A Control Centre's Journey to Its First Successful Galileo LEOP

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ABSTRACT

As operator for Galileo, Europe's Global Navigation Satellite System (GNSS), the DLR Space Applications Institute mbH (DLR GfR) handles spacecraft operations from its control centre in Oberpfaffenhofen. While already proficient in operating 26 satellites simultaneously, Galileo's 11th launch (L11) of 2 spacecraft nonetheless represented a remarkable project milestone for multiple reasons. It marked the very first LEOP (Launch and Early Orbit Phase) under DLR GfR responsibility, as contractor for Galileo Service Operations (GSOp).

This work describes the main activities and challenges encountered during the preparation and execution of Galileo's L11. In addition to a global pandemic, the preparations were heavily shaped by the virtualisation of the Ground Control System (GCS), setting up a ground station network together with several agencies and ensuring encryption of communications from first contact after separation. These extensive preparations led up to a highly successful launch, which itself was marked by multiple delays and a potential collision avoidance manoeuvre in parallel. Lastly, the LEOP Lessons Learned are presented in anticipation of Galileo's 12th launch.

1. Introduction

The Global Navigation Satellite System (GNSS) satellite constellation known as Galileo is not only Europe's single largest satellite constellation, it is also the world's most accurate satellite navigation system, delivering metre-level positioning with free access to the public [16]. The Launch and Early Orbit Phase (LEOP) activities discussed here mark the eleventh launch (L11) for the constellation, with all launches being performed by Arianespace.

With L11, there are 28 Galileo First Generation satellites in orbit, with 10 more due to be launched in the next years for constellation completion and replenishment [2]. While the Galileo constellation already offers Initial Services since 2016, additional satellite deployments are needed before Full Operational Capabilities (FOC) can be announced. The Galileo Reference Constellation consists of 24 operational satellites distributed over 3 circular orbits, each having an inclination of 56 degrees. This results in a geometry of 8 satellites per plane (8/8/8) plus typically 2 spare satellites per plane (8+2/8+2/8+2) [4, 5]. With the two additional satellites launched with L11 (8/8+1/7), the robustness of Galileo's constellation was increased, bringing it closer to its Full Operational Capabilities so that a higher lever of service guarantees can be provided [6]. The additional, future launches will further expand Galileo's constellation and act as backups and spares for satellitest that reach their end-of-life.

Previous to L11, Galileo's LEOP activities were entrusted to the French National Centre for Space Studies (CNES; French: Centre National d'Études Spatiales), due to its capabilities and extensive launch experiences. Within this approach, once CNES was responsible for the main LEOP activities wherein they ensured that the launched satellites were in a healthy state and on the way to their operational orbit. The overall LEOP timeline and activities are detailed further in section 2. Once these tasks were completed successfully, the LEOP was concluded and the Command and Control (C&C) of the satellites was handed over to the Galileo Control Centre (GCC), operated by the the Galileo Service Operator (GSOp). These satellites are manufactured by OHB and operated by SpaceOpal as GSOp for the EU Space Program Agency (EUSPA), which, in turn, operates the mission on behalf of the European Commission.

This document describes Galileo's main contractor's development journey to its first LEOP and crucial Lessons Learned from it. Therein, section 2 details the activities executed during LEOP up to the incorporation of the newly launched spacecraft into Galileo service provision. In section 3, both the Ground and Space system pre-requisites are presented which were required to go-ahead with Galileo's L11. Similarly, section 4 presents the training required for all operational teams to ensure confidence in dealing not only with all of the LEOP systems presented in section 3 but also with a manifold of incidents and anomalies that might affect the LEOP. In section 5 the execution of Galileo's L11 is summarized which successfully added two new spacecraft to the Galileo constellation. To build upon these experience, section 6 lists some of the critical Lessons Learned from this LEOP to ensure and further improve future LEOPs. Lastly, section 7 presents the expectations for the future Galileo launches.

