Galileo Performance Verification in IOV Phase

M. Gotta+, F. Martinino+, S. Piazza+, F. Lo Zito+, E. Breeuwer*

+Alcatel Alenia Space Italia S.p.A.,
e-mail: monica.gotta@aleniaspazio.it, Phone: +39–06–41513134
*European Space Agency ESTEC,
e-mail: Edward.Breeuwer@esa.int, Phone: + 31–715653519

Abstract. The Galileo IOV (In Orbit Validation) Phase is an intermediate step of the Galileo system deployment. The main objective of the IOV Phase is to demonstrate that the Galileo Full Operation Capability (FOC) requirements (as specified in the Galileo System Requirements [2]) can be met, with the support of analyses and simulations, before to complete the deployment of the full system. To this respect, the IOV is a "break" in the deployment to get sufficient confidence that the final system will properly work.
The direct consequence of the above statement is twofold:

a) the IOV system configuration is reduced with respect to the final one, but it has to be designed in order to be easily upgraded to the FOC configuration. Therefore, the design, the development and the deployment of this configuration has to be driven by the FOC requirements
b) the IOV configuration may require additional functions/means to support the verification campaign that are not strictly required for the final system.

The authors of this paper, members of the Galileo System Integration and Verification (SI&V) team are responsible for the definition and execution of the IOV test campaign within the industrial consortium called Galileo Industries (GAIN) that is currently building the Galileo IOV configuration. This paper presents the current state of definition of the IOV Test Campaign.

Taking into account the constraints of the IOV configuration, a specific approach had to be developed to allow the verification in IOV of all GSRD requirements ([2]). In this paper the verification approach is presented, with particular focus on the System Performance Verification.

1 Introduction

The main constraint in defining the Verification activities in IOV Phase is linked to the fact that IOV Configuration is heavily reduced w.r.t. FOC configuration (see [6] for complete description of Galileo System in FOC Configuration), versus which the design of the Galileo System is performed (Fig. 1). In fact IOV Configuration foresees to include 4 satellites out of 30, 20 Sensor Stations out of 40, 5 Up-Link Stations out of 9, 2 Telemetry Tracking & Commands (TT&C) Stations out of 5 (see [1]). This implies that the User Service Performance in terms of positioning/timing accuracy, integrity, availability and continuity cannot be tested and assessed completely by test. This is due to the fact that the processing algorithms need to operate on a reduced number of observables and therefore the navigation message parameters will be

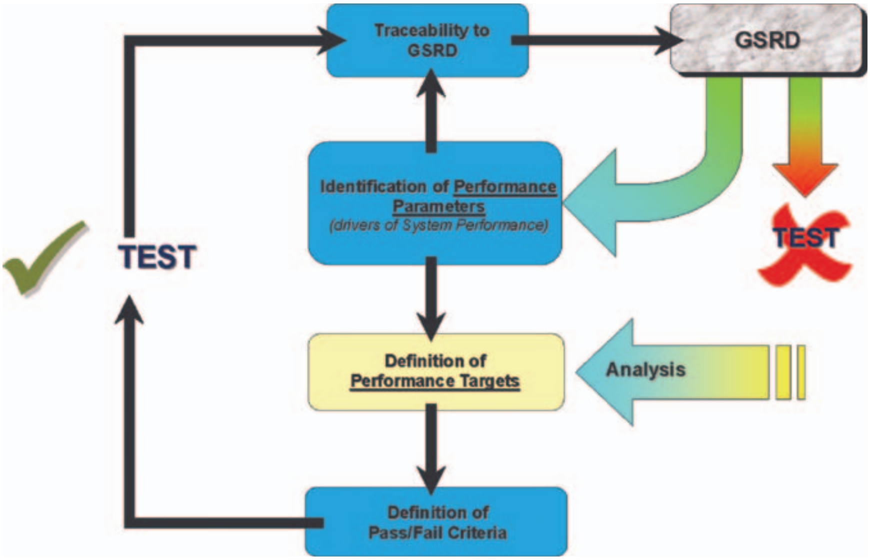

Fig. 1. IOV performance verification approach.

