GALILEO PERFORMANCE ASSESSMENT USING THE GALILEO SYSTEM SIMULATION FACILITY

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1. ABSTRACT

This paper assesses the performance of the Galileo system from In-Orbit-Validation (IOV) towards the Full-Operational-Constellation (FOC). As part of this assessment, the transition phase between 2008 and 2010/12, where starting from a limited number of Galileo satellites stepwise more and more satellites will become available, is investigated in order to identify its potential for an early utilisation. In addition, the application of GPS together with the existing and planned Space-Based Augmentation Systems (SBAS) such as the European Geostationary Navigation Overlay Service (EGNOS), the US-American Wide Area Augmentation System (WAAS) as well as the Japanese Quasi Zenith Satellite System (QZSS) is evaluated and compared to a combined use of GPS and Galileo with respect to navigation performance.

At this stage, the presented analyses are still only indicative in a sense that the objective was to demonstrate the capabilities of GSSF rather than to derive final conclusions.

2. INTRODUCTION

The Galileo System Simulation Facility (GSSF) was developed on behalf of ESA/ESTEC by an international consortium led by VEGA. GSSF is conceived as a simulation environment that reproduces the functional and performance behaviour of the Galileo system. It offers the necessary flexibility and functional scope to support Galileo system simulation needs during the entire program life cycle.

The immediate role of GSSF primarily lies in the Galileo design and definition phase as well as in the validation of Galileo ground elements. For this purpose, GSSF provides a single simulator that uses alternative models depending upon the type of analysis the end-user wishes to perform.

The **Service Volume Simulation (SVS)** capability of GSSF allows the analysis of the navigation and integrity performance over long time periods and over large geographical areas. In particular, GSSF SVS allows the user to assess all relevant Figures of Merit on global or regional grids or for individual positions. Such Figures of Merit are Visibility, Coverage, Geometry, DOP, Navigation Precision, Integrity and Service (including Critical and Redundant Satellites) as well as the associated availability and continuity figures. In addition GSSF provides GPS/Galileo global Interference analysis as well as Link Budget and Error Budget analyses. A comprehensive list of available analyses is provided in [1], while individual implementations are further detailed in [2].

The SVS functionality of GSSF was recently extended to include Signal-in-Space Monitoring Accuracy (SISMA), the latest Galileo Integrity concept, User Dynamics (i.e. mobile users including space-based users) and SBAS /EGNOS support.

The **Raw Data Generation (RDG)** capability of GSSF uses high fidelity models to generate GPS and Galileo observables acquired by Galileo Sensor Stations. This capability includes the definition of Feared Events and is suitable for the validation and tuning of Galileo Ground Mission Segment (GMS) algorithms such as Orbit Determination & Time Synchronisation (ODTS). The RDG provides observables as well as ephemeris and clock data.

GSSF enables simulation of the nominal system and also its various degraded modes, both in a deterministic and a probabilistic manner. GSSF is not limited to Galileo and can also be used to simulate GPS and SBAS systems.

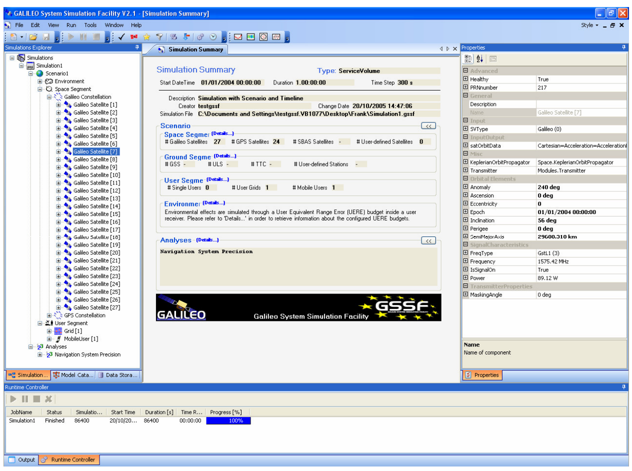

Figure 1: GSSF V2.1 User Interface - Workspace View

3. SYSTEM CAPABILITIES

GSSF was developed on Windows XP (.NET Framework 1.1) in order to exploit the rich functionality of this platform, while models are kept platform independent and are implemented in C++. It provides a modern and flexible User Interface with context sensitive elements such as the Property Grid. This component displays the properties of whichever element is selected in the workspace. Properties of the selection can be viewed but also edited from the Property Grid.

Figure 1 shows the GSSF V2.1 workspace that is divided into three main areas; the tree view on the left allowing the user to browse the simulation scenario, the centre area used to display the simulation summary page and simulation results, and the Property Grid on the right. The Runtime controller on the bottom of the page provides status information and allows interaction with the simulation process during runtime.

A reporting feature is available that allows the export of simulation configuration reports in RTF and PDF format. By this means, the complete simulation/scenario definition, including parameter settings, can be reported via an auto-generated document.

GSSF provides interfaces to read external data from IGS SP3 and YUMA files for initialization of constellations (including actual GPS position data) and from RINEX, TROPEX, IONEX, IGS SP3, IGS ERP, JGM3 and JPL DE405 for replacing environmental models with corresponding external data. The GSSF Export feature allows the user to export RINEX 2.0 clock, RINEX 2.1 observation, RINEX 3.00 observation and IGS SP3-c data. The data produced by GSSF can be injected into other tools for further analysis (RINEX/SP3).

GSSF has been designed to have no run-time dependence on commercial products except for the Interactive Data Language (IDL) that has provided a suitable basis for implementation of the various visualisation elements such as Map and Sky Plots.