2. LEOP Timeline

This section deals with the events starting at lift-off, depicted by a launcher vehicle in Figure 1. For details on the events prior, see section 3.

During a satellite launch, there are several crucial subelement separation events. Of these events, the first is the separation of the launcher fairing from its Cryogenic Main Stage (EPC; French: Etage Principal Cryotechnique), shown as

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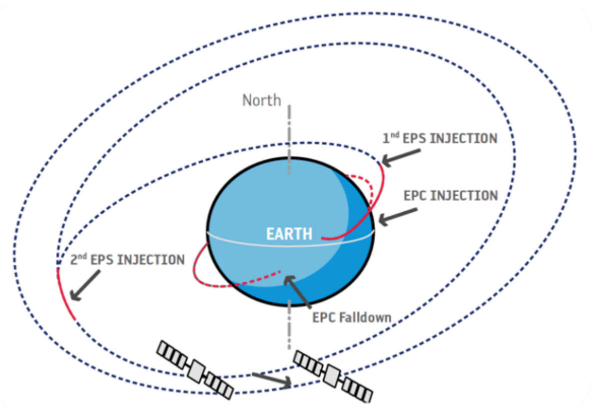

Figure 1: Launcher orbit and satellite launch injection as per L10. [7].

EPC INJECTION. While the already spent EPC is de-orbited and re-enters Earth's atmosphere, the fairing containing the launched spacecraft within continues its orbital climb. This climb is made possible by the fairing's Storable Propellant Stage (EPS; French: Etage à Propergols Stockables), which executes two manoeuvres listed as EPS INJECTION. The first of these two occurs at the fairing's pericenter and increases both orbital eccentricity and maximum altitude, at its apocenter. Conversely, the second EPS injection occurs at the fairing's apocenter, drastically lowering its eccentricity and thus circulating its orbit to close to the satellites designated orbit. Lastly, the spacecraft are separated from the launcher's fairing, symbolised by the left spacecraft in Figure 1. During this injection, which occurs for Galileo over 3 hours after launch, all spacecraft are separated from the fairing one at a time. For L11, this event marked the satellite responsibility handover from Arianespace as launcher to the Galileo Service Provider. After this injection from the fairing, the spacecraft boot up autonomously while being tracked by several ground stations that eargerly await their first sign of live after launch in the form of telemetry. The main timeline for the L11 spacecraft is shown in Figure 2, with the LEOP activities starting at the event denoted as AOS, Acquisition Of Signal. Once a stable communication link to the spacecraft has been established, its Initialisation (Init) Sequence is started and the spacecraft undergoes first basic health checks under close monitoring. The main goal of this phase is to bring the spacecraft to a stable configuration, known as the Breathing Point [9]. To reach this point, the spacecraft must be de-tumbled and a attitude stabilisation must be attained. Additionally, its thermal gradients must be decreasing with the heaters keeping all systems within expected ranged and crucially, the solar arrays are fully deployed and point towards the sun, to ensure continuous power availability to all subsystems. Once the Sun Acquisition Mode (SAM) is attained and the Breathing Point is confirmed, the Post-Init Sequence may begin. During this phase, the thrusters as well as all redundant units are checked [10]. Once these systems are confirmed to be in a healthy and nominal state, the Reaction Wheels Run-In is started. Here, the reaction wheels, which are crucial for attitude control and stabilisation, are sped up to their maximal speed and after successful checks are brought back to nominal working speeds. While the reaction wheels are being tested, the spacecraft also undergoes Early Spacecraft In-Orbit Testing (S-IOT), to demonstrate that the P/F has not been damaged by the severe conditions of a launch and that its specifications are still met for being introduced into the Galileo constellation [15, 14]. Afterwards, the spacecraft is transitioned to its Earth Acquisition Mode (EAM), as required for Galileo navigation service provision. Noticeably, prior to this point the spacecraft are continuously rotation with respect to Earth, which results in the need for polarisation swaps of the space-ground link. Galileo spacecraft have two main communication antennas, one at their front and one at their back, with one transmitting in right-Handed circular polarisation and the other in left-handed circular polarisation, respectively. Once EAM pointing has been achieved, the spacecraft is placed in its nominal orbit via Drift and Fine Positioning manoeuvres, symbolised in Figure 1 by the transition arrow between the depicted spacecraft. With the spacecraft finally in its nominal orbit, its payload commissioning is completed and undergoes additional In-Orbit Testing (IOT). The scope of this campaign is to verify and demonstrate that the payload performance in space is comparable to the on-ground measurements and that it the other Galileo spacecraft in their routine navigation service provision.

