Galileo Payload In-orbit Test Preparation and Execution

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After the successful dual spacecraft launch on 21st October 2011, the Launch and Early Operations Phase and Platform Commissioning Phase, the In-Orbit Test and Ground Mission Segment Commissioning campaign was conducted to test Galileo's performance, services and functionalities. The In-Orbit Test phase is identified by the first activation of the Galileo payload up to an initial configuration for testing, followed by the Ground Mission Segment commissioning and completed through payload mode transition to nominal mode to guarantee all Galileo services and benefits. The generation of navigation signals by the Galileo payload requires a highly accurate timing reference, provided by the atomic clocks as input for the navigation signal generator unit. This paper addresses the complex Flight Operations Plan concept and its implementation for payload In-Orbit Test operations. The Flight Operations Procedures, which are part of the Flight Operations Plan, cover payload and platform activities as well as the interface to ground operations and In-Orbit Test activities. For In-Orbit Test operations two additional Galileo specific aspects impact the Flight Operations Plan concept; the dual spacecraft launch and the involvement of three different operations sites for the test case execution. The main challenge for the In-Orbit Test concept is to guarantee a smooth and safe test execution and interaction between all involved facilities. Thus the Flight Operations Plan is designed to build up the high level plan for the In-Orbit Test including activities at the Galileo Control Centre in Germany for all spacecraft operations, at the Galileo Control Centre in Italy for GMS commissioning and mission operations and at the In-Orbit Test site in Redu, Belgium for In-Orbit Test measurements always prioritizing the safety of the satellite.

I. Introduction

Galileo is Europe's program for a Global Navigation Satellite System (GNSS), providing a highly accurate, guaranteed global positioning and timing service. The complete Galileo constellation will consist of 30 satellites in three orbital planes at an angle of 56 degrees to the equator. With the satellites taking about 14 hours to orbit Earth at altitudes of 23 222 km, there will always be at least four satellites visible anywhere in the world. DLR Gesellschaft für Raumfahrtanwendungen (GfR) mbH is a company of the German Aerospace Center DLR, having its seat at the Galileo Control Center Oberpfaffenhofen. On 21.10.2011 the successful launch of the first two Galileo satellites took place, initiating the operations of Galileo with the so called In Orbit Validation (IOV) phase. The described activities are carried out under a Contract via Spaceopal GmbH within a program of and funded by the European Union. The views expressed in this paper shall in no way be construed as reflecting the official opinion of the European Union and/or of the European Space Agency.

II. Payload In-Orbit Test Operations Procedure development

The In-Orbit Test (IOT) of the satellite payload will satisfy several objectives including verification that all systems have survived launch and that full system redundancy is available. Additionally the IOT will verify that the performance of the payload is as expected and consistent with ground testing, and that calibration/initialization of all equipment is completed successfully thus achieving readiness for service operation. All these aspects are reflected in the payload IOT Flight Operations Procedures. The following chapters describe the way forward of IOT procedure development.

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A. Flight Operations Procedures development

Flight Operations Procedures (FOPs) development was based on Flight Control Procedures (FCPs), a database and further documentations provided by the satellite manufacturer. The database is transferred into the operational database and FCPs are transposed into FOPs, all according to the Galileo specific ground segment and operational requirements/constraints adapted. In specific, the development of synthetic parameters, sequential procedure design, manual operations execution and the development of limits, pre-transmission checks, etc. are taken into account.

The FOPs are categorized by their type of usage (nominal and contingency) and execution phase:

- Common
- Routine
- IOT/commissioning

Routine and IOT/commissioning FOPs are developed as high level procedures calling and combining common FOPs. Common FOPs include all unit and system activities for platform and payload.

