Assessment of GALILEO performance based on the GALILEO System Test Bed experimentation results

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BIOGRAPHY

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Erik van der Wenden is Software Engineer supporting the Galileo Project Office at the European Space Agency in Noordwijk (The Netherlands). He holds a Master's Degree in Aerospace Engineering from the University of Delft, The Netherlands. His main tasks are the software and hardware implementation aspects, from the specification phase to the operational phase, of GSTB-V1 and the Galileo Ground Mission Segment.

ABSTRACT

The Galileo System Test Bed (GSTB) represents an integral part of the Galileo Design Development and Validation in order to mitigate the associated development risks. The GSTB is implemented in two experimentation phases – the first one currently on-going using GPS observable (so called GSTB-V1) and the second one using the navigation signals transmitted from Galileo Experimental Satellites (so called GSTB-V2) to be launched in 2005.

The development of the GSTB-V1 has been completed early 2004. It consists of a worldwide network of stations collecting high quality GPS observables at 1 Hz, an Experimental Precision Timing Station, located at IEN Time Laboratory, providing the reference time scale steered to UTC/TAI, and a Processing Center located at ESA ESTEC for the generation of navigation and integrity core products based on Galileo-like algorithms.

The paper presents the experimentation results, assessing feasibility of some of the important assumptions and performance objectives of the final Galileo system in a realistic environment, for the following fields:

- ✓ Experimental Galileo System Time (E-GST) and steering to UTC/TAI
- ✓ Orbit Determination and Time Synchronization (OD&TS) and Signal In Space Accuracy (SISA)
- ✓ Integrity computation.

The timing, navigation and integrity core products are available to external users through the ESA web site (http://www.gstb-v1.esa.int/).

INTRODUCTION

During the GalileoSat Definition Phase, a Galileo System Test Bed (GSTB) has been defined as an integral part of the Galileo Design Development and Validation Phase in order to mitigate Programme risks. The GSTB is subdivided in two main development steps, Version 1 (V1) and Version 2 (V2), with the following scope:

- GSTB-V1: measurements from the GPS system are processed to verify Galileo concepts for Orbit Determination & Time Synchronisation (OD&TS) and Integrity algorithms in collaboration with the scientific community (e.g. International GPS Service (IGS), UTC Time Community, etc.).
- GSTB-V2: consists of an experimental Galileo satellite to be launched by mid 2005 and an extension

of GSTB-V1 Ground Segment including Galileo receivers and processing algorithms.

The GSTB-V1 main objective is to reduce Galileo Programme risk on ground segment development by anticipated experimentation on OD&TS (Orbit Determination & Time Synchronisation) and Integrity concepts. Algorithms pre-development are conducted to support the refinement of the critical ground segment algorithms and the assessment of related performances in parallel with the Galileo Design Development and Validation Phase. So, GSTB-V1 is a design and verification tool for the mitigation of the Galileo risks related to algorithms as well as an experimentation framework gathering the experience from European industries, institutes and agencies towards common objectives.

GSTB-V1 consists of a core infrastructure, which makes it possible to set-up, run and analyse different test cases. Figure 1 gives an overview of GSTB-V1 core infrastructure:

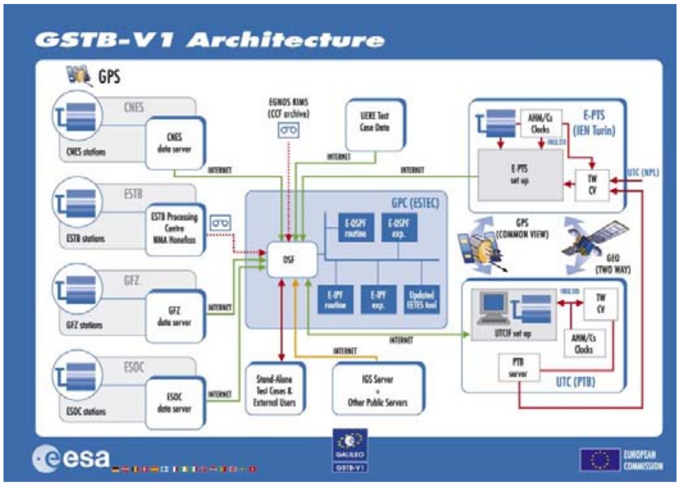

Figure 1 – GSTB-V1 Overview

GSTB-V1 uses GPS navigation data, which is collected via Sensor Stations on data servers. These stations are equipped with a GPS receiver, which stores the GPS data in RINEX format and transmits them to data servers at CNES, ESOC and GFZ. GPS data from the EGNOS System Test Bed (or EGNOS RIMS) can be retrieved via tape. The RINEX data is collected at a rate of 1 Hz during experimentation periods.