4. MODELLING ASSUMPTIONS

Service Volume Simulation

GSSF SVS implements models to cover all relevant elements of the Galileo system: Space Segment, Environment, User Segment and Ground Segment. The fidelity of participating models was specified in such a way that they satisfy the required modelling accuracy for SVS-type analyses while maintaining a sufficient runtime performance [2].

The GSSF space segment can contain one or more satellite constellations which are created based on three different methodologies. The standard way of adding a satellite constellation to the space segment is to add a nominal (pre-defined) constellation based on Galileo or GPS satellites. The tool also supports creating user-defined satellite constellations based on the definition of individual satellite parameters, using Walker parameters or based on data read from Yuma Almanac files. The orbit of each spacecraft is based on a simple unperturbed elliptical Keplerian orbit scheme.

GSSF allows the modelling of user receiver grids of static user positions with common characteristics as well as single static or mobile users including aircraft in flight and satellites in Low Earth Orbit (LEO). Grid boundaries are specified by the minimum and maximum longitudes and latitudes, where the resolution is either constant or specified as a function the geographical latitude.

The Ground Segment in the GSSF SVS consists of configurable Ground Station Networks that can be composed out of Galileo Sensor Stations (GSS), Mission Up-Link Stations (ULS) and Telemetry, Tracking and Control (TTC) Stations.

To model environmental effects in the SVS, a User Equivalent Range Error (UERE) Budget is applied, representing errors that result from tropospheric effects, ionospheric effects, receiver noise, ephemeris fit, satellite clocks, receiver clock and multipath. The UERE is modelled using a specified distribution profile, where the standard deviation and mean for different values of elevation are calculated by linear interpolation.

For applicability of UERE budgets, and which predefined UERE budget tables are recommended and available with the GSSF installation, please refer to [1]. Please note that the user can also define his/her own UERE budget tables as necessary.

Raw Data Generation

The RDG functional architecture is divided into three major segments, the Space Segment, the Environment and the Ground Segment. Within these segments, different algorithms and models are available. Alternatively, GSSF by design facilitates import of external files providing orbit, clock and environmental data during run-time (RINEX, IONEX, TROPEX, SP3).

Note, the user segment is not of immediate relevance to RDG. The following sections provide an overview of the modelling assumptions for GSSF RDG.

Environment Segment

The environment models in GSSF are user switchable, providing a high degree of flexibility to simulate with changing environmental conditions. All models are designed to be able to trigger a Feared Event scenario, where deliberate degradation of functionality can be achieved to simulate worst-case scenarios.

- Free Space Delay: Simulates the delay due to free space of a signal propagating from a transmitter to a receiver, with or without “Eccentricity” and “Sagnac” effects, which individually add an offset to the ideal free space delay.

- Ionospheric Delay: The Ionospheric Model uses ITU-R NeQuick to calculate the Total Electron Content (TEC). The TEC as provided by the ITU-R NeQuick model is a function of time of day, user location, satellite elevation angle, season and further environmental parameters [3]. The resultant values are used to define the Ionospheric delay.

- Tropospheric Delay: The Tropospheric Model computes tropospheric delay as the sum of the dry and wet tropospheric zenith delays, mapped to the satellite elevation angle. The tropospheric delay algorithm is based on the Hopfield model and the tropospheric attenuation algorithm is based on a simple oxygen attenuation model [4].

Using the transmitter to receiver range for a valid transmitter/receiver combination, computed by the Visibility module, the Total Environment Delay of the signal from its time of emission to time of reception is calculated by summing the Free Space Delay, the Ionospheric Delay and the Tropospheric Delay for each broadcast frequency.

Space Segment

The GSSF space segment allows the user to define constellations based on Walker parameters or initialised using YUMA almanac files. In addition, predefined reference constellations for Galileo and GPS are specified.

- Satellite Orbit Propagation: The Orbit propagator model applies a fourth-order Runge-Kutta integrator to compute orbital position and velocity. For higher precision an eighth-order Adams-Moulton integrator is available. The orbital position and velocity are determined based on the acceleration resulting from all forces acting on the satellite, applying the JGM-3 Earth gravitational model (15x15 harmonics) [2]. GSSF also provides a feature to read orbit data from SP3 files during run-time to replace the numerical orbit propagation.

- Satellite Orbit Perturbation: The following orbit perturbations are considered: Lunisolar gravity perturbations, solar radiation pressure, Earth tidal effects, relativistic corrections and user settable spacecraft propulsion forces.

Ground Segment

The Galileo Sensor Station (GSS) is a derivative of the static user receiver model used within GSSF. It consists of a receiver front-end model, which receives the Galileo and GPS signals from the visible satellites and computes the observations to be included into a RINEX file. The GSS can be applied to both the Galileo and GPS systems, by specifying the Receiver type and channels accordingly. The receiver front-end will select which signals to track, based on the configuration of the signal tracking channels. The RDG is currently being upgraded to include the effect of Earth Solid Tides on station positions.

- Pseudorange: The pseudorange values are simulated by adding measurement errors to the range (time) information provided by the environment model. These measurement errors are a function of noise, multipath effects and group delay (interfrequency bias).

- Total Signal to Noise: The total signal to noise ratio will be computed from received power, signal propagation noise, intrinsic receiver noise, and interference noise. This total signal to noise ratio is compared to the user-specified acceptable threshold and the signal is rejected if the noise level exceeds the limit.

