GSTB-V1: The First Step Towards the Development of Galileo Navigation Algorithms

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Introduction: The GSTB-V1

The Galileo System Test Bed V1 (GSTB-V1) is an ESA project for the development of an experimentation platform to mitigate risks associated to the Galileo Mission Segment (GMS). The GMS is the responsible for the generation of Galileo navigation and integrity data. The GSTB-V1 project is carried out by a consortium leaded by Galileo Industries, and includes prototypes of several GMS elements:

- ✓ E-OSPF (Experimental Orbitography and Synchronisation Processing Facility)
- ✓ E-IPF (Experimental Integrity Processing Facility)
- ✓ E-PTS (Experimental Precise Timing Station)

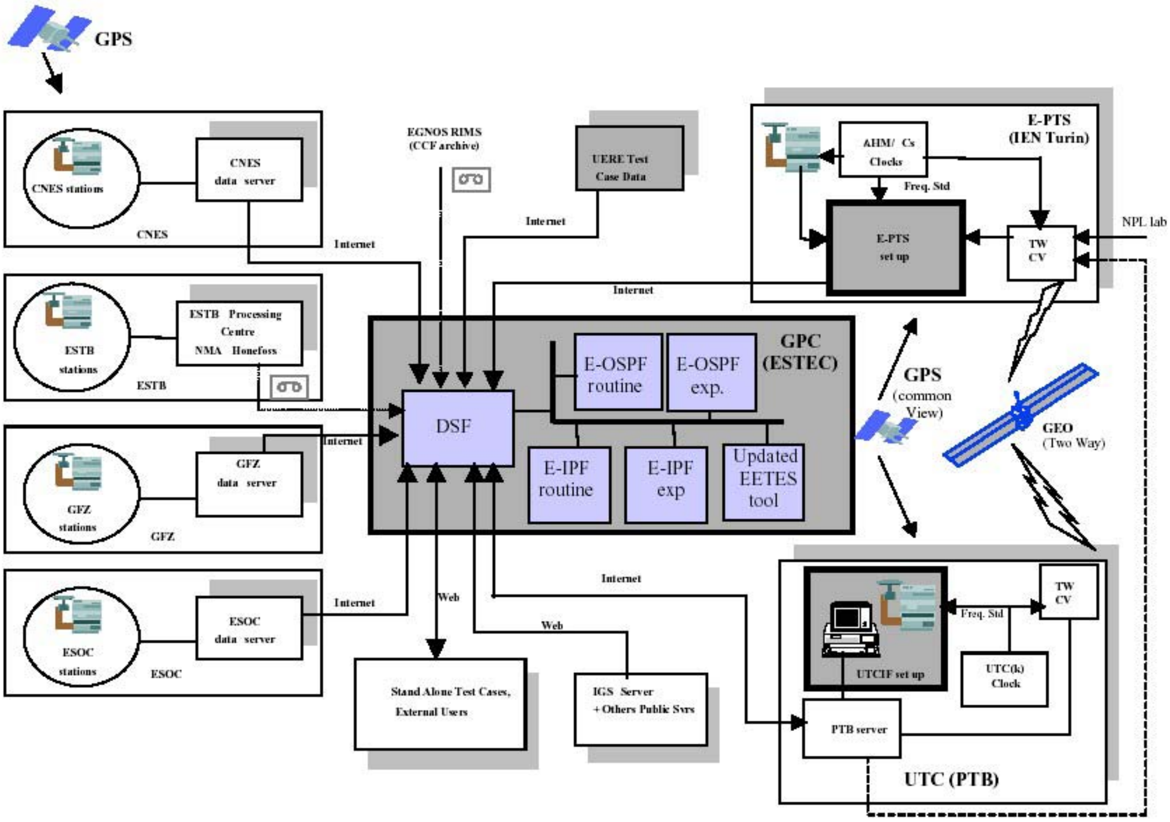
The GSTB-V1 experimentation will be based on the processing of real GPS data, which is believed to provide quite useful information for the design of Galileo algorithms due to the similarities in the dynamics and the navigation signal characteristics (despite the different number of frequencies). A number of GSTB-V1 Sensor Stations (GSSs) collect tracking measurements (pseudo-range and carrier phase) which are transferred to the GSTB-V1 Processing Centre (GPC), where they are archived in the Data Server Facility (DSF) and made available to the processing facilities (E-OSPF and E-IPF).

