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Generating Galileo Raw Data – Approach and Application

Frank Zimmermann, Thomas Haak, Eduard Steindl,
Sathish Vardarajulu, Osman Kalden

Vega Informations Technologien GmbH
Hilpertstraße 20 A
64295 Darmstadt
Email: frank.zimmermann@vega.de

Chris Hill

Institute of Engineering Surveying and Space Geodesy
University of Nottingham, University Park
Nottingham NG7 2RD, UK
Email: chris.hill@nottingham.ac.uk

Abstract

This paper introduces the Raw Data Generation (RDG) capability of the Galileo System Simulation Facility (GSSF) and identifies potential applications of this capability within Galileo. After a brief introduction to the functional scope of GSSF, the modelling assumptions are stated and the approach chosen for the validation of GSSF is outlined. Example validation results demonstrate trustworthiness of the generated raw data. The paper will further present an example simulation meant to illustrate a potential application of the RDG.

1. Galileo System Simulation Facility

The Galileo System Simulation Facility (GSSF) is being developed on behalf of ESA/ESTEC by an international consortium lead 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.

1.1. Simulation Capabilities

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 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].

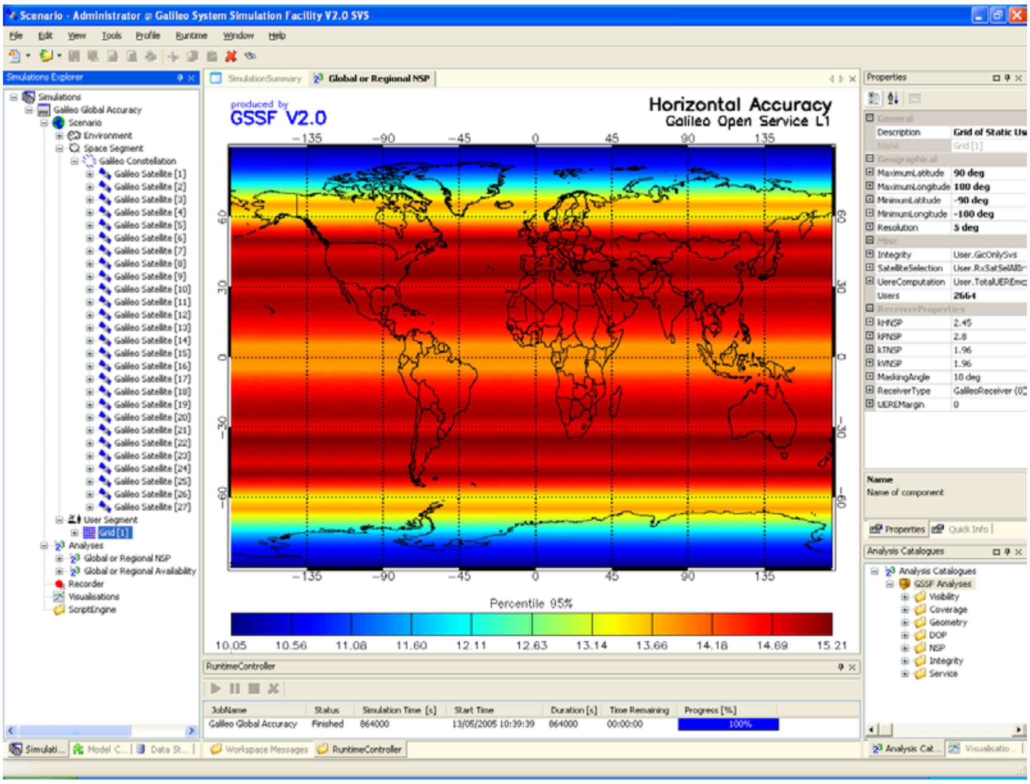
- The Raw Data Generation (RDG) capability of GSSF uses high fidelity models to generate GPS and Galileo observables acquired by Galileo Sensor Stations. This capability includes the definition of Feared Events and is suitable for the validation and tuning of Galileo Ground Mission Segment (GMS) algorithms 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 since it also provides GPS related models.

1.2. System Capabilities

GSSF is 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 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 results, and the Property Grid on the right.