5. THE VALIDATION OF GSSF

The Service Volume Simulation capability of GSSF V2.0 was successfully validated against simulation data either obtained from trusted sources or produced by means of an independent implementation of the related functionality at University of Nottingham. The validation of the recently added features (GSSF V2.1) as presented in this paper, such as SISMA, the latest Galileo Integrity concept and SBAS/EGNOS support is currently ongoing. Results on unit level already indicate that the results are trustworthy.

The raw data produced by GSSF has been rigorously validated against real data. RINEX files from Kourou station were extracted from the GSTB-V1 test data set (TDS), together with various data products, such as the IGS ephemeris and clock files. The TDS is a set of data from the GSTB Early Data Archive, consisting of 31 receivers and covering a one-week period (June 18th to 24th, 2003). Intended for use in the GSTB factory and acceptance testing, it is also useful as a standard data set for a variety of other testing purposes.

In the validation, simulated code, carrier and Doppler measurements were compared with those obtained from the real Kourou data in the TDS. The process adopted an incremental approach, where real data sources were one by one replaced with the corresponding GSSF models. At each step, the increasing differences between the real data and the simulated data were assessed, based on the results of the earlier unit level tests of these models. The final increment resulted in a full simulation of the real data, using all appropriate GSSF models, providing a characterisation of the level of fidelity that can be expected from GSSF. This campaign was concluded successfully as further de-tailed in [6]

In addition, an independent validation was carried out by ESA/ESOC in Darmstadt. The ESOC Navigation Office has extensive experience in processing GPS observations by means of its Analysis Centre for the International GPS Service. Therefore, the main objectives were to characterise the GSSF orbit propagation models used for the generation of raw observation data in terms of model fidelity and validity of implementation and to verify that the data (RINEX and SP3) produced by GSSF can be processed as if it was real measurement data, using the standard Precise Orbit Determination software that is used at ESOC for IGS product generation. This analysis therefore forms an independent system-level check of the entire GSSF system, because it takes the GSSF output and analyses this data with software that is known to be consistent with international geodetic standards.

This campaign was carried out successfully. ESOC could achieve a 64 mm RMS orbit fit over 24 hrs and the tracking data fit exhibits post-solution tracking residuals in the order of 20 cm RMS for code data and 3 cm RMS for phase data. As a conclusion it can be stated that ESOC was able to fit the GSSF orbits with high accuracy and that GSSF Raw Data is a valid representation of real measurement data. For further information on this independent validation, please refer to [7].

Based on these efforts, a Galileo Test Data Set (TDS) was created that is considered representative from a performance point of view with respect to GPS, and at least from a functional point of view with respect to Galileo. Both the In-Orbit Validation (IOV) constellation and the Fully Operational Constellation (FOC) are considered, together with GPS. The data is compliant with the latest consolidated RINEX 3.00 standard [5].

Further additional upgrades to specific RDG models are currently being applied in order to allow for a TDS that is also representative from a Galileo performance point of view. Each of these upgrades requires validation, and several will require calibration, for which real measurement data from the GIOVE-A satellite will be considered.

6. SIMULATION RESULTS

The following paragraphs provide simulation results that were obtained by means of the SVS capability of GSSF in order to assess the Galileo performance together with GPS and space-based augmentation systems. For sample results on the Raw Data Generation capability, please refer to [6].

6.1. SBAS Support

GSSF supports the analysis of stand-alone GPS/SBAS systems as well as GPS/SBAS combined with Galileo and or GPS. Since Space-Based Augmentation Systems (SBAS) exist in other regions, GSSF not only supports the European Geostationary Navigation Overlay Service (EGNOS) satellites, it can also be extended to include other SBAS satellites as well, and is not limited to Geostationary (GEO) satellites. The following study provides a comparison of the performance achievable by means of GPS, EGNOS as well as the Wide Area Augmentation System (WAAS) and the Japanese Quasi-Zenith Satellite System (QZSS), all for single frequency. A further comparison identifies the potential of using dual frequencies for a joint use of GPS and SBAS as well as for GPS and Galileo.

Table 1: EGNOS, QZSS and WAAS Constellations

PRN#	Semi-major axis[km]	Eccentricity	Inclination [deg]	RAAN [deg]	Arg. of Perigee [deg]	Mean Anomaly [deg]
EGNOS Constellation						
120	42164.169637	0	0	0	0	121.446
124	42164.169637	0	0	0	0	124.946
126	42164.169637	0	0	0	0	84.446
QZSS Constellation						
71	42164.000000	0.099	45	85	270	0
72	42164.000000	0.099	45	205	270	240
73	42164.000000	0.099	45	325	270	120
WAAS Constellation						
48	42164.169637	0	0	0	176.5	0
51	42164.169637	0	0	0	202.2	0