This navigation data is transferred via the Internet from the data servers to the GSTB Processing Centre (GPC). The GPC is responsible for:

- Data collection
- Data formatting, archiving, distribution and management
- Web services and file transfer
- Monitoring & Control of the core infrastructure
- Data processing (OD&TS, Integrity, System Time).

For the Precision Timing experiments there is a connection to UTC(k) laboratories.

The GSTB-V1 Processing Facilities perform the routine processing of GPS data, delivering orbit and clock as well as integrity products in Galileo style, over a continuous period of time in order to be able to extract meaningful statistics. These activities include:

- Data collection
- Data preprocessing
- Orbit and clock offset prediction and determination
- Integrity computation
- Navigation message generation.

A final, very important activity, needed to conclude the experimentation consists in the translation of all results, which are based strictly on GPS data processing, to a Galileo environment, which differs significantly from GPS in:

- Different satellite orbits (higher, longer orbital period)
- Different number of spacecraft
- Different atomic clock properties
- Different signal properties.

The scientific community is able to retrieve the GSTB-V1 results and core products from the GSTB-V1 servers (http://www.gstb-v1.esa.int/) and perform their own analysis on the GSTB-V1 results and core products.

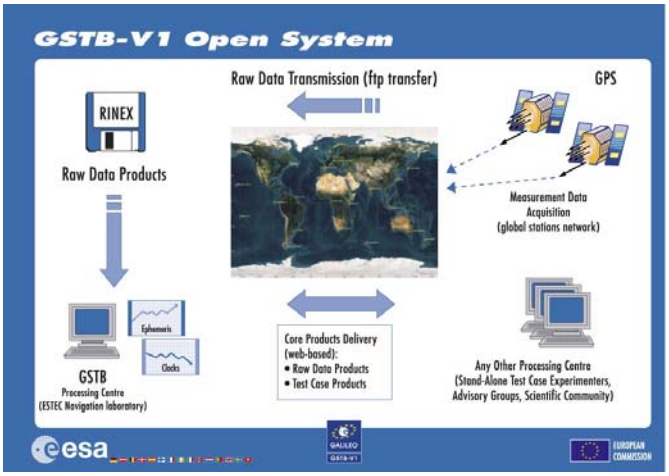

Figure 2 – Co-operation with scientific community

SENSOR STATIONS

Figure 3 lists the GSTB-V1 ground stations used for experimentation. CNES, ESOC, GFZ, IGS and Norwegian Space Centre operate these stations as part of their network.

It has to be noted that at least the following pre-conditions apply for the usage of a station during experimentation:

- Dual frequency receivers acquiring at least L1, L2 (Phase), C1, P1, P2 (Code) observables
- Observables sampled at 1 Hz with carrier smoothing disabled for those stations to be used for integrity monitoring
- Sensor stations equipped as far as possible with free-running atomic clocks.

At the beginning of the experimentation, a commissioning activity has been conducted in order to select the list of Sensor Stations to be used for navigation and integrity processing (out of some 41 available stations).

	Figure of Merit	Target-Threshold	Remarks
Files Availability	Weekly availability of station files	90%	Value obtained multiplying the 2 FOM
	Weekly Percentage of taken with respect to expected observations		
Measurements Availability	Total availability of L1, L2, C1, P1, P2 Masking 10 deg (daily mean)	90%	Limited to 3 days observation files
	Number of short data gaps (< 2 s) Masking 10 deg (daily mean)	< 100	Limited to 3 days observation files
Measurement Quality	Multipath and receiver noise	Mean MP1/MP2 RMS for each station < 2.5 x Mean MP1/MP2 RMS of all stations	Limited to 1 day observation files, Masking 10 deg
	Daily Cycle Slips on L1/L2	< 50 per day (all satellites)	Limited to 1 day observation files, Masking 10 deg
Processing Quality	Stability of Sensor Station Clocks	Estimated ADEV < 10 x Estimated Average ADEV among all stations	300 s, 1000 s, 3000 s (less than 300s not supported by E-OSPF routine configuration) Computed over 2 days
	Clock drift, drift rate	Estimated Drift (Drift rate) < 10 x Estimated Average Drift (Drift rate) among all stations	Computed over 2 days
	Antenna phase center location	Known with a precision < 5cm (1σ)	To be compared with E-OSPF computed value

