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Flight Dynamics Experience on Galileo Station-Acquisition Operations

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Abstract

December 5 2021 marked the start of Galileo's eleventh launch, L11, from the Guiana Space Centre in Kourou with a Soyuz carrying the latest two Galileo spacecraft, GSAT0223 and GSAT0224. For the first time, the Flight Dynamics operations was under the full responsibility of DLR GfR - in close cooperation with DLR German Space Operations Centre's Flight Dynamics team - conducted from within the Galileo Control Centre in Oberpfaffenhofen, Germany. The preparation and execution of the Galileo station-acquisition operations are described, focusing on the close collaboration between both Flight Dynamics teams. The paper explains the mission analysis to define a manoeuvre strategy of three drift-start manoeuvres, three drift-stop manoeuvres and up to six fine-positioning manoeuvres after separating from the Soyuz launcher. While the target acquisition method was laid out and the Flight Dynamics teams were trained and prepared for mission execution, sources of dispersion were introduced during L11 operations, causing the operational manoeuvre strategy timeline to diverge from the nominal timeline originating from the mission analysis. By investigating the divergence between station-acquisition manoeuvre plan and manoeuvre execution, this paper shows an assessment on the robustness of the mission planning and operation procedures of the Flight Dynamics teams. Outlining the refinements that needed to be introduced during operations - in order to react to these sources of dispersion - are an important aspect of this paper. The main sources of dispersion mentioned in this paper are: (1) four launch delays, which is more than covered by the ESA-required mission analysis including two delays; (2) injection assessment and separation; (3) orbit determination and propagation; and (4) thruster activity early in the spacecraft's life. Analysing the effect of these sources of dispersion led to valuable insights and lessons learned for upcoming launches. An example recommendation is to extend the time in between fine-positioning manoeuvres in order to improve the orbit determination process. In its turn, it allows for a better assessment in the decision-making process whether to execute an additional fine-positioning manoeuvre to reach the target slot. Ultimately, the successful L11 stems from an efficient collaboration between both Flight Dynamics teams so that GSAT0223 reached its target slot B03 after 10 manoeuvres: three drift-start, three drift-stop and four additional fine-positioning manoeuvres. GSAT0224 needed one additional fine-positioning manoeuvre to reach its target slot B15.
Keywords: Flight Dynamics Operations, Galileo, Station Acquisition, Manoeuvre Strategy

Nomenclature

$\frac{d^2\boldsymbol{r}}{dt^2}$	Acceleration of the spacecraft (second time derivate of spacecraft's position vector)
$\boldsymbol{f}$	Acceleration acting on the spacecraft
r	Spacecraft distance to Earth
$\boldsymbol{r}$	Position vector of the spacecraft
μ	Earth's gravitational parameter

Acronyms/Abbreviations

AoL	Argument of Latitude
CNES	French Space Agency
CSG	Guiana Space Centre
DLR	Deutsche Zentrum für Luft- und Raumfahrt / German Aerospace Centre
DSFP	Drift Stop and Fine Positioning, covering manoeuvre phases C and D
ENOC	External Network Operations Centre
ESA	European Space Agency
FD	Flight Dynamics

GCC	Galileo Control Centre
GCC-FD	DLR GfR's Flight Dynamics
GfR	Gesellschaft für Raumfahrtanwendungen / Space Applications Institute
GSAT	Galileo spacecraft
GSOC	German Space Operations Centre (DLR)
GSOC-FD	DLR GSOC's Flight Dynamics
GSOp	Galileo Service Operator
L	Launch
LEOP	Launch and Early Operations Phase, covering drift-start manoeuvres phase A
OCM	Orbit Control Manoeuvre
OD	Orbit Determination
TTCF	Telemetry, Tracking and Control Facility

1. Introduction

On December 5 2021, the latest two Galileo spacecraft (GSAT0223 and GSAT0224) were launched from the Guiana Space Centre (CSG) in Kourou as Galileo's eleventh launch (L11). Galileo, Europe's global spacecraft navigation, timing and positioning system, now counts 28 spacecraft after the successful launch of the two new members in the Galileo spacecraft family, the first pair of the third batch of Galileo First Generation spacecraft. The constellation of Galileo spacecraft serves over two billion users around the globe, offering the most precise spacecraft navigation system to date. With GSAT0223 (from nominal slot) and GSAT0224 (from auxiliary slot) operational and four other Galileo spacecraft not usable or unavailable, the Galileo family is one short of the planned 24 operational spacecraft in nominal slots. Ultimately, together with six auxiliary spacecraft, the Galileo constellation will consist of 30 spacecraft positioned at an altitude of 23,222 km with an inclination of 56 degrees, spread over three different orbital planes.

For the first time, the Launch and Early Operations Phase (LEOP) for L11 was under the full responsibility of the DLR Space Applications Institute (DLR GfR), conducted from the Galileo Control Centre (GCC) in Oberpfaffenhofen, Germany. L11 kicked off the transition to full independency of the Flight Dynamics (FD) operations by GCC's internal DLR GfR's Flight Dynamics team (GCC-FD), with DLR's German Space Operations Centre (GSOC) Flight Dynamics team (GSOC-FD) as support and back-up. In contrast, during previous LEOPs for the Galileo constellation, the station-acquisition operations were performed sharing responsibility, with external support from the European Space Agency (ESA) and the French Space Agency (CNES) [1-4].

This paper focuses on the flight dynamics experience gained during the station-acquisition operations for Galileo's eleventh launch. The goal of this work is to analyse and reflect on the manoeuvre strategy and execution for station-acquisition operations applied to L11, to share lessons learned and to provide insight into the FD operations, in recognition of the upcoming Galileo station-acquisition operations.

After outlining L11 within the bigger setting of the Galileo constellation in section 2, the paper addresses the organisational facets of the collaboration between GCC-FD and GSOC-FD in section 3, dissecting the responsibilities of the FD system within the Ground Segment of the GCC, together with a description of the teams, their interfaces and their shift composition. In order to share the flight dynamics experience gained during the L11 Galileo station-acquisition operations, the manoeuvre strategy and target acquisition method are explained in detail in section 4, paying special attention to the operations of the drift-start, drift-stop and the fine-positioning manoeuvres. Section 5 describes the operational FD activities performed during launch, LEOP, drift stop and fine positioning to bring GSAT0223 and GSAT0224 into their target slots, followed by a discussion on lessons learned and experiences gained during the station-acquisition operations. The conclusion and outlook on next Galileo launches in section 6 completes this paper.