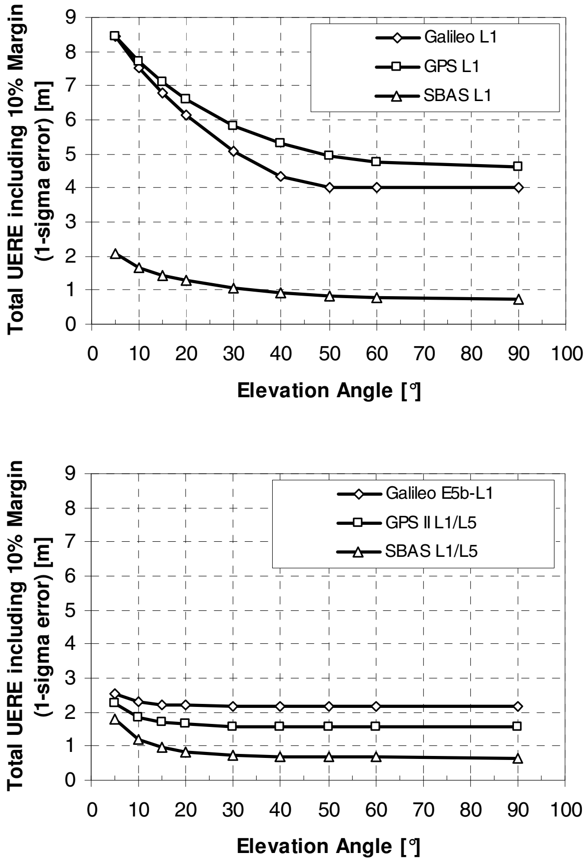

Figure 2: Applied UERE Budgets for on Single Frequency L1 and dual frequencies

Table 1 summarises all relevant orbit parameters, where for QZSS the Option 1 according to [8] was chosen, showing an asymmetrical 'figure-8' ground track. The support for SBAS systems can be assessed by means of visibility analyses as well as for navigation system precision and integrity-related simulations. This section provides an example in which a comparison is carried out of the navigation system precision that is achievable with and without SBAS support. For this example the geostationary satellites relevant for EGNOS were used, namely INMARSAT 3 F2 (AOR-E), ESA ARTEMIS and INMARSAT IOR-W (III-F5). For WAAS, the orbit parameters for the two participating GEO satellites were taken from [9]. Please note that the example simulation does not assess whether a user within the service area (i.e. the visibility area of the SBAS satellites) will have the required ground support to benefit from the SBAS service. Instead the example tries to identify how Navigation System Precision could ideally be improved within the service area assuming all necessary ground support is made available.

The calculation of the NSP is mainly driven by the corresponding applicable UERE budget. For a user being able to receive the SBAS signals and being located in the service area a different UERE budget applies as compared to users located outside the service area. Figure 2 provides an overview of all UERE budgets applied within this example, where the WAAS and QZSS budgets were assumed to resemble the EGNOS budget. A masking angle of 10° is applied for all simulations that are carried out over a period of one day starting 1st August 2006 at 00:00 hrs, with a 300 sec time step and a user grid with 5° separation. These settings allow for fast simulation execution on a state-of-the-art desktop PC, while maintaining a sufficient resolution. Figure 3 and 4 show the minimum and maximum number of visible WAAS, QZSS & EGNOS satellites as well as the ground track of the QZSS. Figure 5 shows the mean number of satellites visible to a user assuming a full scenario of GPS, Galileo, WAAS, EGNOS and QZSS satellites. The number of visible satellites varies between 16 and 26, where increased numbers are observed in areas served by SBAS as expected.

If, for the same assumptions, the NSP is calculated (assuming single frequency, L1), the accuracy achievable within the service area (visibility cones of WAAS, EGNOS and QZSS satellites) is increased as compared to GPS only. This is illustrated in Figures 6 and 7, where the mean accuracy improves from 14 for GPS only to 2 m for a combined use of GPS with SBAS systems.