The GSTB-V1 station network is composed of some 30 sites world-wide, most of which actually belong to the IGS. The GSTB-V1 Sensor Station Data Servers (SSDS) are responsible for the collection of data from the stations under their responsibility. All the data collected by the SSDS are routinely transmitted to the DSF through Internet connections. The GSTB-V1 SSDS are ESOC, CNES and GFZ. Some IGS JPL sites are also used.

In addition, data from the EGNOS System Test Bed (ESTB) stations can be made available at the GPC upon request, by means of physical media (no network connection to the ESTB Data Centre). There are also specific interfaces with time laboratories such as the PTB for dedicated experimentation on timing aspects.

GSTB-V1 stations provide data at 1-Hz rate, mainly needed for the real-time integrity algorithms running in the E-IPF, although the E-OSPF also takes benefit of the high rate data.

The picture below shows an overview of the GSTB-V1 architecture. Items developed within the project are highlighted in grey.



Although the GSTB-V1 is an experimental platform, stringent development standards have been followed to ensure the quality of the developed items, and an operation plan has been defined aimed at the generation of navigation and integrity products in a routine and near-real time basis.

When writing this paper, the project has finished the development phase, and undergone a commissioning period aiming at tuning the system set-up prior to starting the operations phase.

GMV activities within the GSTB-V1 include the development of the E-OSPF, the experimentation in the OD&TS and SISA areas, support to Timing test cases and experimentation coordination tasks. More information about the GSTB-V1 and the GMS Risk Mitigation activities can be found in [3].

Navigation experimentation within the GSTB-V1

The GSTB-V1 includes an experimental Orbitography and time Synchronisation Processing Facility (E-OSPF), which implements prototype algorithms for the Navigation data and the Signal In Space Accuracy (SISA). The generation of the navigation data is based on an Orbit Determination and Time Synchronisation (OD&TS) process, which produces the precise orbit and clock predictions that constitute the basis for building the Navigation Message.

It should be noted that the Galileo OD&TS function shall consider not only the orbit and clock accuracy but also aspects such as the product reliability (closely related to the provision of the Galileo Integrity Service) and operational constraints. For example, the CPU time spent in the process may be a critical issue, when considering the limitations posed by the available certifiable hardware platforms and operating systems. Also, the final (safety-of-life qualified) OSPF shall be operated like a "black box" (i.e., with no operator intervention, 24 hours a day and 7 days a week). This means that there is no possibility to inspect the outputs and re-run after changing some parameters or removing a faulty station, for example. Hence, the OSPF aims at **Reliable Orbit and Clock Prediction** rather than Precise Orbit and Clock Determination.

The considerations above are key drivers for the algorithm selection and architectural design of the Galileo OSPF and have been taken into account (to a limited extent, due to its experimental nature) also for the GSTB-V1 E-OSPF.

The Navigation experimentation within the GSTB-V1 consists of a large number of Test Cases that have been specified and documented. These include the accuracy assessment of the orbit, clock and navigation message products obtained in the operations and also additional experimentation (on dedicated platforms), testing alternative algorithms and configurations.

Special attention is paid to the assessment of the process robustness against feared events or abnormal situations, which is critical for the final Galileo OSPF, as outlined earlier.

An important driver for the OD&TS performances is the availability and quality of the tracking data. The GSTB-V1 station network is composed of some 30 sites (number representative of the planned Galileo network). However, some of them are not used in the current baseline configuration since their performances are not considered sufficient yet.

The GSTB-V1 makes extensive use of IGS data and products within the experimentation:

- ✓ Data from IGS sites are used to feed the OD&TS process
- ✓ IGS final products are used as 'truth' reference, to assess the performances of the E-OSPF products

Finally, a thorough analysis shall be performed to extrapolate the GPS-based results obtained with the GSTB-V1 to the Galileo environment, considering:

- ✓ The differences between the GPS and the Galileo systems (orbit altitude, satellite attitude law, signal characteristics, additional frequencies, etc)
- ✓ The differences between the prototype and the final safety-of-life operational implementations (HW and OS restrictions, CPU time constraints, “black box” operation, etc)

The evolution of the OD&TS algorithms to the Galileo environment is currently under analysis, together with the development of a Galileo Raw Data Generator.