Table 1 –Sensor Stations Evaluation Criteria

Table 1 presents the evaluation criteria adopted for the selection. These criteria are of course not the same that would be applied for the operational Galileo system, nonetheless they represent a practical case based on already existing stations infrastructure.
Based on the above evaluation criteria, 22 stations have been selected for navigation and 32 stations for integrity processing. The retained network is presented in the following figure.

Within this network the E-PTS stations is used as reference time for experimentation (located at "Instituto Elettronico Nazionale", being the Italian UTC Laboratory) with PTBG as back up (located at PTB, being the German UTC Laboratory).

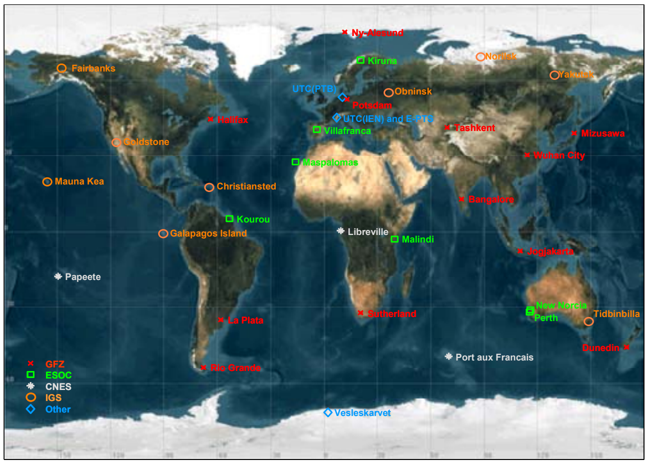

Figure 3 – GSTB-V1 Sensor Stations Network

EXPERIMENTAL GALILEO SYSTEM TIME

In order to be able to perform navigation and integrity related experimentation, the starting point is the build up of a very stable reference time scale.

The Experimental Precise Timing Station (E-PTS) has been implemented at the Istituto Elettrotecnico Nazionale "G. Ferraris" (IEN), Turin, Italy. The E-PTS partially re-uses the infrastructure of the IEN Time and Frequency laboratory, in particular the IEN clock ensemble and the remote transfer equipment, allowing to limit the procurement of new hardware at the GSTB-V1 experimental stage.

The E-PTS accomplishes the following main timing functions:

- 3 Cesium and 1 Hydrogen Maser clocks ensemble
- Hardware generation of Experimental Galileo System Time (E-GST)
- Local measurement system
- Time Scale generation
- Link for TAI Steering with other UTC laboratories
- Sensor station to feed the navigation and integrity processing with E-GST referenced data.

The link with external UTC laboratories (PTB, NPL), which is needed for the verification of the TAI steering of E-GST, is realized with the GPS Common View (CV) and the Two-Way Satellite Time and Frequency Transfer (TWSTFT) comparison systems.

The following table indicates the Timing products accuracy distinguishing between the requirement of the operational GALILEO system and the GSTB-V1 experimentation target. Note that GSTB-V1 E-PTS E-GST vs. TAI/UTC experimentation targets were initially less stringent than the Galileo operational system due to reuse of existing infrastructure and absence of Time Service Provider (extrapolation to 50 ns offset and 28 ns uncertainty has been done by analysis).