3. System Requirements

Before a control centre can execute its very first LEOP, there is a manifold of necessary systems that must designed, deployed, verified and validated. Here, many of these ground and space systems are discussed, as well as some of their driving requirements. In Figure 2, the system related activities are those left of the launcher. There, a critical first milestone is the success of the System Compatibility Test Campaign (SCTC), detailed further in subsection 3.1. Once this compatibility is ensured, all teams must document all their possible LEOP activities, both for nominal and contingency scenarios, during the Procedure Preparation phase. With this documentation in place, the Operational Validation Readiness Review (OVRR) may be kicked off during which all systems are end-to-end tested, validated and verified, listed as the Ground Segment Setup phase in Figure 2. Crucially, an end-to-end Key Loading Verification Test (KLVT) is executed, since for Galileo's L11 spacecraft communication is done exclusively via encrypted connections from the moment the spacecraft boot up after fairing separation, as described in section 2. Once all test campaigns are passes and the systems are accepted a system Freeze was set in place. In Figure 2, this event is symbolised by the lock upon successful Operational Readiness Review (ORR). This freeze was required to be at least one month long, with only extremely urgent system changes being accepted, to mitigate any system risks prior to the launch.

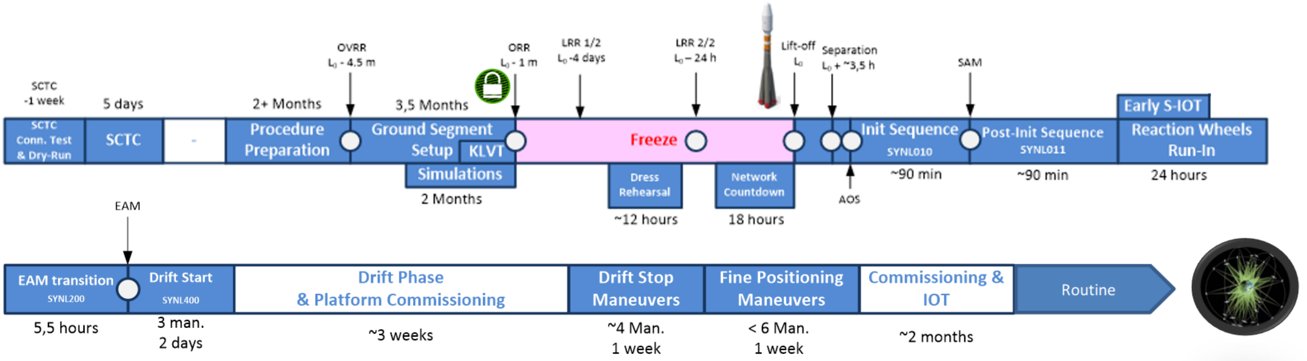

Figure 2: Timeline for 11th Galileo Launch and Early Orbit Phase (LEOP) [12].

