Galileo Ground Mission Segment: End to End Simulator
First Experimentations, Lessons Learned and Perspectives

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INTRODUCTION

The Engineering Tool Environment (ETE) was developed by Thales from mid 2005 to end of 2007, to support the design and the processing algorithm of the IOV Galileo Ground Mission Segment (GMS). This End-To-End simulator presented during the SESP 2006 is now qualified and operational from the beginning of 2008 in its version V2. The paper recalls shortly what the ETE is, presents some GMS performance experimentation **results** and the **learned lessons** from the V2 version, and finally considers the **potential evolutions** for the two next years. These evolutions would extend the ETE Platform capabilities in the frame of the GALILEO Full Operational Constellation (FOC) development.

RECALL OF THE ETE

Galileo system is basically composed of a Space Segment of 27 satellites and a Ground Segment including a Galileo Control Segment (GCS) which M&C the satellites and of the Galileo Mission Segment (GMS) (see [2]). The GMS provides worldwide positioning services with improved Accuracy, Integrity and Availability than any existing GNSS systems. The ETE V2 is dedicated to the simulation of Galileo Ground Mission Segment (GMS).

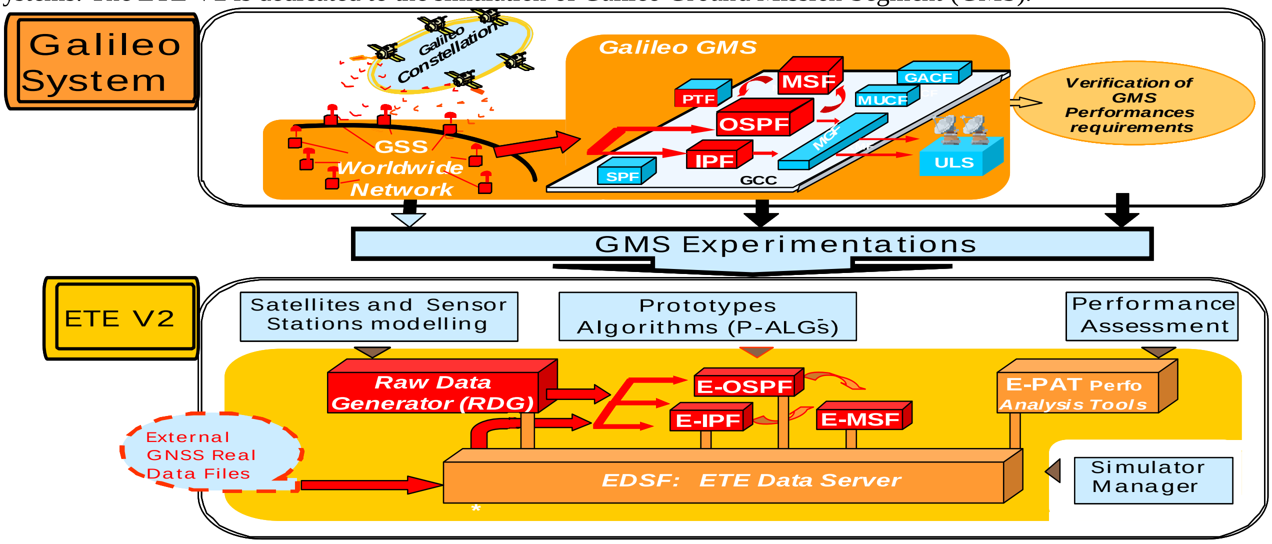

Figure 1: GMS simulation with ETE

The Figure 1 upper part shows the GMS outline, where a worldwide network of 40 Galileo Sensor Stations (GSS) collects the SIS measurements and sent them in real time to a Control Centre (GCC) housing the GMS Data Processing Elements. This GMS Data Processing Chain (DPC), highlighted in red colour in the picture, generates the Galileo Navigation and Integrity messages before to forward them to the 11 UpLink Stations (ULS). Finally, the ULS broadcast these messages to Galileo satellites.
The Figure 1 lower part shows ETE simulator outline broken down in six modular ETE Elements, the four Elements enhanced in red colour underline the respect of the GMS DPC architecture in its simulation within the ETE.
In a more precise manner the roles of each ETE element is the following:

- v The RDG (Raw Data Generator) generating with a high degree of modelling, synthetic GSS data measurements including accurate models of SIS perturbations and GSS nominal and degraded ionosphere environment
- v The P-ALGs (Prototypes Algorithms representatives of the GMS operational algorithms):
  - E-OSPF Orbit and Synchronisation Processing Facility representative of the OSPF
  - E-IPF Integrity Processing Facility representative of the IPF
  - E-OAT Orbit Assessment Tool representative of the MSF
- v The E-PATs (Performance Assessment Tools) that provide a toolkit of Performance Analysis
- v The E-DSF (Data Server Facility), which is the key Element of the ETE. It allows operating in a consistent way all the previous ETE Elements: simulation preparation, scheduling and automation, on-line data files retrieval and storage, operation monitoring and control.

For more information about ETE architecture refers to first paper issued for SESP2006 [1].

ETE V02 EXPERIMENTATION RESULTS

The Performance Experimentations for GMS Critical Design Review (CDR) held in March 2008 were, from the start, the main and short-term objective of the ETE V2 version. This version was requested to allow TAS/GMS Performance Team, to verify the main performance requirements at early stage of the project with fully representative processing algorithms expected to reach a successful GMS CDR and get the subsequent qualification credits (about Accuracy, Integrity, Continuity & Availability) in view of the GMS qualification. This paper is not devoted to detail the successful results achieved for this review in term of performance (see [2]). It rather presents, from an ETE point of view, the type and the representativeness of results, which have been produced. It details also the usage of the ETE by the GMS Performance team.

Type of results produced

It is difficult to talk about the results produced by the ETE without defining the input of the ETE algorithms. The GRS (GMS Reference Scenario) are synthetic data sets produced from the RDG: They comprise 16 Background scenarios and 24 Feared Event scenarios.
<u>Background scenarios</u> are the scenarios representing the nominal steady-state behaviour of the system. Accuracy and availability, as well as integrity and continuity, are verified with these scenarios. They have a typical duration of 13 calendar days, due to algorithm convergence constraints and performance observation window of 10 days (repetition cycle of Galileo constellation).
<u>Feared Event scenarios</u> represent the cases with extreme low probability when system is abnormally functioning. They allow verifying, in relation with Reliability Availability Maintainability and Safety analyses (RAMS), that requirements linked to safety-of-life (integrity and continuity) are maintained with a sufficient probability.

The results produced by the ETE are synthetic graphical results allowing the GMS performance engineer on a Pass Fail Criteria (PFC) basis to check the compliance of the key performances (Accuracy, Integrity, Continuity & Availability), according to the GRS input used and with respect to the GMS requirement. The following figures illustrate a typical result for the ranging error (accuracy) and SIS error over bounding (integrity) verification.