2. Mission Description

To enable the world's most precise spacecraft navigation positioning system, flight VS26 launched from the CSG on December 5 2021 at 00:19 UTC after four launch postponements. L11, carrying GSAT0223 and GSAT0224, brought the launched Galileo spacecraft tally to 28. GSAT0223 replaced the earlier relocated GSAT0204 in the nominal slot B03, while GSAT0224 was placed in the auxiliary slot B15. The current status is such that 23 spacecraft are operational and providing service in the nominal slots, while GSAT0224 is usable from an auxiliary slot. GSAT0201 and GSAT0202 are not usable and were placed in eccentric orbits. GSAT0104 and GSAT0204 are not providing service from the auxiliary slots C14 and B14, respectively. The constellation status is depicted in Fig. 1, with the green and orange dots representing spacecraft in nominal and auxiliary slots, respectively [5].

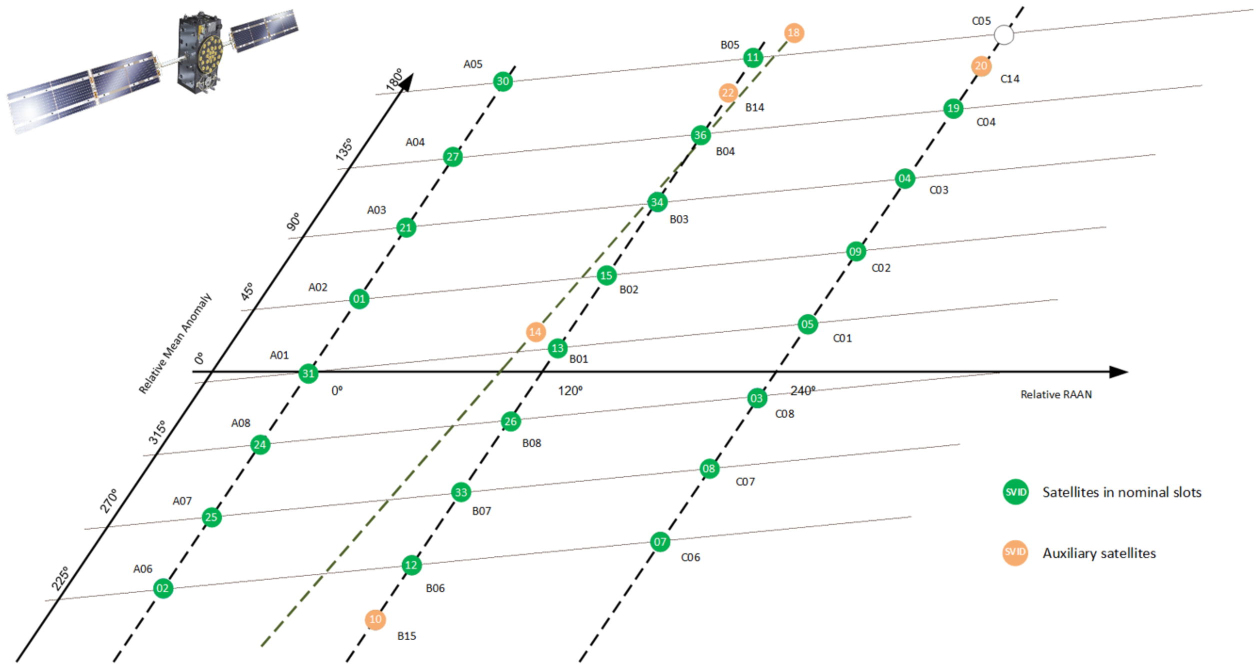

Fig. 1. Current status of the Galileo constellation [5].

3. Flight Dynamics Organisation

On an organisational level, L11 marked the start of independent FD operations from within the GCC in Germany. To allow for a smooth transition to full independency, a redundant FD system was introduced as back-up system for verification and validation. While GCC-FD was ultimately responsible for the entire FD operational activities, products generation and distribution, GSOC-FD closely contributed and collaborated to activities such as the injection assessment, orbit determination and manoeuvre strategy, planning, implementation and calibration.

With the GCC-FD – consisting of seven engineers (six LEOP-operations engineers, one routine and special operations engineer for the constellation) - and GSOC-FD – consisting of six engineers - collaborating from separation to target-slot achievement, the preparation, training and execution of L11 required streamlined and effective teamwork between the two teams.

An FD-integrated operational shift plan was developed, ensuring compatible and fully-harmonised nominal and back-up solutions within the overall Galileo Service Operator (GSOp) shift plan for the L11 LEOP. Specifically, per shift, the FD tasks - such as orbit determination, manoeuvre sequence updates, product generation, quality checks and product distribution - were performed by minimum four FD engineers: two in GCC and two in GSOC. This approach allowed for cross-validation, guaranteed product quality and promptness. Additionally, in case of unavailability during one of the planned shifts, one engineer per team was available as back-up, whereas two engineers per team were on-call to provide support outside of the FD shifts.

Operationally, the shifts - consisting of two shift teams - were composed so that the responsibility of one spacecraft belonged to one dedicated team. Although mainly working on critical activities of one spacecraft, the same team performed non-critical operations on the other spacecraft, such as orbit determination, too. Each shift started two hours prior to the start of a manoeuvre window and finished at the end of a manoeuvre. Since the critical activities of the spacecraft had to be separated as per ESA requirements, a shift overlap was not guaranteed.

During the critical phases of LEOP and the station-acquisition operations, L11 greatly benefited from the integrated, efficient and effective teamwork delivering prompt, thorough and reliable products that led to successful target acquisitions for both spacecraft.

4. Mission Analysis

The manoeuvre strategy, the groundwork that led to successful target-slot acquisitions, stems from a mission analysis performed for L11, with the objective to define valid manoeuvre sequences for GSAT0223 and GSAT0224. This mission analysis was performed for the planned launch day (December 1, 2021) and for the two following days, as per ESA requirements.

The aim of the manoeuvre strategy (see section 4.1) is to correct for errors in the separation orbit and to achieve the dedicated target slot within the Galileo constellation with the required accuracy, in accordance with all applicable constraints, as discussed in section 4.2.

4.1 Target Acquisition Method

Each manoeuvre strategy consists of three drift-start (LEOP manoeuvres, phase A) and three drift-stop manoeuvres (Drift Stop and Fine Positioning (DSFP) manoeuvres, phase C), which are separated by a manoeuvre-free drift phase (phase B). The subsequent fine positioning (DSFP manoeuvres, phase D) may consist of maximum six further manoeuvres, such that in total a maximum of 12 manoeuvres is required to achieve the target slot.

