The Challenges of a Multi-Control-Centre Mission Planning

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This paper describes the implementation of the planning concepts with respect to the different mission operations phases as part of the European Navigation Satellite System Galileo. Considered are interlaced operational aspects of flight activities, ground activities, security, and payload activities which are executed by the different involved Control Centres and scientific-technical supporting centres involved. The challenges of Galileo planning lies within the complexity of the interactions, the international co-ordination between the multiple sites, and the scheduling of routine and special operations activities in parallel regarding an increasing number of satellites. The planning solutions of the Galileo Control Centre at DLR GfR mbH, Oberpfaffenhofen and the lessons-learnt from the first launch campaign are further presented here.

I. Introduction

GALILEO is Europe's programme for a Global Navigation Satellite System (GNSS), providing a highly accurate, guaranteed global positioning and timing service. The complete Galileo constellation will consist of 27 satellites plus 3 spare satellites in three orbital planes with an inclination of 56 degrees. With the satellites taking about 14 hours to orbit Earth at altitudes of about 23 200 km, there will always be at least four satellites visible anywhere from the Earth (except terrains with shading).

The first two Galileo satellites Natalia and Thijs (also labelled as Prototype Flight Model (PFM) and Flight Model 2 (FM2)) were launched on the 21st October 2011, initiating the operations of Galileo with the so called In Orbit Validation (IOV) phase.

The spacecraft were launched by a Soyuz launcher from Guiana Space Centre in Kourou, French Guiana. After separation the LEOP Operations Control Centre (LOCC) was responsible for operating the spacecraft during the first days until the drift orbit was reached, which would bring the satellite to its final orbit. The responsibility for spacecraft operations was handed over to the Galileo Control Centre Oberpfaffenhofen (GCC-D), managed by DLR GfR mbH, to plan and execute the Platform Commissioning, Drift-Stop/Fine-Positioning Manoeuvres, and spacecraft routine operations using the Ground Control Segment (GCS). In addition, the GCC-D plans and supports the In-Orbit-Testing (IOT) of the payload, and the Ground Mission Segment (GMS) Commissioning.

DLR Gesellschaft für Raumfahrtanwendungen (GfR) mbH is a company of the German Aerospace Centre DLR, having its seat at the Galileo Control Centre Oberpfaffenhofen.

The GMS is ground counterpart of the spacecraft's payload. It is responsible for the generation of the navigation signal. This includes the collection of L-Band measurements from the worldwide Galileo Sensor Stations (GSS) for the determination of precise orbits, from which the navigation signal is up-linked to the spacecraft. This navigation message is then transmitted by the Galileo satellite and received by the navigation devices of the end-user.

In all the above mentioned GCC activities several sites are involved: GCC-D operating the GCS, GCC Fucino (GCC-I) operating the GMS, IOT site in Redu, TT&C Ground Stations in Kiruna and Kourou, Up-Link Station (ULS) in Kourou, GSS in Fucino, and LOCC in Toulouse. Since all special operations were completed the GCC-D

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is now performing routine operations on the spacecraft and supporting various system tests. With the next launch of two spacecraft they will build the constellation of four spacecraft for the IOV phase as shown in Figure 1[3].

One special characteristic of the Galileo programme is the multi-centre environment sharing the responsibilities throughout the different phases of the Mission. Each phase has its own specific configuration of several operational activities carried out by dedicated sites in parallel. Especially at the beginning of the Mission the interactions between the centres throughout Europe are interlaced and its planning is a special challenge for the entity where it is centralised.

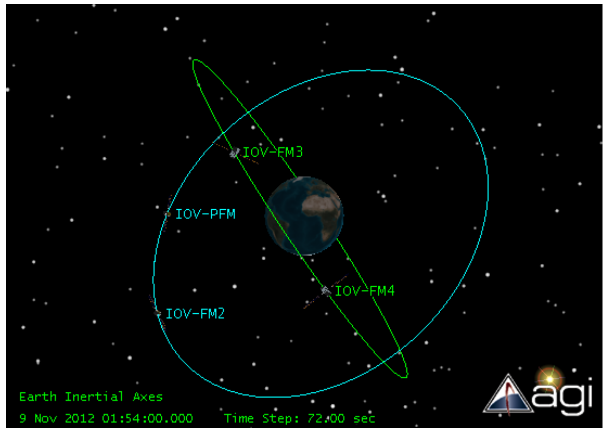

Figure 1. Nominal IOV Constellation. *The four IOV spacecraft are located in two planes. dRAAN = 120°,* $du_{inplane}$ *= 40°,* $du_{FM2\text{-}4}$ *= 26.7°*

After separation the LOCC is responsible for operating the spacecraft during the first days until the drift orbit is reached which will bring the satellite to its designated slot. As soon as the satellites are handed over from LOCC to the GCC-D the coordination of all operational activities is centralised at the GCC-D.