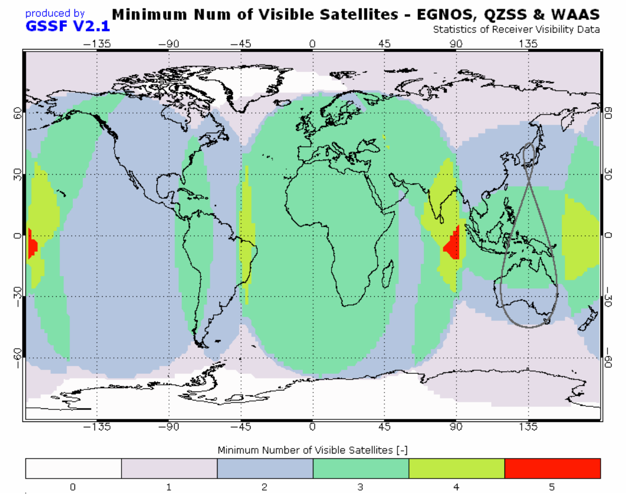

Figure 3: Minimum Number of Visible SBAS Satellites over One Day

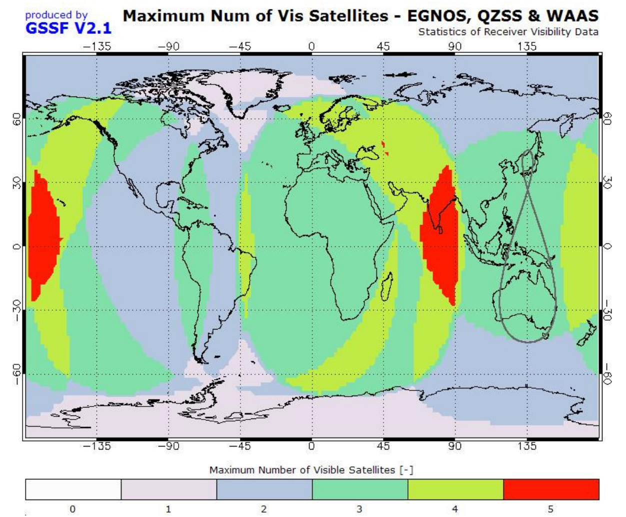

Figure 4: Maximum Number of Visible SBAS Satellites over One Day

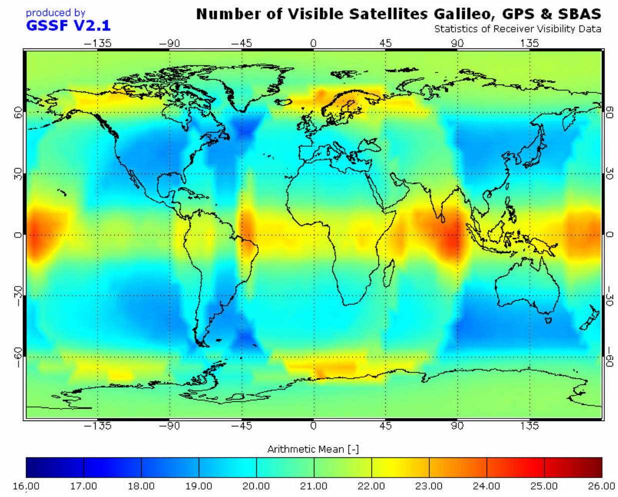

Figure 5: Mean Number of Visible Satellites for Galileo, GPS & SBAS (EGNOS, QZSS & WAAS)

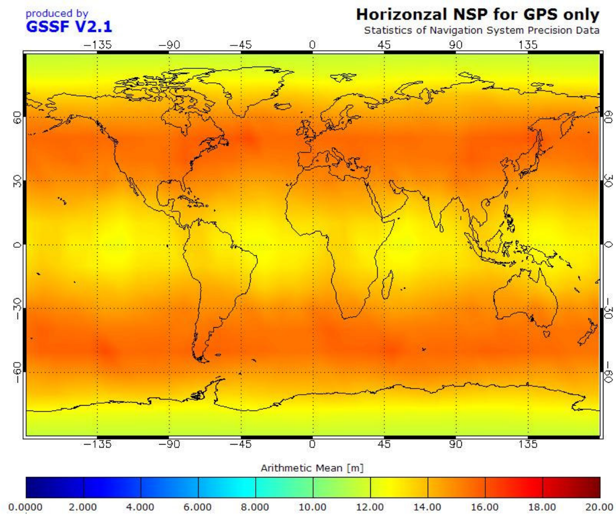

Figure 6: Horizontal NSP for GPS only on L1

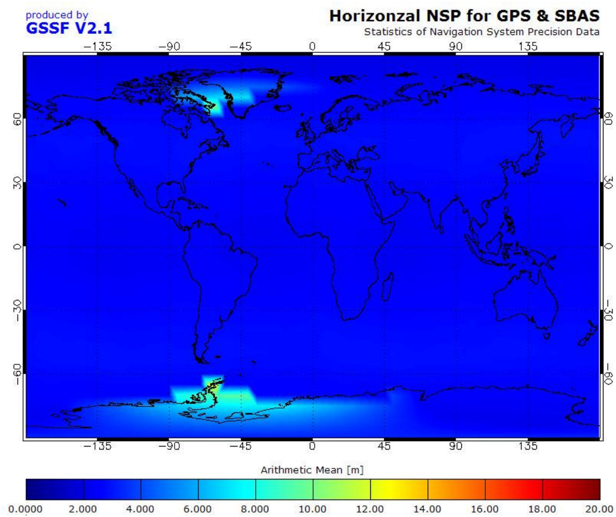

Figure 7: Horizontal NSP for GPS & SBAS on L1

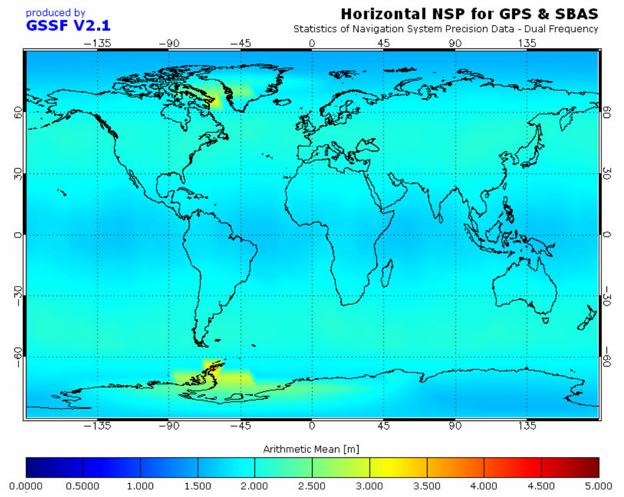

Figure 8: Horizontal NSP for GPS & SBAS on Dual Frequencies

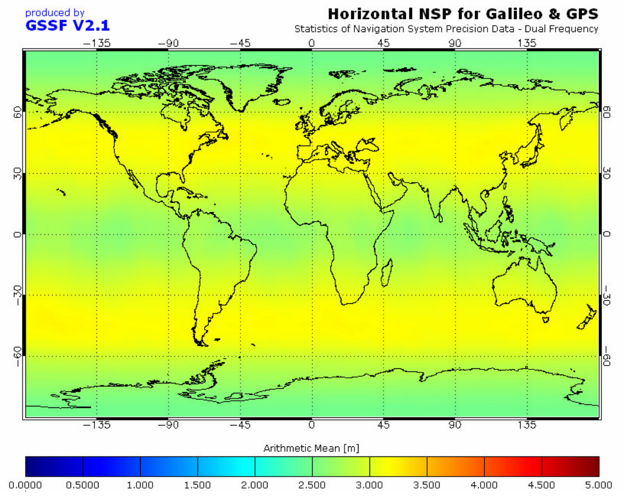

Figure 9: Horizontal NSP for GPS & Galileo on Dual Frequencies

Figure 8 provides, for the same scenario, a result where dual frequencies are assumed for GPS and SBAS (L1/L5 for GPS and L1/L5 for EGNOS, WAAS and QZSS). The figure shows again a mean value in the order of 2 m, implying that the accuracy improvement achieved by using SBAS systems is predominant over the use of dual frequencies applied to the same system composition. Furthermore, Figure 9 shows the horizontal accuracy achieved using GPS & Galileo (L1/L5 for GPS and E5b/L1 for Galileo). The mean horizontal accuracy is in the order of 2.5 to 3 m, thus slightly worse than for a combined use of GPS & SBAS for the same conditions. This justifies the use of SBAS systems even once Galileo is available.