	GALILEO Requirements	**GSTB-V1 Experimentation Target**	**Remarks**
Offset of E-GST vs TAI/UTC	| E-GST –UTC| < **50 ns** with an uncertainty of 28 ns (95%)	| E-GST –UTC| **< 1 µs** with an uncertainty of 33 ns (95%)	Available monthly when BIPM circular T is issued
Stability of E-GST vs TAI/UTC	**5.5 * 10-14** over 1 day	**5.5 * 10-14** over 1 day	Available monthly when BIPM circular T is issued

Table 2 – Timing Accuracy

The Experimental Galileo System Time is computed using the E-PTS clocks, subsequently the H maser frequency is determined and corrected by means of a micro stepper (Auxiliary Offset Generator). Together with TAI prediction results, computed ensemble time is then steered versus TAI, allowing the generation of E-GST in real time as a hardware time scale. E-GST is then directly fed to the GPS geodetic receiver in the Sensor Station as reference time scale for navigation and integrity processing.

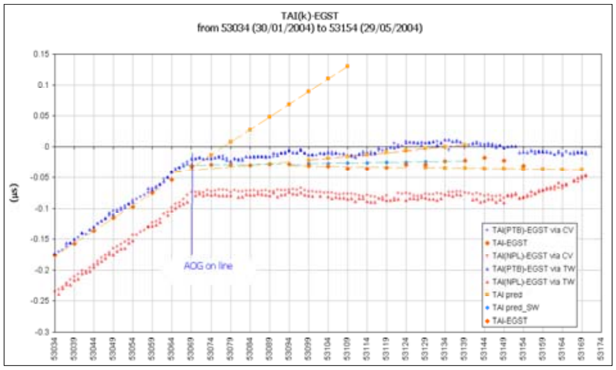

Figure 4 – TAI – E-GST Offset

The behavior of E-GST versus TAI is reported up to May in Figure 4, with the last available BIPM Circular T, while the behavior of E-GST versus TAI(PTB) and TAI(NPL) are reported up to end of May 2004. It can be seen that E-GST started at about –30 ns with respect to TAI and that this offset is quite well maintained in the first months of operation, much better than the initially set target of 1 µs.

It has to be remarked that when the E-GST timescale started to be corrected with the frequency values generated by the steering algorithm (AOG on line) the offset vs. TAI was about 30 ns. This offset value could be eliminated imposing a jump to the timescale; it was chosen not to correct this initial offset in order to have an E-GST without a jump since the beginning of operation. Therefore the above data and the relative plots have to be analyzed taking into account that the two time scales E-GST and TAI have an initial offset of a known value.

The behavior of on line E-GST is quite satisfactorily with respect to TAI because the accumulated error remains within a region of 18 ns (Figure 5), and the stability is also very good. The extrapolated value at τ = 1 day is equal to 1.36E-14 (1 σ), therefore it is compliant with the specified requirement asking for ADEV < 5 10 -14 @ 1 day (2 σ).

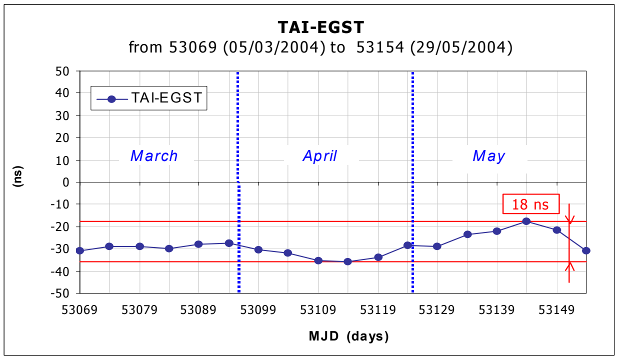

Figure 5 – TAI – E-GST Uncertainty

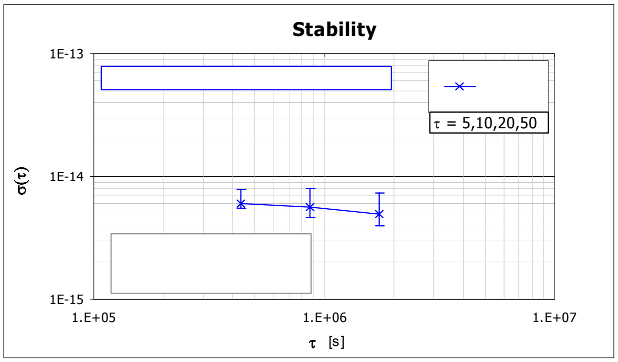

Figure 6 – Stability of E-GST vs TAI

Note that for a final assessment of the timing accuracy at least several months of BIPM data is needed in order to perform a robust evaluation and to confirm the above very promising results.