The input to the mission analysis is fourfold:

- the injection state vectors, stating the separation orbit parameters for the nominal launch date and two consecutive days as back-up launch opportunities;
- the injection dispersion values in all orbital elements;
- the target state vectors for day 60 after separation (for the nominal launch date);
- the ground station network, consisting of 18 ground stations as presented in Table 1 listing the location, antenna ID, network and mission phase applicable to the station.

Table 1. LEOP and Galileo Routine Network ground stations.

Location	Antenna ID	Network	Mission Phase
South Point, USA	ESP1 ESP2	SSC / Prioranet	LEOP, DSFP
Dongara, Australia	EDON		LEOP, DSFP
Yatharagga, Australia	EYSS		LEOP, DSFP
Santiago, Chile	EGO3 EG04		LEOP, DSFP
Hartebeesthoek, South Africa	EHBX	CNES	LEOP, DSFP
Kerguelen, France	EKER		First acquisition
Kourou, French Guiana	EKUX		LEOP, DSFP
Kourou, French Guiana	EKOU	ESA	LEOP, DSFP
Weilheim, Germany	ES67 ES69	DLR	LEOP, DSFP
Kourou, French Guiana	ES21	Galileo Routine Network	DSFP
Kiruna, Sweden	ES28		
Papeete, French Polynesia	PA01		
Noumea, New Caledonia	NU01		
Redu, Belgium	RE01		
Reunion, Réunion	RN01		

4.2 Flight Dynamics Mission Constraints

The manoeuvre strategy was optimised considering the following constraints:

- Operational constraints:
  - The first drift-start manoeuvre shall not be performed before successful Earth Acquisition Mode of both spacecraft;
  - Two manoeuvre slots on the same spacecraft shall be separated by at least 26 hours;
  - Two manoeuvre slots on different spacecraft shall be separated by at least five hours;
  - The drift phase shall end at 2022/01/10. This date shall be kept for launch delays up to seven days;
  - The fine positioning shall be finalised latest 60 days after separation;
  - Manoeuvre slots of four hours shall be fixed in advance for mission planning purposes.

- Ground station visibility constraints:
  - A1 manoeuvre on each spacecraft shall be performed with double station coverage;
  - For each manoeuvre slot, continuous ground station visibility shall be given for one hour before and after the manoeuvre slot;
  - No swap of ground station shall be necessary for one hour before until one hour after each manoeuvre slot.
- Sensor constraint:
  - No double inhibition of the infra-red Earth-horizon sensor by the Sun or the Moon (at any time) or by Earth polar regions (during hemisphere winter) shall occur during the orbit control manoeuvre (OCM).
- Conjunction constraints:
  - No close conjunctions with constellation objects with collision probability higher than 10e-5;
  - A minimum distance of 100 km to all other objects in the constellation shall be respected.
- Power and thermal constraints, among others:
  - OCM shall be entered only with fully-charged battery. In case of an eclipse before the OCM, the battery discharge must be computed;
  - Eclipses shall be entered only with fully-charged battery. In case of an eclipse after a manoeuvre, the battery discharge must be computed.

4.3 Manoeuvre Strategy

In the end, 36 manoeuvre strategies were optimised for minimum ΔV, considering the input and constraints described in sections 4.1 and 4.2, respectively: for nominal injection and injection with ±3sigma dispersion for each launch day (nominal launch day and two back-ups), for two target slots (B03 and B15) and for two spacecraft (GSAT0223 and GSAT0224). Not so much the optimisation of single manoeuvres, but rather the optimisation of the manoeuvre sequence - complying to all constraints - forms a challenge, resulting in an iterative process of adapting four-hour manoeuvre slots to obtain the minimum ΔV. Furthermore, rather than the timing and size of the manoeuvres, it was essential to fix the four-hour manoeuvre slots for mission planning purposes. Table 2 shows the result of the mission analysis for L11. It shows the proposed manoeuvre plans for the three launch days, for both spacecraft going to their respective optimal target slot and the total ΔV for nominal injection and injection with ±3sigma dispersion. All presented manoeuvre plans are feasible in terms of required ΔV and applicable constraints.

Table 2. Summary of proposed manoeuvre plans for all launch days.

Launch day	**Spacecraft**	**Target slot**	**Total ΔV (m/s)**		
			Nominal	**+3σ**	**-3σ**
2021/12/01	GSAT0223	B03	19.271	26.942	17.360
	GSAT0224	B15	17.771	24.740	16.112
2021/12/02	GSAT0223	B03	19.609	26.734	26.227
	GSAT0224	B15	17.752	23.892	15.223
2021/12/03	GSAT0223	B03	21.851	31.040	19.522
	GSAT0224	B15	17.757	24.248	21.557

The spacecraft assignment to target slots (GSAT0223 to B03 and GSAT0224 to B15) was based on the minimum total ΔV, considering each spacecraft going to each of the target slots for each of the injection options (nominal, ±3sigma). During mission execution, the assignment was finalised based on the determined injection orbit.

5. Operations

With the manoeuvre strategy in place and both GCC-FD and GSOC-FD fully trained and prepared for mission execution, the FD operations were performed in December 2021 and January 2022. This section reports on the FD operations: from launch and injection orbit to the LEOP and DSFP manoeuvres, from a performance analysis to an overview of lessons learned during L11.

As for any space mission, there are sources of dispersion that cause the operational manoeuvre-strategy timeline to diverge from the nominal timeline laid out during the mission analysis. The main sources of dispersion that affected L11 are discussed throughout this section and are fourfold:

- launch delay;
- injection assessment and separation;
- orbit determination and propagation;
- thruster activity early during LEOP.

5.1 Launch and Injection

Due to adverse weather conditions at the CSG, L11 - initially scheduled for December 1 2021 - was postponed. Additional launch attempts were made on the three consecutive days - as unfavourable weather conditions and tracking issues on the ship (required for monitoring the Soyuz ascent phase) resulted in further launch delays – before launching the latest Galileo spacecraft on December 5 2021.

The launch delay of four days caused the same amount of launch operations interruptions happening a handful of minutes before the expected launch epochs. Consequently, both GCC-FD and GSOC-FD had to efficiently react to ensure a prompt re-planning which accounted for the earliest-targeted new launch date announced by the launch authorities.