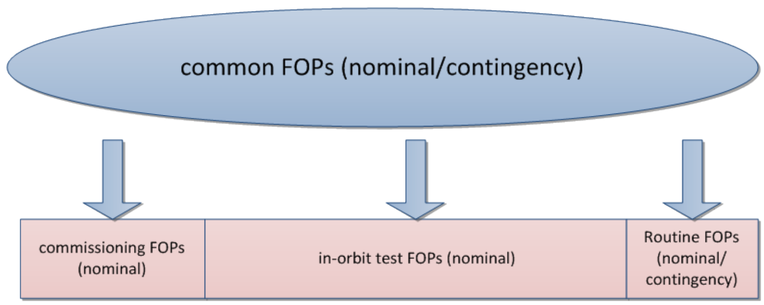

Figure 1: FOPs categorization

Since the IOV satellites of the first launch are identical, the common and routine FOPs are generic and valid for the first two satellites. Spacecraft dependencies in terms of limits are reflected in a generic FOP design but spacecraft specific databases. Whereas IOT FOPs are developed to hard code all spacecraft differences like different RF output setting, spacecraft identification etc. Therefore one dedicated set of IOT FOPs is defined per spacecraft. The next chapter will explain the design concept leading to this approach.

B. In-Orbit Test Flight Operations Procedures design and development

The general FOPs IOT development approach is to cover all activities considering the sequence of events, site interaction and spacecraft differences hard coded in dedicated FOPs per test case allows an efficient and error minimized test execution. Also a flexible test case order for optimized use of visibilities is a general aspect of the concept. However during the entire IOT phase the safety and health of the IOV spacecraft have absolute priority. All combined resulted in one consolidated flight operations plan including all IOT FOPs needed for the first launch of the two satellites.

In addition the FOPs development is based on some defaults. On one hand the Galileo specific requirements/constraints as mentioned in the previous chapter have direct influence on the development, whereas the dependencies/specifications impact mainly the design concept which acts as baseline for the development. The dependencies are defined by external and internal constrains and spacecraft operations as listed below.

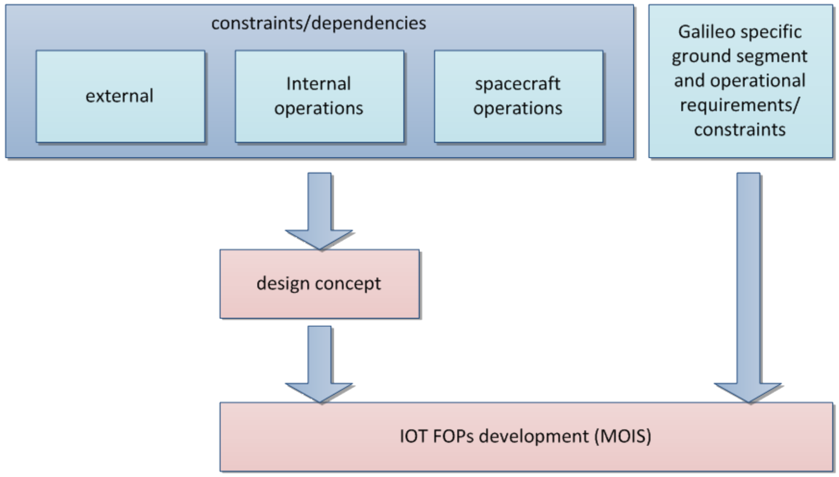

Figure 2: IOT FOPs development concept

External dependencies are predetermined by the manufactures and reflecting the IOT system and the spacecraft and test specifications, and therefore mandatory for the FOPs development. First of all the capabilities of the IOT Measurement System, the frequency coordination, interference avoidance and other system constraints need to be taken into account. Secondly the platform commissioning and Payload IOT plan including all test case definitions constitute as a baseline for FOPs development and test case sequence. The test case definitions forces a certain order of procedure execution limiting the flexibility of operations execution and embedding the payload activation sequence in the IOT test cases in order to minimize the re-configurations of the spacecraft.