ORBIT DETERMINATION AND TIME SYNCHRONISATION

The following table indicates the OD&TS related requirements specified for the operational GALILEO system, and the level of compliance achievable according to the GSTB-V1 experimentation results.

	Requirements	**Experimentation Results**
Predicted Clocks UERE Contribution	**130 cm** Worst Instantaneous Ranging Accuracy Applicable to each individual satellite (95% percentile over 100 minutes)	Typical SV **45 cm** Maximum SV **62 cm** Worst Instantaneous Ranging Accuracy Applicable to each individual satellite (95% percentile over 100 minutes)
Predicted Orbits UERE Contribution		
Signal in Space Accuracy	**85 cm** Upper value (1 σ , applicable over 100 minutes and with a confidence level >0.9999)	Typical SV **43 cm** Maximum SV **46 cm** (1 σ , applicable over 100 min. Confidence under assessment)
Orbit Domain Restituted Orbits Error	**10 cm** Averaged error within the arc Applicable to each individual satellite (67% percentile over the arc duration)	Typical SV **7 cm** Maximum SV **8 cm** Averaged error within the arc Applicable to each individual satellite (67% percentile over the arc duration)
Restituted Clocks Error	**0.3 nsec** Averaged error within the Restituted arc Applicable to each individual satellite (67% percentile over the arc duration)	Typical SV **0.4 nsec** Maximum SV **0.6 nsec** Averaged error within the Restituted arc Applicable to each individual satellite (67% percentile over a 2 days arc duration)

Table 3 – OD&TS Accuracy

The following analyses synthesize respectively orbit determination and prediction accuracies, and block IIR clock performances. These results have been obtained analysing two months of Core from January 26 until March 28 2004.

Note that Block IIR satellites have been considered because their specification is close to the Galileo Rubidium Atomic Frequency Standard.

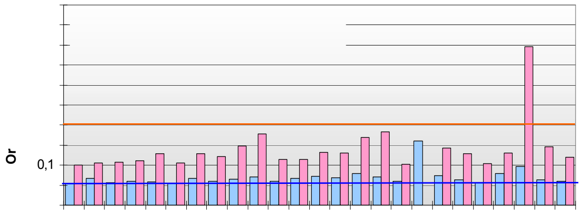

Figure 7 – Orbit Determination and Prediction Accuracy

Figure 7 shows the orbit determination error (vs. the IGS reference) for each of the considered satellites (light blue) where the blue horizontal line sets the experimentation target for orbit determination accuracy. In the same figure is also shown the orbit prediction error (6 hours prediction interval vs. the IGS reference) for each of the considered satellites (violet) where the red horizontal line sets the experimentation target for orbit prediction accuracy.

Note that in the IGS weekly summaries for the considered analysis time interval, satellites PRN-24 and PRN-29 are mentioned to have certain modeling problems, and are sometimes left out of the IGS statistics, for this reason they have not been considered.

Figure 8 shows the clock estimation error (vs. the IGS reference) for block IIR satellites (light blue) where the blue horizontal line sets the experimentation target for clock determination accuracy. In the same figure is also shown the clock prediction error (6 hours prediction interval vs. the IGS reference) for block IIR satellites (purple). The red horizontal lines set the experimentation target interval for clock prediction accuracy.

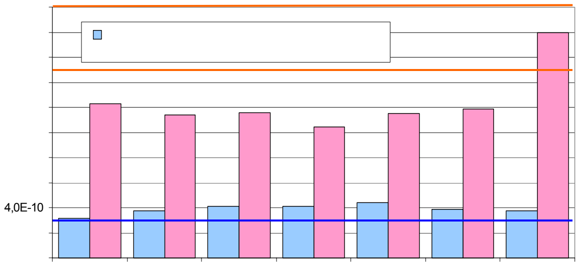

Figure 8 – Clock Determination and Prediction Accuracy

In conclusion, orbit and clock quality is very close to the target level specified for estimation (10 cm and 0.3 ns respectively), and fulfills by far the target levels specified for prediction (130 cm in total for both contributions):

The Signal In Space Accuracy (SISA) is defined as the prediction of the minimum standard deviation (1-sigma) of an unbiased Gaussian distribution, which over-bounds the Signal In Space Error (SISE) predictable distribution for all possible user locations. As observed in Table 3, the SISA upper value targeted by the Galileo operational requirements (85 cm) is clearly met.