degraded w.r.t. final performance. Moreover the user testing equipment will not be continuously able to solve for its position due to the reduced constellation and the holes of visibilities of the complete set of 4 satellites during the test campaign. Therefore the approach selected to verify the System Performance is:

- To identify, through the System Performance Allocation, a set of lower-level parameters that are directly linked to the User Service Performance and that can be observed in the IOV configuration. This set of parameters will allow the system to be accepted when the related IOV Performance Target (tailored to IOV reduced configuration) is met according to the correspondent Pass/Fail Criteria.
- The GSRD requirements ([2]) that are linked to the identified parameters are verified according to the verification methods identified in the Requirement Verification Matrix ([3]), by eventually complementing the verification by test with analysis/review of design/simulation.

Performance verification activity makes use of an integrated platform called GALileo System Evaluation Equipments (GALSEE). In the frame of the performance verification activities, GALSEE is deeply exploited for both Galileo algorithm performance targets verification and IOV Test Campaign performance targets verification.

Taking maximum benefit from the reuse of tools already available from Galileo segments, GALSEE will support the performance verification activity by processing real data flowing into a controlled environment compliant with the one under which the GSRD service requirements has been specified, but flexible enough to allow System Sensitivity Analysis on the identified performance targets

The Performance requirements and parameters to be verified during IOV Test Campaign have been grouped into the following Verification Scenarios:

- Sensor Station Data Quality, including tests of Galileo Sensor Station data quality
- Signal In Space Monitoring, including monitoring of Signal RF characteristics
- Navigation, including tests of Navigation Determination Processing Function
- Integrity, including tests of Integrity Determination Processing Function, including verification of the Time-To-Alarm
- Timing, including tests of Galileo System Time (GST) Generation and Steering Function
- Search And Rescue, including one test end-to-end of the Galileo supporting function to Cospar-Sarsat External System
- UERE, including tests on filed to assess the User Equivalent Range Error impacting User Service Performances.

In the following the logic of the System Integration and Verification activities is provided in order to present the overall frame in which the IOV Test Campaign is placed, representing the last 6 month of the overall System Verification, dedicated mainly to System Performance Verification.

2 System Integration & Verification Logic

The purpose of the System Verification activities (concluding with the IOV Test Campaign) is to demonstrate that the System has been designed, implemented and tested to meet the GSRD requirements ([2]), as customized for IOV Configuration. In particular the IOV Test Campaign focuses on the verification of the System Performance, being the verification of Functional and Inter-Segment/External Interface concentrated at the maximum extent during Phase D, prior to IOV Readiness Review 1 (IOV-RR1).

In order to provide the overall picture of the Verification Strategy in which IOV Test Campaign is planned, an overview of the System Verification Phases and content is provided in the following.

The System Integration and Verification activities are infact divided into three main categories:

- The Ground Segment Integration & Verification, including the Integration of Ground Mission Segment (GMS) and the Ground Control Segment (GCS) inside the Galileo Control Centre (GCC), the integration of the Remote Sites with the GCC and the verification of the Interfaces between the GMS and GCS and their compliance versus relevant ICD
- The System External Entities Integration & Verification, including the Integration of all the Galileo External Entities to the Ground Segment and the verification of their interfaces and their compliance versus relevant ICD
- The Overall System Integration & Verification, including Ground-Space Compatibility Testing (with the satellite on-ground), System Functional Test and Overall Integration with Space Segment and Test User Receiver (after Satellite Hand-over to Galileo Control Center)
- The IOV Test Campaign that is the In Orbit Verification of the System Performances against System Requirements as tailored w.r.t. the IOV reduced configuration.