Internal operational dependencies are defined by the operations team with the main objective of safe operations and the safety and health of the IOV spacecraft as absolute priority during the entire IOT phase. Transferring the concept of safe operations, the IOT FOPs are designed non-generic and one dedicated set of FOPs per SC is defined to minimize sources of error and to make the operations execution more smooth and efficient. Each spacecraft has a unique identifier and radio frequency output power settings. Secondly one flight operations procedure is developed per test case for flexible re-arrangement of test cases. Furthermore no specific IOT contingency procedures will be developed in advance, however they may be developed in real-time by the specialist teams on-site during the payload IOT in the unexpected event that such procedures become necessary. Any kind of spacecraft contingency situation is covered by common contingency FOPs valid for all mission phases. To optimize the use of the time allocated for the IOT some measurements may be run concurrently with other measurements on the same satellite subject to no test equipment conflicts arising and no SC re-configuration is necessary. Hence no dedicated IOT FOPs are developed for these test cases. Additionally, IOT FOPs are developed generically if test case definition allows, in order to swap test cases for optimal allocation of test slots according to visibility and to guarantee a flexible IOT sequence design. Also the site interactions with Redu and the Ground Mission Segment (GMS) are affiliated in the FOPs to guarantee/support a smooth and efficient work flow. Finally the effective use of available test time and resources is a major driver for the development process.

Spacecraft operations dependencies are concentrating on spacecraft limitations and specifications for operational execution like unit warm up time and signal stabilization time to support IOT measurement accuracy. This is leading to IOT FOPs development including defined breakpoints in case of end of visibility. In addition, the need of power, thermal and data handling aspects are covered by IOT FOPs to represent the whole satellite system. Failure, Detection, Isolation and Recovery (FDIR) handling is implemented to ensure spacecraft safety.

The procedures are developed to support these specific requirements and characteristics and implemented by using the Manufacturing and Operations Information System (MOIS) tool[1]. Validation of FOPs will be addressed in chapter IV. The design concept allows only a limited flexibility of test case order and test case re-arrangement/reuse, however guaranteeing an advanced/sophisticated safe operations concept.

III. System Level Operations Approach

A. Multi-site Galileo Operations

The Galileo specific system level operations approach was designed to link the operations across three sites during the IOT phase. This includes the Galileo Control Center Oberpfaffenhofen (GCC-D), the Galileo Control Center Fucino (GCC-I) and the Galileo IOT station in Redu/Belgium. Dedicated operations plans have been developed across the involved sites covering different areas of the Galileo System Operations. These include mainly the Flight Operations Plan (FOP), the Ground Operations Plan (GOP) and the Mission Operations Plan (MOP). Each of the specific plans contains the relevant procedures for Satellite control, ground control and Galileo specific mission operations dealing with the navigation information of the Galileo system. The satellite and ground control activities are conducted form the Ground Control Segment (GCS) located in GCC-D whereas the mission operations activities are conducted from the GMS located in GCC-I.

B. The Galileo System Level Operations Plan

The System Level Operations Plan (SLOP) defines the system level scenarios allocated in the overall Mission Timeline with system level procedures for each scenario. The payload IOT operations, as one mission phase of Galileo satellites, are defined in the related SLOP scenarios. According to the IOT test to be conducted, the SLOP scenario links together the required Flight Operations Procedures, Ground Operations Procedures, and Mission Operations Procedures. Figure 3 shows the structure of the Galileo System Level operations.

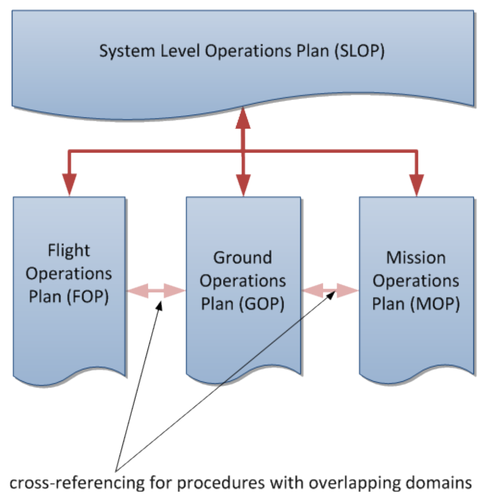

Figure 3: Galileo System Level Operations

The SLOP is the driving document of all operations conducted in both control centers during the IOT phase and provides the link to the IOT station in Redu/Belgium. This way a very consistent and well-structured flow of operational activities has been designed by the approach of the SLOP.