The verification of the SISA actual bounding properties is only possible under certain assumptions on the Satellite Residual Error in the Worst User Location (SREW) distribution, and even then, with just a certain confidence level. The maximum 1E-04 probability, for the SISA sub-bounding, specified in the Galileo Operational requirements, has been interpreted within the GSTB-V1 experimentation as the probability for the estimated SISA value to be smaller than the actual 1σ SREW value under the hypothesis that its distribution is Gaussian.

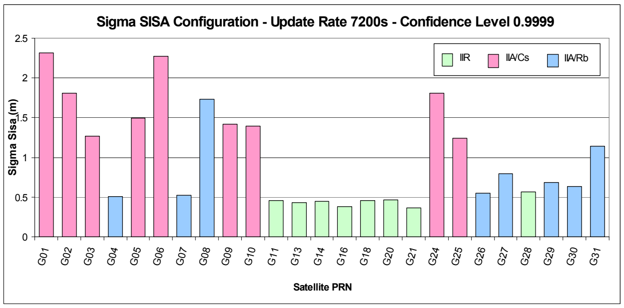

Figure 9: SISA Configuration (based on 2 months of data)

Figure 9 represents the SISA configuration. Note that there was little available data for PRNs 2 and 6, therefore, for such satellites more data would be necessary to compute a valid sigma SISA estimation. With respect to PRNs 24 and 29, they have some modeling problems (especially PRN 24) and therefore, they cannot be considered as representative.

Figure 10 represents, per GPS satellite, the histograms of the SREW in absolute value, derived from 2 months of data as well as its theoretical probability density function defined consistently with GSTB-V1 assumptions. A visual inspection makes clear a significant agreement between the SREW hypothesis and the experimentation results.

Nevertheless it is important to highlight that the values presented here are still preliminary: to have a representative SISA, at least the following conditions should be met:

- Enough independent samples to assess an “optimal” inflation factor, in terms of number of data to process and in terms of independency of the samples.
- Statistics convergence, which is still not achieved for all satellites.

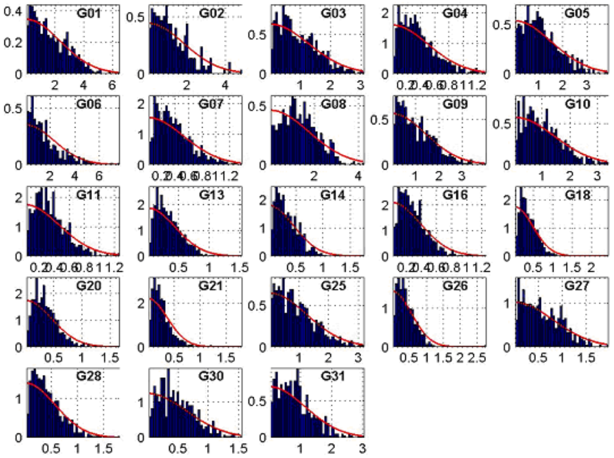

Figure 10 – SREW histogram and SISA

The broadcast SISA will contain the navigation message orbit format and clock format resolution limitations, which should be added to the previous results (in the worse case it amounts to few cm).

The SISA has exhibited a reduced dependency along time, within the analyzed data set, what would justify broadcasting just a single scalar value during the 100 minutes of the navigation message applicability period.

The GSTB-V1 experimentation allows validating the suitability of a scalar and linear time dependent SISA representation versus a vector and linear time dependent one; being the first the actual approach specified for the operational Galileo system. Table 4 provides, for GPS Block IIR satellite and as an average, the scalar SISA, the vector SISA, as well as each of its components, namely along track, across track, radial and clock.

Scalar σ_{SCALAR}	Along σ_a	Across σ_c	Radial σ_r	Clock σ_c
0.43	0.32	0.15	0.07	0.36

Table 4 – SISA Performance

Assuming that the vector SISA orbit radial and clock components are weakly correlated, the ratio between the scalar SISA and the combination of the clock and radial components is given by the following expression:

$$\frac{\sigma_{SCALAR}^2}{\sigma_r^2 + \sigma_c^2} \approx 1.17$$

Therefore, it is not expected a significant improvement by broadcasting the vector SISA, at least as far as the above assumptions in Table 4 on the vector SISA components stays valid. Experimentation will continue on this area.