3.1. Space System Requirements

Naturally, most of the space system requirements are directly reflected on the spacecraft themselves. Once the spacecraft to be launched were successfully assembled and integrated, they were shipped to the European Space Agency's (ESA) spacecraft test centre ESTEC (European Space Research and Technology Centre) for a three-months test campaign, before they can be accepted by ESA and declared ready for flight. Within these tests campaigns, the spacecraft are exposed to environments similar as those experienced by the spacecraft in space such as vacuums and extreme temperature profiles under close monitoring of the spacecraft's behaviour. Equally, the spacecraft undergoes heavy testing to ensure they are capable of surviving the noise and vibration from the launch without any detriments. Additionally, the spacecraft must also undergo an SCTC to ensure the compatibility of the spacecraft and the Galileo Control Centre. During this campaign, all nominal routine activities are executed which are expected of the spacecraft once in orbit. These activities include platform commissioning, payload activation, software patches and flight dynamics tests. Contingencies are also testing, which include triggering the spacecraft safe mode, its recovery from this mode, as well as LEOP contingency scenarios in case of issues during INIT or POST-INIT, see Figure 2. As shown in Figure 2, the SCTC is the first major milestone that had to be cleared for Galileo's L11 [3]. Noticeably, the SCTC equally tests the Galileo Control Centre's capabilities, as detailed further in subsection 3.2.

3.2. Ground System Requirements

The implementation of systems capable of supporting a Galileo launch were quite specific due to the large nature of the constellation. A particular difficulty came from the LEOP support systems needing to be independent from those used for routine operations. This was required to ensure that any impact on the LEOP system could not affect the system used for routine operations, and vice-versa. Equally, the LEOP system needed to have a reliable connection to the routine one to facilitate a seamless transition of the spacecraft handling from LEOP to routine operations. This feat was managed by essentially creating a miniature version of the already existing system, with this new version being independent from the main version in its setup, having its own redundant and backup systems. This made it possible to use already existing interfaces with external entities, as well as supporting elements and systems. However, another major change in system design needed to be considered as well: The entire system architecture was modernised, switching from server-based elements to entirely virtualised ones. This modernisation brought with it the advantage that elements could be maintained centrally and that if any physical server experienced any issue, the affected virtual machines could be automatically transferred to another physical server. With this added layer of redundancy, the affected physical server can be recovered with vastly lesser impact on operations on the affected virtual machines. Noticeably though, this modernisation also vastly increased the necessary validation as not only did every capability need to be tested for possible regression, all the new system capabilities needed to be validated as well.

Additionally, there were also other entirely new systems that needed to be set up, such as secure network connections to the launch site at the Guiana Space Centre (CSG; French: Centre Spatial Guyanais), in Kourou, French Guiana. Due to the necessary separation of the LEOP from routine activities, none of the six ground stations available exclusively for commanding the Galileo constellation could be used. Thus, an entire new network needed to be established to connect to the launch site and the necessary LEOP antennas, which is detailed further in subsubsection 3.2.1.

To test the new spacecraft as described in subsection 3.1, the new LEOP systems needed to be already well established in time for the SCTC described above, resulting in a much earlier deployment and validation which unfortunately coincided with strict Covid lock-downs. For this validation, the most impacting restriction was the strict limit of the maximum number of people that could be at any given time in a room. To minimise impact on the timeline, only exacerbated by sheer extensiveness of the validation activities, operation teams were split up into two sub-teams. These sub-teams were then assigned to a shift pattern, allowing for program working days which were effectively double as long as usual with one shift starting extremely early and the other one ending late at night.

3.2.1. Ground Stations Network

Since the many additional LEOP ground stations are only required for a limited time span, the support of an external Network Operations Centre (NOC) was enlisted to facilitate the connection to these external antennas. For this task, the German Space Operations Centre (GSOC) was chosen as partner due to its experiences with other missions and already existing partnerships to ground station providers. A major task of the NOC was to coordinate station availabilities and bookings, together with data provision and network management [1]. With this contract, twelve ground stations were available for L11, ensuring continuous global coverage of the spacecraft in orbit as well as antenna redundancy for particularly critical phases such as INIT, Post-Init or manoeuvres.