Another interesting aspect of the IOT operations phase is the execution of IOT operations in parallel with the routine House-Keeping operations. The young Galileo constellation currently consists of two satellites, which implies that parallel operations activities will need to be carefully planned. The overall planning process together with system and operational constraints is presented in Ref.2. Furthermore the dual satellite IOT concept is described in Ref.2 taking into account the evolution of the constellation.

C. In Orbit Test contingency handling

In case of major contingencies during the IOT operations, the recovery will be scheduled in the next possible contact. The trouble shooting procedure will be executed to collect/dump the necessary data so that the recovery can be performed in the next possible contact. Every warning / alert (even soft limit violation) during IOT operations observed at GCC-D has to be clarified before continuing the operation. Depending on the event/warning the corresponding Test Case will be paused / stopped to ensure spacecraft safety

IV. In Orbit Test Procedure Validation

A. In-Orbit Test Flight Operations Procedure validation

The general validation concept is based on four different validation methods to guarantee a successful IOT campaign and to optimize the validation schedule and resource planning. First FOPs are validated standalone using the simulator environment. Furthermore several validation campaigns for nominal and contingency cases are used for training and re-validation of FOPs in order to minimize effort and optimize resource planning (personnel and hardware) followed by validation in Spacecraft Compatibility Test Campaigns (SCTCs). Finally a rehearsal completes the general validation process as illustrated in the following figure. Validation reports per procedure are created to track validation status of each FOP and the overall validation status.

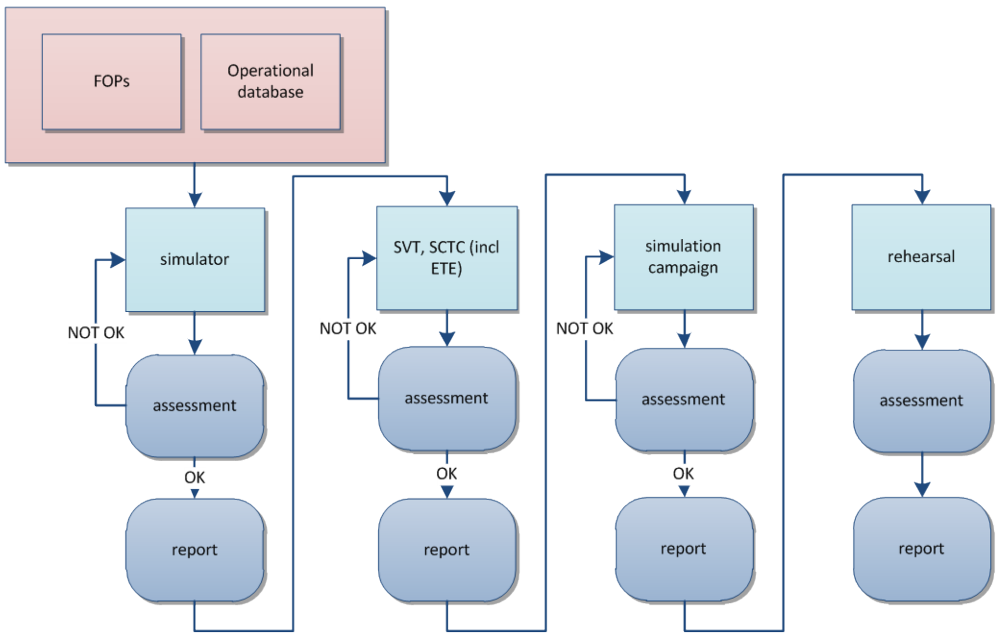

Figure 4: Operational validation process

1. Simulator

Validation of the operational database and FOPs constitutes the first step in the validation process. Operational database and FOPs incl. the payload IOT procedures are validated standalone using the simulator. The simulator recreates the full spacecraft operational functionality combining platform and payload, needed to validate the IOT FOPs. Intermediate spacecraft configuration can be stored and re-stored for any kind of need using saved breakpoints for an optimized validation process. All FOPs whose functionality is available on the simulator are validated at least once with the simulator. Realizing an efficient time and resource management the re-validation of FOPs with minor changes (update description, comments etc.) was either scheduled within a simulation campaign or an SCTC. However, major changes (update TC, TM check, etc.) are re-validated at least on the simulator. When the validation of these operational data-sets is successful, the subsequent validation activities can be started.