The planning within the Ground Control Segment (GCS) is performed with the help of the Spacecraft Constellation Planning Facility (SCPF) at GCC-D. Based on orbital information provided by Flight Dynamics (FD) its task is scheduling the ground contacts and allocating all activities in a timeline which result in a Short-Term-Plan. During the Commissioning and IOT phase it is the central planning facility where the needs of all involved centres are coming together. Later, during routine operations, and when the spacecraft are fulfilling their mission, it is coordinated with the GMS. Planning considers mostly flight and secure operations activities, but also ground, flight dynamics and mission operations as far as they impact spacecraft operations.

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The views expressed in this paper should in no way be construed as reflecting the official opinion of the European Union and/or of the European Space Agency.

II. From Hand-Over until end of IOT

After the satellites of the first Galileo launch are handed over from LOCC the coordination of all operational activities is centralised at the GCC-D which is operated by DLR GfR mbh. The first priority is given to the Routine Contacts which have to be scheduled once per orbit (~14h period) for each spacecraft. For that purpose the two TTCFs (Tracking Telemetry and Control Facilities) in Kiruna and Kourou are used as part of the GCS (Ground Control Segment). All remaining possible contacts are then used for conducting the Platform Commissioning. The commissioning activities are interrupted as the satellites' drift-stop approaches. The focus is then on collecting enough ranging measurements to ensure an optimised manoeuvre strategy based on good quality orbit determination. To support this, three additional TT&C stations from the LEOP network are included in the planning. Since the LEOP provider is responsible for the flight dynamics aspects of positioning the satellite in its final slot, a close coordination w.r.t. the station usage and manoeuvre planning is necessary. When the spacecraft have reached their final position, the remaining Platform Commissioning activities are completed, followed by IOT of the payload. For allocating the IOT Test Cases the visibilities of the IOT Station in Redu also have to be considered and the Test schedule communicated to the team at the IOT Station. Since the different Galileo signals are tested in this context, the order of tests and payload configurations have to be coordinated between the GCC and IOT teams in Redu. In this early phase of the mission the GMS is also performing the GMS Commissioning for which the ULS in Kourou has to be involved in the planning. As stated before, in all the described phases the routine housekeeping of the satellites has always to be scheduled with highest priority. All these aspects make that phase a challenge from a

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[3] *dRAAN* is the difference in RAAN [°] between the two orbital planes
$du_{inplane}$ is the difference in argument of latitude [°] between two spacecraft in the same orbital plane
$du_{FM42\text{-}4}$ is the difference in argument of latitude [°] between FM2 and FM4 (adjacent planes)

planning point of view as they contribute to the complexity and criticality. The different activities performed during that phase are illustrated in the Figure 2 and described in more detail later on.

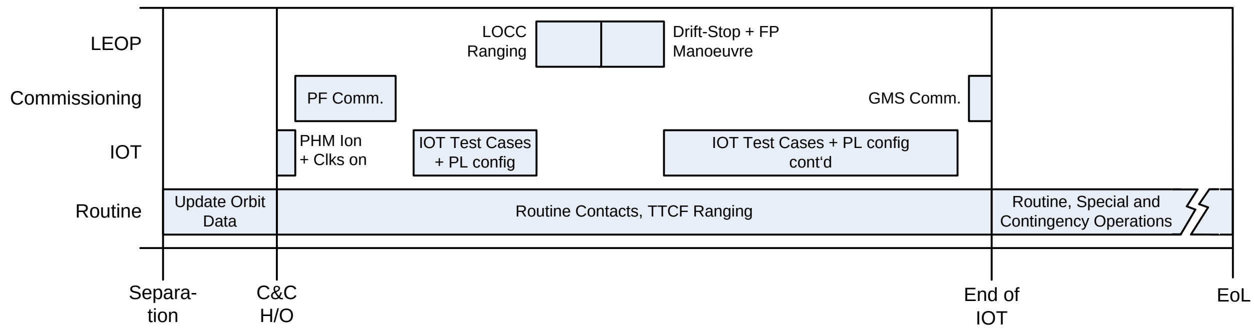

Figure 2. First Galileo Mission Phases. *The GCC-D Operations start with the Command & Control Hand-Over (C&C H/O) and lead through Platform Commissioning, IOT, Drift-Stop & Fine Positioning and GMS Commissioning to Routine Spacecraft Operations.*

The details of the activities to be performed as well as their order of execution, the corresponding constraints, and the references to flight operations procedures are defined in the System Level Operations Plans which are then planned into the available TT&C contacts by the planning facility at the GCC-D. The generated output is twofold. There is a graphical visualisation of the timeline (Gantt chart, see Figure 3) on the one hand and a detailed listing called Sequence of Events (SoE) on the other hand. The SoE contains exact times and detailed instructions on activities to be executed step by step by the spacecraft control team.

