Integrity, Orbit Determination and Time Synchronisation Algorithms for Galileo

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Abstract

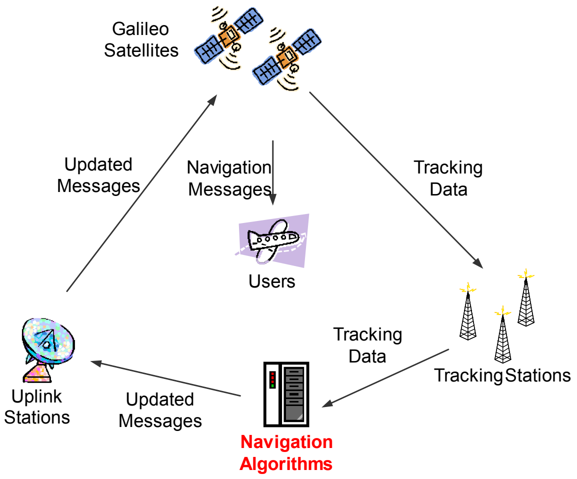
Galileo is the European Global Navigation Satellite System, under civilian control, and consists on a constellation of medium Earth orbit satellites and its associated ground infrastructure. Galileo will provide to their users highly accurate global positioning services and their associated integrity information. The elements in charge of the computation of Galileo navigation and integrity information are the OSPF (Orbit Synchronization Processing Facility) and IPF (Integrity Processing Facility), within the Galileo Ground Mission Segment (GMS).

Navigation algorithms play a key role in the provision of the Galileo Mission, since they are responsible for computing the essential information the users need to calculate their position: the satellite ephemeris and clock offsets. Such information is generated in the Galileo Ground Mission Segment and broadcast by the satellites within the navigation signal, together with the expected a-priori accuracy (SISA: Signal-In-Space Accuracy), which is the parameter that in fault-free conditions makes the overbounding the predicted ephemeris and clock model errors for the Worst User Location. In parallel, the integrity algorithms of the GMS are responsible of providing a real-time monitoring of the satellite status with timely alarm messages in case of failures. The accuracy of the integrity monitoring system is characterized by the SISMA (Signal In Space Monitoring Accuracy), which is also broadcast to the users through the integrity message.

Keywords: Integrity, Orbit Determination, Time Synchronisation, Algorithms, Galileo

1. Introduction

The users of a Global Navigation Satellite System (GNSS), such as Galileo, need to accurately know the position of the satellites and the offset of their on-board clocks with respect to the system time, whenever they want to compute their own position (and time). This information is provided by the system in the navigation message broadcast by the satellites, which includes predictions for their orbits and clocks. The accuracy of these predictions degrades with time, so they are re-calculated regularly by the Navigation Algorithms running in the Ground Segment and processing tracking data collected by a network of tracking stations, and then uploaded to the satellites to refresh the data in the navigation message. This process is represented in the following picture.



Current Orbit Determination and Time Synchronization (OD&TS) techniques allow estimating the satellite positions and clock offsets in the past with high accuracy. Once this is done, prediction for the satellite positions in the future can be computed also very accurately, since the physics that drive the orbits are quite well known. However, this is not the case for the on-board clocks, which show a significant random behavior. Such random behavior (which depends on the clock device's physical characteristics) actually drives the validity time of the clock offset prediction and ultimately the update rate of the navigation message.