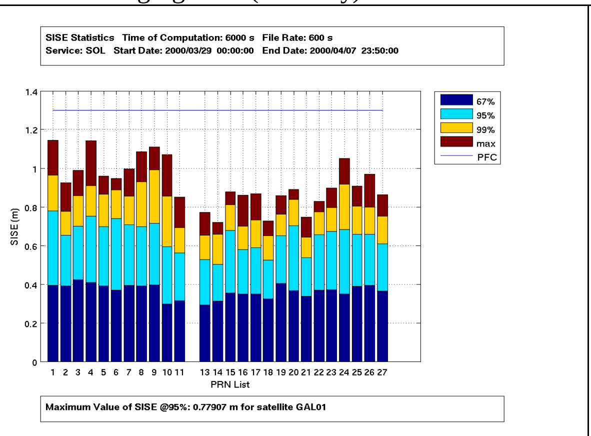

Figure 2: ranging accuracy

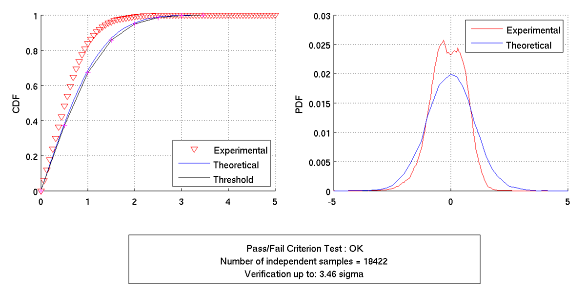

Figure 3: SISMA integrity verification

The requirement is indicated by the coloured bar; thus, it is easy to see if the performance behaviour is correct or not and if the PFC threshold is overtaken or not. When the engineer detects a problem, deeper analysis can be launched in order to provide troubleshooting results.

Representativeness of the results

To give confidence at early stage of the GMS project with the operational facilities performances, prototypes sharing the same processing algorithms have been developed through the ETE. Due to the unavailability of Galileo signal, the usage of synthetic data through verification scenarios (GRS) has been extensively and carefully discussed since the beginning of the project. These GRS are also used at element level for performance verification in order to have a common basis for algorithm tuning, troubleshooting and error identification. Finally, there are used by the GMS AIV (Assembly, Integration and Verification) to feed the operational elements. The results obtained during the GMS experimentation represent the expected behaviour of the Galileo system.

Logic of ETE usage

The design of the ETE, moreover the architecture, was defined with the elaboration of an operational concept. It defines the way to use the ETE in the frame of an End-to-End simulation. During the GMS experimentation, the GMS Performance team uses the ETE in a step-by-step functionality approach as described below. This has been possible thanks to the operational concept, the modular approach and the flexibility of the ETE.

Dataset production and verification activities

In a first phase, the GMS Experimenter has produced the GRS dataset. During this time frame, the RDG and the E-PATs have been used in standalone mode; the RDG to produce the data set and the E-PATs to verify them. This phase lasted during a long period for several reasons:

- first, due to the number of datasets (40 scenarios: 16 background and 24 feared events) which represent quantitatively more than 250 days of simulated data (180 days for background scenarios and 70 days for feared event scenarios), and 3 Terabytes of data, with a generation time of 3 weeks.
- Second, due to the verification process that allowed to find anomalies in the different models managed by the RDG (90 models).
- Third, due to the calibration of the RDG models, that is to say the tuning of around 30,000 parameters.

So, all these facts lead to generate and regenerate the dataset to finally obtain definitive input reference data for the ETE algorithms.

GMS Performance Simulations activity

ETE allows definition and execution of any partial sessions derived from the reference ETE complete session (missing sessions output being replaced by already catalogued data). Then, in addition to the complexity (maximal for ETE complete sessions), a high flexibility is also required to ETE for sessions content definition.

Moreover, each element session is configurable and thousands of parameters can be potentially defined for an ETE session (scenario parameters for RDG, algorithm tuning parameters for each prototype and analysis session definition parameters). For those reasons, in a second time, all the algorithms have been run separately (in single ETE sessions) with different configuration to check progressively each of the GMS performances.

GMS Performance Regression activity

Once the configurations of each algorithm and their performances have been achieved independently, during the regression phase of the GMS experimentation, the algorithms have been run globally integrated in ETE sessions. Such session allows real-time interaction between the algorithms, for global GMS performances verifications as shown in the next figure.

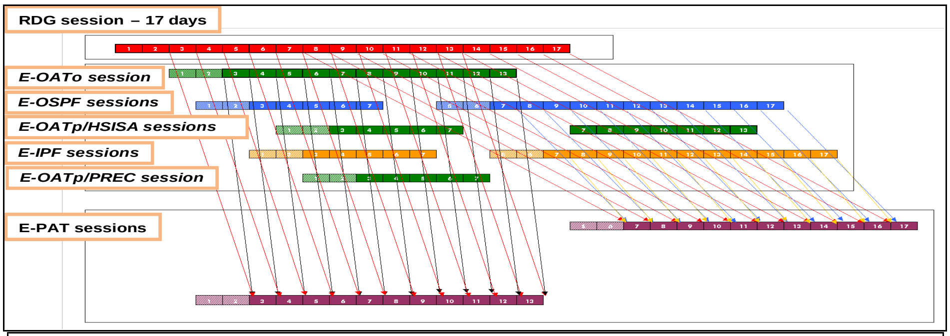

Figure 4: Global ETE session

LESSONS LEARNED

This chapter will tackle the lessons learned from the design and development point of view after the first utilisation of the ETE during GMS experimentation; in particular, the processing capacity, the incremental development, the prototyping of some elements; and, at last the coherency of the developed element with respect to the operational ones. All these points have been the key drivers for the ETE achievement.