General	
Description	Grid of Static Us
Name	Grid [1]
Geographical	
MaximumLatitude	90 deg
MaximumLongitude	100 deg
MinimumLatitude	-90 deg
MinimumLongitude	-100 deg
Resolution	5 deg
Misc	
Integrity	User.GicOnlySvs
SatelliteSelection	User.RxSatSelAllr
UereComputation	User.TotalUEREmc
Users	2664
ReceiverProperties	
kHNSP	2.45
kPNSP	2.8
kTNSP	1.96
kVNSP	1.96
MaskingAngle	10 deg
ReceiverType	GalileoReceiver (0
UEREMargin	0

JobName	Status	Simulation Time [s]	Start Time	Duration [s]	Time Remaining	Progress [%]
Galileo Global Accuracy	Finished	864000	13/05/2005 10:39:39	864000	00:00:00	100%

Figure 1: The GSSF User Interface - Workspace View

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, TLES, YUMA, RINEX, TROPEX, IONEX, IGS ERP, JGM3 and JPL DE405 files for initialization of constellations (including actual GPS position data) and replacing environmental models with corresponding external data (Ionosphere/Troposphere). The GSSF Export feature allows the user to export RINEX 2.0, RINEX 2.1, RINEX 3.0 and SP3 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 advanced visualisation features, where the Interactive Data Language (IDL) is used.

2. Modelling Assumptions for RDG

The RDG functional block as illustrated in Figure 2 is divided into three major segments representing the corresponding relevant Galileo system elements - namely Space Segment, Environment and 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).

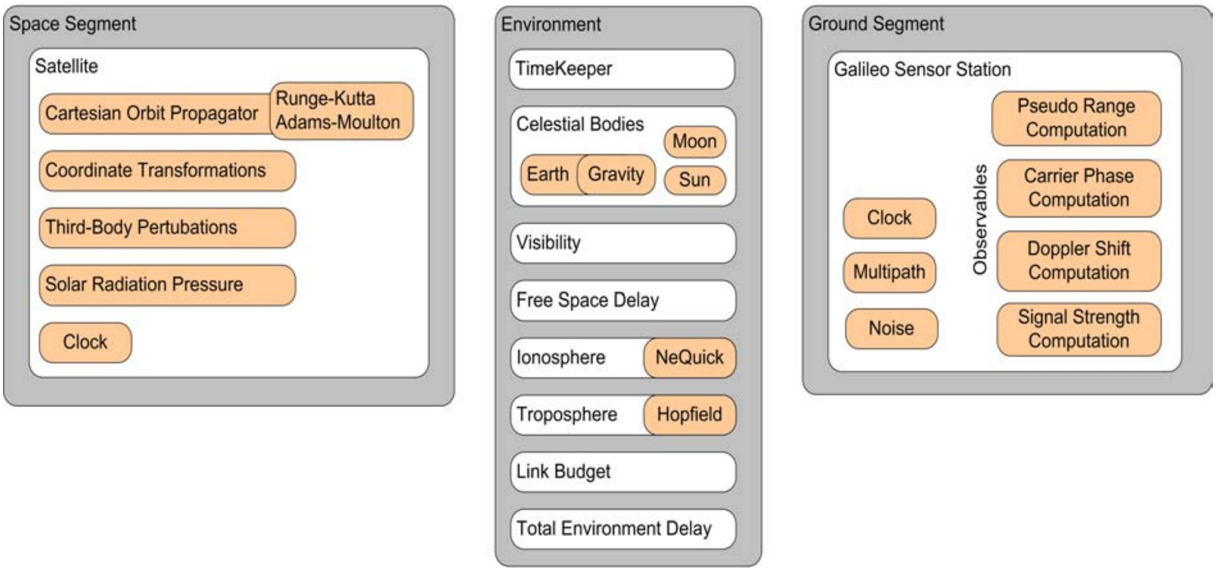


Figure 2: Functional Block of GSSF (RDG) Architecture

Note, the user segment is modelled in GSSF by means of user receiver locations and internal algorithms to analyse navigation and integrity performance at user level. However, this segment is not of immediate relevance to RDG and therefore not included above. The present paper is primarily targeted towards the RDG functionality of GSSF. For information and example results concerning SVS type applications, please refer to [6]. The following sections provide an overview on the modelling assumptions for GSSF RDG.