As it can be seen from the charts in Figure 3, Kiruna visibilities are shorter than Kourou visibilities due to their geographical location. In Kiruna they can reach up to 7 hours, whereas in Kourou they can be longer than 13.5 hours. Further, the gaps between visibilities are between 7 and 11 hours for Kiruna and between 19 and 22 hours for Kourou. That means, that with Kourou only it would not be possible to schedule a contact every orbit. With Kiruna only, it would be possible to allocate routine contacts regularly, but not much visibility time would be left for special operations anymore. Combined, they provide a good, complementary visibility pattern, which makes both, routine and special operations possible.

Due to the very close position of both spacecraft, the visibilities are parallel to a large extent for PFM and FM2, especially at the beginning of the drift phase. As the spacecraft are moving further apart throughout the drift, the visibilities also start to shift. But even at the end of the drift phase the visibilities are overlapping a lot, because of the spacing of only 40° between the two satellites PFM and FM2.

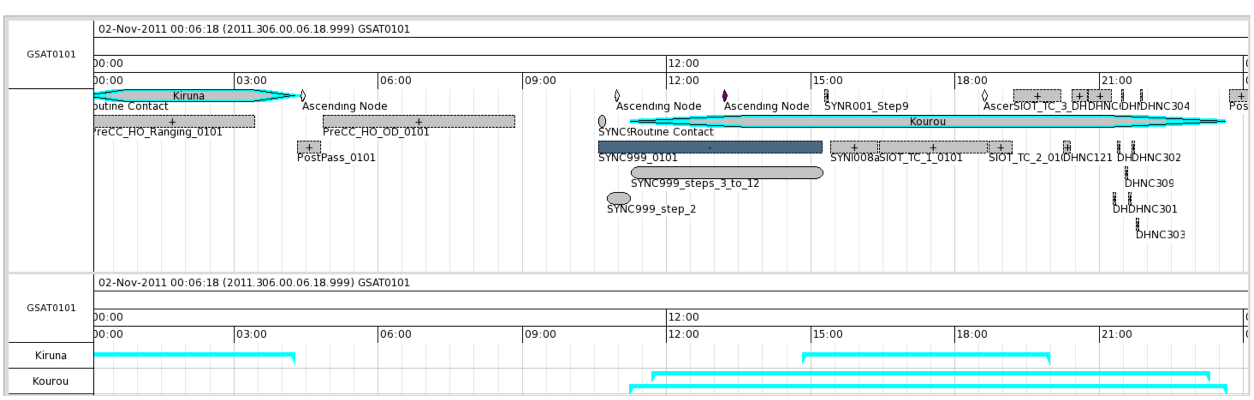

Figure 3. Graphical Visualisation of the Timeline for PFM. *The lower part shows the visibilities from the two TT&C ground stations Kiruna and Kourou starting at 5° elevation. For Kourou there is an additional visibility with a 10° elevation cut-off. The upper part visualises the contacts (bars with blue borders) labelled with the station name. The grey rectangles are scheduled tasks. The bars with oval ends are sub-activities of a task. This figure is a screenshot of the SCPF, which was developed by SciSys, UK.*

The consequence is that a general rule is applied for scheduling, i.e. the Kiruna visibilities are usually used for Routine Contacts to perform the normal housekeeping activities like TM dump, on-board mission timeline (MTL) update, etc. The visibility durations suit very well for performing the routine contacts consecutively. The long Kourou contacts are used mainly for performing special operations which very often require several hours of contact.

The charts in Figure 3 also show how routine contacts are scheduled for the two spacecraft during Kiruna passes and the special operations like the hand-over in this case are allocated in long Kourou passes.

III. Routine Operations[4]

As already mentioned before, during the routine operations phase the main planning task is to ensure that every spacecraft has at least one hour per orbit contact to one of the TT&C stations (~14h period) for performing normal housekeeping activities like TM dump or MTL update. In parallel, ranging sessions are performed during the routine contact to provide Flight Dynamics with measurements for orbit determination. Furthermore, on a weekly basis, the on-board orbit propagator is updated.

In the routine phase the Galileo Short-Term-Plan is issued weekly and covers nominally 10 days (see Figure 4). In case of public holidays it may cover a longer period. All routine activities and the corresponding rules and constraints are maintained in the planning database. If there are additional activities to be performed, a formal Planning Request (PR) is raised by the affected entity (Flight Operations, Secure Operations, Ground Operations, or Mission Operations). It is then reviewed and approved by the operations management and implemented by the planner.