Since L11 was delayed by four days, which is more than anticipated and accounted for by the L11 Mission Analysis (conform ESA requirements, as discussed in section 4), the FD operations were greatly impacted:

- concerning the first two launch delays (i.e. within the foreseen two days back-up launch opportunities), the impact was mainly limited to additional coordination activities with the operations teams, to ensure that the already defined, verified and validated manoeuvre strategies were implemented correctly in the operational timeline and relative shift plan. The GCC-FD team was on the front line, acting as a single point of contact for the GCC-Mission Director and all the operational teams within GCC with the goal to smoothen communication.
- concerning the following two launch delays outside the foreseen launch window, the FD operations were affected further due to the need to define, verify and validate valid manoeuvre strategies for each spacecraft for each targeted new launch date and due to the contribution to the re-generation of a new operational timeline. The main tasks can be summarised as follows:
    - manoeuvre strategy computation for each spacecraft;
    - manoeuvre strategy verification and validation;
    - event file generation for the planning team;
    - pointing products generation for External Network Operations Centre (ENOC) and Telemetry, Tracking and Control Facility (TTCF) ground stations;
    - Flight Dynamics system configuration set-up in accordance with new launch epoch.

  Both GCC-FD and GSOC-FD teams were greatly involved in the critical phases of defining a qualified operational timeline, working on very tight deadlines. Thanks to the GCC-FD and GSOC-FD integrated operational concepts, the FD team was able to cope with the additional launch delays - and all the activities that followed - efficiently and effectively by leveraging the usage of the two FD-systems to speed up the needed duties and cross-validate the results before distribution.

After launch and separation, a preliminary assessment on the injection orbit is needed in the CSG control room within the first 20 to 40 minutes after separation. For L11, this information was communicated by the GCC-FD team - after cross-validation with GSOC-FD's independent assessment - to the Mission Director in the frame of the Mission Status evaluation.

Specifically, the preliminary assessments were performed at separation time plus 22 and 37 minutes. From the comparison between the actual ground station azimuth and elevation and the respective expected values, no indication of major failures was found. The azimuth and elevation evolutions were well enclosed within the envelope of evolutions expected under any recoverable injection error, considering the available ΔV.

After 1hr 25min from separation, a qualitative assessment of the spacecraft injection orbit was performed, excluding off-nominal injection and thus providing the GCC operations team with the go-ahead to proceed with the next LEOP phases. The first official orbit determination was performed during the post-initialisation phase, when at least one orbit (i.e. ~14 hours) of measurements were available, and triggered the refinement of the originally-planned drift-start manoeuvre strategy for each spacecraft.

The delicate and time-critical assessments following the spacecraft separation greatly benefited from the GCC/GSOC-FD integrated operational approach, both for the purpose of cross-validating the results and building up the confidence of the FD teams conducting the first LEOP under the full responsibility of DLR GfR.

5.2 LEOP and DSFP Manoeuvres

The aim of the following section is to provide a descriptive analysis of the Orbit Determination (OD) processes employed through all the LEOP phases. Firstly, the sensor network, along with tracking data statistics associated to both spacecraft are presented.

The ground stations network of the LEOP and Galileo routine phase is introduced in Table 1. Overall, a total number of 18 ground stations provided high-frequency two-way ranging to track the two newly injected spacecraft. As shown, the ground network can be divided in Galileo Routine TTCF stations and LEOP-ENOC stations provided by ESA to support the early orbit phase. The ENOC ground stations were in charge of tracking during injection, drift-start, drift-stop and fine-positioning manoeuvres, providing measurements in phase-modulation mode. The routine TTCF Galileo ground stations were assigned to provide data in spread-spectrum mode during drift-phase, drift-stop and fine-positioning manoeuvres.

The geographical location of the ENOC stations is shown in Fig. 2, showing that the tracking is optimised for the orbital plane of the injected spacecraft. The selection of the stations, in fact, ensures high visibility and dual coverage during critical mission operations.

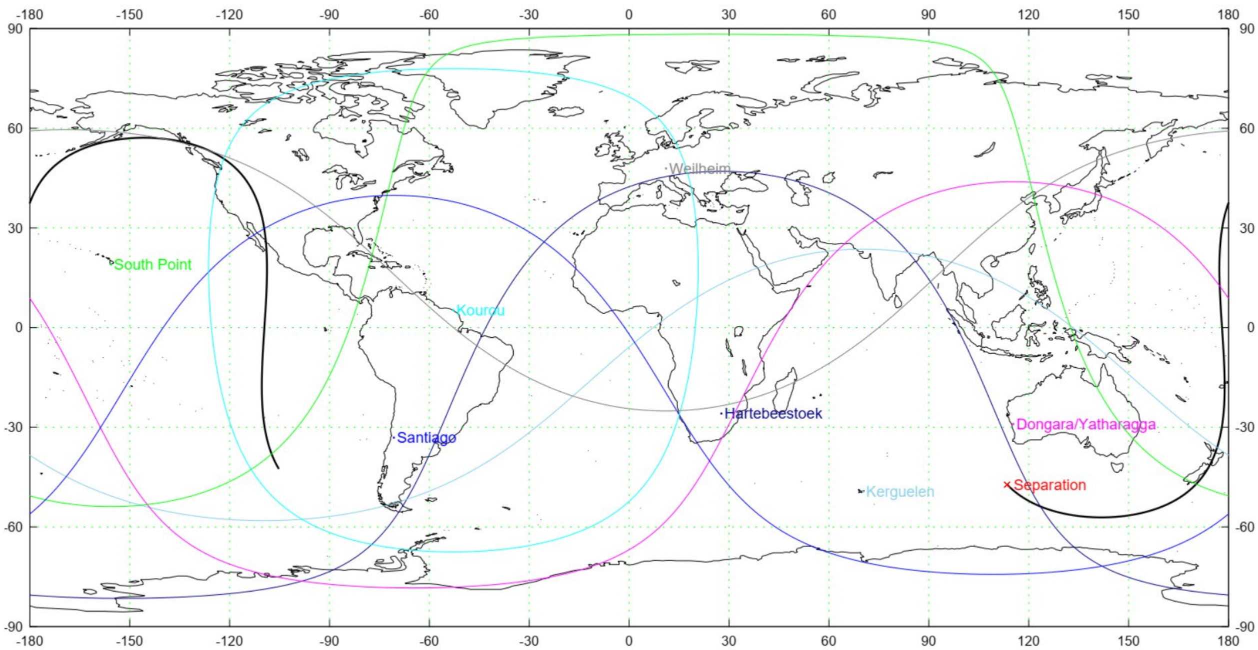

Fig. 2. Geographical location of ENOC ground stations for the Galileo LEOP.