2.1. 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 NeQuick to calculate the Total Electron Content (TEC). The TEC as provided by the NeQuick model is a function of time of day, user location, satellite elevation angle, season and further environmental parameters. The effect of Ionospheric storms on delay are accounted for by the use of modified CCIR data files [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].
- **Total Delay:** 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.

2.2. Space Segment

The GSSF space segment allows the user to define constellations based on Walker parameters or initialised using YUMA or Two Line Elements (TLE) 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) [5]. 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: Luni-solar gravity perturbations, solar radiation pressure, Earth tidal effects, relativistic corrections and user settable spacecraft propulsion forces.

2.3. 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.

- **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 signal propagation noise, intrinsic receiver noise, and interference noise. This total noise is compared to the user-specified acceptable threshold and the signal is rejected if the noise level exceeds the limit.

3. GSSF - Validation

The raw data produced by GSSF has been rigorously validated against real data. Rinex files from Kourou 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, which is described below.

3.1. Validation Approach

Step 1 - Baseline scenario: The process started from a scenario which aimed to minimise the differences between the measured and simulated data, by replacing the individually validated GSSF models with data sources which represent the prevailing conditions in the measured data from the TDS.

Step 2 - Incremental tests: The process then incrementally replaced these real data sources 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. The final increment resulted in a full simulation of the real data, using all appropriate GSSF models. The results of the comparison with the real data at this stage provided a characterisation of the level of fidelity which can be expected from GSSF.

Step 3 - Load test: The final stage in this test was to repeat the full simulation under conditions of greater load on GSSF. For this purpose, a large network of sensor stations has been configured, and the test simply checks that GSSF generates the same data for Kourou as it did in the final incremental test. The resulting data set is currently being used for further validation by post-processing in the ESOC ODTS function. For this test, a continuous period of 48 hours of Rinex data from the full receiver network has been generated, and the satellite orbits have been propagated for a further 12 hours. This configuration will allow the ESOC ODTS function to use the Rinex data to recover the orbits during those first 48 hours, and then to propagate the resulting orbits for a further 12 hours for comparison with the 'truth' of the GSSF orbits. The expectation is that the comparison of the prediction with the 'truth' will have the same characteristics as a routine prediction based on orbit restitution with real data. This test is currently ongoing.

Since the purpose of the baseline test was simply to validate the end-to-end process of generating raw data, it aimed to minimise all possible causes of discrepancy between the simulated and real data. Accordingly, the GSSF models were configured as follows:

- **Orbit propagator:** To match the measured data as closely as possible, GSSF used the IGS SP3 ephemeris file in place of the built-in high fidelity propagator. This ensured that any differences between the measured and simulated data were not due to ephemeris differences.
- **Satellite clock model:** The clock offset values from the IGS Rinex clock file were used instead of the GSSF clock model. As with the orbit component, this ensured that the measured data and simulated data have exactly the same satellite clock contributions.
- **Troposphere and Ionosphere models:** To minimise the differences between the atmospheric effects in the real data and those in the simulated data, the simulated atmospheric delays were derived from IONEX and TROPEX files corresponding to the period of the measured data. In the case of the troposphere, this is currently the standard method of configuring the GSSF model, since the meteorological parameters that are input to the Hopfield delay model are by default obtained from a TROPEX file. In the case of the ionosphere, the IONEX file provided ionospheric TEC values to the delay model where normally these would be provided by the NeQuick model.
- **Multipath model:** At the unit level, the multipath model has been characterised with typical parameters for various environments and receiver types. However, use of these characteristic parameters simply ensures that the general characteristics (amplitude, frequency, elevation dependence) are similar, but the model does not attempt to reproduce the actual multipath errors in any given scenario. Thus, to avoid introducing differences that were due to different multipath delays, the GSSF multipath model was set to zero (in this baseline test only).
- **Receiver clock model:** As with the satellite clock model, the GSSF receiver clock model was replaced with clock offset parameters derived from the measured data and included in the IGS Rinex clock file.
- **Receiver noise model:** As with the multipath model, the noise model has been characterised so that it is able to produce noise characteristics that would be expected for a given receiver and signal. However, since it is driven by a random function, the individual noise values from a given receiver cannot be reproduced (but rather the overall standard deviation and mean). Thus, to again avoid introducing unmodelled differences between the real and simulated data, the GSSF noise model was set to zero (in this baseline test only).