2. Simulation campaign

Within the scope of the simulation campaigns dedicated payload IOT scenarios are executed covering the two main aspects. The validation of all operational aspects include the validation of payload IOT test procedures and operational interfaces to Redu and GMS (Exchange of Short Term Plan, Exchange of Orbit files, Voice Loop connection, TM flow from GCC-D to IOT Redu/GMS). Furthermore, a re-validation campaign of payload IOT FOPs is executed where necessary. Second focus is concerning team training and covers the validation of IOT teams for payload IOT activities and training of shift handover.

3. Spacecraft Compatibility Test Campaigns

Defined IOT payload scenarios are validated in Spacecraft Verification Tests (SVTs) and within Spacecraft Compatibility Test Campaigns (SCTCs) embedded in an End-to-End test scenario as the last step of the validation process. Concentrating on mixed payload configuration (combination of prime and redundant units) as part of IOT scenarios and the End-to-End situation covering the mission aspects by GMS (e.g. upload of navigation data) is especially tested to get full and final satisfaction of the IOT FOPs, SC compatibility and for IOT execution.

4. Rehearsal

The rehearsals constitute the fourth part of the validation process. The mission readiness will be demonstrated through the results of these tests.

B. In Orbit Test system validation

The purpose of an IOT system validation is divided into two parts:

1. Technical Validation

Technical Validation is targeting the subsystems, facilities (measurement system, antenna) etc. integrated together forming the IOT ground system, also including the validation of the payload IOT Mission Procedures.

2. Operations Validation

The core of the IOT Operational Validation is the validation of the interaction between the IOT System and the external entities (e.g., GCS), the organizational and logistic aspects and the overall planning and scheduling of the execution of the payload IOT Mission Procedures. Payload IOT Mission Procedures cover all activities to be performed by the IOT team at Redu site. The ones that require a high level of interaction with the GCS are re-validated focusing on whole system validation. Therefore, the main focus of the operational validation is the validation of the correct interaction among the different entities involved in the payload IOT Mission Procedures and the IOT FOPs executed by GCC-D. Therefore, the Operational Validation is the last step required to verify the readiness to perform the IOT Campaign.

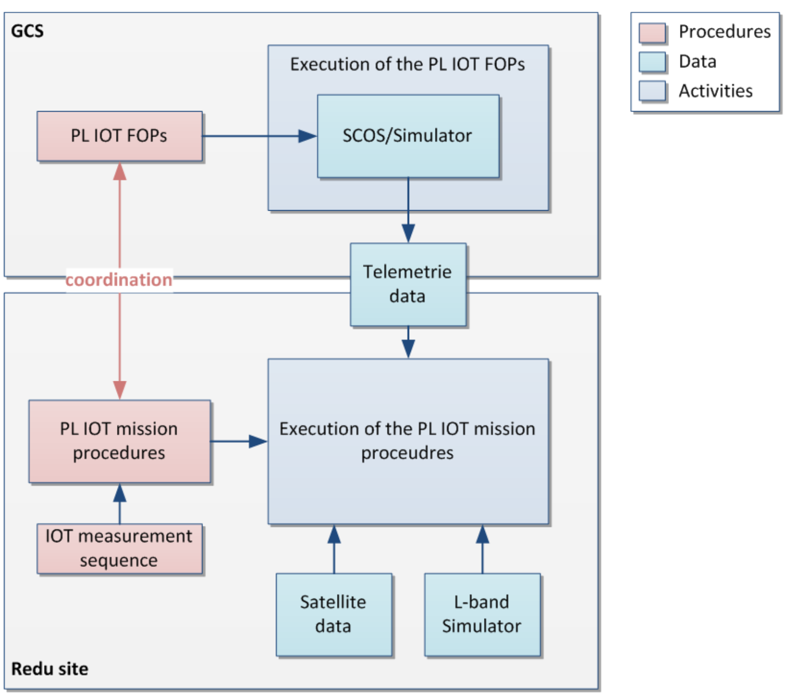

Figure 5: IOT Operational Validation Process

The connection between payload IOT FOPs and payload IOT Mission Procedures is mainly represented by the close coordination between activities executed at each site. The accurate timing of the spacecraft re-configuration is an essential element for the successful IOT test execution. Therefore, the approach to validation of payload IOT