The accuracy of the orbit and clock predictions is driven by the amount and quality of the tracking measurements and the accuracy of the algorithms and models used in the estimation and prediction processes. In addition, there are three additional contributions to the error in the satellite ephemeris and clocks the users get:

- The need for using a simplified model to broadcast the orbit and clock predictions to the users, as opposed to the full-accuracy predictions computed by the Navigation Algorithms. This is due to the limitation in the amount of data that can be distributed in the navigation signal
- The limited number of bits available to accommodate the parameters of the simplified orbit and clock models within the navigation message, which lead to round-off inaccuracies
- The time needed by the system to compute the updated Navigation Messages and upload them to the satellites, which implies that the predictions are already “old” (and hence less accurate) when available to the users. This timeline is illustrated in the following picture (not to scale)

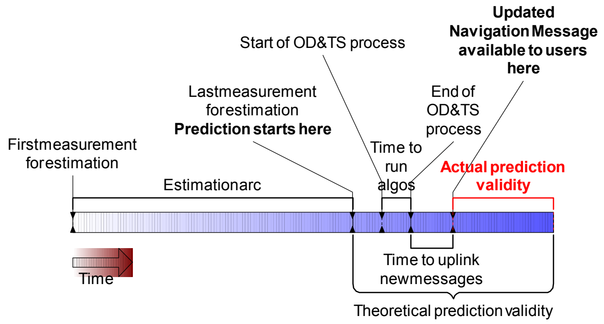


Figure 1. Timeline for the OD&TS process

It should be stressed that the objective of the Navigation Algorithms is to provide reliable orbit and clock predictions, rather than precise orbit and clock determination. Aspects such as robustness, reliability and computational resources are essential for the definition of the Galileo OD&TS function.

The Galileo navigation algorithms are implemented in the so-called Orbitography and Synchronization Processing Facility (OSPF), an element of the Galileo Ground Mission Segment (GMS), which collects tracking data from a world-wide distributed network of tracking stations (the Galileo Sensor Stations, GSS) and computes the Navigation Message to be sent to the users. The OSPF is an unmanned facility, hence the importance of the algorithms' robustness and reliability.

Galileo will also provide its users with an Integrity Service, which will broadcast information allowing the users to trust the system performances. This information is composed of parameters allowing the user to decide whether the system performances suit his needs (basically, a bound of the Signal-In-Space errors), and alerts warning the users when the system (or certain satellites) shall not be used because it is not possible to compute the error bounds or these are not considered reliable enough. The definition of the Integrity Service has been subject of deep studies and has suffered significant evolutions (in comparison with the navigation algorithms), associated also to evolution of the system design and services definition.

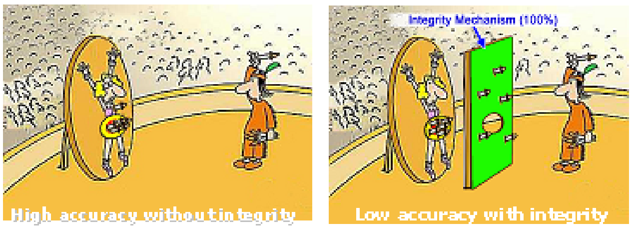


Figure 2. Schematic representation of the Integrity Concept

For each satellite, the navigation message includes, among others, its ephemeris and clock model, together with the so-called Signal In Space Accuracy (SISA), which gives an indication of the accuracy of the message. On the other hand, the integrity messages contain both the Integrity Flag (IF), indicating whether the information provided by the navigation SISA is valid or not, and the Signal In Space Monitoring Accuracy (SISMA), giving an indication of the measurement error obtained when computing the Integrity Flag.

The Galileo user will take the information provided by the navigation and integrity messages to compute the integrity risk, so as to decide whether the operation should be started.

2. Galileo Navigation Algorithms, the OSPF

The essential mission of the OSPF (Orbitography and Synchronisation Processing Facility) is the determination of the navigation data products to be disseminated to the Galileo users through the Galileo Signal-In-Space.

The navigation data products computed by the OSPF include:

- Satellites ephemeris in Galileo Terrestrial Reference Frame (GTRF)
- Satellites clock correction parameters in Galileo System Time (GST)
- Satellites Signal-In-Space Accuracy (SISA) indicators
- Ionospheric correction parameters for single frequency users (SFIONO)
- Ionospheric Disturbance Flag (IDF)
- Broadcast Group Delay (BGD) correction parameters

The OSPF implements all the algorithmic processes needed to compute the above products in a single facility, including the necessary monitoring and control capabilities to allow its operation by ground operators. The OSPF has been designed to operate in a near autonomous manner with minimum supervision from the operators. The different OSPF performance requirements include in particular some integrity requirements aimed to limit the risk of generating misleading information at the output of the OSPF.