Processing capacity

ETE HW/SW: Architecture, Technologies, Linux, Cluster, multi processors, SAN, RAID, Powerful, and Obsolescence

All the exchanges between the six ETE Elements are done through data files. The average volume of data exchanged between only two ETE Elements can reach 30MB/s. This very important feature had determined the HW and SW architecture choice. Therefore, the ETE platform architecture was based on the Storage Area Network (SAN) technology for high data storage capacity and optimised data exchanges. The SAN is built with disk array (12 disks of 300/400 GB of capacity) connected to servers through Fibre channel switch (2Gb). Each disk array is formatted according to RAID5 technique (striped disks with parity), which combines twelve disks in a way that protects data against loss of any one disk. The 6 servers connected to the SAN are 2,6 Ghz quadric and octo Opteron processors with 16 to 64GB of memory. Each Server runs Linux 4.2 Operating system locally installed on their only two local disks fitted in hardware mirrored SCSI disks. The shared access to the SAN by all the servers is possible through a clustered file system called GFS (Global File system) compatible with Linux operating system.

The technology is always evolving and the material chosen 3 years ago like the disk arrays and servers, is now already replaced on the manufacturer catalogue by new models more powerful running only on the most recent Operating System releases. So, in order to keep the ETE operational in the GMS use length (HW maintenance cost increasing exponentially from the filth year old), it is needed to study right now the ETE HW renewing and the impact on the COTS and SW application developed and qualified on top of it.

ETE Processing time follow-up/management -> *Dual Core / Memory*

During all the ETE development, the Processing time of each Element has been monitored and followed. Main reason was to be able to process the GMS Full configuration (max satellites and stations) representing the acquisition of data for 17 days, in less than 68 hours. In that frame, the ETE and its SW Elements have been designed to cope with the multi-processing architecture. Despite of the efforts provided by Elements Providers, for some Elements the required performances were not completely reached, and the ETE Hardware capability to be upgraded has been exercised. Some servers quadric processors have been replaced by octo processors and as well as they have been upgraded for memory capacity from 16Gb up to 64 Gb. These actions allowed the ETE to reach its performance.

The monitoring of such parameter has allowed tuning as close as possible the HW performances of the ETE. The gold rule to select an HW platform with potential upgrade margin has been once again demonstrated for the ETE project.

Incremental development, prototyping and reuse of the elements

ETE Development & AIV (Subcontracting, Versioning, Proprietary ICD & GNSS Standard format, GSWS & Qualif,)

The ETE has been developed according to the GSWS (Galileo Software Standard) at DAL E level (Development Assurance Level associated to the criticality of the software depending on the impact of failures). The ETE simulator User Requirements definition, as well as the system design and HW & SW architecture, Interfaces definitions, then the Integration, validation and qualification have been done integrally by THALES. The ETE Elements SW developments have been entrusted to different European companies (DEIMOS for RDG and E-OATs, GMV for E-OSPF and E-IPF, INDRA for E-DSF, THALES for E-PATs). All these SW have been qualified through the process described in GSWS. The ETE design shows very complex exchanges between the developed Software; all these exchanges are described in an ETE ICD (Interface Control Document). The main part of the file types used within the ETE are GNSS standard such as (Rinex, Sinex, Sinex-tro, etc …), but for some cases it was needed to develop a proprietary format (called Binary Format) to reduce the size of certain types of data (observables and Integrity data); the immediate effect of a such format was to increase the data files exchange performance within the ETE. The ETE AIV phase has been performed in an incremental way: this versioning allowed integrating and validating progressively the Elements within the ETE. After each reception of new version of an Element, an ETE version has been managed. From the beginning to the end of the V2, more than 60 versions of the ETE have been tested.