To summarise: by replacing the orbit, and both the satellite and receiver clocks, with external data sources, by seeding the ionospheric and tropospheric models with data sources corresponding to the measured data, and by setting the multipath and noise models to zero, the aim was to produce simulated data which closely matches the measured data. Discrepancies should be due to:

- Small inaccuracies in the SP3 ephemeris and negligible ephemeris interpolation errors.
- Small inaccuracies in the clock data and negligible clock interpolation errors.
- Errors in the atmospheric delays represented by the IONEX and TROPEX data. These were expected to be the largest errors at this stage.
- Unmodelled multipath at the chosen measurement site.
- Small inaccuracies in the receiver clock offsets in the RINEX clock file, and negligible clock interpolation errors
- Small, well-characterised, Gaussian noise in the measured data.

In the incremental tests, the sources of real data used in the Baseline Scenario were replaced with the equivalent GSSF models. After each model substitution, the differences between the real and simulated data were reassessed in the light of the expected fidelity of each model. Once all of the data sources had been substituted, the resulting scenario represented a full test of the GSSF RDG capability. The order in which the models were introduced was not critical, but attempted to place them in order of increasing expected difference from the real data.

- **Tropospheric Model:** Since GSSF uses a troposphere model which is seeded with data from an external source (TROPEX files) the baseline model of the tropospheric delays already corresponded to the operational model of this phenomenon.

- **Receiver Multipath:** The multipath model was configured with minimal settings, to represent the expected multipath environment for the tracking station at Kourou.

- **Receiver Noise:** The noise model was configured to match the expected performance of the receiver at Kourou.

- **Satellite Clocks:** In order to ensure that the simulated satellite clocks matched the real clocks, it was necessary to first parameterise the satellite clocks in terms of their Allen variance and their polynomial characteristics. This parameterisation was limited to the Block IIR satellites, with the consequence that the comparison with the real data was limited to the Block IIR satellites. The increase in the differences between real and simulated data was expected to be due to minor differences between the real satellite clocks and their parameterised equivalents, differences which were known *a priori* from the results of the parameterisation.

- **Receiver Clock:** The receiver clock model is the same model as the satellite clock model. It was therefore necessary to parameterise the receiver clock at Kourou. As with the satellite clocks, the increase in the differences between real and simulated data was expected to be due to minor differences between the real receiver clock and its parameterised equivalent, although these differences were expected to be larger than for the satellite clocks, due to the expected poorer stability of the receiver clock. Again, these differences were known *a priori* from the results of the parameterisation.

- **Ionospheric Model:** The IONEX file was replaced with the NeQuick model, as the source of TEC data for the ionospheric delay calculation. This was expected to introduce an error due to mismodelled ionospheric delays.
- **Satellite Ephemeris:** The final step was to replace the SP3 precise ephemeris with the GSSF high-fidelity orbit propagator, initialising the orbit propagation from an Almanac corresponding to the test date. Despite using a high fidelity propagator, it was expected that the integrated ephemeris would not accurately match the true ephemeris, since the starting elements and force model parameters would need to be fine-tuned with real observational data to achieve this. However, it was expected that the resulting differences between real and simulated data should show characteristics that are typical of an ephemeris prediction 'error', ie cyclic differences with the orbital period.

3.2. Example Validation Results

For each validation test, the measurements contained in the simulated Rinex file were directly compared with their equivalents in the real Rinex file. Pass/fail criteria for each test were derived from knowledge of the fidelity of each model, both from external references and from the results of the unit testing and characterisation of each model.