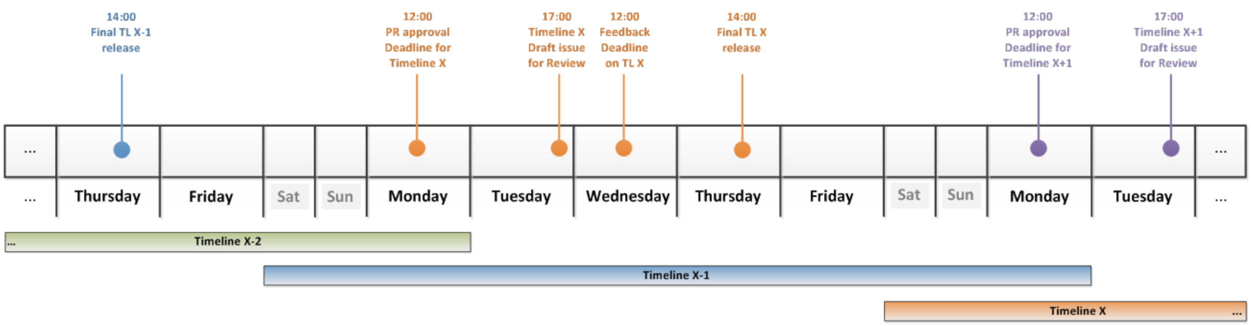

Figure 4. Weekly Planning Cycle. *Every Thursday a timeline is issued covering 10 days, starting from Saturday 00:00 GST.*

One difference in the planning concept between the Routine Operations phase and the Commissioning/IOT phase is the depth of detail the tasks and activities are defined. Whereas in the Routine Operations phase commands, command sequences and even complete procedures shall be referenced in tasks and activities, these are only placeholders for the dedicated high level procedures in the Commissioning/IOT timeline indicating that the appropriate procedures called by the high level procedure shall be executed in the reserved period of time. The main reason for this difference in the way of planning is the method operations are done in these phases. During Routine Operations automation is supposed to be used as much as possible which requires commands and command sequences being available in the automatic stack of the Monitoring and Control (M&C) tool SCOS. Operations of the Commissioning/IOT phase are done via the manual stack of SCOS allowing a much higher degree of operational flexibility and the application of quick changes.

[4] In this context, Routine Operations refers to spacecraft operations only. That means the spacecraft is in its nominal mode, including platform and payload, and the normal housekeeping activities are performed regularly. It does not mean that the Mission Operations or the complete Galileo system is already in Routine Operations. The GMS is still under completion and mission provision has not started yet.

IV. Manual vs. Automated Planning Environment

A. Characteristics of Manual Operations

The most significant characteristic of manual operations is the role of the spacecraft controller, of course, who executes all activities manually and step-by-step. This implies that the output of the planning system has to be human readable in format and contents. The procedures also have to be written with a certain structure, e.g. with textual explanation, no formal parameters, etc. The planning system and the control system do not necessarily have to share databases. For the planning engineer the work is standard for the most part. First on the list is the contact scheduling, then all tasks are placed, considering all approved planning requests. The output is a detailed listing of activities, a Sequence of Events, as input to the spacecraft controller, rather than a plan which is executable by a machine. That process is visualized in Figure 5.

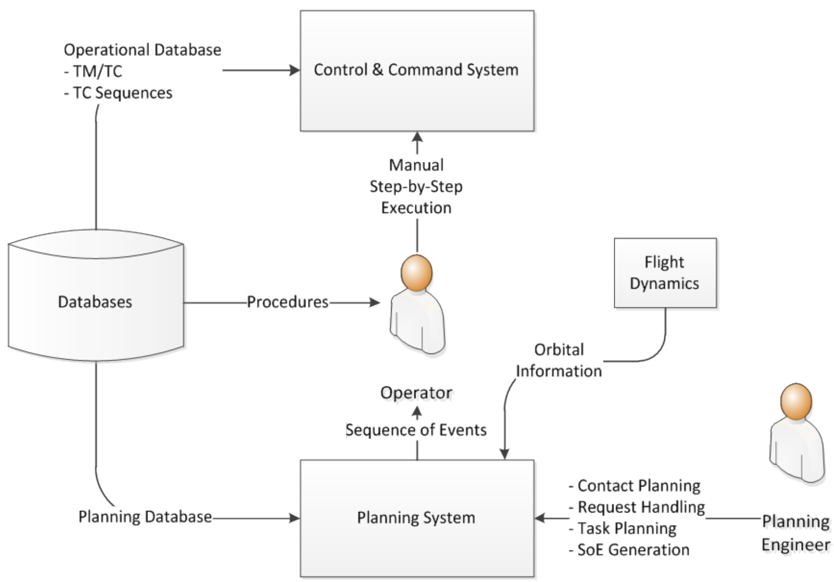

Figure 5. Manual Operation. *The key role in manual operations is the Operator performing a step-by-step executing of the Sequence of Events provided by planning.*

B. Characteristics of Automatic Operations

In contrary to manual operations, for automated operations there is no need of a human-readable detailed Sequence of Events. The output of the planning system is tailored to the definition of the interface between machines. The short-term-plan is imported by the automation component of the control system and executed automatically. Nominally, the spacecraft controller is only monitoring the execution in real-time, except for steps where per procedure definition an operator interaction is requested. But there are possibilities for the operator to intervene and modify the Short-Term-Plan online to a certain extent. For this reason, the command system has to have the same planning database available as the SCPF. Further, the procedures have to be available as executable files (so called PLUTO procedures) and also have to be written in a way, the command system can understand, e.g. using formal parameters.