The incremental ETE integration had led to identify as soon as possible problems in interfaces implementation, instead to discover all problems at the end of elements development. The same process is reused for the GMS operational Elements nevertheless it was observed on ETE than more than 3 versions were needed to get all the 6 Elements running correctly together.

ETE line of code drift (Estimated 500 000 loc à Real 1M loc)

Because one main usage of the ETE was to support the GMS algorithm design, the ETE development was launched as part of the GMS earlier development. At this stage the knowledge about the complexity both of the Synthetic data to generate and of the GNSS algorithms was not fully characterised. So the ETE assessment was made mainly from translation with the previous simulation Tools developed in the EGNOS project, and taking into account reused software. This estimation was about 500,000 l/c, but algorithms models turned out to be much more complex and reuse less possible than estimated, for finally overtake the 1 Million of line of code for the ETE V02.00 version. Of course the impact of this inflation of line of code has increased the project duration for more than 30%. Nevertheless, thanks to ETE Element deliveries versioning policy, this delay has not jeopardised the CDR Experimentation planning.

If the reuse of software appears often attractive, it stays really difficult to correctly evaluate its level of suitability at the time of decision. In any case it introduces a big risk in the project.

E-PATs (EPAT & EPATp) Analysis specification and prototyping

For the development of the E-PATs tools of the P-ALGs outputs, the project has dealt with difficulties to converge on stable requirements, because these kind of tools need, additionally to the deep knowledge of algorithms outputs, a first preliminary assessment of which measures and associated precisions will be the best appropriate to evaluate and graphically display the different performances of these algorithms. This means, for some analysis, the necessity to perform prototypes development and tuning of these prototypes, before to define clearly the specifications.

For these analysis tools, which are software of little size, the standard GSWS life cycle used has consumed a lot of effort, and finally did not allow covering all the GMS experimentations needs in time with the EPAT-ALG tool as initially foreseen. Therefore the E-PATp prototypes initially dedicated to the specification, have been consolidated, qualified and integrated to the ETE platform, and finally used as complement to the E-PAT-ALG tool.

The development of such Analysis tools requests to be entrusted to a team used to this kind of particular tool and developed very closely with the final users. The life cycle to be used for this development shall be an incremental one, where flexibility and adaptations is easily and quickly possible. Hence, this kind of tools cannot be sub-contracted to external partner.

Coherency between ETE algorithms and GMS operational Algorithms

This point is perhaps the most important one. In effect, the coherency between the prototype algorithm developed in the frame of the ETE and the operational algorithm implemented within the real GMS element has been the key driver for the ETE development. First of all, it started with the prototype algorithm specification, which is directly derived from the operational algorithm: this link is done through the GMS DOORS requirement database. It continued with the development of the prototype and the real algorithms which are entrusted to the same company: (OSPF, IPF) to GMV and S-MSF to DEIMOS; thus, they can easily report any design modification on the prototype to the operational element and conversely. This alignment is foreseen until the acceptance of the GMS. It finished with their verification, either within the ETE AIV, either within the GMS AIV: any anomaly detected in a prototype will be reported in the real algorithm and vice versa.

Such requirement for the development of an element seems to be a huge constraint but at the end it allows to save time and schedule for the prototype as well as for the real element.

EVOLUTIONS

ETE Evolution Presentation

The planed ETE Evolutions are based on the ETE V2 qualified version with the objective to enlarge the ETE usage in the next Galileo FOC contract with two main axes:

- to extend the ETE capacity to replay Real Data for easy performance validation and troubleshooting (i.e. operability improvement to manage Real Data replay)
- to integrate new functionalities in the ETE oriented to the user services performances assessment

Because these evolutions could be performed in two steps we will so-call the final target version as ETE V4.
The Figure 5 illustrates the proposed ETE V4 architecture built from the ETE V2 architecture.

The **ETE V2** architecture is represented by the orange boxes.

The **ETE V4** delta architecture is represented the additional numbered red boxes.