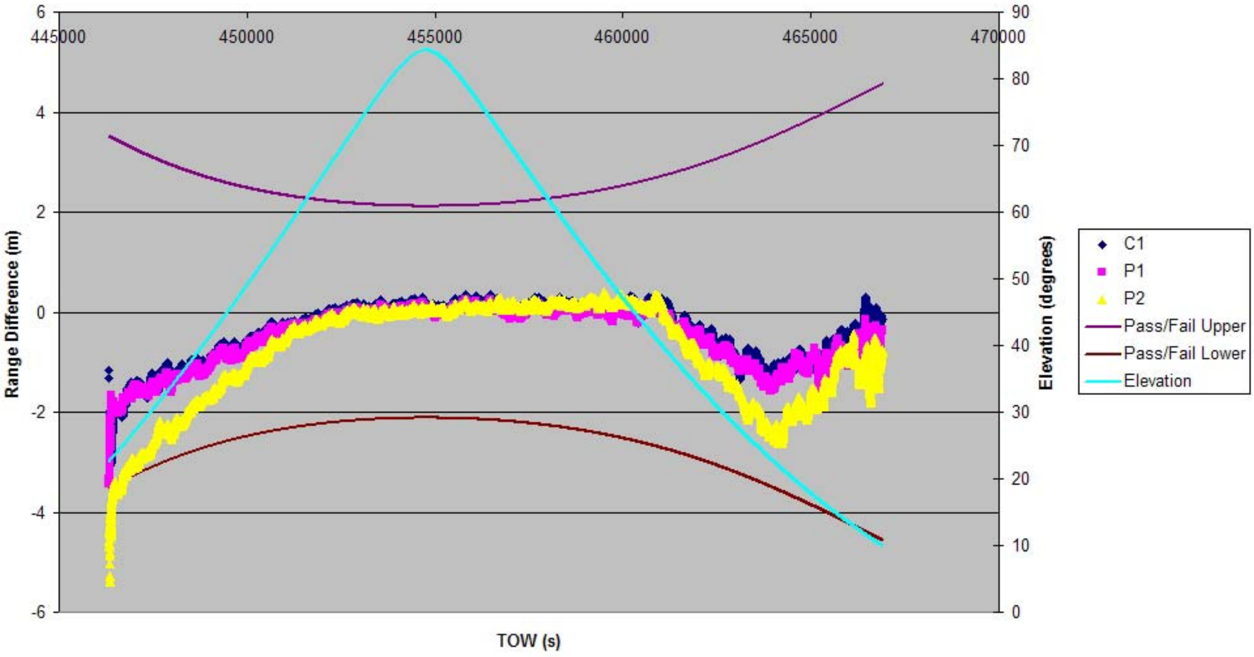


Figure 3: Sample validation results from the Baseline Test

In Figure 3, the differences between the simulated and real pseudorange data are plotted for one satellite, for the baseline test. Using the the Rinex naming convention, the C1 data type is the C/A-code pseudorange on the L1 frequency, and the P1 and P2 data types are the P-code pseudoranges on the L1 and L2 frequencies respectively. The satellite elevation is also plotted for reference, as are the pass/fail bounds, which are elevation-dependent due to some model uncertainties which depend on elevation (ionosphere and troposphere).

Figure 3 illustrates that the measured and simulated pseudoranges agree to better than 2 m for the majority of the satellite pass, and that all but a few of the P2 pseudoranges are comfortably within the pass/fail bounds. Using ionospheric delays derived from the real P1 and P2 pseudoranges, the major features of the differences, such as the differences at the start of the pass and the 2 m differences peaking at ~464000, were traced to differences between the IONEX-derived ionosphere and the real ionosphere.

Figure 4 shows the results for the same satellite from the penultimate step of the incremental tests, in which all the external data sources, apart from the SP3 ephemeris, were replaced with their equivalent GSSF models. The final increment, in which the SP3 ephemeris was also replaced by the internal high-fidelity propagator, is not very illustrative for this paper, since the measurement differences are dominated by the ephemeris prediction differences, which are an expected feature of any orbit propagation. In Figure 4, the pass/fail bounds have a greater magnitude, due to the increased uncertainty concerning the accuracy of the GSSF models, compared to the external data sources. Apart from these increased pass/fail bounds, this figure is very similar to the previous figure, with the majority of the measurements agreeing to better than 2 m. This illustrates that the full configuration of GSSF, using all of its internal models and an external SP3 ephemeris, is capable of reproducing raw measurement data that is very similar to the real data, provided the models are correctly parameterised.