In terms of vector SISA bounding properties, the same approach, as for the scalar SISA, has been followed. The histograms for each SISE and associated vector SISA component, are represented in Figure 11, which shows again a reasonable agreement between the theory and the experimental results, with the same reserves as for the scalar SISA (conclusion applies to any GPS SV).

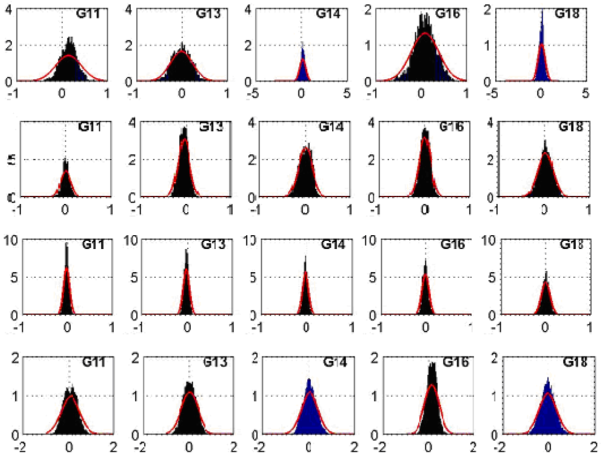

Figure 11 – SISE and vector associated SISA components

INTEGRITY

The Galileo system foresees a real time monitoring of each broadcast satellite navigation message, which will state each second and per satellite, the level of coherency observed between the satellite predicted clock & orbit and the actual Signal in Space Error (SISE). This real time monitoring function has been allocated in the Integrity Processing Facility (IPF), in the Galileo Ground Segment; which has been prototyped within the GSTB-V1 activities.

The outcome of this real time monitoring is a qualified integrity flag per satellite, with the following conceptual states: “Satellite OK”, “Satellite Not OK” or “Satellite Not Monitored”. In the first case, the Signal In Space monitoring accuracy is made visible to the user, making possible, to decide, at a certain point in time and location, whether the navigation based on Galileo signals can support a certain service level.

The Signal In Space Monitoring Accuracy is defined as a prediction of the minimum standard deviation (1-sigma) of the unbiased Gaussian distribution that over bounds the SISE estimation error as determined by the integrity monitoring system. The SISMA value is strongly dependent on the relative geometry between the satellite and the ground-based sensor stations monitoring it, as well as on the tracking error characteristic of those sensor stations.

Table 4 summarizes the exact system level expectations for the operational Galileo system. Two upper bounds for the broadcast SISMA are specified; a first one to be met with a probability higher than 0.947, and a second one to be met with a probability higher than 0.99.

	GALILEO Requirements	**GSTB-V1 Experimentation Results**
Nominal Broadcast SISMA	**70 cm** Worst Instantaneous Monitoring Accuracy Applicable to each individual satellite Upper value with the Nominal Galileo Sensor Station Network, which is available with a probability of 94.73% (1 σ , applicable over 30 seconds and with a confidence level > 0.999865).	**120 cm** Worst Instantaneous Monitoring Accuracy Applicable to each individual satellite Upper value with the Nominal GSTB-V1 Sensor Station network, assuming an availability of 100% (1 σ , applicable over 1 seconds and with a confidence level under assessment).
Degraded Broadcast SISMA	**130 cm** Upper value with the Degraded Galileo Sensor Station Network. Probability of having an either Nominal or Degraded Sensor Station Network is 99.96%	

Table 4 – Integrity Performance

The verification of the SISMA upper bound achievability, is quite a challenge, due to the following facts:

- Availability of 1 Hz data provided by the GSTB-V1 sensor stations is low compared with that specified for the Galileo operational real time monitoring network

- Current GSTB-V1 Sensor Stations network synchronization algorithm performance is conditioned by GPS satellites clock & orbit error: degradation results mostly from GPS satellites Block IIA with on-board clocks less performant than Galileo satellites clocks (with specification closer to GPS Block IIR)
- Short-term instability of some GSTB-V1 sensor station atomic clocks provokes cycle slips and resets of the E-IPF pre-processing function.