Mission Procedures cannot be seen in isolation and must be seen within the context of the overall integration, verification and validation flow instead, whereas IOT FOPs can also be validated ‘standalone’ as described above.

V. First Operations Results

After the LEOP and Platform Commissioning the first Galileo Payload switch-on was performed from the GCC-D. The switch-on activities were performed by a special operations team composed of highly skilled flight operations engineers in the area of payload, data-handling, power and thermal subsystems under the supervision of the spacecraft operations manager, supported by spacecraft controllers for command and control. The transmission of the first Galileo signal was the beginning of the IOT measurements. The IOT execution was conducted with the same team composition together with the engineering team at IOT site in Redu. The extensive combined operational validation activities between the GCC-D and IOT site Redu resulted in a very smooth, time accurate and therefore successful execution of the defined IOT test cases with excellent measurement results from the IOT measurement system. After the commissioning of the redundant Payload, the engineering team could be decreased as consequence of lessons learnt and gained experience and the remaining test activities were conducted with an efficient team resourcing. The IOT completed with the prime payload activation and nominal transmission of all there Galileo signals of both satellites.

VI. Conclusion

With the completion of a very successful IOT campaign of the first Galileo dual spacecraft launch, the defined development and design process of the IOT FOPs, FOP and SLOP has been proven to be a reasonable and valid approach. The flexibility of the implemented concept was limited by a fixed sequence of pre-defined test cases. In view of the Galileo launch sequence, in order to reach the full constellation, an optimization of the Payload IOT durations is envisaged. Two main areas have been identified in order to optimize the sequence flexibility and IOT duration in an efficient way. As the dual spacecraft IOT sequence was based on four consecutive cycles (two satellites with prime and redundant payload), i.e. four repetitions of the basic test sequence, a good amount of experience was gained. As far as possible, after each cycle, the knowledge has been flown back into the next one- This way a know-how return link has been established in real time. Several test cases were grouped which were originally planned sequentially which reduced the total test duration. For the second Galileo launch the test sequence will be reworked. In order to increase the flexibility of the test sequence the operations procedures will be adapted to be more independent from the related test case definition. This will provide more transparency for the planning process.

Appendix A
Acronym List

DLR GfR mbH	DLR Gesellschaft für Raumfahrtanwendungen (GfR) mbH
FCP	Flight Control Procedures
FDIR	Failure, Detection, Isolation and Recovery
FOPs	Flight Operations Procedures
FOP	Flight Operations Plan
GCC-D	Galileo Control Center Germany
GCC-I	Galileo Control Center Italy
GCS	Ground Control Segment
GMS	Ground Mission Segment
GNSS	Global Navigation Satellite System
GOP	Ground Operations Plan
IOT	In-orbit Test
IOV	In Orbit Validation
LEOP	Launch and Early Orbit Phase
MOIS	Manufacturing and Operations Information System
MOP	Mission Operations Plan
NSGU	Navigation and Signal Generator Unit
SCTC	Spacecraft Compatibility Test Campaign
SLOP	System Level Operations Plan
SOE	Spacecraft Operations Engineer
SOM	Spacecraft Operations Manager
SVT	Spacecraft Verification Test

References

Computer Software
[1]MOIS, Manufacturing and Operations Information System version 6.0.7, RHEA SYSTEM S.A. / Wavre, Belgium

Unpublished Papers and Books
[2]Brajovic, J., and Fischer, H.-J., "The Challenges of a Multi-Control-Centre Mission Planning" to be published at SpaceOps 2012