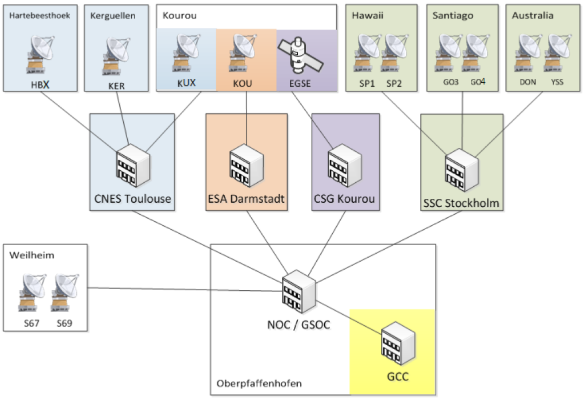

Figure 3: Ground Station Network overview. [1].

These antennas were provided by the German Aerospace Center (DLR) antenna network in Oberpfaffenhofen (2 antennas), the Swedish Space Corporation (SSCspace; 6 antennas), CNES (3 antennas) and the European Space Tracking network (ESTRACK; 1 antenna), see Figure 3. Additionally, NOC also manages the network connection to the launch site, listed as Electronic Ground Support Equipment (EGSE) for the CSG. For the end-to-end testing campaigns between the Galileo Control Centre and actual spacecraft in-orbit, via both NOC and all antennas, flying Galileo spacecraft were used that nominally use the same communication frequencies as the L11 spacecraft.

4. Team Training

In parallel to the Ground Segment Setup phase described in section 3, all LEOP operational teams must undergo extensive training on all LEOP phases, both for all nominal and potential contingency scenarios. This is achieved by means of Simulations, which attempt to recreate the actual LEOP scenario as close as possible [8]. In these simulations, all team members nominated for LEOP are brought together in their respective shifts, oftentimes together with the supporting external entities, to train and execute all LEOP phases which are detailed in section 2. While these phases are only executed by one given LEOP team during the actual LEOP, it is of utter importance that all teams are familiar with all phases in case that the original team cannot. For L11, this was more so a concern due to the implications of a single team member being Covid positive, which could have led to the entire team being put in quarantine.

For L11, there were four independent shift teams that underwent training in four distinct LEOP phases: INIT and early PostInit, PostInit, SAM2EAM (Sun Aquisition to Earth Aquisition Mode) and MAN (Manoeuvres) phases. For details on the individual activities executed during these phases see section 2. These simulation trainings were spread out over the course of two months, with a simulation unit taking up an entire working day. To ensure the reproducibility of the simulations across teams, so called simulation breakpoints were used which act as an instantaneous snapshot in time of the spacecraft state, both in terms of its configuration and its location. Noticeably, as for L11 two spacecraft were launched which lead to the teams having to coordinate the monitoring and commanding of these spacecraft simultaneously. For certain phases, such as SAM2EAM, it is possible to leave one spacecraft in a stable configuration which merely required babysitting activities, allowing the teams to fully concentrate on the activities of the other spacecraft. For other activities however, such as INIT and PostInit, both spacecraft must to be managed simultaneously putting additional load on all teams. To prepare all teams in dealing with LEOP anomalies, many of the simulation trainings included the injection of issues of varying degrees. Therein, the training managers made sure that all operational teams were confronted with issues in their respective field of expertise, even including cases were a spacecraft could be entirely lost. For the Space Segment teams, contingency scenarios included issues of varying degrees on solar array deployment, heater issues, tank pressure issues, loss of spacecraft sub-units, thruster issues and misconfigurations due to the flipping of bits induced by radiation. On Ground Segment, contingency scenarios included loss of antenna availabilities, antenna uplink and downlink failures, network issues, loss of entire control facilities due to server issues and the evacuation of the control rooms due to fire drills [11]. Supporting teams, both internal and external to the Galileo Control Centre were also included in these simulation campaigns. This included database analysts, product assurance, planning and flight dynamics teams for the preparation of inputs to operations and the coordination of mitigation measures on-the-fly during contingency operations. The spacecraft manufacturer (OHB) as well as the European Space Agency also joined these simulations to offer support in their respective fields of expertise. Equally, shift handovers were also simulated due to the large formal information and documentation handover required between shifts.