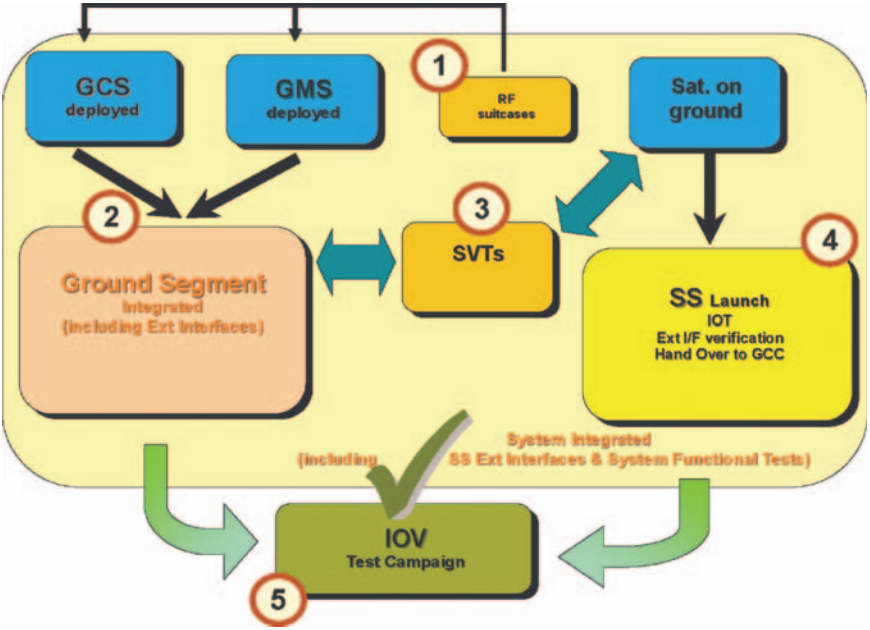

Fig. 2. System integration & verification activity flow.

The SI&V activity flow showing the staggered approach described above is depicted in Fig. 2 (numbering represents activity sequence). For more information on Galileo System Architecture and Design on which System Integration & Verification (SI&V) approach is built (including Segments composition and Interconnections) please refer to [6].

The System Integration will be performed, in an incremental way up to the IOV Readiness Review 1 (IOV-RR1) involving the Overall Galileo Ground Segment, the Galileo System External Interfaces and, following the handover of the Space Segment, the Overall Ground Segment Integration with the in-orbit Satellites, the External Interfaces with Satellite and the integration of the Test User Segment (TUS) with the satellite. The System Integration activities will be conducted as part or in parallel with the completion of verification and qualification activities at segment level.

The completion of the System Integration Activities will ensure the correct integration of all the elements of the Galileo System, including the Satellite in orbit.

The System Verification testing activities will be mainly developed in parallel with System Integration activities, starting from the Qualification Review (QR) of the Segments. The verification activities are performed into two separate steps:

- Verification activities to be performed during the system integration up to the first readiness of the IOV system (IOV-RR1)
- Verification activities to be performed during the IOV Test Campaign on which basis the system is accepted by the Customer.

The scope of the verification activities is to support the verification of the internal interfaces between segments and the external interfaces of Galileo system. In order to minimize the risks, verification activities concerning the compatibility of Space Segment with Ground Segment will be performed first with satellite on-ground and after with the satellite in-orbit, in the frame of In-Orbit Test (IOT), conditioning Satellite Acceptance.

The first In-Orbit Testing (IOT) after first launch before Space Segment Hand Over 1, will be performed in conjunction with completion of integration activities and prior to IOV RR1. The IOT of the last two satellites will be executed in parallel to IOV Test Campaign execution and before Space Segment Hand Over 2 (SS-HVR2).

The completion of the System Verification activities will ensure the correct verification of System Interfaces and System Functional Requirements and will allow starting the IOV Test Campaign, that is the final set of Tests focused on System Performance Verification.

The first task to be performed in preparation to IOV Test Campaign is the Start-Up of the System. This activity aims to inject in the system the necessary data in order to start all the processes and to initialize the System in its operative status. The Start-up of the System is executed by Operations after Space Segment Hand Over 1 (SS-HVR1) and is to be concluded at IOV-RR1. IOV Start up will be considered successfully concluded (allowing readiness to be declared) only once the System has reached its operative status, delivering Services that are functionally working (SIS broadcasted by each Satellite available and no more transmitting dummy frames, but real frames as operationally generated on-ground).

The IOV Test Campaign will start, organized in a certain number of System Acceptance Verification Scenarios, as provided in the following section, aiming to provide testing of main system/segment performance parameters that are considered affecting the overall Galileo Service Performances (Table 1).