2.1 Navigation Algorithms

The navigation algorithms have been studied in the Galileo project since its very early stages, mainly for two reasons:

- The satellite orbit and clock errors are important contributions to the User Equivalent Range Error (UERE) budget, and hence they need to be properly assessed and taken into account in the definition of the system performances

- The computation and dissemination of the navigation data requires an associated infrastructure (tracking and uplink stations, processing facilities and communications network) which may constitute a cost driver for the Galileo System

The starting point for the development of the navigation algorithms is the UERE budget associated to the orbit and clock predictions, which was set to 65 cm (1-sigma) at the very beginning of the project, and which up to date has not changed (although the associated conditions and hypotheses under which this target has to be met have been further elaborated). The validity interval of the predictions was set to 100 minutes, originally driven by the expected clock stability and later on, when the clock stability was found to be better, by the integrity service constraints. Initially, the budget apportionment to the orbits and clocks was evenly set (45cm or 1.5 ns each, 1-sigma).

The design of the Galileo Navigation algorithms was performed in different steps. The following figure is showing the main relationships between algorithmic activities (represented in the left side of the figure) and the Galileo development activities (represented in the central and right side of the figure).

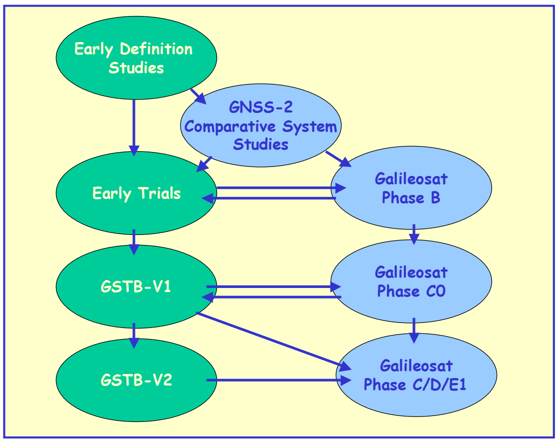


Figure 3. Links between algorithmic and development activities

The GNSS-2 Comparative System Studies was one of the very first projects defining the future European GNSS. Trade-offs were performed for key system aspects, such as the constellation (number of satellites, type of orbits) and the performances (positioning accuracy, availability, etc). In the case of the navigation algorithms, the study addressed aspects such as:

- The tracking data to be used (one-way or two-way ranging, use of the navigation signal)
- The location of the OD&TS function (On-Ground facility or On-Board the satellites)
- The type of OD&TS modeling (geometric, dynamic, reduced-dynamics) and filter (batch, sequential)
- The size of the tracking network and the impact of the measurements' quality (noise, bias)
- The clock synchronization approach (independent, combined with orbit estimation)

Results obtained in the GNSS-2 Comparative System Studies were used as an input for the Galileosat Phase B. However, at this stage several unknowns had to be solved, and an experimentation campaign was setup to progress in the algorithm definition: **The Galileo OD&TS Early Trials**. This campaign was based on GPS, and real data from the International GPS Service (IGS), due to the similarities between the OD&TS problem in Galileo and GPS, since most of the orbit and measurement models required are common to both systems. Existing POD (Precise Orbit Determination) SW was used (with improved clock estimation capabilities), and specific tools were developed for clock prediction. The main goals were:

- The first assessment of the Navigation performances (orbit and clock prediction) in a real environment
- The assessment of potential design drivers such as the number and location of the tracking stations, sampling rate, length of the data arc to be processed in each batch
- Analysis of potential failure modes, in view of a future implementation for an un-manned facility with a high availability requirement (e.g. impact of satellite maneuvers, data gaps, spurious measurements, etc)

Early trials results constituted at that time an important input for consolidating some critical Galileo Design Drivers during the Galileosat Phase B.