The review cycle defined in chapter III can also be applied in the automated environment using the visualisation capabilities of the planning system. In this way it is ensured that a human review of the timeline is performed prior to the official release and distribution.

At the point when Galileo is providing the navigation signal, i.e. fulfilling its mission, the planning entity at Mission Segment level is providing a Mid-Term-Plan, which the SCPF takes as basis for further planning. Any activities on GCS side which have mission impact are sent to the GMS for approval. The described processes are shown in Figure 6.

While the workload for operations execution decreases with an increased level of automation, the workload for the development and validation increases. The operations preparations have to focus on well-defined and consistent planning databases development as well as on intense and thorough validation of both, databases and procedures.

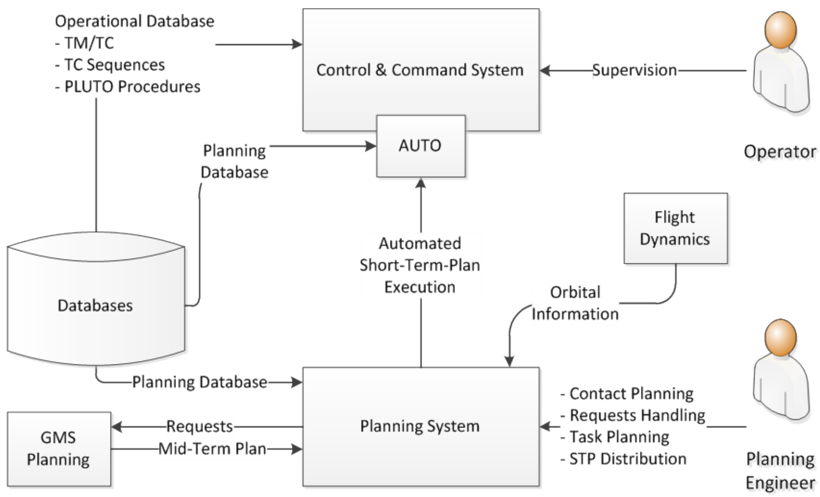

Figure 6. Automated Operations. *In an automated environment, the key components are the planning databases and the executable procedures, which are both used by the Command System (including the automation component) to execute the Short-Term-Plan.*

V. Planning Challenges Faced at GCC-D after the First Galileo Launch

A. Command & Control Hand-Over

With the three first manoeuvres on each spacecraft they are brought to their drift orbit. As soon as they are completed, the next long ground contacts from Kourou (one per satellite) are used for the command and control hand-over from the LOCC to the GCC-D. During the hand-over process, the spacecraft is first in contact through the Kourou antenna from to the LEOP station network to the LOCC. It is then handed-over to the GCC via the Galileo TTCF Kourou. In this way, a double coverage is ensured during the whole contact and the spacecraft can easily be handed back in case of a contingency.

The special planning aspect of this activity starts already several passes before the hand-over. The GCC-D is informed by the LOCC about the contacts and is already following the on-going operations. In a suitable pass prior to the hand-over, the GCC-D planning coordinates with LOCC to obtain a slot for a ranging campaign. Flight Dynamics performs an orbit determination and cross-validates the orbit vector received by the LOCC. If all pre-hand-over activities are successful, the hand-over can take place. More details on hand-over operations can be found in Ref. 4.

B. Platform Commissioning

During the remaining long contact, in the first place the clocks are switched on, followed by platform check-outs and platform commissioning tests. The next long contact with Kourou is reserved for the hand-over of the second spacecraft. Once both spacecraft are handed-over the platform commissioning activities are continued on the first spacecraft. Only when it is accomplished for the first satellite, it is then continued on the second spacecraft.

From a planning point of view, the Platform Commissioning is straight forward. No interaction outside the GCC is needed; only the platform constraints as per spacecraft user manual have to be taken into account. Nevertheless, the planning team has to be prepared for unexpected spacecraft behaviour and the necessity of an emergency re-planning.

C. Drift-Stop and Fine-Positioning

At this point the spacecraft are still in a drift orbit, this means that at dedicated orbital positions manoeuvres have to be performed in order to stop the drift and to fine-position the spacecraft in its final orbit. During that phase no other special operations are performed. The responsibility for the spacecraft position is still with the LOCC at that time, while the GCC-D is responsible for executing all necessary commanding to the satellite. That means, that detailed information about the activities has to be received by the external control centre and their planning has to be closely coordinated with the GCC-D. There are two main tasks to be harmonised between the centres: Ranging Campaigns and Manoeuvre Execution.