As a last preparation activity, a formal Dress Rehearsal is executed several days before the actual launch. Here, the nominal scenario for the launch day will be rehearsed for the last time, comprising the connectivity tests to the tracking stations used for First Acquisition.

5. LEOP Execution

As per launcher availability, the provided launch window for L11 between November 22nd and December 24th, 2021 with the launcher being operated by Arianespace and commissioned by ESA. Having this window, together with the constraints highlighted by planning and flight dynamic teams the formerly chosen date became the 2nd of December, 2021. Thus, the L11 Dress Rehearsal for the opeartional teams at the Galileo Control Centre was executed on the 2021-11-26, with the Network countdown rehearsal with the ground stations being executed on 2021-11-29. After a meticulously of these test results, all ground segment elements reported GREEN at the Launch Briefing on 2021-11-30.

However, the L11 launch needed to be postponed on 3 separate attempts due to either bad weather conditions, a red flag from a tracking ship during the launch countdown and again due to abnormal weather conditions 8 minutes before lift-off [13]. While the launcher itself would have been able to reach its destination without issues despite the weather conditions, the potential trajectory of discarded launcher elements posed irreconcilable safety concerns. The tracking concern in question is a mobile tracking station, employed by the launch service provider to ensure continuous tracking of the launcher as it crosses the atlactic ocean while still having low altitude.

After this three-day delay, on Dec. 5, at 00:19 GMT the pair of 715 kg Galileo satellites 27 and 28 were successfully launched on Soyuz launcher VS-26 from Europe's Spaceport in French Guiana. All launcher stages performed nominally and the spacecraft separation occurred as expected on 05.12.2022 at 04:11 GMT, around 3 hours and 54 minutes after liftoff. After a suspenseful moment, the spacecraft booted successfully and their first telemetry after launch was correctly acquired by the expected ground stations, for 27 at 04:16 GMT and for 28 at 04:13 GMT. The telecommand (TC) capability was confirmed on both spacecraft with a test command being acknowledged on both spacecraft at 04:23 GMT. Equally, the Breathing point was reached on both spacecraft within the expected time frame at around 05:19 GMT. At this point, both spacecraft had reached Sun Acquisition Mode, with their Solar Arrays correctly deployed ensuring the batteries' charging. Equally, Post-Init, S-IOT and EAM activities were completed nominally, see section 2 for details on these phases. With all of these checks cleared, the spacecraft initiated their drift and fine positioning manoeuvres to reach their working orbit at 23,222 km using their on-board thrusters, while simultaneously having their payloads gradually commissioned for operational use. All of the manoeuvres performed nominally, their execution dates within the slots foreseen in the initial L11 mission timeline, leading to the final handover of the L11 spacecraft to the routine team on 2021-12-14. Except for the need to re-defined the LEOP timeline due to several launch delays, the L11 LEOP itself was fully nominal and none of the planned backup slots were required to be used. This feat demonstrated an excellent maturity of the procedures and products prepared for this LEOP and of the overall teams sizing and level of training.

6. Lessons Learned

During the successful execution of all the LEOP phases, several Lessons Learned emerged that will be taken into consideration for the next Galileo launches.

While spacecraft launches are planned for a specific time slot, launch delays are not uncommon to ensure the payloads safety. Naturally, a high number of postponements typically ends up in increased work loads, in particular for planning teams. Not only do all flight constraints need to be checked and respected, such as the specific available windows for certain activities, antenna availabilities must also be respected.