The System Verification and Acceptance in the IOV Configuration will be reached by providing evidence of the successful testing, during IOV Test Campaign, of all the identified Parameters/requirements, the acceptance criteria for the GSRD

Table 1. IOV Test campaign test matrix.

Test case	Test objective	Elementary tests	Performance parameters
Sensor StationData Quality	To verify a certain set of parameters related to the quality of Sensor Station data (observables) as it directly impact the performance of Galileo processing algorithm (mainly navigation and integrity Determination functions)	GSS data availability Test GSS Output Quality Test	GSS data availability GSS data continuity GSS Cycle slip GSS Multipath and Receiver Pseudorange and Carrier Phase Noise

(*Continued*)

Table 1. IOV Test campaign test matrix—cont'd

Test case	Test objective	Elementary tests	Performance parameters
Navigation	To test the accuracy of OD&TS products (orbit and clock estimation and prediction accuracy) and SISA computation representativeness of real SISE. It has to be noted that OD&TS orbit and clock prediction accuracy directly impacts UERE budget and, at the end, User Service Performance	OD&TS Computation Accuracy Assessment Test	OD&TS Orbit and clock estimation accuracy OD&TS Orbit and clock prediction accuracy SISA and SISA/SREW ratio
		OD&TS Modelling Quality Test	Iono Model Performance Broadcast Group Delay (IFB) performance
		Satellite Station keeping accuracy Test	Across track orbit keeping (relative RAAN variations) Relative inclination variations Relative along track orbit keeping between any two adjacent operational satellites in the same orbit plane
Integrity	To test the Integrity Processing main actors, namely Integrity Algorithm synchronization error verification, SISMA values, TTA	IPF Sensor Station Synchronization Test	Sensor Station Synchronization Error
		Min/Max SISMA values	SISMA
		TTA Test	Time-To-Alarm
Search And Rescue	To verify the Galileo External Interface to SAR (namely GMS to Return Link Service Provider Interface) main performance (RLM Delivery Time)	SAR Return Link Service Delivery Time Test	SAR Return Link Service Delivery Time
Timing	To verify the main Timing-related Performances, both at System Level and at User Level	GST to TAI Time and Frequency offset Test	GST and TAI. time and frequency offset
		GGTO Performance requirements Test	GGTO computation accuracy
		UTC Time and Frequency accuracy distribution Test	time offset and frequency offset between the physical realization of GST and the GST (and UTC) Time as reproduced at user

Table 1. IOV Test campaign test matrix—cont'd

Test case	Test objective	Elementary tests	Performance parameters
			level by a standard timing/calibration laboratory Galileo receiver receiving Galileo SIS.
UERE	To test the UERE as the main contributor (apart from geometric diluition of precision) to User Service Performance	Open and PRS Service (Single Frequency) UERE Test Open Service (Dual Frequency) UERE Test SOL Service UERE Test	Open and PRS Service (Single Frequency) User Equivalent Range Error Open Service (Dual Frequency) User Equivalent Range Error SOL Service User Equivalent Range Error

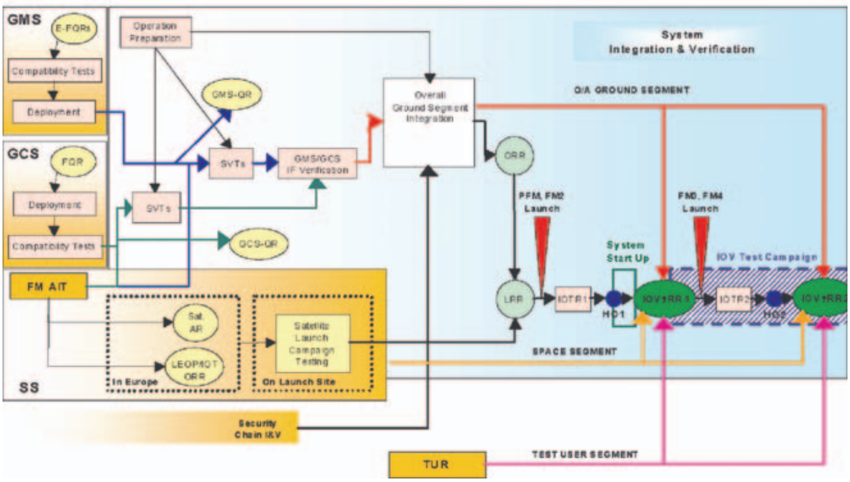

Fig. 3. System integration & verification process overall logic.

requirement ([2]) being defined as the achievement of all criteria relevant to all parameters concurring in that requirement. This should lead to IOV Review (IOV-R), when the IOV Test Results are reviewed to release the System Acceptance and consequently the Segment final acceptance at Segments Final Acceptance Review (FAR). The overall SI&V logic is provided in Fig. 3.

