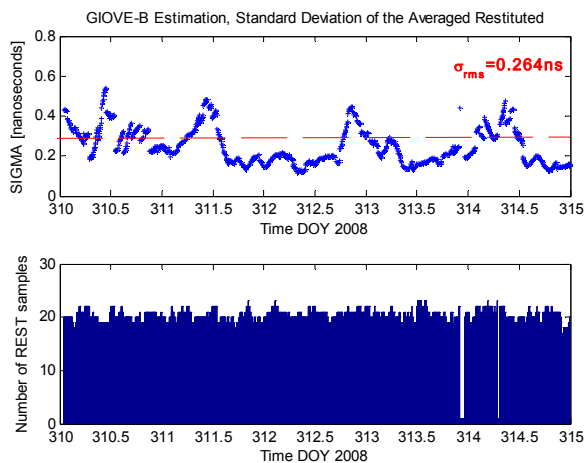
### Reference Restituted computation

The length of the routine ODTS restituted arc is generally set to 2 days, and two consecutive ODTS arcs may have 1 or 2-hours overlap, depending on the E-OSPF configuration. The comparison of the clock estimates from two consecutive arcs in the overlap period can be interpreted as a further key performance indicator for the clock estimations, the so-called *estimation self consistency or estimation precision*. However it has to be reminded that the precision is a necessary but not sufficient condition for accuracy. Nevertheless, it is a valuable indicator, as it can be affirmed that in case of precision

degradation, which can be detected through the KPI Tool routines, as a consequence, also the accuracy is compromised as well.

The E-OSPF absolute accuracy can be assessed only by comparing the *a posteriori* estimations with the SLR measurements. This has been performed by the GIOVE-M experimentation team, lead by GMV, demonstrating good ODTs performances.

For example, the upper plot in Fig. 3 shows epoch by epoch, over a period of 5 days (DOY 310-315 2008), how the standard deviation of the averaged clock restituted varies. The lower plot in Fig.3, shows the number of restituted samples belonging to the different overlapping restituted arcs (Fig. 2 ), which have been considered for the statistic analysis.

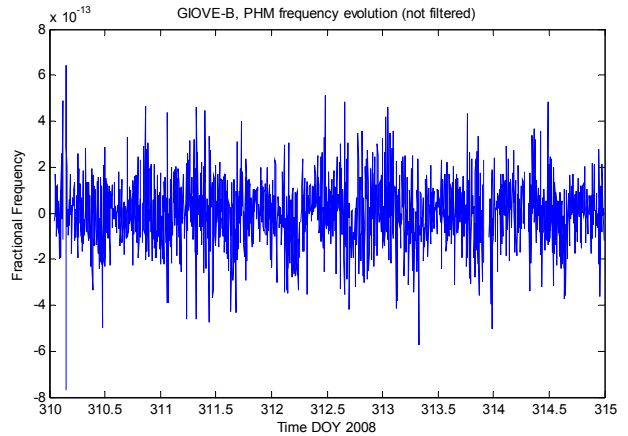


**Figure 3 – Standard deviation of the Averaged Restituted**

It is also clear that the E-OSPF estimation consistency is not constant, rather being a function of time and depending of several factors, such as the satellites degree of coverage (DOC).

Moreover, residual errors in the ODTs estimation itself determine an additional issue to be dealt with. The most evident consequence is the on-board atomic clock apparent frequency periodic oscillation (Fig.4). Even if these fluctuations on rubidium atomic clocks (RAFS), both on GPS and GIOVE-A satellites, are documented to be a consequence of the orbit thermal environment, the latter appears to be only partially the cause of the phenomenon on the highly thermal stabilized Passive Hydrogen Maser (PHM). Indeed, even if the PHM unit is maintained at an extremely stable temperature, the