OD&TS Algorithms

As mentioned earlier, the E-OSPF hosts the prototype OD&TS algorithms, functionally grouped in:

- ✓ Data pre-processing and validation
- ✓ Orbit Determination and Time Synchronisation, which also generates the orbit prediction
- ✓ Clock Prediction, based on the clock estimates from the OD&TS
- ✓ Navigation Message Computation, based on the predicted orbits and clocks

Baseline algorithms and configuration have been defined, based on the past experience on GPS processing. Such definition is believed to provide results compatible with the targets (see preliminary results later), and once fine-tuned after the commissioning period, will be used for the routine operations of the GSTB-V1. In the GSTB-V1 operational processing, the E-OSPF is run 12 times per day of data and updated orbit, clocks and navigation messages are generated every 2 hours.

In addition, some alternative strategies have been implemented and will be tested during the experimentation. The main interest of the alternatives is the potential increase of process robustness or the reduction of the CPU time, in view of the operational constraints of the final Galileo development already mentioned.

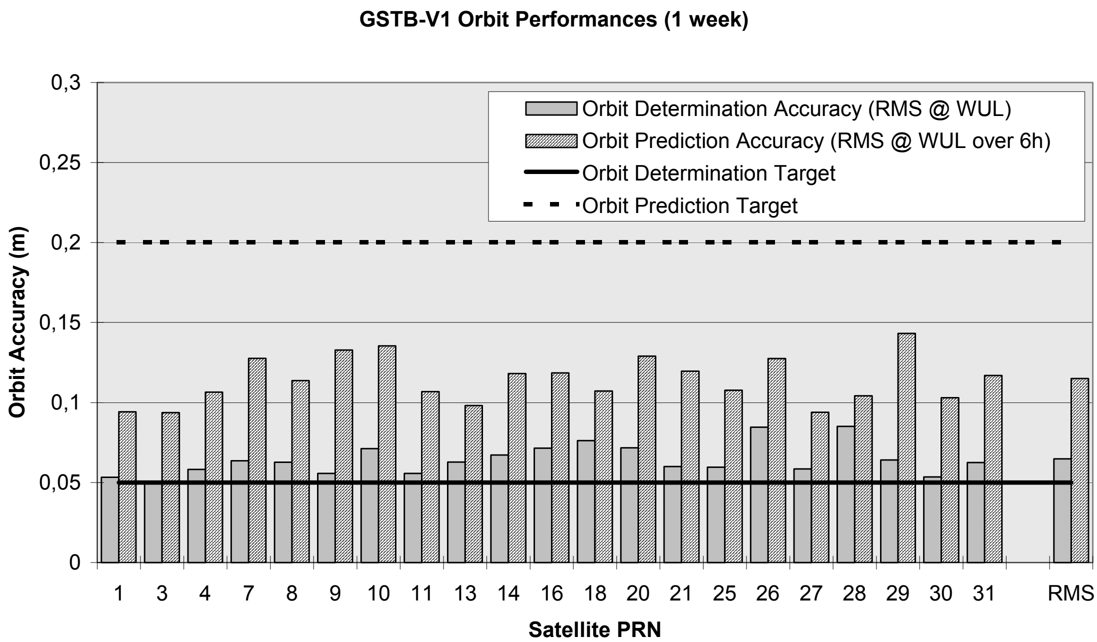
The OD&TS models are based on the IERS Conventions 1996 [1]. In particular, the Rock models for Solar Radiation Pressure are implemented. In addition, it is possible to estimate empirical accelerations to compensate for mismodellings. The process' baseline observables are undifferenced carrier phase and pseudorange measurements, and the filter is a batch least squares with a priori information. The parameter estimation includes the estimation of carrier phase ambiguities as pass-dependent biases, the constrained estimation of station coordinates and Earth Orientation Parameters, and the estimation of time-dependent station tropospheric zenith delays. Other interesting features are:

- ✓ Powerful cycle slip detection and repair algorithms, making use of the available 1-Hz data
- ✓ The alternative of using smoothed pseudoranges as observable (potentially leading to a significant CPU time reduction while keeping the accuracy within the specification)
- ✓ Candidate strategies for attempting to solve ambiguities in the pre-processing, thus reducing potentially the CPU time of the OD&TS function
- ✓ The correlation between the snapshot clock unknowns and the other parameters are considered in the normal matrix, potentially leading to better clock estimates with low number of stations
- ✓ The alternative of estimating model parameters for the clocks, instead of snapshot values, potentially reducing the CPU time and increasing the robustness under low coverage conditions

Preliminary Experimentation Results

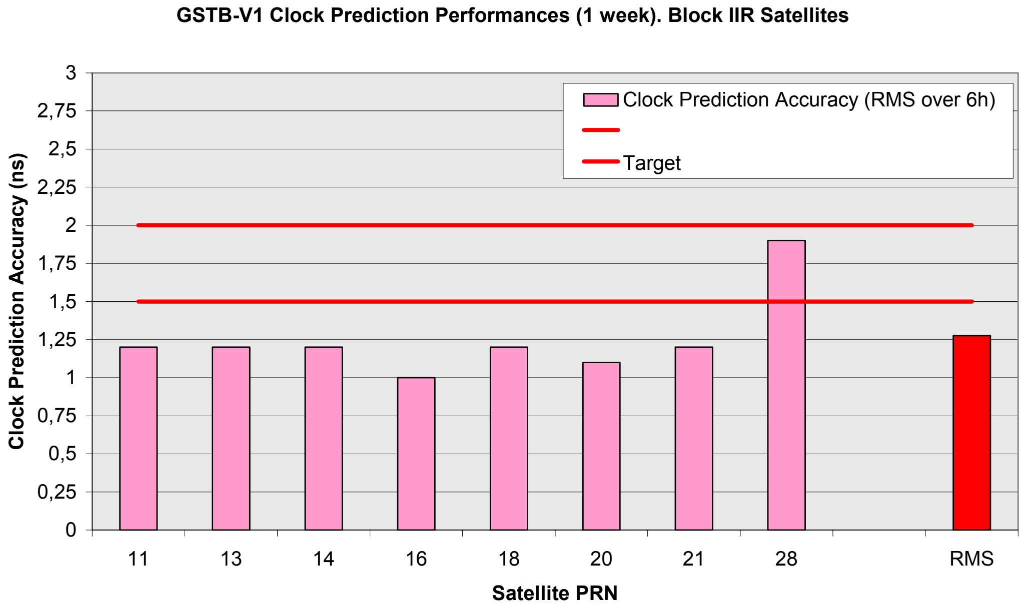
In this section, some preliminary results, obtained in the frame of the commissioning activities, are presented to show the promising performances of the E-OSPF. These results have been obtained from 1 week of data, running 12 sessions per day and using the baseline algorithms and configuration.

The following picture shows the orbit accuracy, computed as the RMS of the difference between the E-OSPF orbits (estimated and predicted) and the IGS final ones, projected into the Worst User Location (WUL) and computed over the arc (2 days for estimations, 6 hours for predictions). The GSTB-V1 targets (20 cm for prediction and 5 cm for estimation) are also shown in the figure for reference:

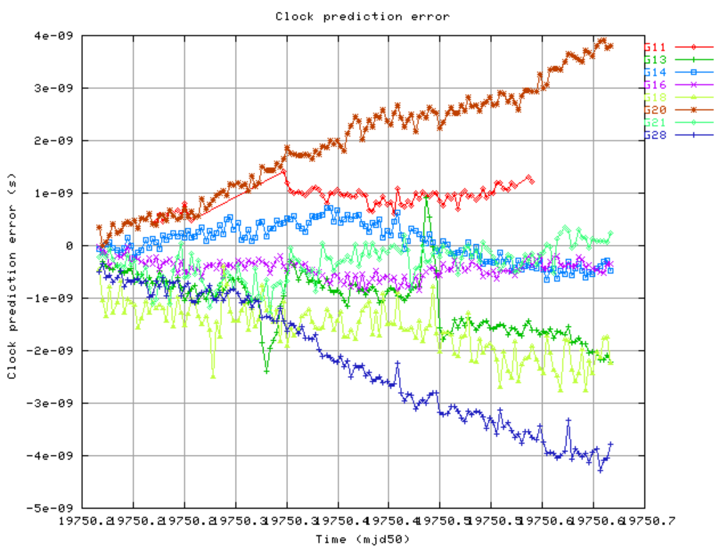


It can be seen that the prediction target is achieved with an important margin, and the estimations are somewhat above the target. This level of performances is quite promising, and allows setting confidence in the goodness of the SW and the proposed initial configuration. It should be noted that from the user point of view, the prediction performances are the most critical ones.