3 IOV Test Campaign Logic

The first main area of activities to be executed during the first months of IOV Test Campaign is represented by the GSS Data Quality Test Case. The main focus of this Test case is to verify a certain set of parameters related to the quality of Sensor Station data (observables) as it directly impact the performance of Galileo processing algorithm (mainly navigation and integrity Determination functions). The Test Case foresees the verification of the Sensor Station UERE (User Equivalent range Error), mainly receiver and multipath noise after the compensation of propagation errors (local components therefore giving an indication of quality of measurements as impacted by Sensor Station itself) and GSS Cycle slip occurrence monitoring. As the correctness of the signal has been verified during IOT, any problems occurred during GSS Output Data Quality should be reasonably due to Sensor Station themselves; SIS ICD ([7]) verification is, in this sense, a pre-condition for the Sensor Station Data Quality Test Case. Moreover the verification of the availability and continuity of the GSS data at Galileo Control Centre (GCC) is verified as part of this Test Case, as the loss of link and exchanged data can affect the System Performance in term of Navigation and Integrity Accuracy and Availability. It comes out that Navigation and Integrity Test Cases, at least, cannot be verified until the assessment of the input quality is carried out.

At the same time, the Test User Receiver can start to acquire the SIS and carried out on-field tests to verify with the real Signal that the Test Receiver is functioning correctly and with the expected performance (focusing on the function and performance strictly characteristic of the receiver itself and leaving out the propagation effects). Therefore the Signal/Receiver Parameters verification is expected to be carried out by TUS in the first months of IOV Test Campaign in order to get the confidence that the receiver (than will be used by System Verification Team during UERE Test Case) is verified and that minor contribution ca be expected by TUS itself in case of UERE Test anomalies; in this sense the on-field verification of TUS is a precondition for UERE Test Case.

Once the GSS Data Quality Test Case is completely carried out, the Navigation Test Case can start by including tests of accuracy of OD&TS products (orbit and clock estimation and prediction accuracy) and Signal-In-Space Accuracy (SISA) computation representativeness of real Signal-In-Space Error (SISE). It has to be noted that OD&TS orbit and clock prediction accuracy directly impacts UERE budget and, at the end, User Service Performance. Also the assessment of the representativeness of some internal OD&TS modeling will be carried out, in particular for what regards the Broadcast Group Delay and the Ionospheric Model Implementation (for more details on SISA, SISE and the others parameters, please refer to [6]). Moreover the verification of the Satellite Station keeping accuracy is carried out within the present Test Case, as its performance impacts OD&TS accuracy itself (the system is designed in such a way that satellite does not need a maneuver for a time span of several years and Ground Control Segment will generate the necessary maneuvers to guarantee that the satellite does not violate the “deadband” during a determined time span, that is, a maneuver-free time span); it will be performed based on offline OD&TS estimation of satellite position and extrapolation over the maneuver-free time to demonstrate that the station keeping thresholds are not violated in the whole maneuver-free time span (extrapolation of IOV measurements will be needed).

When Navigation Test Case is carried out and at least SISA Computation representativeness of SISE is confirmed, the Integrity Test Case can start by including the testing of the Integrity Processing main actors, namely Integrity Algorithm synchronization error verification, Signal-In-Space Monitored Accuracy (SISMA) values. In parallel the TTA Test is carried out with the aim of measuring the delay of several parts of the system and to evaluate the complete TTA (Time-To-Alert), being TTA defined as the time occurred between the beginning of a sampling period, in GSS receiver, during which a satellite SIS Misleading Information (MI) will be received (start event) and the time of reception of the last bit of the navigation message (containing an Alert condition) at the input of a user receiver (end event).