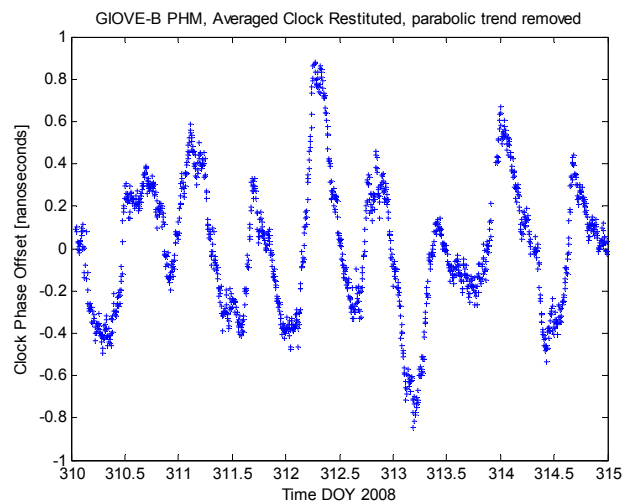
other elements of the payload chain, such as the antenna and the NSGU, are exposed to significant thermal variations, which may result in a broadcast group delay and a consequent apparent clock signal fluctuation.



**Figure 4 – GIOVE-B PHM frequency evolution**

#### Clock Bias Computation smoothing

In order to generate a valid and smoothed reference restituted, we average all the possible different arcs overlapping in the same time window. In addition, a sigma criterion is applied, to discard data which is clearly out of the bounds (Fig. 5).

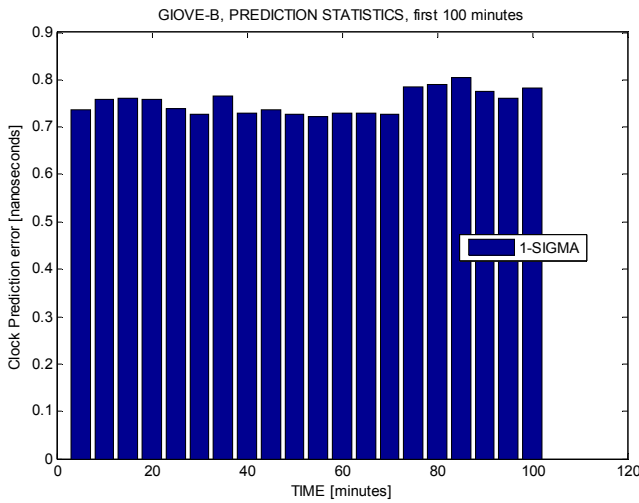


**Figure 5 – Averaged Restituted, parabolic trend removed**

Assuming an estimation length of 48 hours, it is possible to obtain a clock bias at any given epoch as the average of at most 48 different values (assuming hourly E-OSPF sessions). Consequently, the resulting smoothed arc is expected to be more reliable than a single one in terms of outliers

removal, whereas clearly the estimation accuracy itself cannot be enhanced during post-processing.