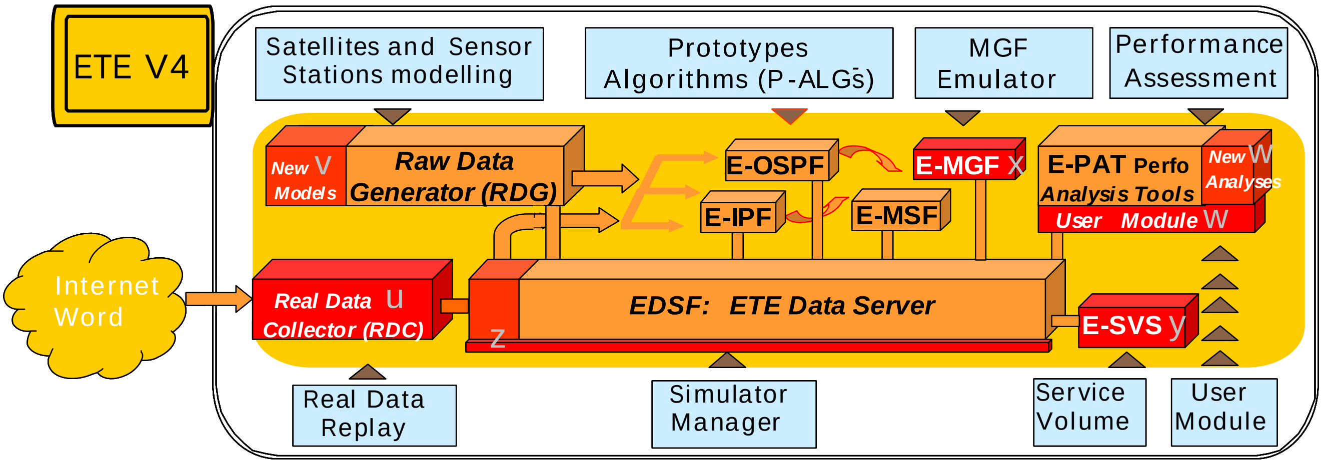

Figure 5: ETE V4 Evolution

The main improvements include:

- A new RDC U Element to improve the ETE operability in automating the collecting of Real Data from internet servers and to convert it in ETE format
- A complement of RDG V models link to Real Data analyse feedback and the capability to generate measurements for dynamic users.
- A complement of E-PAT W analyses for GMS performance and troubleshooting analysis and its enlargement to host an User Module to User Segment simulation
- An E-MGF X new element allowing to emulate the MGF functionalities regarding the navigation and integrity messages scheduling and dissemination (integrating the GMS uplink scheduling prototype)
- An E-SVS y new element allowing performing advanced analysis on the powerful ETE platform with a high level of resolution and of representatively using synthetic data as well Real Data.
- Several limited evolutions of the E-DSF Z in order to manage the previous evolutions (e.g.. MMI, ETE ICD).

Real Data Collector Element (RDC) U

Why an RDC: the migration from Synthetic data to Real Data is an important step for the verification of such sub-system as the GMS and for the Galileo system itself. It could be risky waiting for tests with complete system and satellites, to get an evaluation of the performance of the GMS. So, it is really important to test the GMS algorithms in front of the Real Data all along the deployment of the Galileo GMS and constellation in term of behaviour and of GNSS performances. This approach allows taking benefit of three undeniable advantages of the ETE with respect to the Operational algorithms:

o Prototype algorithms offer more intermediate outputs to observe the algorithm behaviour,
o More productivity with a processing time seven time faster,
o Processing for a same period GPS Real Data and synthetic data and to compare the algorithm behaviour.