The UERE Test Case is the main IOV Test Case as UERE is the main contributor (apart from geometric dilution of precision) to User Service Performance. The Test should be executed as the last one, as all the parameters tested within the other Test Cases (especially Navigation and Integrity) impact UERE.

However, in order to fit the tight schedule of IOV Test Campaign, the UERE Test Case is considered to start in parallel to Navigation Determination. In this case the OD&TS contribution to UERE can be estimated separately though the Navigation Test Case and can be eventually subtracted by UERE itself in order not to waste UERE assessment in case OD&TS error experiences strange behavior as its verification is not yet complete. A certain number of UERE budgets need to be assessed in order to cover the different kind of services and users specified in GSRD. Actually an assessment is ongoing trying to optimize the UERE Test Set-up and Configuration as to combine more that one UERE test under a common configuration allowing still matching the tight schedule.

Parallel Tests can be conducted that are quite self-standing: Timing Test Case, and SAR Test Case.

Timing Test Scenario is focused to verify the main Timing-related Performances, both at System Level and at User Level. In particular the verification of Galileo System Time Performance in terms of GST Offset and Frequency Stability w.r.t. UTC/TAI will be evaluated, together with the capability of the user to retrieve UTC by receiving the SIS (and broadcasted navigation message), within the specified performances.

Moreover the GGTO computation performance will be evaluated as part of present Test Scenario. Please note that GST will be available also prior to satellite launch and the Timing Test Scenario is planned to start just after the IOV Readiness Review, in order to allow sufficient data collection to be able to verify the performance with a statistically significant sample.

The SAR Test Case is currently foreseen to cover mainly verification of Galileo External Interface to SAR (namely GMS to Return Link Service Provider Interface). In particular the verification of the Delivery Time of SAR Return link Message to the User will be provided as part of SAR Test Case. Furthermore, performances related the External Interface to the Cospas-Sarsat organization will be tested already in advanced, as part of In Orbit Test. The verification of all those performances that are related to the Cospas- Sarsat Capabilities and performances (including MEO Local User Terminal – MEOLUT – ones) is expected to be performed as a part of the European Union's 6FP programme activities.

An activity of Signal-In-Space Monitoring is run throughout the IOV test campaign, in support to System Test Results Analysis and Troubleshooting. This activity will be conducted by means of adequate infrastructure inside GALSEE (GALSEE Signal Monitoring Facility) and will allow to support IOV Test Results analysis and the troubleshooting activities, with the possibility to correlate strange behavior in on-field measurement collection for UERE Tests with the behavior of the monitored SIS in terms of RF characteristics and TUS receiver in terms of tracking performances.

The above mentioned activity consists in to monitoring the RF and Code & Data characteristics of both the Open signals and the PRS signals (TBC) and allow both real-time and post-processing analysis of the Galileo/GPS signals received on ground (nominal power level, spectrum of modulated signals, in-band and out-band interference, etc.) during the IOV Test Campaign.

The SIS Spectrum of one pre-selected satellite in time is monitored in order to allow its tracking with a high-gain steerable antenna.

Moreover some important parameters that impact the Quality of the TUS Receivers output data are monitored through GALSEE, in particular:

- C/NO analysis of all the tracking channels of the receiver and comparison with expected values based on link budget analyses;
- Code and Carrier Phase measurements statistical analysis (e.g., least square fitting and standard deviation of error);
- Doppler measurements statistical analysis (e.g. least square fitting and standard deviation);
- Correlation Function evaluation;
- Multipath Analysis computation;
- Chip rate and modulation evaluation.

A dedicated Spectrum Analyzer and Test User Receiver monitoring Galileo SIS will be operated during the IOV test campaign as part of GALSEE.

Different analyses can be provided during the SIS monitoring activity allowing the characterization of several parameters such as signal bandwidth, minimum received power level, C/NO, signal carrier stability, interference, code phase and carrier phase error, etc.

The provided activities implementation and logic of activities precedence is depicted in Fig. 4. Please note that exact duration of each Test Case is not yet defined, therefore, at the time being, the provided figure should be considered only as qualitative. The exact planning of IOV Test Campaign will be provided as soon as the assessment on each test duration will be carried out and the planning will be updated accordingly.