During the drift, when special operations are being executed, the TTCFs are utilised for performing the ranging campaigns and the tracking data is provided to the LOCC. Before, during and after the manoeuvres, the 2 TTCFs are not enough to determine the spacecraft's orbit with the required accuracy to plan and calibrate the manoeuvres. For that purpose the LOCC is additionally performing tracking campaigns with their station network and the campaigns have to be coordinated between the centres. For their ranging campaigns the LOCC provides the GCC-D Planning Team with a ranging plan containing times and the stations needed. The LOCC can also request additional ranging campaigns during the drift phase if the nominal campaigns are not sufficient for any reason. This process is illustrated in Figure 7.

These activities are a special challenge for the planners because the ranging strategy is to perform sessions of 10-15 minutes every hour, during up to 3-4 orbits before and after each manoeuvre, depending on the type of the manoeuvre. To give an impression on the special nature of this planning task, here is an example: For only one ranging campaign over two orbits and for two spacecraft it already results in 56 planning requests, i.e. 56 tasks to plan. One can imagine the huge amount of planning data the planning engineers have to process.

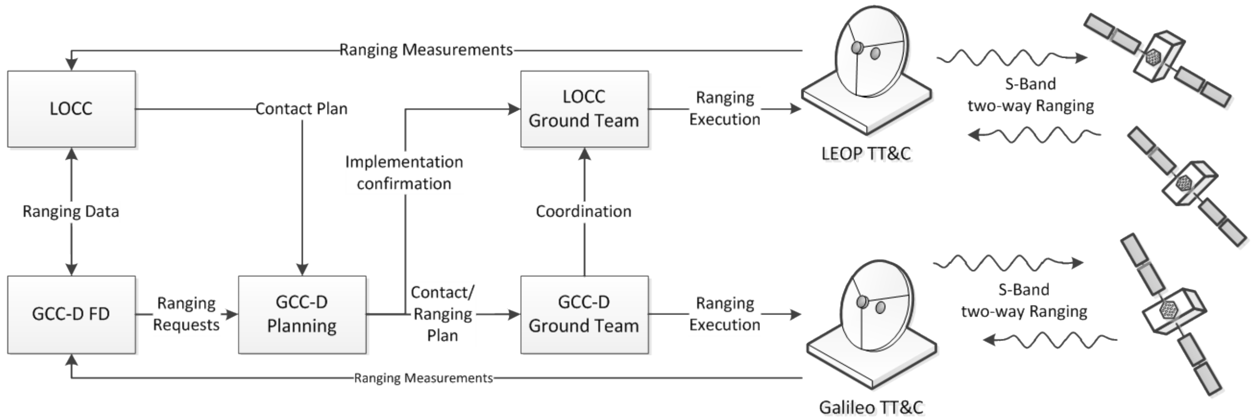

Figure 7. Execution of Ranging Campaigns. *Both, Galileo TT&C stations and the LEOP TT&C network are used for ranging during the manoeuvre phase. Contact/Ranging Plans are merged in the GCC-D Planning and distributed to the involved entities. After the Ranging execution, the measurements are sent directly back to the LOCC and GCC-D FD.*

With three drift-stop manoeuvres and up to five fine-positioning manoeuvres (the number depends on the performance of the previous manoeuvres), the spacecraft are brought to their final orbit. The exact manoeuvre parameters are only known a couple of hours in advance. Therefore rough manoeuvre slots have to be communicated by the LOCC in advance and implemented into the timeline by the planner. But the planner still has to be prepared to update the timeline on a short notice in case of major changes due to over- or under-performances of the previous manoeuvre.

D. IOT and GMS Commissioning

After the Platform Commissioning is completed, the execution of IOT is started. Within IOT, the different Galileo signals on the three frequencies (L1, E5, and E6) are switched on and tested. The planning of the IOT Cases has to be well coordinated between the GCC-D and the IOT Site at Redu. The IOT phase planning process is shown in Figure 8. The baseline for the order and the constraints of the Test Cases is also given by System Level Operations Plan which is implemented by the Planning Team. The IOT cases are implemented in the Short-Term-Plan as records reserving time for IOT Team activities, whereas the corresponding payload configurations are planned with information about the payload procedure to be executed by the Flight Control Team. An extract of the Short-Term-Plan is then sent to the IOT site for additional constraint checking. If a negative feedback is received, the Planning Team adapts the Short-Term-Plan and re-issues it.