The Galileo System Test Bed, version 1 (GSTB-V1) was the next step in the development of the Navigation Algorithms. Still based on the use of real GPS data, it addressed extended experimentation on a number of open points for the Ground Mission Segment, including not only navigation but also integrity and timing.

In the area of Navigation Algorithms, an Experimental Orbitography and Synchronisation Processing Facility (E-OSPF) was developed from scratch (no SW reused), implementing the candidate OD&TS and SISA algorithms as well as some options for experimentation. The GSTB-V1 objectives for the navigation area were:

- New SW development using strict Galileo standards
- Ability to work in an operational environment (minimal user intervention)
- Extensive data processing for performance assessment with long-term statistics. Improved evaluation of clock estimation and prediction performances thanks to the higher number of Block IIR satellites available
- Improved data quality (through agreements with some IGS data providers, such as ESOC, GFZ and CNES)
- First prototyping of SISA function
- First prototyping of product quality check evaluation and implementation of robustness mechanisms
- Implementation of options not available in previously used existing SW (computation of the GPS-like Navigation Message, clock models in estimation process, improved pre-processing algorithms including code smoothing with outlier and clock jump detection). Flexibility to experiment with such options

Once the GSTB-V1 project was finished, work on navigation continued in the **GalilleoSat** studies, supported by internal R&D activities. The following pictures show the orbit and clock performances achieved with the latest prototypes and configuration. RMS values for all satellites (in the case of the orbits) and the Block IIR ones (in the case of clocks, highlighted in the X-axis) are also provided.

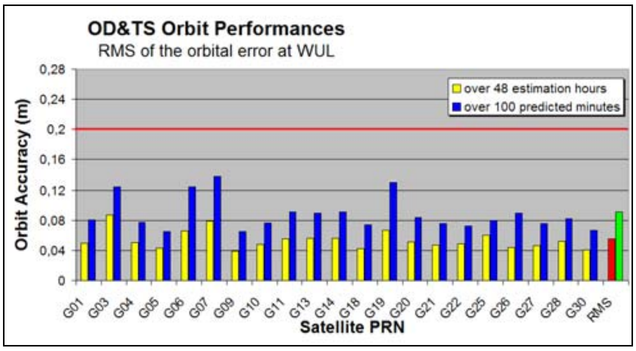


Figure 4. OD&TS Orbit Performances

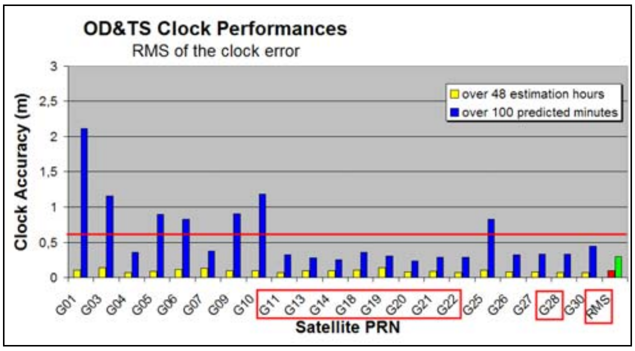


Figure 5. OD&TS Clock Performances

The final performances at user level (including the contributions from the navigation message approximation and discretisation) are shown in the following figure:

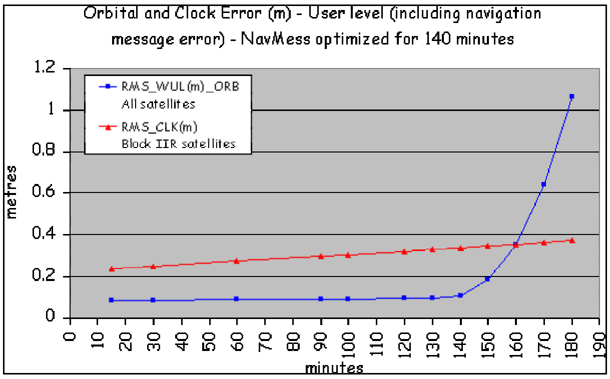


Figure 6. OD&TS Performances at user level

A critical issue identified, the insufficient CPU time budget, was dealt with by splitting the OD&TS process into two sub-processes. The rationale behind is that a significant amount of information is shared between two consecutive OD&TS processes, due to the important overlap of their data arcs. Hence, the values of a number of estimated parameters (including the orbit ones) do not need such a frequent estimation as the clock ones, and hence can be taken from a previous arc. Barriers that should prevent the propagation of misleading information into the system (process divergences caused by a faulty station or satellite) will be implemented. These will be based on mechanisms to identify spurious measurements either during the pre-processing (e.g. measurements' check vs. range or range-rate thresholds defined by geometry conditions) or during the estimation process (analysis of the residuals), and on product quality checks after the process has finished.

2.2 The OSPF Facility

The development of the operational OSPF, has started in spring 2005. Additional prototyping activities are foreseen and currently undergoing as part of this development, mainly aiming at adapting the algorithms baseline defined in the previous phases to the final operational environment, and at testing the Galileo-specific algorithms outlined above, not prototyped in previous phases.

The final breakdown of the navigation algorithms, as to be implemented in the OSPF is shown in the following picture (Figure 7). In the diagram, the black arrows corresponds to a direct interface between the algorithms while the red arrows represent navigation message generation, broadcasting, reception and processing. From the figure, it can be seen that except for the direct links between the OD&TS long batch and Pre-Processing and Validation (PPV), OD&TS long and short batch and between IFB, IONO and Disturbance Flags algorithms, data will be exchanged through the PPV algorithm.

The operational OSPF facility is an industrialization of the algorithmic processes needed to compute the OSPF navigation data products and endowed with the necessary monitoring and control shell. The main OSPF design drivers are:

- The main OSPF monitoring and control functions will be implemented in dedicated processors, isolated from the pure algorithmic functions.
- The OSPF HW architecture will be built around well proven technology, whose usage must be proven suitable for safety critical applications.
- As much as possible the OS, SoL and PRS specific processing will be internally separated allocating them to different processors.
- The selected HW will enable the execution of all processes in nominal Galileo FOC configuration without exceeding 50% of the available CPU (average), RAM (never-to-exceed) and local storage capacity (never-to-exceed). In the so-called maximum expandability configuration, the usage of computer resources will not exceed 80%.
- The acquisition of input data will be performed through two Ethernet ports, one connected to a real-time network supplying hard real time data (e.g.; GSS observations) and another one reserved for monitoring and control.
- The OSPF will acquire an external IRIG-B signal (synchronized to GST), which will be used as the time reference for internal synchronization of processes, input data validity check and time stamping.
- The OSPF will provide a specific Test Port to supply internal processing data to support AIV, testing and troubleshooting. It will be dimensioned to enable the Test Port activation when the facility is in operational mode without any disturbance in its operation.
- The amount of DAL C safety critical SW will be minimized, via proper isolation from non safety critical processes.