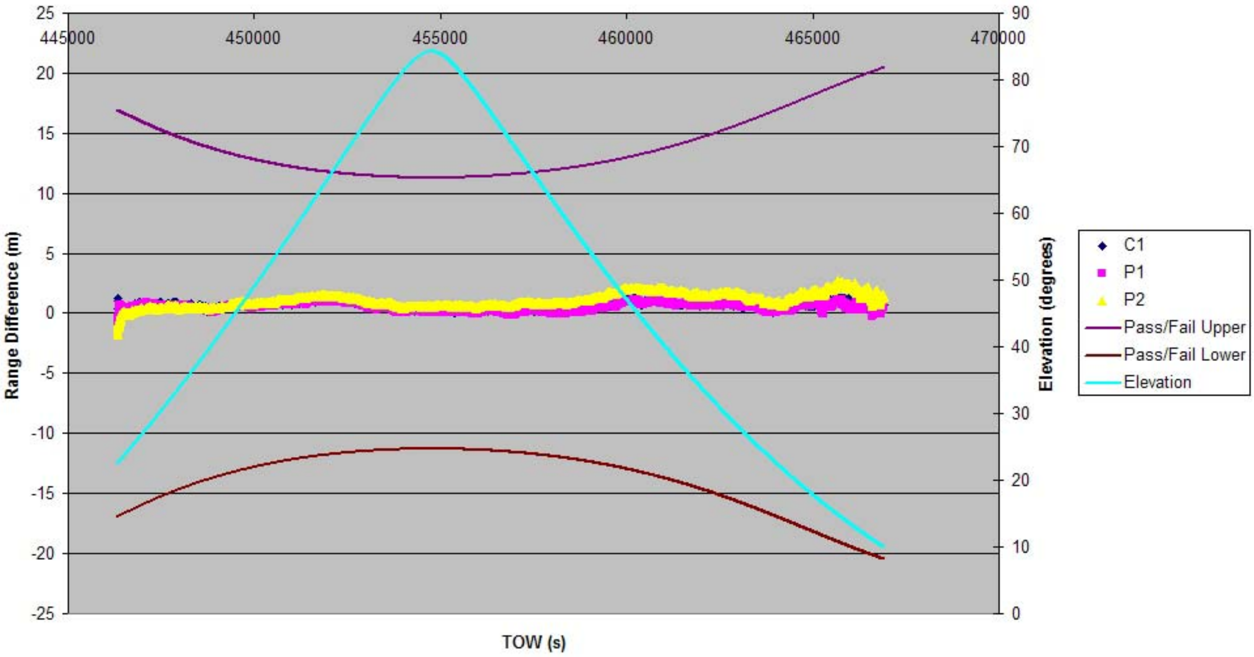


Figure 4: Sample validation results from the penultimate Incremental Test

4. Raw Data Generation

The following example shows the effect of a clock jump, imposed as a Feared Event during the simulation on a Galileo Satellite (Internal ID 211) observed at a Galileo Sensor station (Kourou, internal ID 9). The clock jump is defined by an additional bias of –0.0003 s applied at 30 min after the simulation start time. Figure 5 illustrates the history of the True Range and the Measured Range, both calculated during the simulation (time step 1 s). The initial offset between the two quantities is to be expected due to environmental delays on the signal and clock offsets. When the Feared Event is applied, the Measured range history exhibits a jump of 90 km that is in accordance with the applied bias multiplied by the speed of light.