In addition to the two TTCFs, the visibilities of the IOT ground station in Redu also have to be considered. As far as possible all S-Band activities (TM/TC) are planned during TTCF visibility only so the Redu coverage can be used for IOT as completely as possible. The payload configuration is done shortly before the Redu acquisition of signal and as soon as the configuration can be confirmed by the measurement system (when the spacecraft is first seen from Redu) the actual IOT Test Case can be performed. Depending on the payload configuration needed for the following test, the payload is reconfigured after the completion of the current IOT Test.

The IOT is started with one spacecraft and its redundant payload units. After its successful completion the redundant payload units of the second spacecraft are tested. The spacecraft are then reconfigured to the prime payload and IOT is performed for one spacecraft after the other and in the end they are both already in the configuration required after all IOT tests are completed.

Details on IOT and Payload operations can be found in Ref. 3.

Lastly, Special Operations, GMS Commissioning and Secure IOT are performed. The approach is the same like for IOT, only that the Ground Station used is in Fucino, Italy and the Short-Term-Plan iteration is not necessary.

Except the planning iteration with IOT, another special characteristic of this phase is the fact that depending on the success of the test a re-planning is needed within a couple of hours. That happens if tests take longer or shorter than planned or the IOT strategy is re-defined after unexpected results or because of a shortage of time. The experience from the first launch is, that a re-planning is necessary daily.

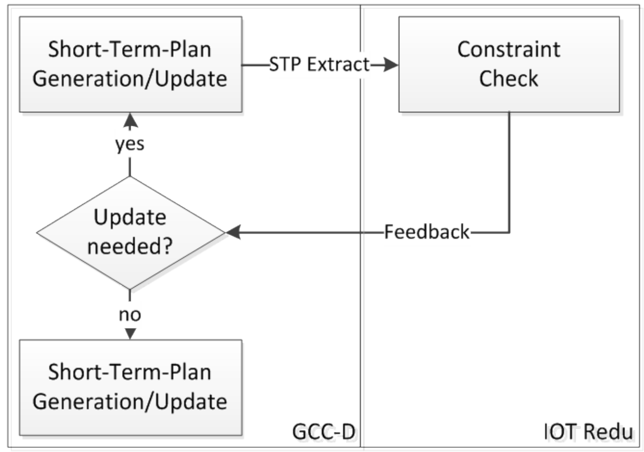

Figure 8. IOT Planning Process. *The IOT team checks the plan against specific constraints and triggers a Short-Term-Plan update in case of a violation.*

E. Communication Challenge

In Figure 9 all inter-site interactions are summarised. It is obvious that with so many sites and companies involved, which are spread all over Europe and beyond, one essential challenge is the communication and information flow between all parties. Not only the electronic interfaces between the machines have to function smoothly, also the ‘interfaces’ on a personal level have to work. Many different specialists with different fields of expertise come together and have to be aligned in order to achieve a common goal.

To accomplish that clear communication rules have to be set up. The chain of information flow has to be well-defined and strictly followed. We also experienced that the following common space management rules have to be taken serious for a successful planning:

1) On engineering level, the rules for the voice loops usage between the centres have to be defined. It has to be clear what is communicated on which loop and which information is communicated in which way. Before/after all special operations a briefing/de-briefing should be held with pre-defined agendas and participants.
2) On management level a daily planning meeting with representatives of all parties was essential. There, all lately performed activities are reported and upcoming activities are discussed. It has to be made sure that the right people attend, i.e. persons who are in the position to make decisions, that the agenda is clearly defined and the meeting is well-structured.