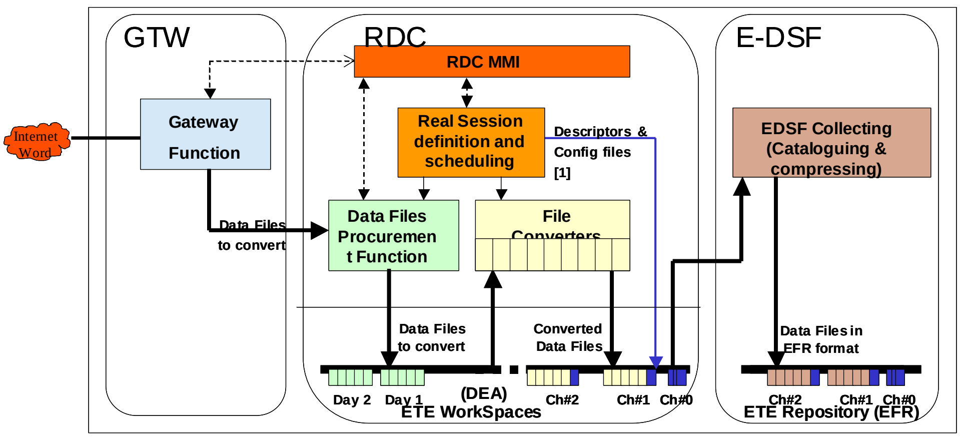

Figure 6: RDC architecture

This introduction will allow testing the current ETE algorithm with Real Data and seeing in advance the potential problems. The following scheme gives an overview of the RDC architecture within the ETE.

The RDC is a Real Data collector and shall be designed to:

- Create P-ALG data configuration representative of a deployed constellation and sensor stations network (Giove, Galileo, Gps, ...) from RDC MMI,
- Generate P-ALG data initialisation requested to start up automatically the ETE P-ALG processing,
- Retrieve archived Real Data from internet servers to the RDC Repository (GPC server for Giove data, GACF/SPF for Galileo IOV/FOC data, IGS servers for Gps data)
- Convert if needed the imported Real Data to the ETE format, ready to be automatically archived by the E-DSF

Some key points are important to be listed for an easy integration of the RDC within ETE:

- The RDC design doesn't imply any significant modification on ETE Element in particular for the E-DSF;
- The ETE ICD is not impacted: RDG /E-DSF I/F can be reused for the RDC;
- No additional concept for ETE Operation: operations with Real Data are the same as with simulated data.

User Module Function W

The current ETE design focuses on performance assessment for GMS Processing chain (Navigation Determination): OSPF, IPF and MSF. The GSS & PTF performances are considered as input (simulated in RDG). Within the ETE, the dissemination is roughly featured in analysis tool (E-PATp) with an arbitrary selection of navigation message. However a separate prototype (uplink scheduling tool) developed by TAS in the frame of the MUCF element development follow-up exists and is able to generate dissemination planning for the navigation and integrity messages.
Therefore the development of a user module will be of highest interest to:

- Early assess the impact at user level of GMS performances (Extreme conditions, Degraded condition, Sensitivity analysis) and troubleshooting
- Evaluate performance of specific Galileo users with realistic measurements and navigation/integrity message (synthetic data): Aircraft, urban, pedestrian, Galileo+GPS, Impact of receiver algorithm
- Assess system performance in temporal mode: Impact filtering, coupling with RAIM algorithm, Definition of scenarios (landing, urban canyon …)
- Assess global system performance (performance maps in the user domain)