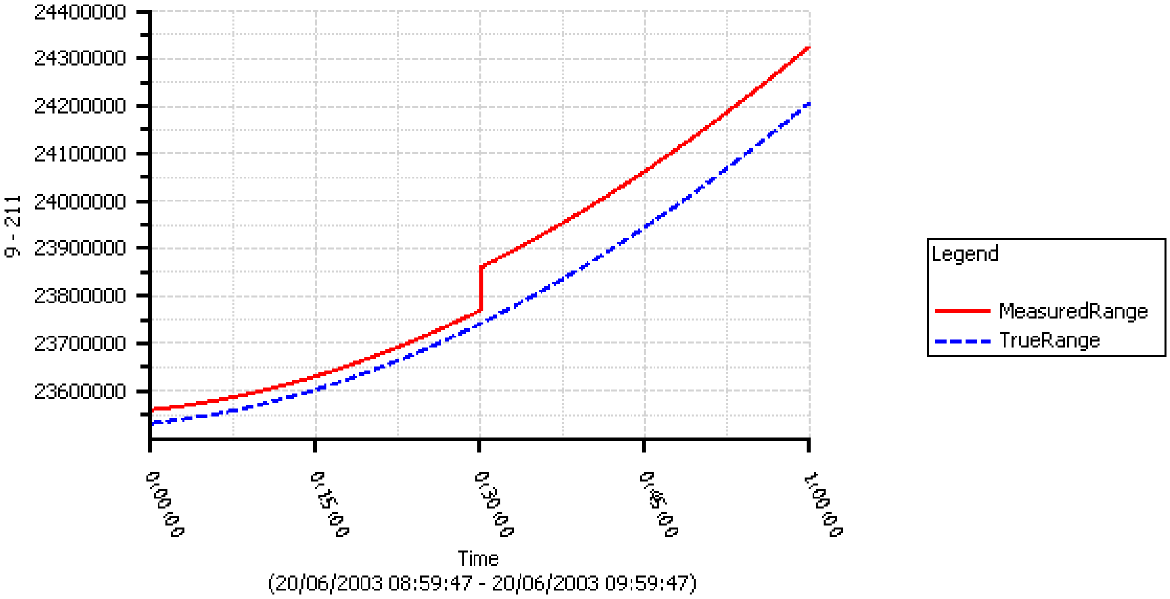


Figure 5: Measured Range [m] and True Range [m] subject to a clock jump

This effect will affect the Pseudorange quantity accordingly and will thus be recorded in the associated RINEX file. The scenario used for this example simulation is defined in Appendix A.

Appendix B illustrates the RINEX file for this Example over the simulation period of one hour, however for a time step of 5 min and without a Feared Event being applied. The RINEX file format follows a proposed standard for Galileo according to [5] and can be exported by means of GSSF. If present in the simulation, the RINEX file will additionally include the GPS observables.

5. Conclusion

GSSF has a role in the development of Galileo and the software tools that will be used in its operation. It allows data to be generated from user-defined scenarios, using high-fidelity models, so that many aspects of the system can be tested prior to the availability of the system itself.

For instance, using data sources that represent the conditions for a given date, time and place (eg TROPEX and IONEX files, clock files), it is possible to generate measurement data for not only the GPS satellites that were present at the time, 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. Such test data sets would allow the software tools that will be used to generate the Galileo ephemeris, clock and integrity data to be rigorously tested, not only for nominal conditions, but for cases where various Feared Events might lead to degraded performance unless appropriately handled by the ground segment.

References

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[5] W. Gurtner (AIUB), L. Estey (UNAVCO): Proposal for RINEX Version 3.00 Observation Files, May 3, 2005

[6] Zimmermann, F., Haak, T., Hill, C.: Galileo System Simulation Facility, 8th International Workshop on Simulation for European Space Programmes, SESP 2004, ESTEC, 19-21 October 2004

Acknowledgments

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Appendix A - Simulation Scenario for Example Simulation

Start Time 20/06/2003 08:59:47 UTCG, Stop Time 20/06/2003 09:59:47 UTCG, Time Step 1 s

<u>Space Segment</u> (Galileo Reference Constellation)