The following Figures 10 and 11 show sky plots that illustrate the tracks that the visible GPS satellites and QZSS satellites follow as seen from Tokyo, Japan, over a period of one day. Only a limited number of 9 GPS satellites are seen under high elevations (75°-90°) and only for a limited period of time.

One objective of the QZSS is to cover both Japan and Australia, while maintaining continuous visibility at high elevations, making it applicable to urban canyons. This is achieved by the three satellites moving in three different orbits but following the same ground track over the pacific region. Figure 12 shows the elevation vs. time for the three QZSS satellites over one day. The constellation is defined such that one of the three satellites always maintains an elevation between 75°-90° for 8 hrs, before the next satellite takes over.

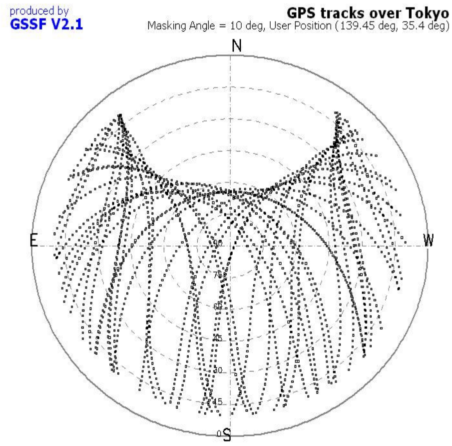

Figure 10 – Sky Plot showing GPS tracks over Tokyo

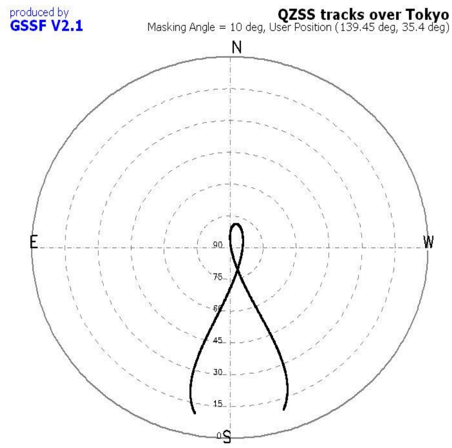

Figure 11 – Sky Plot showing QZSS tracks over Tokyo

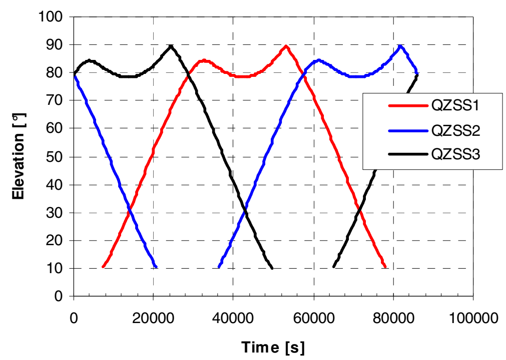

Figure 12 – Elevation vs. Time for QZSS Satellites over Tokyo during One Day

6.2. Sub-Constellation Analysis

This assessment is concerned with the accuracy gain that can be expected for a combined use of GPS and Galileo assuming single frequency. The Galileo constellation is considered to become available stepwise with an increasing number of satellites, starting from the IOV configuration with 4 Satellites in two planes and moving on with 12, 18 and finally 27 satellites in three planes. The orbital parameters for the sub-constellations are summarised in Table 2 below.

Table 2: Orbital parameters applied to the GPS & Galileo sub-constellation analysis

Galileo Sub-Constellation (4 Satellites, IOV)						
PRN#	Semi-major axis[km]	Eccentricity	Inclination [deg]	RAAN [deg]	Arg. of Perigee [deg]	Mean Anomaly [deg]
111	29600.318	0	56	0	0	0
112	29600.318	0	56	0	0	40
113	29600.318	0	56	120	0	13.33
114	29600.318	0	56	120	0	53.33

Galileo Sub-Constellation (12 Satellites)						
PRN#	Semi-major axis[km]	Eccentricity	Inclination [deg]	RAAN [deg]	Arg. of Perigee [deg]	Mean Anomaly [deg]
111	29600.318	0	56	0	0	0
112	29600.318	0	56	0	0	90
113	29600.318	0	56	0	0	180
114	29600.318	0	56	0	0	270
121	29600.318	0	56	120	0	30
122	29600.318	0	56	120	0	120
123	29600.318	0	56	120	0	210
124	29600.318	0	56	120	0	300
131	29600.318	0	56	240	0	60
132	29600.318	0	56	240	0	150
133	29600.318	0	56	240	0	240
134	29600.318	0	56	240	0	330