The following picture shows the prediction clock accuracy for Block IIR satellites (new PRNs 22 and 19 have not been considered during commissioning), computed as the RMS over 6-hour prediction time of the difference between the E-OSPF predicted clocks and the final IGS ones[1]. Only Block IIR satellite clocks are considered representative of the Galileo ones. Again, the target performances (between 1.5 and 2 ns) are shown as reference:

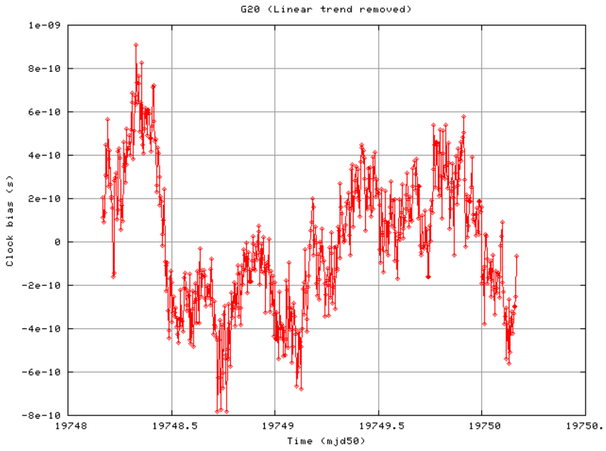


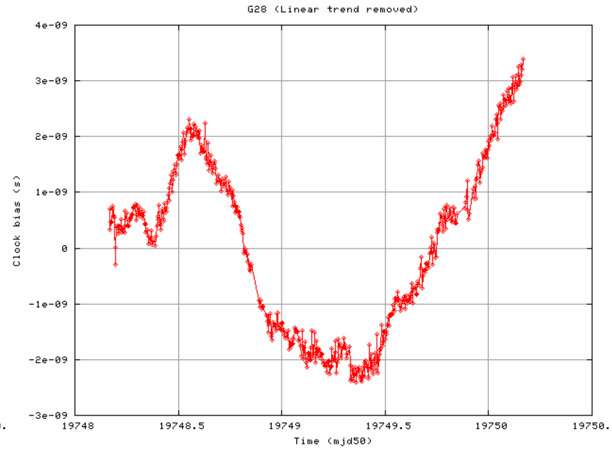
Again, very promising performances are obtained. In this exercise, a linear model has been used to predict, and its parameters have been adjusted from 14 hours of snapshot estimates. As an example, the following picture shows the prediction error as a function of the prediction time, for the Block IIR satellites, corresponding to one of the E-OSPF runs (a single arc):



1The E-OSPF uses a master clock (H-MASER) as time reference. In order to compare with the IGS, the difference between the time references has to be removed. This is preliminarily done by computing and removing an average of the satellite clocks.

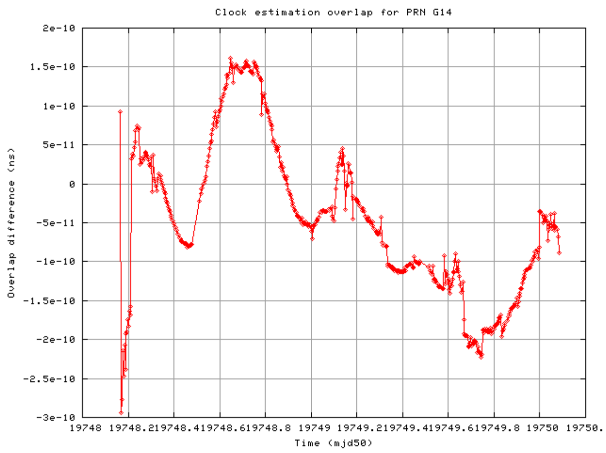
It can be seen that, except for PRNs 20 and 28, the error is quite stable with time, which suggests that in most cases the model is adequate to represent the deterministic behaviour of the clock. The clock estimates from which the model was built are shown (linear trend removed) for PRNs 20 and 28 below:

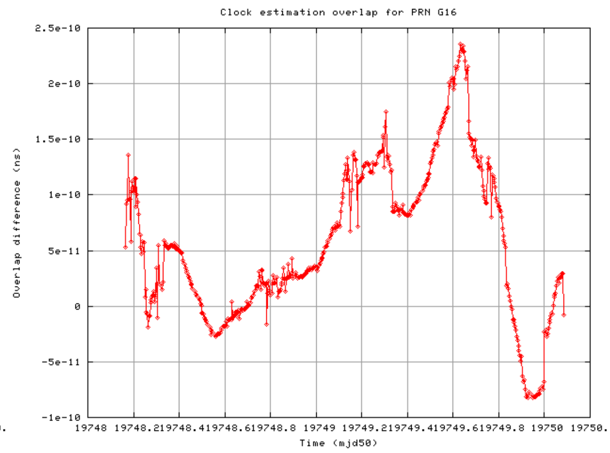




Depending on the clock behaviour and the target validity time of the predictions, further optimisation of the model (linear or quadratic) and the fit interval may be achieved. This topic will be deeper addressed during the experimentation.

Finally, the following pictures show overlap plots of two satellite clocks (difference between estimates coming from two consecutive E-OSPF runs, which have a 46-hour data overlap) to illustrate the consistency of the process:





The level of consistency achieved is quite promising.

The Signal In Space Accuracy

The Signal In Space Accuracy (SISA) is a novel concept, introduced for providing the Galileo Integrity Service together with the so-called Integrity Flag:

The SISA is a bound of the error of the broadcast orbit and clock, at Worst User Location, with a certain confidence level and a certain validity time. It will be broadcast by each satellite together with its Navigation Message. This bound will be used to establish the Galileo integrity (i.e. guarantee of service), but since it is a prediction, it can not cope with the full integrity risk. The SISA will bound the error only in the so-called “fault-free” state (no feared events), and the Integrity Flag will provide a real-time error monitoring to complement the SISA and provide the full integrity service when feared events occur.

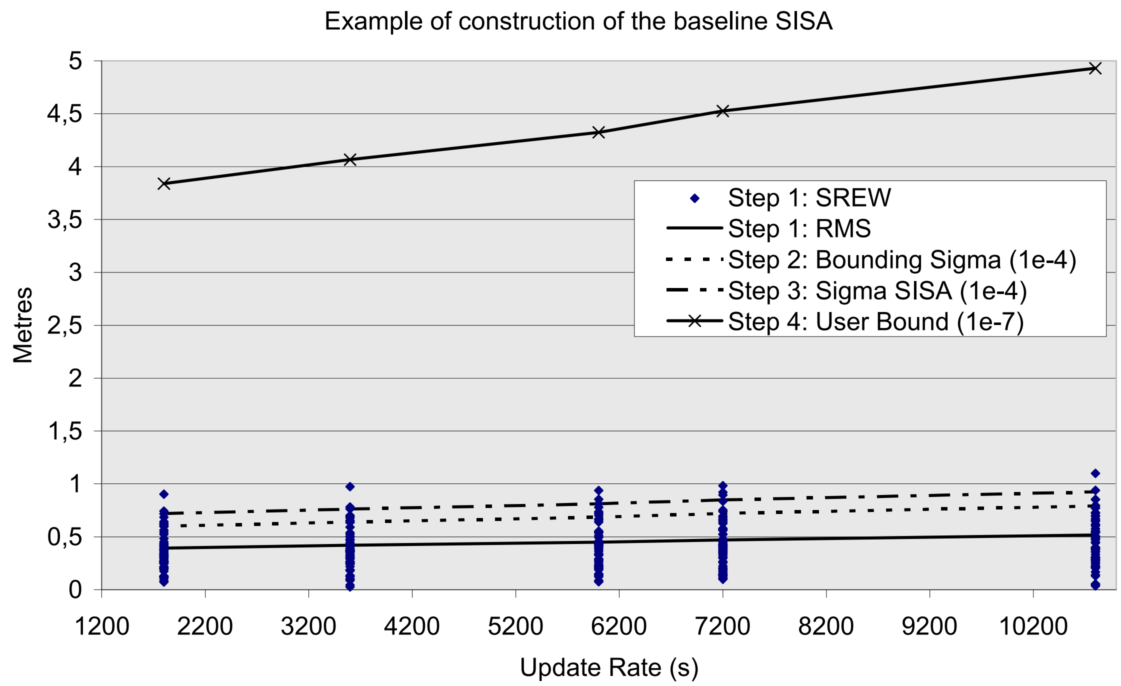
The baseline SISA algorithm is based on off-line analyses of past predictions, aiming at finding the sigma of a Gaussian distribution that bounds the actual error distribution in the CDF[2] sense, with a certain confidence level. More details about the "overbounding" concept can be found in [2].