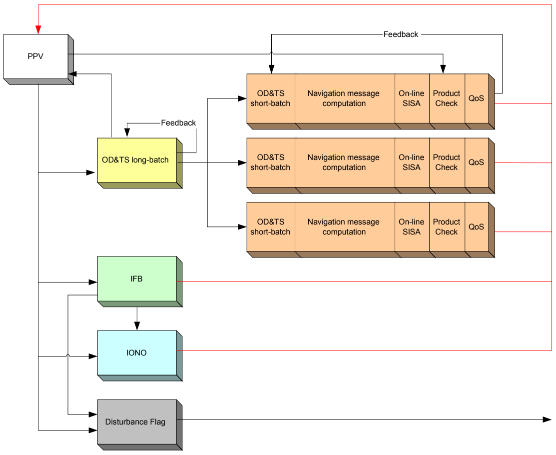


Figure 7. OSPF Navigation Algorithms

3. Galileo Integrity Algorithms, the IPF

3.1 Galileo Integrity Concept

In order to validate the navigation message being broadcast by the satellites, an independent estimation of the Signal In Space Error (SISE) is performed in real-time. This estimation, which is also a process with certain accuracy, allows verifying if the distribution characterized by the SISA is in fact over-bounding the real SISE distribution. The assumption made in this case is that the difference between the true SISE projected at worst user location (SREW) and the estimated SREW can be overbounded in the CDF sense by a Gaussian distribution with the standard deviation equal to SISMA. In this context, the SISMA can be considered to be an indication of the estimation error of the element from the Galileo GMS in charge of validating the navigation message: the Integrity Processing Facility (IPF). As the OSPF, the IPF is an unmanned facility, hence again the importance of the algorithms' robustness and reliability.

SISA and SISMA are used by the IPF to validate the navigation message of the satellites. The validation is based on IPF's estimation of the SREW. According to the assumptions mentioned earlier, the estimated SREW is overbounded by a Gaussian unbiased distribution, which variance is a function of SISA and SISMA:

- Real SREW overbounded by N(0, SISA)
- Estimated SREW Error overbounded by N(0, SISMA)
- Estimated SREW overbounded by N(0, $\sqrt{SISA^2 + SISMA^2}$)

Under these assumptions, the threshold applied at IPF level in order to decide if a navigation message is valid or not is given by the variance of the distribution characterizing the estimated SREW, together with the required false alarm probability:

$$T = k_{fa} \cdot \sqrt{SISA^2 + SISMA^2}$$

$$Estimated \quad SREW \ > T \Rightarrow IF = Do \ not \ use$$

Thus, if the estimated SISE projected to the worst user location is higher than the allowed threshold, the satellite is flagged as "DO NOT USE", in order to indicate the user that its navigation message is not valid. The following figure illustrates the Integrity threshold (T) and false alarm probability (Pfa):

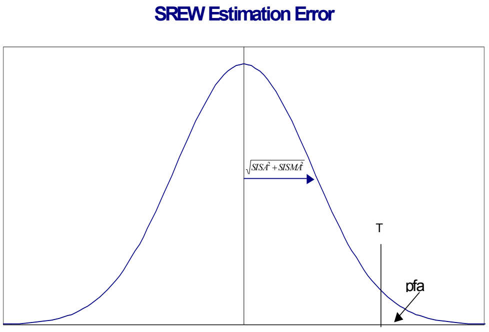


Figure 8. SREW Estimation Error

The current specification of the IPF element envisages a maximum false alarm probability in the order of 10-7, which gives a Kfa factor of 5.212. Considering that the required values for SISA and SISMA are 0.85 and 0.7 meters, respectively, in case no more barriers were implemented, the minimum detectable errors by the IPF would be in the order of 6 meters.

All parameters defined up to now play an important role in Galileo user integrity equation. In particular, the user will not use those satellites with IF set to "DO NOT USE". Furthermore, the SISA and the SISMA will be introduced in the equations in order to compute the so-called integrity risk (IR), which is the probability of having Hazard Misleading Information.