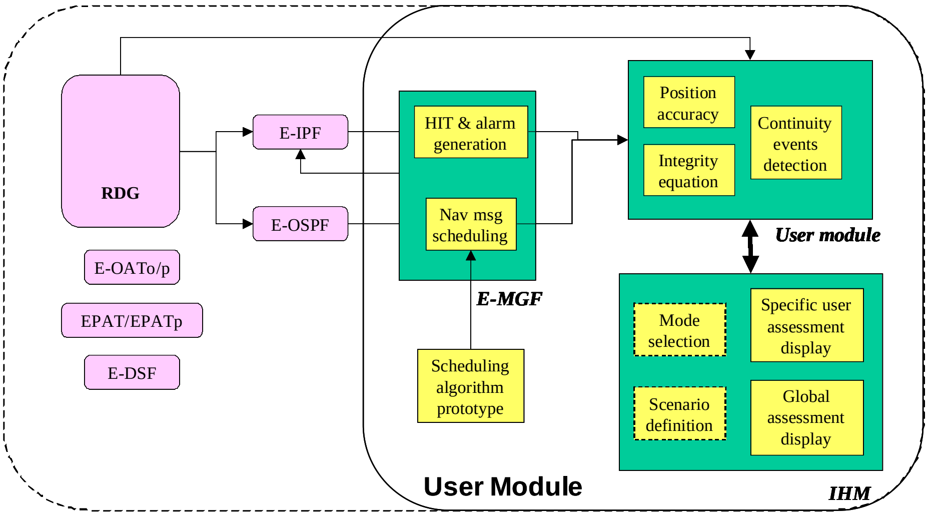

Figure 7: User module architecture and interfaces

User module overview

- Configuration: User location (for "Specific user" mode), error model, masking angle, dynamic model, Phmi specification & alarm limits.
- Outputs: Accuracy (horizontal, vertical, time), integrity: availability, protection radius, Phmi, continuity: detection of events.
- 2 different modes: "Specific user" mode outputs (2D plots with time in x-axis), "Global assessment" mode outputs (2D world maps).

Uplink Function Element (E-MGF) x

The main objective of the E-MGF module is to emulate the MGF functionalities regarding the navigation and integrity messages scheduling and dissemination. Therefore, in order to simulate realistic mission data dissemination in input of the user module, it is foreseen to integrate an uplink scheduling tool whose main objective is to generate the satellite to antenna allocation tables (one per ULS) and to provide them to the MGF to be used for emulate the navigation and integrity data (content and refresh rate) that will be received by the user according is geographical position (see Figure 7).

Service Volume Function Element (E-SVS) y

The E-SVS objective is to assess on wide area the expected performance for GNSS systems in general and more specifically for GALILEO. One of the design keys to obtain realistic simulations relies on the capability of the E-SVS to mimic satellites based navigation system with a representative behaviour. An other key issue for a service volume tool is to be versatile enough for a constant use of the tool during a GNSS project life cycle. Its integration within the ETE will allow to perform complete service volume analysis coverage for the GALILEO development. With this capability, it will be possible to perform Synthetic or Real data advanced analysis on the powerful ETE platform with an unmatchable granularity of results.

Other evolutions

RDG new models v

The RDG already generates realistic sensor stations observable thanks to the modelling of Satellite and constellation parameter, Signal propagation environment and Monitoring station.
So it is foreseen to complete or optimise these models by new ones for the generation of raw observable from the Real Data analyses feedback as well as measurements for dynamic user receiver.

New Converters u

Additional converters will be defined in order to cover more completely the connection of GMS Operational Element intermediate outputs with the ETE. The aim is to have available for the GMS deployment phase, a complete converters battery capable to verify and/or investigate as far as possible the GMS Operational Element performances (such as OSPF/IPF and S-MSF) using synthetic or real data.

New EPAT Performance Analysis w

Considering that the P-ALG algorithms design will be maintained with respect to the operational one all along the Galileo project, the EPATs becomes a key tool to obtain realistic performance assessment of the GMS.

Besides, in order to support the GMS AIV, S&IV, FOC specification and design definition, it is foreseen:

- To develop complementary analysis to cover all GMS performances (in particular the ones related to single frequency user: ionosphere and broadcast GST estimation),
- To develop complementary analysis for AIV troubleshooting,

CONCLUSION

The challenging development of such ambitious and complex simulator, demonstrates today all the power and efficiency that it can bring to a GNSS navigation system design with the generation of synthetic data as long as the limitation are also identified and controlled.

Today all the GMS performance requirements have been verified by simulation thanks to the ETE V2. The experimentation results expected have been produced, reviewed and endorsed during the successful IOV GMS CDR.

Tomorrow, with the capacity to process Real Data collected from the first Galileo satellites, completed by the implementation of new functions identified in this paper, the ETE will see its application domain growing to GNSS performance troubleshooting, validation and qualification phases.

In the next future, capitalizing upon the experience acquired during the development phase, the ETE will introduce a substantial contribution to the support of the Galileo GNSS Performance follow-up Operations.

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