In addition, the deterministic error coming from the use of a model to broadcast the ephemerides is computed and added. Given this broadcast sigma-SISA, the user will apply the corresponding factor of the Gaussian distribution to derive the error bound with the desired *user confidence level* (not to be confused with the *confidence level used to build the sigma-SISA*), for example 5.33 for a confidence level of 10^{-7}

A major effort is devoted in the GSTB-V1 to analyse the feasibility and performances of the SISA concept. One of the objectives of the GSTB-V1 routine operations is the accumulation of a large number of samples to properly characterise the orbit and clock prediction errors and build the SISA with the highest confidence possible. Actually, the GSTB-V1 is the first experimentation platform available to test the SISA in a realistic environment (GPS). In particular, the following aspects will be studied:

- ✓ Confidence level
- ✓ Update rate (validity time)
- ✓ Bounding performances
- ✓ Number of parameters to broadcast (SISA format: scalar, vector, 4x4 matrix)
- ✓ Time dependability during the validity time (constant, linear)

The process of building and using the baseline SISA consists of four steps, which are illustrated in the following example and explained below:



1. Analysis of the prediction error as projected in the WUL (called Satellite Residual Error at WUL, or SREW), from past data

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[2] Cumulative Density Function

2. Computation of the sigma of the bounding distribution, with a certain confidence level. Note that the higher the confidence level is and the smaller the data sample is, the higher the statistical sigma will be.
3. Addition of the deterministic part (error of the broadcast model)
4. Computation of the user error bound with the desired user confidence level, as explained earlier

In addition to the baseline strategy, experimentation will be carried out on the alternative approach based on *OD&TS indicators*. An OD&TS indicator is a parameter coming from the OD&TS process that is potentially correlated with the SREW (e.g. a statistical figure of the measurement residuals, or the Allan Deviation of the satellite clock as computed from the snapshot estimates). If such type of correlation is found, these indicators may be used to increase the baseline SISA, by means of a multiplying factor. A thorough analysis of the performances is needed to establish the feasibility of this concept, or even define new possible indicators such as the depth of coverage during the OD&TS arc.

Conclusions

- ✓ An **experimentation environment** has been set up to experiment with prototypes of algorithms for Galileo GMS, using real GPS data. It includes an **E-OSPF**, hosting prototype OD&TS and SISA algorithms.
- ✓ The element development has followed stringent **standards**, ensuring a high product quality and reducing the commissioning effort
- ✓ Experimentation has been defined and planned, together with the generation of products (including orbits, clocks and navigation messages) in a routine and near real time basis. Extensive use will be made of IGS data (to feed the OD&TS process) and final products (to assess the performances)
- ✓ The E-OSPF features both **baseline and alternative algorithms** for OD&TS and SISA, which performances will be assessed during the experimentation period
- ✓ The E-OSPF goal is **reliable orbit and clock prediction**, rather than precise orbit and clock determination. Aspects such as robustness, reliability and CPU time are key for the definition of the Galileo OD&TS function
- ✓ The product reliability is closely related with the **SISA concept**, an element of the Galileo Integrity Service. This concept will be thoroughly analysed within the GSTB-V1

References

[1] Dennis D. McCarthy, *IERS Conventions (1996)*, IERS Technical Note 21, U.S. Naval Observatory, 1996

[2] Bruce DeCleene, *Defining Pseudorange Integrity – Overbounding*, Proceedings of ION GPS, 2000

[3] Marco Falcone, *Risk Mitigation in the Ground Mission Segment using the Galileo System Test Bed*, Proceedings of the IGS Workshop, 2004