Galileo users will compute the Integrity Risk by combining the horizontal and vertical errors, and in both cases, the fault-free situation and the one where there is one failing satellite. The basic underlying assumptions allowing the user to determine the integrity risk of his position solution at any global location are:

- In a "Fault-Free-Mode" the true SISE for a satellite is overbounded by a zero-mean Gaussian distribution with a standard deviation equal to SISA
- In general, the IPF will detect the faulty satellites and they will be flagged to "don't use"
- For each instance in time one satellite of those flagged "OK" is considered to be faulty but not detected ("Failure Mode"). For this satellite the true SISE is overbounded by a Gaussian distribution whose mean is the "Minimum Detectable Bias" (MDB) and the standard deviation is equal to SISMA;
- The probability that more than one satellite at each instance in time is faulty but not detected is negligible for the user equation

Under these assumptions, the user integrity risk is computed as the sum of the vertical and horizontal integrity risk contributions (IR), each of them combining the fault-free (FF) situation with that one where one satellite is failing (1F). Once the user has computed his integrity risk, he will compare it with the maximum integrity risk allowed by the system to start the operation. In case the obtained user integrity risk is lower than the required value, the operation will be started.

3.2 The IPF Facility

The IPF is a real time element as it must provide the integrity information for the navigation data and GSS measurements from one second to the next. The IPF design copes with the 1 Hz algorithmic tasks of computing the integrity information with the batch task of performing an optimum GSS clock synchronization and tropospheric delay estimation. IPF provides integrity information for PRS and SoL in an independent way. Thus, two instances of the same IPF algorithm shall be executed one for each service. However, from the design point of view the only difference will be the configuration parameters and, of course, the input data.

For one particular instance of the IPF algorithm, the configured service is processed. Each service will receive mainly the following information: already broadcast navigation and integrity messages and raw ranging measurements from the network of the Galileo Sensor Stations (GSS), including two measurement chains in each GSS, named A and B. The IPF processes the information from both chains independently up to the moment when the SISMA estimates for each chain have been estimated. At that point, the Product Check algorithm merges the SISMAs from both chains and consolidates the final values to be broadcast.

The processing for a given chain that conducts to the SISMA estimates per chain starts by a Pre-Processing and Validation (PPV) of the raw measurements and navigation data. The following step is the synchronization of the GSS clocks to a common time reference and the estimation of the tropospheric delay. These two points have been identified as the main drivers of the final IPF performance. The classical approach to time synchronization is to use a Kalman filter using as observables the smoothed pseudo-ranges of those satellites seen in common view by two or more GSS. However, the IPF team is developing an alternative algorithm based on a batch weighted least-square algorithm that takes advantage also of the carrier phase measurements. It is estimated that the clock synchronization error would be of the order to 0.4 ns and the zenith tropospheric delay error of 1-2 cm. The price to pay for this improvement is RAM memory and CPU time which are highly constrained in a real-time operational system.

The Integrity Determination (Int_Det) algorithm estimates the SISE and its covariance matrix and provides the SISMA value when projected onto the worst user location. The process is represented in the following figure:

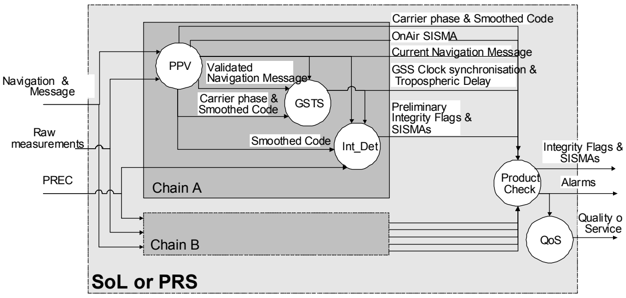


Figure 9. IPF main algorithmic functions

4. The Galileo System Test Bed, GSTB-V2

The first Galileo experimental satellite, GIOVE-A, was launched at the end of December 2005. An additional satellite, GIOVE-B, is expected to be launched during the last quarter of 2006. These satellites will secure the frequencies currently allocated for Galileo and they will allow testing the Galileo navigation algorithms under a more realistic environment. One of the main experimentation topics is to evaluate the performances of the new developed clocks for Galileo. While the GIOVE-A will be equipped with a Rubidium clock the GIOVE-B will be equipped with a Passive Hydrogen Maser clock fully representative of the final Galileo clocks.