The tracking performance of all ground stations involved during the entire station acquisition is shown in Table 3. For each spacecraft, the total number of ranging measurements is compared to the used tracking data by the OD solver. Overall, more than 70,000 measurements were provided for both spacecraft with an average of roughly 4,000 per tracking station. The OD process estimated the orbits of both spacecraft considering more than 92% of the total number of observations as valid observations.

The tracking data has been processed to constantly determine the orbits and calibrate manoeuvres throughout the entire LEOP campaign. Fig. 3 shows ranging measurement residuals for the spacecraft GSAT0223 during three drift-stop and four fine-positioning manoeuvres. As illustrated, the timeline spans approximately 10 days in which a total number of seven manoeuvres (red vertical lines) were performed. Within this timeframe, all stations of the ground network contributed to the orbit estimation by providing measurement data. It is important to note how the observation frequency changed before approaching the fine-positioning manoeuvres: their consistently-reducing magnitude requires more data for a proper calibration and final target acquisition assessment. In general, the differences between model observations and actual tracking data is always less than 50 meters, revealing an overall excellent orbit estimation accuracy.

Table 3. Ground station tracking statistics (05 Dec. 2021 – 20 Jan. 2022).

Ground Station	Total available number of range-tracking data		Used range tracking data	
	GSAT0223	GSAT0224	GSAT0223	GSAT0224
EKER	540	285	0	0
EDON	1845	750	1827	0
EKOU	6740	5438	6740	5438
ESP1	7253	3990	7050	3700
ES67	2236	2475	2236	2277
ES21	10883	12462	10616	11803
EGO3	3540	2640	3540	2144
EYSS	8160	9732	8070	9700
PA01	6195	3422	6195	3103
RN01	7167	3801	7167	3760
ESP2	600	1650	600	746
ES28	3522	7056	3418	6999
NU01	4477	6900	4477	5679
ES69	780	355	780	355
RE01	3155	6436	3155	6436
EKUX	0	1710	0	1478
EGO4	450	1425	450	1134
EHBX	3750	1140	3270	851

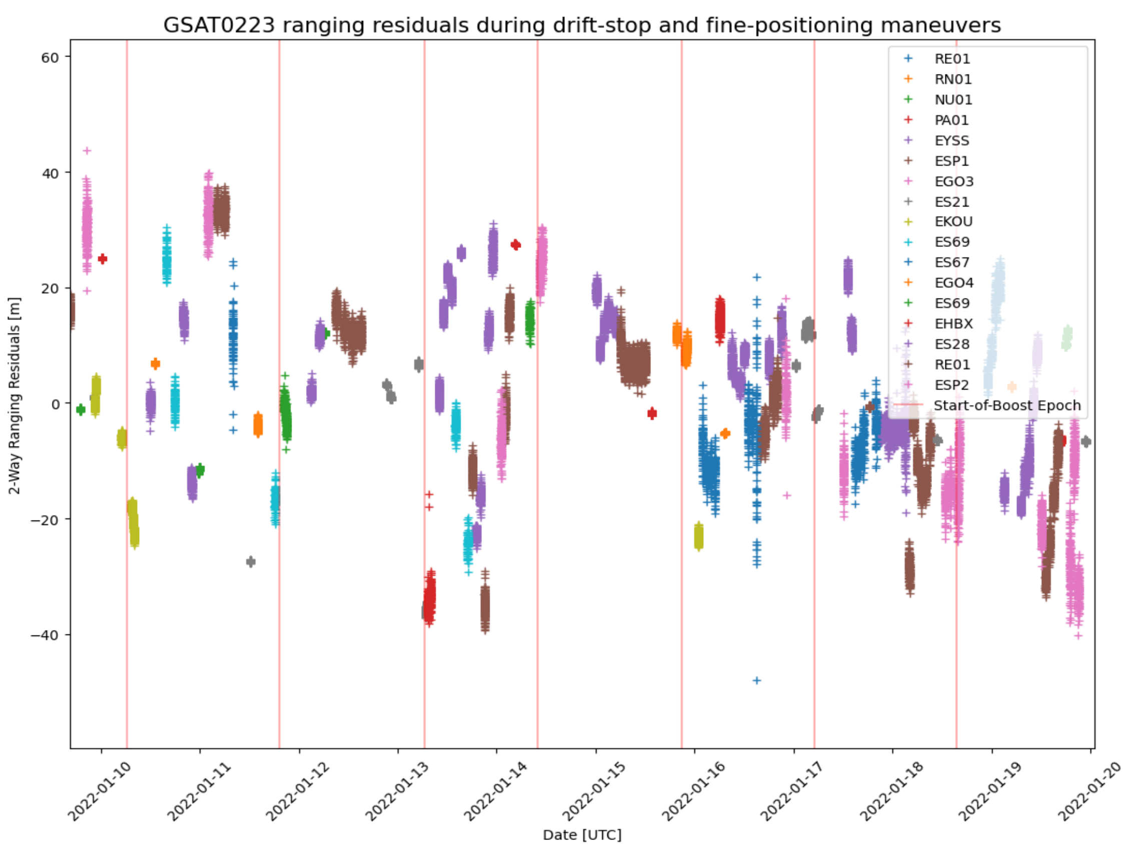

Fig. 3. Range residuals for spacecraft GSAT0223 during drift-stop and fine-positioning manoeuvres.

A more detailed example of OD performance is provided in Fig. 4, where the range residuals associated to the calibration of the first fine-positioning manoeuvre (D1) of GSAT0223 are provided. An OD arc of roughly 48 hours (centred around the start of boost) is provided. As shown in Fig. 4, the residuals are well centred around zero, indicating no major divergence from the commanded manoeuvre. Five different stations were tracking the spacecraft around D1. For the South Point, Yatharagga and Santiago de Chile data, the residuals are not exceeding an absolute value of seven meters, while for the observations associated to Weilheim and Kourou, the accuracy of the estimation is higher, with residuals below 2.4 meters.