For these reasons, backup plans had been made for Galileo's L11 LEOP. Nevertheless, for future launches measures will be taken to facilitate dealing with the exceptional workload and the time constrains resulting from unexpected events which require updates to the sequence of events, or the creation of new contact plans. This includes a fine tuning of the number of resources involved, and their availability. The experiences made with the L11 LEOP will enable better frame agreements with external antennas, to ensure availability despite delays. In addition, ways to enhance and make the available planning tools more robust and flexible to deal with unexpected, additional delays are under investigation. Lastly, the planning team will be set on-call for the whole duration of the LEOP. This is expected to foster better decision making in cases where activities need to be postponed or delayed, by allowing a thorough analysis of potential issues, and their effects on the mission timeline.

Similarly, the impact of launch postponements onto our flight dynamics teams have brought forward some lessons. As extensive launch delays require the required re-computation, verification and validation of manoeuvre strategies to enable their event file generation and the creation of antenna pointing products, flight tools improvements similar to those of the planning tools are envisaged. For high intensity phases where the workload for the flight engineers was exceptionally high, such as INIT and PostInit, an additional flight dynamics team member is envisaged. Regarding flight products, antenna pointing files will be distributed at a higher frequency, specially for periods with higher orbit uncertainties such as separation and orbit manoeuvres. This measure, together with providing ground stations with pointing data that begins before their start of contact is expected to further enhance ground station pointing robustness. Additionally, for the next Galileo launches, carrier polarization swaps will be looked into deeper. During such a swap, commanding is unavailable since the ground station carrier is turned off before it can be turned back on with a different polarisation. While disturbing to operations, these swaps cannot be avoided. Having estimates of their occurrences can be used for planning, highlighting windows with lower commanding availability. While rare, such occurrences include cases where both spacecraft transmitter are pointing perpendicular relatively to ground stations, resulting in insufficiently weak links for commanding.

While a launch requires unavoidable, continuous monitoring and controlling over several days, future Galileo launches will ensure a proportionate and fair distribution of shifts between teams. Where possible, it will be attempted to maintain the shifts of teams as consistent as possible to allow staff to settle into sleep cycles, without the need to re-adjust sleeping patterns often.

On networks side, the data exchange node will be cleaned up periodically to prevented exchange delays or even overloads, which is particularly important during periods of high data exchange. This measure will be implemented either by a periodical script or by automatic file deletion after it has successfully been delivered.

Lastly, spacecraft manoeuvres handling will be adjusted. Such manoeuvres foresee a buffer time of 4 hours, with the definite timeslots for the thruster boosts being defined shortly beforehand, once orbit uncertainties are low enough. After a manoeuvre, it is of utter importance to execute as many high-quality ranging measurements as feasible, to improve orbit determination uncertainties and thus improving any orbit predictions. To avoid potential planning conflicts, no rangings are planned within the manoeuvre buffer slot. Conversely, it was experienced as more robust to schedule rangings which are executed autonomously at regular intervals. With this approach, operational teams can cancel all not needed rangings and in case that the manoeuvre is executed at the beginning of the buffer slot, no manual execution of the rangings is required while being able to let automation take over.

7. Future Launches

With the overwhelming success of L11, as detailed in section 5, future Galileo LEOPs will also be executed under responsibility of GSOp from the Galileo Control Centre. Pending launcher confirmation, the 12th (L12) and 13th (L13) Galileo launches are envisaged for 2024, with the 14th (L14) launch being potentially executed in 2025. This would inevitable result in preparation activities for L13 being in parallel to the finalisation activities for L12. Possibly, pending confirmation for L14, the final L12 activities might even coincide with the L14 preparations while L13 is being executed. While this poses a certainly exciting period for all operational teams, precautions must be met so that any risks to the timeline and the safe execution of activities is mitigated. Naturally, the Lessons Learned listed in section 6 will be incorporated, while keeping track of any other improvements for operations.

8. Acknowledgements

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