Please note that the staggered approach as presented in Fig. 4 is still to be confirmed, pending its feasibility to be carried out in the 6 months allocated for IOV

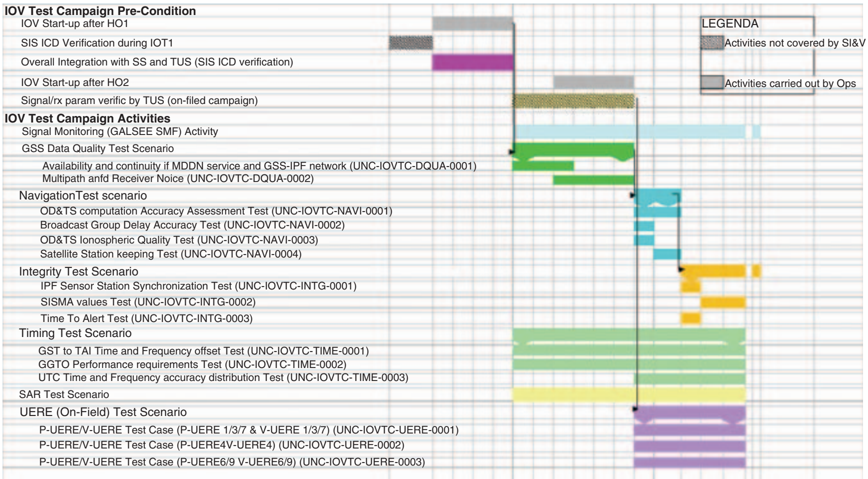

Fig. 4. IOV test campaign planning.

Test Campaign. In case this will be not confirmed (once the exact Tests Duration will be finalized), the approach will be changed (from the staggered one) into the "concurrent" one, that foresees to parallelize – as much as possible – Tests, in order to fit the IOV Test Campaign schedule. It has to be noted that the second approach (the "concurrent" one) implies to accept an increased risk in the IOV Test Campaign activities, as problems occurring with test failures cannot be duly allocated to one area, as everything is tested in parallel. The choice between the 2 approaches is kept open until a detailed assessment on test duration is done that allows to demonstrate which of the approaches is feasible with the time and resources constraint.

Moreover constraints coming from security-related aspects are still under assessment that can lead to re-consideration of provided approach.

4 Conclusions

An overview of the System Verification activities during IOV Phase has been provided in the present paper, with focus on the last 6 months of IOV Test Campaign dedicated to verification of System Performance. The Logic of the activities in terms of identification of Test Cases, preliminary test plan and inter-tests dependency and pre-conditions has been provided, highlighting the main difficulties in terms of schedule and feasibility of tests. In particular a staggered approach for IOV Test Campaign is proposed that is the one mitigating the risks by conducting the tests in the correct sequence as to identify the contribution to test execution in a step-wise approach. It has been highlighted that feasibility of this approach is still to be confirmed pending exact assessment of elementary tests duration that is to be carried out as part of normal work in the following months. In case the feasibility of this approach would not be confirmed, alternative solutions should be envisaged that carries more risks in the overall process of Galileo Verification.

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References

[1] Galileo IOV Implementation Requirements – ESA-EUING-GALCDE1-So W/01000-A4
[2] Galileo System Requirements Document – ESA –APPNS-REQ – 00011
[3] GSRD Requirements Verification Matrix (RVM) – GAL-DVM-ALS-SYST-A/0347
[4] System Integration and Verification Plan – GAL-PLN-ALS-SYST-A/0349
[5] "Galileo In-Orbit Validation (IOV)", F. Gottifredi, F. Martinino, S. Piazza, R. Dellago, 2005 DASIA Conference, Edinburgh
[6] "Galileo: the European Satellite Navigation System", O. Galimberti, M. Gotta, F. Gottifredi, S. Greco, M. Leonardi, F. Lo Zito, F. Martinino, S. Piazza, M. Sanna, ATTI dell'Istituto Italiano di Navigazione, n°178, March 2005
[7] Signal-In-Space Interface Control Document (SIS-ICD) - GAL-ICD-GLI-SYST-A/0258