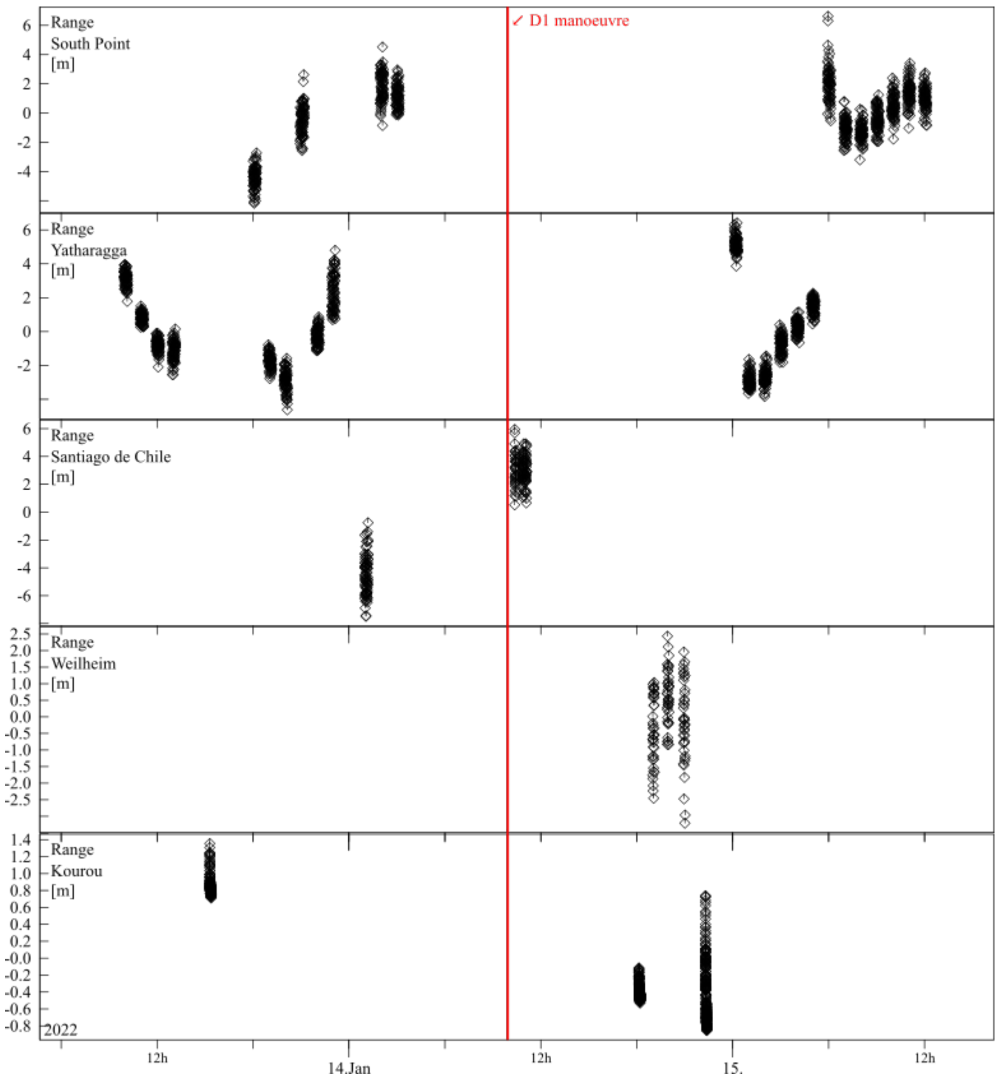

Fig. 4. Range residuals obtained from the OD of calibrating the first station-acquisition manoeuvre (D1) of GSAT0223.

The manoeuvre calibration accuracy is detailed in Tables 4 and 5, where a comparison between commanded and calibrated manoeuvres for both spacecraft is shown. The tables show the execution performance in terms of calibration percentage for each manoeuvre.

The overall situation shows, as expected, better calibration performances for A and C manoeuvres. Their higher manoeuvre magnitudes do not present a challenging scenario for the estimator. In such cases, the execution error resulting from the calibration is never higher than 5%. The best performance is achieved by drift-stop manoeuvre C3 for GSAT0224 with a slight overshoot of only 0.11%.

The fine-positioning manoeuvres present a more challenging scenario. The typical order of magnitude for such manoeuvres is roughly millimetres per second, resulting, on average, in higher over- or undershoots. The worst performance is provided by fine-positioning manoeuvre D2 for GSAT0223. In this case, the calibrated manoeuvre reported a 20% overshoot, leading to a significant correction of the subsequent manoeuvre strategy as a consequence.

Table 4. Manoeuvre history of GSAT0223, showing commanded and calibrated manoeuvre boost-start epoch and total ΔV, and the percentual performance of the calibrated manoeuvre with respect to the commanded manoeuvre.

Man. ID	Parameters	Units	Commanded	Calibrated	Performance
A1	Boost start epoch	UTC	09/12/2021 21:26:55		
	Total ΔV	[m/s]	2.60000	2.46976	94.99%
A2	Boost start epoch	UTC	11/12/2021 04:24:02		
	Total ΔV	[m/s]	4.84038	4.69578	97.01%
A3	Boost start epoch	UTC	12/12/2021 10:31:38		
	Total ΔV	[m/s]	0.07322	0.07025	95.93%
C1	Boost start epoch	UTC	10/01/2022 06:28:15		
	Total ΔV	[m/s]	6.32239	6.29759	99.61%
C2	Boost start epoch	UTC	11/01/2022 19:18:15		
	Total ΔV	[m/s]	7.91771	7.90425	99.83%
C3	Boost start epoch	UTC	13/01/2022 06:29:33		
	Total ΔV	[m/s]	0.12138	0.12912	106.37%
D1	Boost start epoch	UTC	14/01/2022 09:54:06		
	Total ΔV	[m/s]	0.04665	0.04566	97.88%
D2	Boost start epoch	UTC	15/01/2022 20:59:57		
	Total ΔV	[m/s]	0.00125	0.00150	120.39%
D3	Boost start epoch	UTC	17/01/2022 05:00:00		
	Total ΔV	[m/s]	0.00089	0.00097	108.97%
D4	Boost start epoch	UTC	18/01/2022 15:30:12		
	Total ΔV	[m/s]	0.00026	0.00028	107.57%
Total ΔV		**[m/s]**	**21.92413**	**21.61516**	

The OD scenario associated to the early LEOP phase – after separation from the launcher and before the first drift-start manoeuvre - is challenging and is the phase where the last source of dispersion, the thruster activity, is introduced. The sequence of events for the spacecraft initialisation includes spacecraft de-tumbling, attitude stabilisation and solar array deployment. It is a fully automatic and autonomous phase for approximately 45 minutes. During this critical timeframe, the propulsion system is started up, among others, and is used to dump the high-rotation speeds of the injection. At separation, the spacecraft is put in rotation around the deployment direction and thrusting is automatically handled on board to stabilise the attitude of the spacecraft in all three axes, before safely deploying the solar arrays, concluding the initialisation phase. The consequent post-initialisation activities last about 24 hours, during which the FD team is in charge of initialising the OD through processing the first batches of measurements received since injection.