SV#	PRN# (Sat. ID)	Semi-major axis [km]	Eccentricity	Inclination [deg]	RAAN [deg]	Arg. of Perigee [deg]	Mean Anomaly [deg]
1	211	29600.318	0.00	56.00	0.00	0.00	0.00
2	212	29600.318	0.00	56.00	0.00	0.00	40.00
3	213	29600.318	0.00	56.00	0.00	0.00	80.00
4	214	29600.318	0.00	56.00	0.00	0.00	120.00
5	215	29600.318	0.00	56.00	0.00	0.00	160.00
6	216	29600.318	0.00	56.00	0.00	0.00	200.00
7	217	29600.318	0.00	56.00	0.00	0.00	240.00
8	218	29600.318	0.00	56.00	0.00	0.00	280.00
9	219	29600.318	0.00	56.00	0.00	0.00	320.00
10	221	29600.318	0.00	56.00	120.00	0.00	13.33
11	222	29600.318	0.00	56.00	120.00	0.00	53.33
12	223	29600.318	0.00	56.00	120.00	0.00	93.33
13	224	29600.318	0.00	56.00	120.00	0.00	133.33
14	225	29600.318	0.00	56.00	120.00	0.00	173.33
15	226	29600.318	0.00	56.00	120.00	0.00	213.33
16	227	29600.318	0.00	56.00	120.00	0.00	253.33
17	228	29600.318	0.00	56.00	120.00	0.00	293.33
18	229	29600.318	0.00	56.00	120.00	0.00	333.33
19	231	29600.318	0.00	56.00	240.00	0.00	26.66
20	232	29600.318	0.00	56.00	240.00	0.00	66.66
21	233	29600.318	0.00	56.00	240.00	0.00	106.66
22	234	29600.318	0.00	56.00	240.00	0.00	146.66
23	235	29600.318	0.00	56.00	240.00	0.00	186.66
24	236	29600.318	0.00	56.00	240.00	0.00	226.66
25	237	29600.318	0.00	56.00	240.00	0.00	266.66
26	238	29600.318	0.00	56.00	240.00	0.00	306.66
27	239	29600.318	0.00	56.00	240.00	0.00	346.66

Galileo Satellite Clock Parameters (only those relevant for this example are provided)

Satellite ID	Bias [s]	Drift [s/s]	Acceleration [s/s²]	Allan Deviation (t=4800s)
211	1.29E-10	2.08E-11	2.74E-15	7.89E-14

<u>Environment</u>

Ionospheric Delay: IONEX data
Tropospheric Delay: Hopfield Model
Orbit Perturbations: enabled

<u>Ground Segment</u>

Facility Name: KOUROU (Galileo Sensor Station)
Latitude: 5.25 deg, Longitude: -52.81 deg, Height: -25.57 m
Galileo Signal Tracking L1A, Masking Angle 10 deg

Kourou Clock Parameters

Station ID	Bias [s]	Drift [s/s]	Acceleration [s/s²]	Allan Deviation (t=4800s)
9	9.4217E-05	9.47471E-13	1.00801E-18	7.59296E-14

Appendix B - RINEX 3.00 File generated with GSSF

```
     3.00           O                   M                   RINEX VERSION / TYPE
GSSF                GSSF Community      25-May-05 06:57     PGM / RUN BY / DATE
RINEX file generated by GSSF                                COMMENT
KOUR                                                        MARKER NAME
0                                                           MARKER NUMBER
svaradarajulu       GSSF Community                          OBSERVER / AGENCY
RX9                 GSSF RDG            GSSF V2.0           REC # / TYPE / VERS
RX9                 GSSF RDG                                ANT # / TYPE
  3839248.0513 -5059856.0467   579716.8603                  APPROX POSITION XYZ
Approx coords replaced by True simulation coords            COMMENT
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     2                                                WAVELENGTH FACT L1/2
E    4   D1A   L1A   C1A   S1A                              SYS / # / TYPES OF OBSERV
   300.000                                                  INTERVAL
  2003     6    20    9      0    0.0000000     GPS         TIME OF FIRST OBS
                                                            END OF HEADER
 03 06 20 09 00  0.0000000  0  9E11E12E19E25E26E27E32E33E34
        -214.53000   123807764.36800    23559839.38400          61.69200
       -2145.90000   137840533.57800    26230191.16700          58.67600
        1994.99300   127883428.09300    24335412.70900          62.19600
        -596.85200   135983233.72200    25876756.53200          58.90600
       -1763.99700   134236494.87000    25544362.26800          57.29200
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