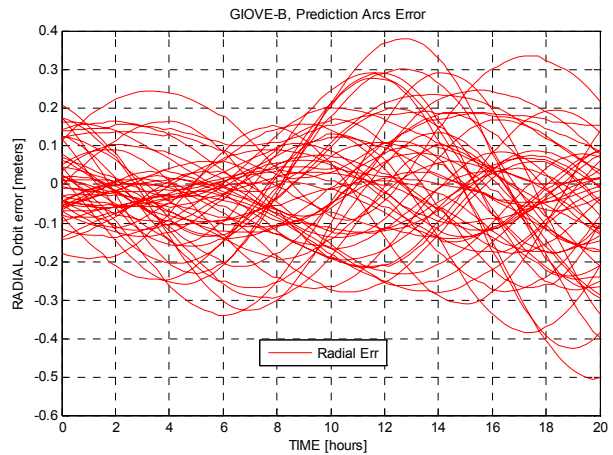
Clock Prediction Performance



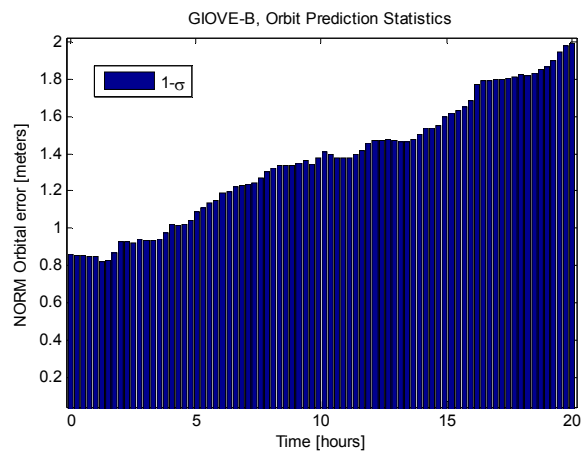
**Figure 6 – Prediction error statistics at 100 minutes**

Restituted vs Predicted Orbits

For orbital prediction accuracy, a KPI, which provides a comparison between the predicted and restituted orbits (estimated *a posteriori*) generated routinely by the E-OSPF at GPC is produced. The aim is to assess the consistency of the predicted orbits with respect to the restituted ones. The process is very similar to the one described in the previous section for the clock prediction accuracy indicator. Restituted and predicted arcs overlapping the time window selected are downloaded through the FTP connection from the DSF and subsequently processed by the KPI Tool. For each prediction arc generated by the E-OSPF, the prediction error is computed with respect to the averaged restituted orbit, along the three orbital components (along track, cross track and radial direction). In Fig. 7 radial orbit errors belonging to different predicted arcs are compared over a period of 20 hours.



**Figure 7 – Predicted orbits accuracy (radial error)**



**Figure 8 – Predicted orbit error overall statistics (norm error)**

Fig. 8 provides a statistical analysis of the orbit prediction performance over the first 20 hours of the analysis. In this case the absolute orbital error, namely the magnitude of the difference between the predicted and restituted vectors is shown.

**BROADCAST NAVIGATION MESSAGE PERFORMANCE**

User Positioning Accuracy

The user ranging accuracy of a GNSS is usually characterized through the User Equivalent Ranging Error (UERE), which comprises different sources of error, such as the satellite clock and ephemeris errors, the ionospheric and tropospheric delays, the receiver noise and the multipath.

In general all these error sources have different statistical properties. However, over a long time period and different scenarios, we can consider all the errors as zero-mean random processes that can be combined statistically into a single UERE as follows [Ref. 4]

$$UERE = \sqrt{\sum_{i=1}^n (UERE)_i^2}$$

$$UERE = \sigma_{UERE} = \sqrt{\sigma_{SISRE}^2 + \sigma_{ION}^2 + \sigma_{TROP}^2 + \sigma_{NOISE+MP}^2}$$

Besides ionosphere, troposphere, noise and multipath errors, in the UERE budget figures also the  $\sigma_{SISRE}$ , the Signal In Space Ranging Error (SISRE), which essentially represent the clock and ephemeris errors affecting the Signal In Space. SISRE is an acronym adopted for the experimental GIOVE-Mission, whereas in the frame of the more complex Galileo integrity concept it is designed as Signal In Space Accuracy (SISA). Nevertheless, to estimate the overall positioning accuracy at user level, the so-called geometrical dilution of precision (DOP), which is determined by the geometry of the satellite constellation observed by the user at a given time has also to be considered. Typically the Horizontal User Positioning Error (HPE) can be estimated as

$$HPE = HDOP \cdot UERE$$

where HDOP is the horizontal dilution of precision. For the final Galileo system, the requirements are 1.1 meters (1 sigma) for the UERE, and 4 meters for the HPE (1 sigma).

In this paper, the analyses have been focused only on the SISRE component of the final UERE error budget. The SISRE, which is intrinsically related to the navigation message data accuracy, is a fundamental indicator of the overall ground processing performances and GIOVE Mission operations timeliness.