The automatic thrusting during the initialisation phase introduces a consistent layer of complexity to the convergence of the premature and early OD process, since there is no possibility to model or predict the attitude stabilisation firing of the propulsion system. On top of that, this early OD stage is characterised by the concurrent estimation of ENOC station biases. As a result, the uncertainty associated to the estimated state of the spacecraft is significant and a bad modelling of the automatic thrusting would lead to a non-converged OD solution.

Table 5. Manoeuvre history of GSAT0224, showing commanded and calibrated manoeuvre boost-start epoch and total ΔV, and the percentual performance of the calibrated manoeuvre with respect to the commanded manoeuvre.

Man. ID	Parameters	Units	Commanded	Calibrated	Performance
A1	Boost start epoch	UTC	10/12/2021 07:00:00		
	Total ΔV	[m/s]	6.00000	5.90822	98.47%
A2	Boost start epoch	UTC	11/12/2021 18:00:00		
	Total ΔV	[m/s]	6.61809	6.70234	101.27%
A3	Boost start epoch	UTC	13/12/2021 03:14:50		
	Total ΔV	[m/s]	0.04190	0.04060	96.88%
C1	Boost start epoch	UTC	11/01/2022 00:28:40		
	Total ΔV	[m/s]	4.30313	4.26964	99.22%
C2	Boost start epoch	UTC	12/01/2022 11:24:08		
	Total ΔV	[m/s]	2.69255	2.74939	102.11%
C3	Boost start epoch	UTC	13/01/2022 19:09:59		
	Total ΔV	[m/s]	0.06067	0.06074	100.11%
D1	Boost start epoch	UTC	15/01/2022 09:29:01		
	Total ΔV	[m/s]	0.10147	0.09580	94.41%
D2	Boost start epoch	UTC	16/01/2022 19:29:46		
	Total ΔV	[m/s]	0.06597	0.06475	98.15%
D3	Boost start epoch	UTC	18/01/2022 01:00:12		
	Total ΔV	[m/s]	0.00425	0.00469	110.16%
D4	Boost start epoch	UTC	19/01/2022 10:24:11		
	Total ΔV	[m/s]	0.00109	0.00123	112.92%
D5	Boost start epoch	UTC	20/01/2022 20:06:34		
	Total ΔV	[m/s]	0.00083	0.00067	80.68%
Total ΔV		**[m/s]**	**19.88995**	**19.89805**	

To model this automatic thrusting, the attitude stabilisation activities were considered as empirical acceleration components of negligible magnitude and are included in the model's differential equation of motion of the OD solver as shown in Eq. 1:

$$\frac{d^2\boldsymbol{r}}{dt^2} = -\frac{\mu}{r^3}\boldsymbol{r} + \boldsymbol{f_{real}} + \boldsymbol{f_e} \quad (1)$$

where the accelerations acting on the spacecraft are split in real accelerations ($\boldsymbol{f_{real}}$) - well-modelled accelerations due to all the perturbing forces acting on the spacecraft - and empirical accelerations ($\boldsymbol{f_e}$) – modelled manoeuvres retrieved from the de-spinning firing times - to make the OD converge while considering the automatic thrusting activity. Fig. 5 shows the two-way ranging residuals for GSAT0223 associated to the converged OD solution during the initialisation and post-initialisation phases. Despite large discrepancies between measured and modelled observations during the first hours of life - where even the introduction of the empirical accelerations does not seem to be optimal - it is important to note how the residuals converge afterwards, leading to a more than acceptable estimate of the spacecraft's state.

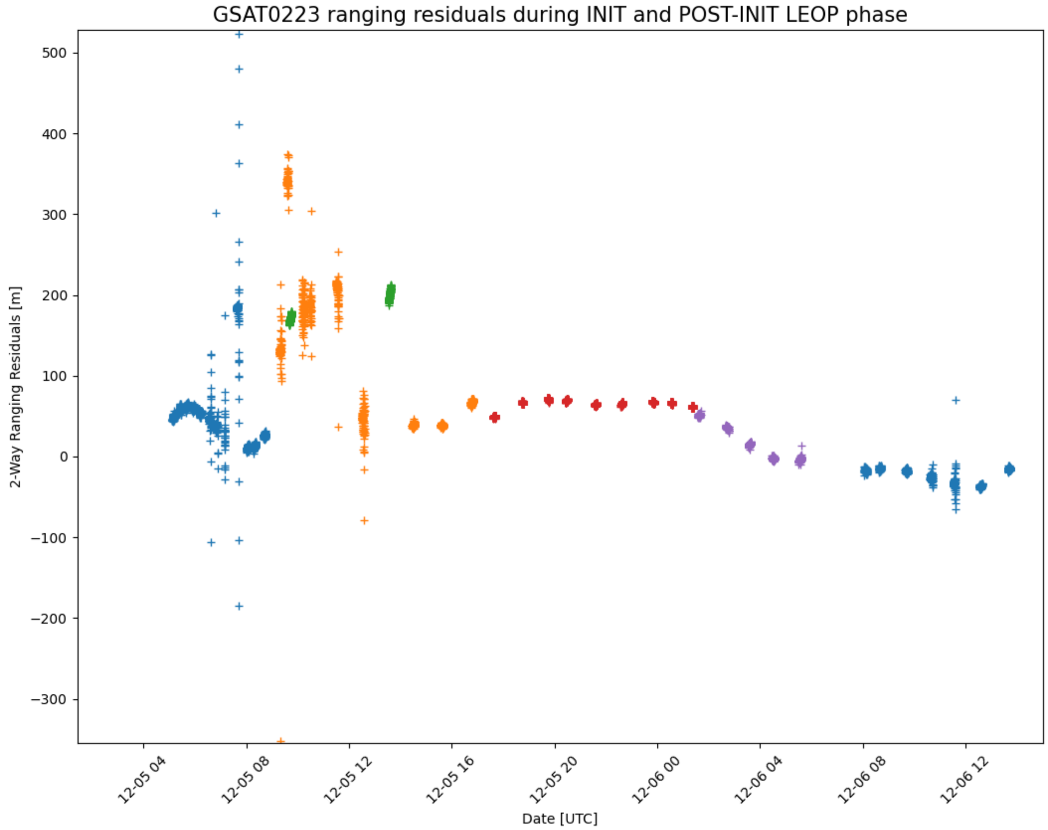

Fig. 5. Two-way ranging residuals for GSAT0223 representing the OD solution with introduction of empirical accelerations during the initialisation (INIT) and post-initialisation (POST-INIT) phases.