A new cycle slip detection algorithm has corrected the third limitation with a solution entirely robust to short data gaps as well as to any level of instability in the sensor stations atomic clock.

The resulting IPF pre-processing output has been propagated through simulation into the SISMA computation algorithm in order to overcome the first two limitations.

The pre-processing error is obtained as the difference between the pre-processed pseudorange, and the reference one, which is derived from IGS final GPS orbits and sensor station coordinates, as well as the IGS final GPS on-board clocks. It reflects the residual error after the mitigation of the multipath, receiver noise, troposphere, and synchronization errors. The Figure 12 represents the pre-processing error histogram, averaged throughout all GSTB-V1 sensor stations and over one day, which has a rms value of about 40 cm.

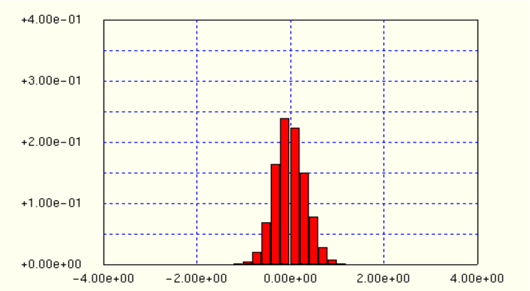

Figure 12 GSTB-V1 IPF Pre-processing error

The pre-processing error (excluding the synchronization component) before and after the upgrade to enhance the robustness against short-term clock instability is shown in Figure 13 for the Villafranca station, which is equipped with one of the less performing clocks in the above sense. On the left side is shown the original E-IPF pre-processing error, on the right the E-IPF pre-processing robust to clock short term instability.

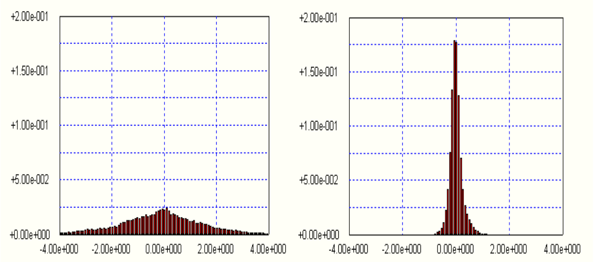

Figure 13: GSTB-V1 IPF Pre-processing error, excluding synchronization, for the Villafranca station.

The theoretical achievable SISMA with the GSTB-V1 sensor station network, and assuming all stations permanently available is represented in Figure 14. Results taking into account realistic availability figures are planned in the next experimentation phase.

To diminish the dependency of the Sensor Stations network synchronization performance with the satellite clock and orbit error, a new synchronization algorithm, more robust and scalable is being developed, based on Common View Kalman filtering approach.

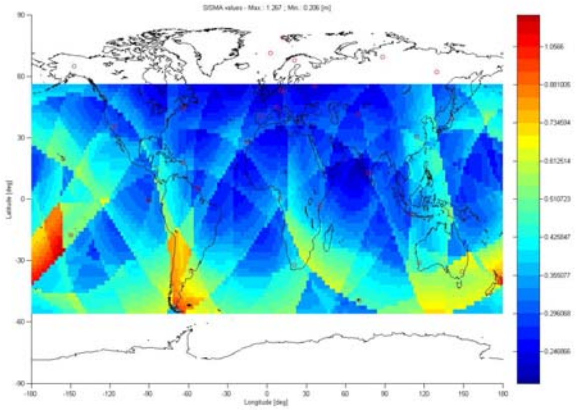

Figure 14. GSTB-V1 SISMA map (simulated)

CONCLUSIVE REMARKS

The GSTB-V1 has proven to bring an added value to Galileo in terms of confidence, design consolidation and accelerated schedule, allowing:

- Actual measurements and comparison of alternative algorithms in a realistic environment
- Galileo timing infrastructure set-up
- Calibration over an extended period of time
- Early verification and tuning of simulators and build-up of adequate analysis tools
- Contribution to the consolidation of the operational concept.

ESA will continue to ensure tight co-ordination of the GSTB-V1 development and experimentation with the overall Galileo Design Development and Validation Phase.

ACKNOWLEDGMENTS

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REFERENCES

All technical documentation on GSTB-V1 core infrastructure and experimentation is available through the ESA web site:
http://www.gstb-v1.esa.int