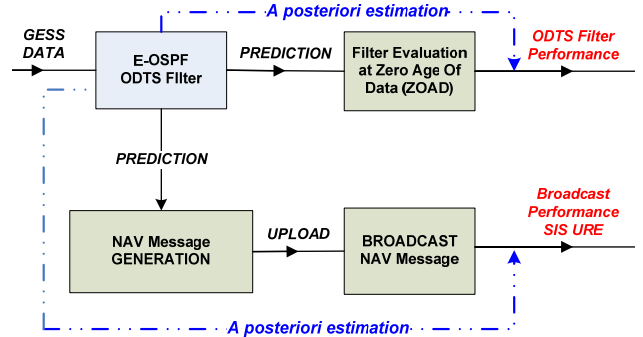
A wide range of studies and publications on GPS navigation message clock and ephemeris accuracy can be found in the literature [Ref. 5 – Ref. 9]. The following section illustrates how an approximate formula may be derived for the GIOVE satellites.

#### Instantaneous GIOVE SISRE computation

In the previous section we have analyzed orbit and clock prediction performances, without dealing with

the broadcast navigation message data. Indeed, what has been done is limited to the characterization of the *ODTS Filter Performance*.

However, a *Broadcast Performance* assessment is required for the SISRE computation. Fig. 9 provides an overview of the process.



**Figure 9 – ODS Filter Performance and Broadcast Performance assessment**

The differences between the broadcast orbit and clock and the *a posteriori* estimation can be projected in the following components

- R, Radial orbit error
- A, along track orbit error
- C, across track orbit error
- CLK, clock error

Moreover, it is useful to introduce the **norm of the orbit error**, **N**, which is related to the previous components as follows

$$N = \sqrt{A^2 + C^2 + R^2}$$

We can combine the previous components into an approximate formula for the SISRE computation [Ref.5]

$$\sigma_{SISRE}^2 = k_R \sigma_R^2 + c^2 \sigma_{CLK}^2 + k_\rho \rho_{R,CLK} \sigma_R c \sigma_{CLK} + k_{C,A} (\sigma_C^2 + \sigma_A^2)$$

where,  $k_R$ ,  $k_\rho$ ,  $k_{C,A}$ , are geometric coefficients  $c$  is the speed of light and  $\rho_{R,CLK}$  is the correlation coefficient between radial and clock errors. The geometry coefficients  $k_R, k_\rho, k_{C,A}$  vary significantly across each satellite's coverage, depending on the line of sight and look angle between satellite and user. Nevertheless, to obtain a single instantaneous SISRE without spatial dependency, with fixed geometry coefficients, we can compute the average of the geometrical error distribution in the satellite's coverage or assume a Worse User Location (WUL).

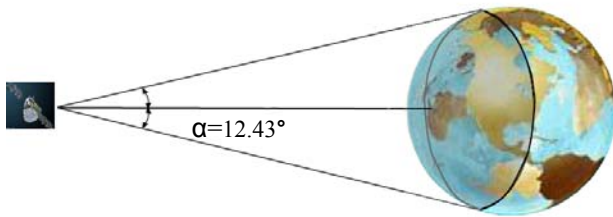
For the GPS constellation the following formula is generally adopted [Ref. 6]

$$SISRE_{GPS,WUL} = \sqrt{(R - CLK)^2 + \left(\frac{1}{49}\right)(A^2 + C^2)}$$

where  $k_{C,A} \cong 1/49$ ,  $k_R = 1$ ,  $k_\rho \rho_{R,CLK} = -2$ .

This equation is rather conservative, but suitable for an overall characterization of the errors.

The geometry coefficients have to be determined for the GIOVE satellites altitude, approximately 296000 Km, resulting into a semi-aperture of the satellite footprint cone of  $\alpha=12.43^\circ$  (Fig. 10)



**Figure 10 – GIOVE Satellite geometrical coverage [Ref. 9]**

In light of the different geometry characterizing the coverage of the GIOVE satellites we derive a slightly modified formula of the SISRE:

$$SISRE_{WUL} = \sqrt{(R - CLK)^2 + 0.215^2(A^2 + C^2)}$$

which can be written in terms of norm error as:

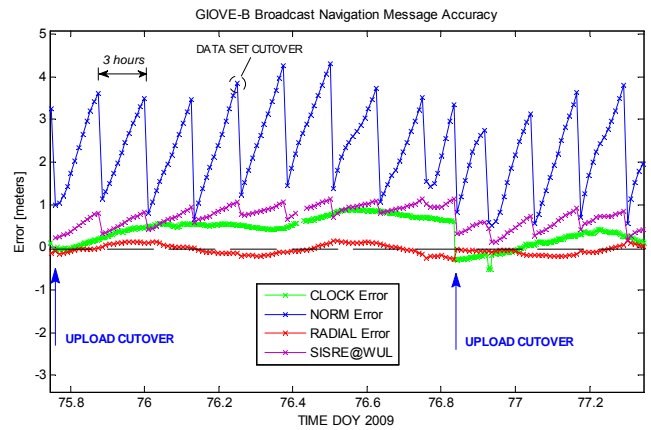
$$SISRE_{WUL} = \sqrt{(R - CLK)^2 + 0.215^2(N^2 - R^2)}$$

by substituting  $A^2 + C^2 = N^2 - R^2$

Thus, the SISRE is essentially a combination of clock and orbital prediction errors.

Fig.12 gives an example of how GIOVE-B Instantaneous SISRE appears over 2 days of normal operations, namely when at least one upload per day is guaranteed.

Each upload is characterized by the instantaneous SISRE resetting to near to zero as a result of the satellite starting to broadcast a new message which has just been uploaded. The transition from the old message data to fresh new message data is known as an “upload cutover” [Ref. 9].



**Figure 11 –GIOVE-B Instantaneous SISRE, DOY 75-77 2009**

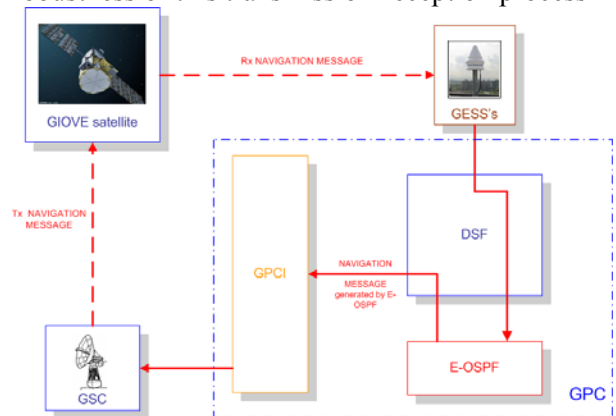
In addition to the large discontinuities at the upload cutovers, there are also other discontinuities occurring at the 3 hours boundaries, rather evident in the orbit norm error (Fig. 11). These smaller discontinuities are the result of the satellite switching from the broadcasting of one 3-hour data set to the next 3-hour data set from the same upload. Indeed, each single upload contains multiple ephemerides or data sets, which are the result of the prediction curve fitting. Each single data set should be transmitted no longer than 4 hours.

The transition from one 3-hour data set to the next one is known as a “data set cutover”.

#### Navigation Message end-to-end assessment

An important experimentation objective is to verify the end-to-end navigation message chain, from its generation by the E-OSPF, through its transfer from the GPC to the GSCs, to the uplink to the satellite and its final acquisition by the GESS receiver (Fig. 12).

As the transmission of the navigation message is a key element of any GNSS system, in order to allow the user to correctly calculate an accurate position, it is important to ensure a correct timeliness and robustness of this transmission-reception process



**Figure 12 – Navigation message closed-loop analysis**

The so-called KPI “Navigation Message Latency”, also referred to as Age Of Data (AOD), provides information about the latency from the time when a navigation message is generated by the Routine E-OSPF at GPC and the time one of the ephemerides contained in that navigation message is firstly received by one of the GIOVE-M Sensor Station (GESS). For each of the GIOVE navigation messages received by any of the GESS, the KPI evaluates the time at which that navigation message was generated at GPC matching it with the archived session from the Routine E-OSPF.