The GSTB-V1 experimental infrastructure has been upgraded to support the experimentation activities with the GSTB-V2 satellites. The navigation algorithms prototypes have been upgraded to be able to handle the new type of data and to make it flexible enough for the extreme GSTB-V2 experimental conditions.

The first GIOVE-A data arrived at the end of May 2006. GIOVE-A code and phase measurements from two stations (ESTEC, Noordwijk and IEN Turin) corresponding to a period from May 25th to May 27th has been processed with the new developed algorithms. In order to synchronise the ground station clocks, also data from the GPS satellites have been used. Satellite Laser Ranging (SLR) data from three ground stations (Monument Peak and Mc Donald in USA and Yarragadee in Australia) have also been processed. The level of fit to the SLR data will provide an indication about the quality of the estimated orbits. For the GPS satellites also XYZ observables derived from IGS orbits have been used. The results achieved in terms of measurements residuals are summarized in the table below:

		GIOVE-A	GPS (RMS)
GIEN	smoothed-code (cm)	28.0	33.0
	phase (cm)	1.1	0.7
GNOR	smoothed-code (cm)	27.0	33.0
	phase (cm)	1.1	0.7
SLR	(cm, one-way)	1.7	--
XYZ	radial (cm)	--	1.7
	along-track (cm)	--	7.4
	cross-track (cm)	--	4.4

Table 1. Measurements residuals for GIOVE-A & GPS satellites

Despite of the very stringent geometrical conditions (only two ground stations) the obtained results are very encouraging showing the good modeling of the GIOVE-A orbits. The GIOVE-A clock has been estimated during the OD&TS process and the stability of the clock is represented by means of the Allan deviation in the following figure:

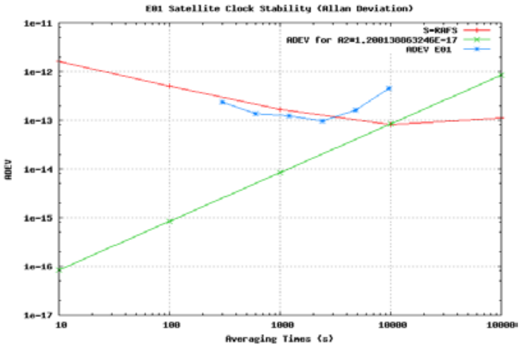


Figure 10. GIOVE-A clock stability (Allan deviation)

The red line in the figure above represents the specifications for the Rubidium clock, while the blue line represent the estimated values for the GIOVE-A clock. Results again are very encouraging, considering the lack of data it has been possible to measure the GIOVE-A clock and the values obtained are in line with the specifications. It has been observed that the clock frequency drift is still high, as represented by the green line, and this is the reason why for medium-high averaging times the Allan variance is higher than expected.

All GIOVE-A results presented here shall be considered as preliminary.

5. Summary and Conclusions

Galileo Navigation Algorithms are considered to be in a quite mature state, allowing the start of the operational OPSF development with high confidence. Prototyping activities have been carried out using real GPS data, and a consolidated baseline has been derived. The target UERE budget for orbit and clock prediction is considered feasible, even with the stringent operational constraints affecting the OSPF. Anyhow, the development of the operational algorithms will be supported with additional prototyping cycles.

Integrity Algorithms are the key for the development of future GNSS-based applications where the service guarantee is essential. Galileo will provide with a global integrity service, and the room for future regional enhancements. The stringent requirements placed on these services make it very complex to derive, justify (at mathematical level) and evaluate the performances of the integrity algorithms. The baseline has been consolidated over several definition phases and prototyping cycles, however still innovative promising solutions have been proposed and are under investigation.

Preliminary results from the GIOVE-A satellite have been obtained and those are very encouraging. Despite of the very limited amount of data the navigation algorithms are providing accurate clocks and orbits.

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