Galileo Sub-Constellation (18 Satellites)						
PRN#	Semi-major axis[km]	Eccentricity	Inclination [deg]	RAAN [deg]	Arg. of Perigee [deg]	Mean Anomaly [deg]
111	29600.318	0	56	0	0	0
112	29600.318	0	56	0	0	60
113	29600.318	0	56	0	0	120
114	29600.318	0	56	0	0	180
114	29600.318	0	56	0	0	240
114	29600.318	0	56	0	0	300
121	29600.318	0	56	120	0	20
122	29600.318	0	56	120	0	80
123	29600.318	0	56	120	0	140
124	29600.318	0	56	120	0	200
123	29600.318	0	56	120	0	260
123	29600.318	0	56	120	0	320
131	29600.318	0	56	240	0	40
132	29600.318	0	56	240	0	100
133	29600.318	0	56	240	0	160
134	29600.318	0	56	240	0	220
133	29600.318	0	56	240	0	280
133	29600.318	0	56	240	0	340

Figure 13 presents the HNSP values evaluated during a 10-day simulation over Europe, applying the single frequency UERE Budgets for L1 as defined in Figure 2. For an increasing number of Galileo Satellites used jointly with GPS for position determination, the HNSP values decrease as expected. The overall average improvement of the Mean HNSP values (i.e. reduction of mean horizontal positioning errors) is presented as a percentage of the accuracy achievable with GPS only. While the improvement seems to grow steadily for an increasing number of Galileo Satellites up to 18, the further improvement up to the full Galileo constellation is slower. More intermediate points are expected to further exhibit a saturation effect. However, the number of satellites at which an early utilisation will be initiated will also highly depend on the launch strategy and not on the pure number by which a significant improvement in accuracy is expected. Thus this analysis is only indicative in a sense that the objective was to demonstrate the capabilities of GSSF rather than to derive final conclusions.

7. CONCLUDING REMARKS

GSSF provides a single simulator that uses alternative models depending upon the type of analysis the end-user wishes to perform. It has to provide more flexibility and openness than traditional space system simulators, with user-defined scenarios allowing coverage of many aspects of the Galileo system prior to the availability of the system itself.

GSSF provides Raw Data Generation for not only the GPS satellites, but also for a full nominal constellation of Galileo satellites. Test data sets can also be produced, in which a range of specific Feared Events are triggered. By this means, software tools that will be used to generate the Galileo ephemeris, clock and integrity data can be rigorously tested for non-nominal conditions. The GSSF SVS capability meant for Galileo definition can also be applied to teaching and outreach. The main strengths of GSSF can be summarised as follows:

- Rigorously validated against real data or trust worthy simulated data
- Specifically tailored towards the needs of the Galileo community
- Maintained by VEGA via the Project Office at ESTEC
- Can be further upgraded by an experienced core team to match evolving requirements

ACKNOWLEDGMENTS

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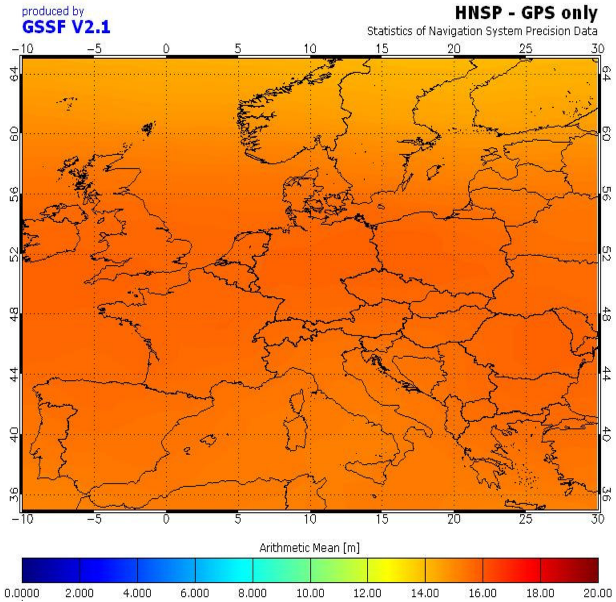