The steps for the KPI computation are:

- Retrieve  $T_k^{\text{th}}$  Received Navigation Message block; this is the GIOVE Navigation Message received from the GESSs, where the ‘k’ index refers to each hour in the configured Time Window, starting from Start Time ( $k=1$ ) to the End Time (step time is 1 hour). The FTP Download module is directed to look at the presence of the GIOVE Navigation Message file in the DSF File Repository for that  $T_k^{\text{th}}$  hour. FTP Download looks at the presence of the navigation message amongst all GESSs in alphabetical order; the first one found is taken.
- Retrieve  $T_j^{\text{th}}$  Generated Navigation block: this is the GIOVE Navigation Message generated by the OSPF, where the ‘j’ index refers to each session in the window starting from  $T_k$  backwards  $T_k - \text{Timeout}$  (step time is 2 hours corresponding to the interval between sessions)..
- Compare Nav. Message from GESS ( $T_k$ ) and OSPF ( $T_j$ ) block: matches the received and generated. In principle this is done on the basis of the SIOD, the *System Issue Of Data*.
- Message Latency Matrix block: the matrix containing the latency information for each of the  $T_k^{\text{th}}$  received navigation messages.

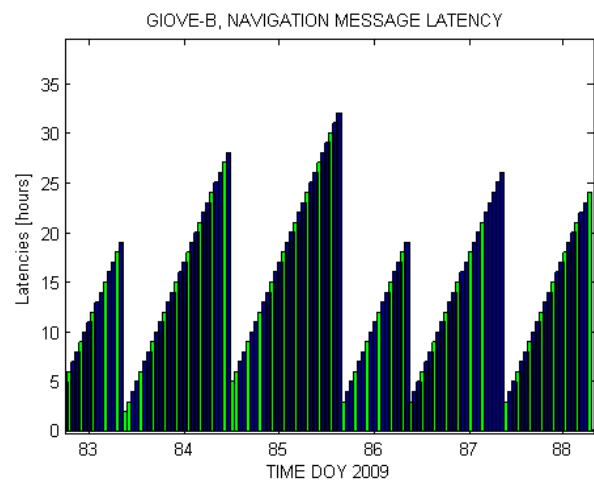
In principle the Nav. Message comparison can be done uniquely on the basis of the SIOD. However a problem could arise: the repetition time of the SIOD (in accordance to SiS ICD). This implies that two different navigation messages are marked by the same SIOD. Consequently the Nav. Message comparison has been derived by the following two criteria:

1. Comparing the SIOD of the two nav. Messages, AND

2. Correlating a number of orbital parameters of the two nav. messages

The logical steps of the computation are:

1. The received and generated navigation messages (from GESSs and E-OSPF respectively) are read and their content inserted into arrays of the 35 elements of the standard navigation message format.
2. The SIOD of the two navigation messages is compared
3. The 15 orbital parameters of the navigation messages are compared by computing a **correlation index**, adopting Pearson’s linear correlation.



**Figure 13 – Navigation message latencies**

In Figure 13, the results obtained over a period of two weeks are shown. On the x axis we have the time, represented in day of year (DOY), while the y axis shows the latency in hours. The x axis is divided in hourly bins, characterized by green or blue bars of the same hourly width. Each single bar height represent the latency of that particular message received at that specific hour. When a bar is green it highlights a new message data set received, different from the one received the previous hour, whereas it is blue if the data transmitted are the same as the previous hour.

Furthermore, it can be noticed a linear trend characterizing the latency bars sequence. In order to understand this, we remind that the E-OSPF generates a multiple navigation message, namely a single file containing a sequence of navigation message data sets which fit the prediction time. The latency is computed as difference between the reception time of the single data set and the generation time of the multiple navigation message. Therefore, this explains the linear latency increase, which

characterizes the data sets belonging to the same multiple navigation message.

## **CONCLUSIONS**

The KPI provide important information concerning the performance of the overall GIOVE Mission segment, supporting both the experimental and the routine operational activities. In particular the analyses have been focused on the validation of the GIOVE navigation message, which though limited to experimentation purposes, shows good performance, with a SISRE below 1 meter during the nominal GPC operations.

The next step is to upgrade and enhance the current GIOVE KPI in view of the IOV phase of the Galileo project.

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