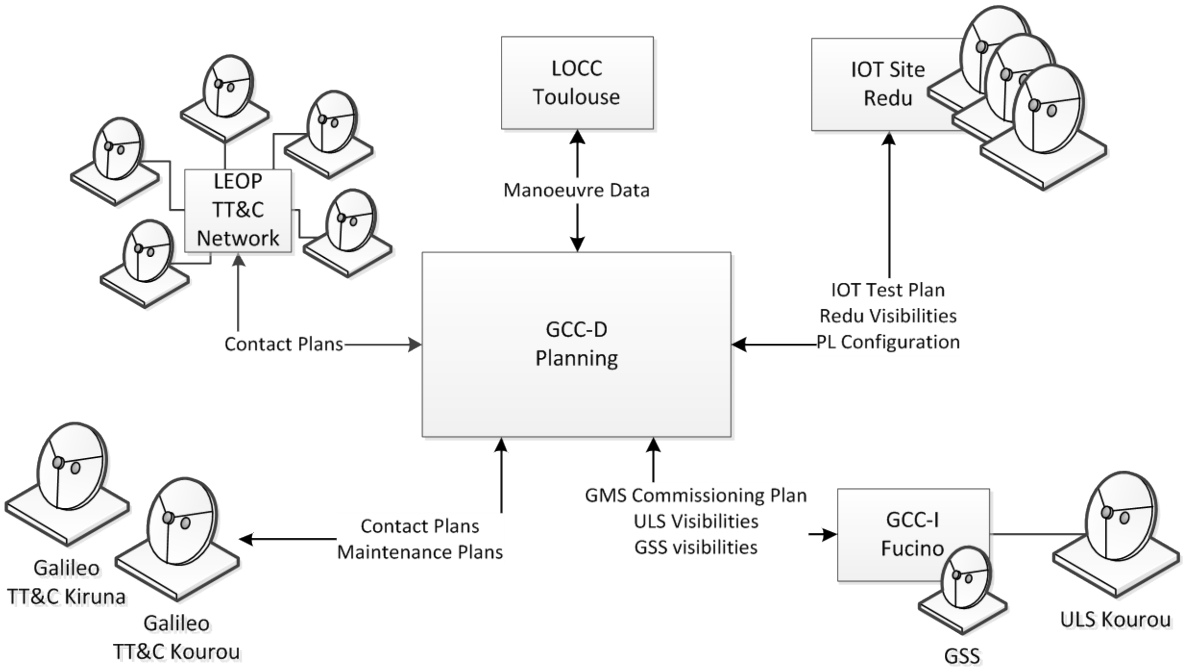

Figure 9. Multi-Site environment involved in the GCC-D planning. *The GCC-D planning considers the LOCC including the LEOP TT&C stations, the IOT site, the Galileo TT&C stations and the GCC-I.*

VI. Lessons Learnt and Conclusion

Having the explanations of the previous chapters in mind, it becomes clear that every phase has specific requirements on how the planning has to be organized and what the planning tool has to support.

The challenge for planning the Commissioning/IOT period is the fact that all those different activities involve different entities/centres which either give input for the planning or need its output. Some of the tasks are highly time-critical and have to be very carefully aligned and defined in detail in advance. In addition, the same activities have to be planned for two spacecraft at a time in a well-coordinated way – and the number of spacecraft will raise significantly within the next future. Further, that phase is also characterised by a highly dynamic behaviour in terms of plan. Unexpected behaviours of the spacecraft, delays and short notice changes have to be taken into account. This requires a very flexible easily editable scheduling tool which makes fast re-planning possible. The system does not have to be very 'intelligent' as the planning is done manually.

For Routine Operations it is not as important to be fast. It is much more important that the databases (tasks, activities, constraints, scheduling, rules and triggers) are very well designed and the system is 'intelligent' in applying those. The system has to be robust, not needing too much manual intervention and thus supporting an automated environment.

From all previous considerations it becomes clear that the more spacecraft are launched, the more resource consuming the manual operations would be. In order to efficiently operate the spacecraft, the routine operations have to be more and more progressively automated. Even for the second launch the two spacecraft in routine operations phase will already have to be operated in an automated mode, while the Commissioning/IOT for the newly launched spacecraft is executed in parallel.

This is a special challenge for the planning system, which then has to support both approaches, i.e. it has to generate a Sequence of Events for manual execution and at the same time generate a Short-Term-Plan for automated execution. In addition it has to be able to distinguish, consistently, between the information which has to be included in the plan. It also has to make both ways of planning possible, the full flexibility needed for Commissioning/IOT and the hard constrained routine operations.

Until now, it has been an advantage to have two dedicated ground stations which support only the Galileo mission and thus can be freely scheduled as needed. Therefore maximum resources were available to accomplish the required tasks. But having in mind that the number of stations will not increase proportionally to the number of satellites (there will be 5 TT&C stations), it is clear that very soon it will be a challenge to perform Commissioning/IOT for the launches to come, having an increasing number of routine spacecraft. In a short time, the Galileo timelines will become oversubscribed, requiring a very well optimized mission planning. Yes, it will be a challenge, but a challenge the GCC-D is prepared to face…

Appendix A
Acronym List

C&C	Command and Control
FD	Flight Dynamics
FM	Flight Model
GCC	Galileo Control Centre
GCC-D	GCC Germany
GCC-I	GCC Italy
GCS	Ground Control Segment
GMS	Ground Mission Segment
GNSS	Global Navigation Satellite System
GSS	Galileo Sensor Station
H/O	Hand-Over
IOT	In-Orbit-Testing
IOV	In Orbit Validation
LEOP	Launch and Early Operations Phase
LOCC	LEOP Operations Control Centre
M&C	Monitoring and Control
MTL	Mission Timeline (On-Board)
OP	Oberpfaffenhofen
PFM	Prototype Flight Model
PLUTO	Procedure Language for Users in Test and Operations
PR	Planning Request
RAAN	Right Ascension of the Ascending Node
SCPF	Spacecraft Constellation Planning Facility
SoE	Sequence of Events
TC	Telecommand
TL	Timeline
TM	Telemetry
TTCF	Tracking Telemetry and Control Facility
TT&C	Telemetry Tracking and Command
ULS	Up-Link Station

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