To analyse the performance of the station acquisitions, a target orbit close to the last fine-positioning manoeuvre is selected. GSAT0223 achieved its target slot, B03, after the D4 manoeuvre, while GSAT0224 needed an additional D-manoeuvre to reach its target slot, B15. The target acquisition assessments of both spacecraft are shown in Tables 6 and 7, presenting as orbital elements: the difference to the target (including the 3sigma uncertainty value from the orbit determination), the target-achievement requirements thresholds (including the 3sigma uncertainty value), the target orbital elements and the achieved orbital elements. The presented difference between the target slot and estimated orbital parameters shows the fulfilment of all target-achievement requirements. Predicting the evolution of these orbital elements, the Argument of Latitude (AoL) is the main driver to perform a first station-keeping manoeuvre. For GSAT0223, this is foreseen to be July 2030, while for GSAT0224, this is predicted to be September 2030.
Analysing the performance based on the total ΔV used, 21.6 m/s were needed to bring GSAT0223 into target (see Table 4) and 19.9 m/s were used for GSAT0224 (see Table 5), which is in both cases marginally higher than was calculated during the pre-launch mission analysis (see Table 2, assuming a nominal injection), as the described sources of dispersion led to a non-optimal station-acquisition manoeuvre execution.

Table 6. Target-slot assessment of GSAT0223 after D4 manoeuvre for epoch: 19/01/2022 09:40:24.051 (UTC).

Parameters	Units	Difference to target + 3σ	Threshold (3σ)	Target (B3)	Achieved
Semi-major axis	[m]	3.22	5	29601414.7	29601416.5
Eccentricity	[-]	2.83E-05	5.00E-04	0.0000828	0.0001111
Inclination	[deg]	2.87E-03	1.00E-02	57.1386	57.1414
Right Ascension	[deg]	2.10E-04	1.00E-02	24.9097	24.9095
AoL	[deg]	3.07E-04	2.00E-03	360.0000	360.0003

Table 7. Target-slot assessment of GSAT0224 after D5 manoeuvre for epoch: 21/01/2022 13:35:10.037 (UTC).

Parameters	Units	Difference to target + 3σ	Threshold (3σ)	Target (B15)	Achieved
Semi-major axis	[m]	3.68	5	29601572.7	29601575.7
Eccentricity	[-]	2.76E-06	5.00E-04	0.0000306	0.0000333
Inclination	[deg]	3.34E-03	1.00E-02	57.1420	57.1453
Right Ascension	[deg]	9.04E-05	1.00E-02	24.8461	24.8462
AoL	[deg]	1.48E-03	2.00E-03	360.0000	360.0015

5.3 Lessons Learned

The robustness of the mission planning and operation procedures of the Flight Dynamics teams are demonstrated by the minor divergence between station-acquisition manoeuvre plan and manoeuvre execution. However, refinements were needed during operations to react to dispersions. Analysing these refinements led to lessons learned from L11, which are:

1. Although a four-day launch delay cannot be foreseen, the Flight Dynamics teams coped with it efficiently and effectively and learned that the four-hour manoeuvre slots for mission planning need to remain stable. For the actual L11 launch, the drift-start manoeuvre slots were shifted by 24 hours per launch postponement of one day, allowing only slight changes of up to 30 minutes, giving stability to the mission plan, but also to the shift planning for all teams involved. For planning reasons and commissioning activities, the DSFP manoeuvre slots were kept the same throughout the manoeuvre strategies.
2. The coordination for the orbit-determination process shall be improved, not only between GSOC-FD and GCC-FD, but also within the teams. As the process of orbit determination is influenced by the operator, it can lead to different results. It is recommended to define the orbit determination parameters, so that there is no room for the interpretation of the operator, at least in a nominal case. By specifying, among others, the data arc, propagation time, station-bias estimation and other estimations such as the drag and solar radiation pressure coefficient, there would be less deviation in the determined orbit and, as a result, less deviation in the derived orbit products. This also applies to manoeuvre calibration, where a procedure shall specify which manoeuvre component(s) (radial, tangential and/or normal) shall be estimated. In case a deviation in the orbit is observed between GSOC-FD and GCC-FD - which scarcely happened for L11 - a procedure shall be set up where it is described how to analyse the deviation: comparing used ranging data, orbit determination parameters, etc.
3. As per the operational constraints, the fine-positioning manoeuvre slots (phase D) were separated by at least 26 hours. However, during operations, the coordination between GSOC-FD and GCC-FD required the necessary manoeuvre information to be delivered five hours before the manoeuvre execution to prepare the manoeuvre command. As a result, the orbit was occasionally determined based on less than 28 hours (or two full orbits) of orbit data, which is identified to be insufficient. The minimum data arc to determine the orbit shall be 28 hours. The lesson learned is to extend the time in between fine-positioning manoeuvres in order to improve the orbit determination process that, in its turn, allows for a better assessment in the decision-making process whether to execute an additional fine-positioning manoeuvre to reach the target slot. With this lesson learned in place, less D-manoeuvres should be required to reach the target.
4. The ranging sessions from the ground station network shall be more reliable. It is recommended to introduce specific requirements for the ground stations to consistently perform ranging every three hours, with one-hour ranging sessions around a manoeuvre. During L11, it occasionally happened that ranging sessions were missing, which negatively influenced the orbit determination and the respective station acquisition.

6. Conclusions

L11, carrying the latest two Galileo spacecraft GSAT0223 and GSAT0224, launched on December 5 2021 from Kourou. This kicked off the Flight Dynamics operations to bring both spacecraft into their target slots, for the first time under full responsibility of the DLR GfR Flight Dynamics team from within the Galileo Control Centre in Oberpfaffenhofen, with support from the Flight Dynamics team of DLR's GSOC. This paper describes the preparation and execution of the station-acquisition operations from a Flight Dynamics perspective. After outlining the close collaboration between both Flight Dynamics teams, the planning of the manoeuvre sequence for L11 is described before focusing on the operations during LEOP. The performance of the Flight Dynamics team is inspected in this paper, showing among others the orbit determination process, manoeuvre strategy and target-achievement accuracy.

In particular, the outcome of thorough assessments and revisions - resulting in lessons learned and elements of improvement - are presented, while demonstrating the Flight Dynamics team's ability and robustness to adapt during mission operation, securing successful target acquisitions and thus bringing the Galileo constellation a step closer to full operational capability. With L11 as stepping stone, GCC-FD is ready to operate fully independently for the upcoming launches.

L11 was the first of a series of six launches, each carrying two spacecraft, planned to be launched rapidly after one another. Due to the suspension of Soyuz launches from the Guiana Space Centre, the five remaining launches (L12 – L16) of the first generation of Galileo spacecraft were put on hold.

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