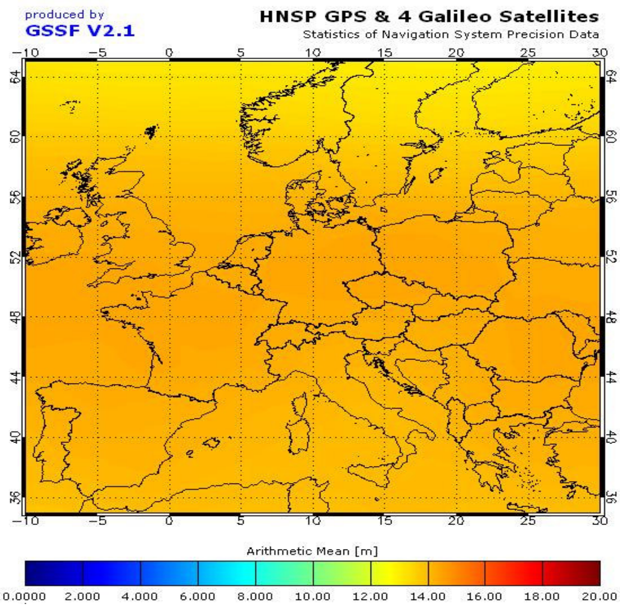

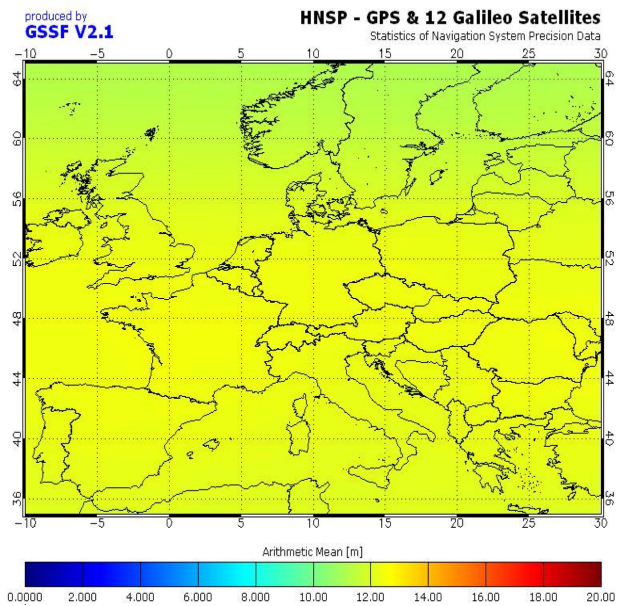

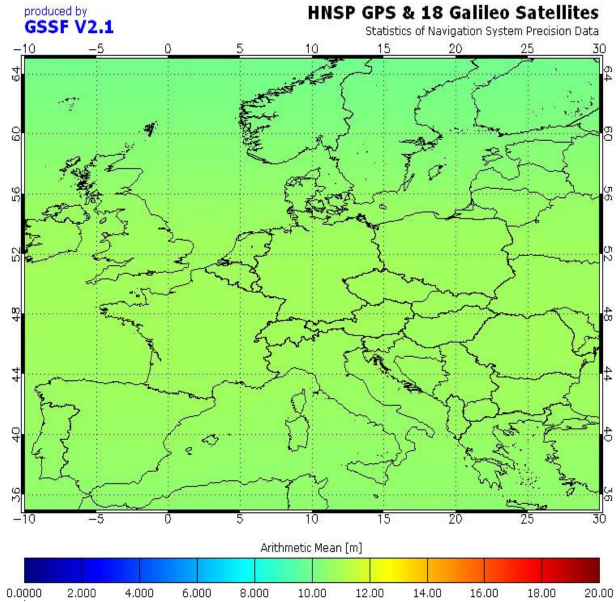

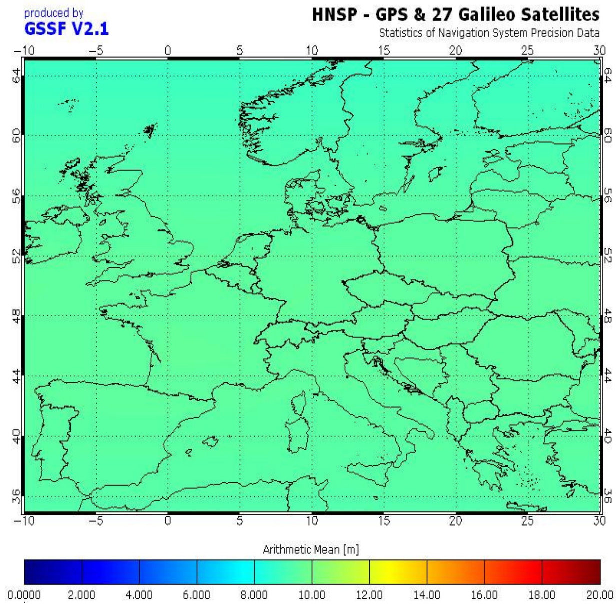

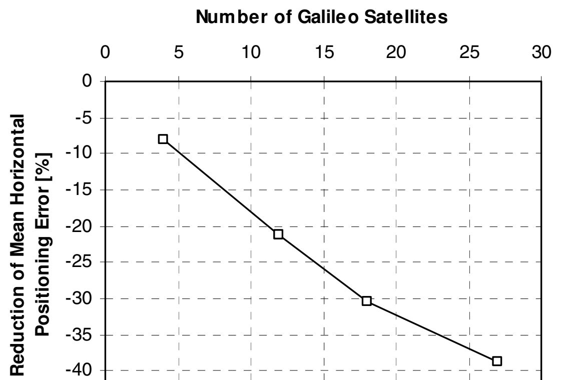

Figure 13: Sub-Constellation Analysis for increasing Number of Galileo Satellites

REFERENCES

[1] GSSF Operations Manual, Volume 1, GSSFP2. OM.001, Issue 5 Revision 2, May 2005

[2] GSSF Operations Manual, Volume 2, Algorithms and Models, GSSFP2.OM.002, Issue 5, May 2005

[3] Leitinger, R.: NeQuick User Manual, 2001

[4] Spilker J.J., Global Positioning System, Theory and Applications, Volume 1, AIAA, 1996, Chapter 13, Troposphere Effects on GPS, Atmospheric Attenuation section IB, and Hopfield model section IIIB.

[5] W. Gurtner (AIUB), L. Estey (UNAVCO): RINEX The Receiver Independent Ex¬change Format Version 3.00, February 1st, 2006

[6] F. Zimmermann, T. Haak, E. Steindl, S. Vardarajulu, O. Kalden, C. Hill: Generating Galileo Raw Data – Approach and Application, Data Systems in Aerospace (DASIA) 2005, 30th May – 2nd June 2005, Edinburgh, Scotland

[7] R. Zandbergen: GSSF Data Validation Tests by ESOC, DOPS-SYS-TN-0001-OPS-GN, Issue 1 (draft), 5 August 2005.

[8] Falin Wu, Nobuaki Kubo, Akio Yasuda: Performance Evaluation of GPS Augmentation Using Quasi-Zenith Satellite System. IEEE Transactions on Aerospace and Electronic Systems, Vol. 40, No. 4, October 2004.

[9] http://gpsinformation.net/exe/waas.html