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# Manoeuvre Optimization in the Galileo L7 Orbit Acquisition

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Galileo is a Global Navigation Satellite System (GNSS) being deployed by the European Union. The satellites GSAT0210 and GSAT0211 were launched on a Soyuz rocket from the Guiana Space Centre in Kourou on the 24th of May of 2016, in the seventh Galileo launch (L7). The Flight Dynamics (FD) team at the European Space Operations Centre (ESOC) performed a Specific Mission Analysis in preparation for the launch. As part of the analysis the manoeuvre slots for the whole acquisition campaign had to be chosen respecting multiple constraints related to the station visibility, the platform, and operations. The Launch and Early Operations (LEOP) and the subsequent manoeuvre campaign to acquire the target orbit slots A2 and A6 of the Galileo constellation were conducted from ESOC by a joint ESOC and Centre national d'études spatiales (CNES) FD team. The LEOP and manoeuvre campaign were carried out nominally, and the acquisition of the target orbit slots was confirmed on the 3rd of July of 2016. In the paper the Specific Mission Analysis is described in detail, as well as the performed manoeuvre campaign, the analysis of the final target acquisition, and the assessment of the Y-bias along-track effect during the acquisition phase.

**Key Words:** Galileo L7, Orbit Determination, Manoeuvre Optimization, Y-bias

## Nomenclature

| | |
|---|---|
| FD | Flight Dynamics |
| FCT | Flight Control Team |
| SMA | Semi-Major Axis |
| RAAN | Right Ascension of Ascending Node |
| AoP | Argument of Perigee |
| AoL | Argument of Latitude |
| SAA | Solar Aspect Angle |
| MET | Mission Elapsed Time |
| OD | Orbit Determination |

## 1. Introduction

Galileo is a global navigation satellite system (GNSS) currently being deployed by the European Union. One of the aims of the Galileo project is to provide a high-precision positioning system that is interoperable with GPS and Glonass. The fully deployed Galileo system will consist of 24 operational satellites positioned in a Medium Earth Orbit (MEO), placed in a 24/3/1 Walker constellation with an inclination of 56 degrees with respect to the Earth equator. The Galileo service has been operational since December of 2016 (the so called Galileo Initial Services), with a total of 16 operational satellites in orbit as of February of 2017.

The seventh launch, called L7, in which the GSAT0210 and GSAT0211 satellites were launched from Kourou in a Soyuz launcher, took place on the 24th of May 2016. The Launch and Early Operations (LEOP) and the subsequent manoeuvre campaign to acquire the target orbital slots A2 and A6 were conducted from the European Space Operations Centre (ESOC) in Darmstadt, by a joint team from ESOC and Centre national d'études spatiales (CNES) known as CNESOC. After a manoeuvre campaign comprising 18 manoeuvres, the target orbital slots were declared to be successfully acquired for both satellites on the 3rd of July 2016.

In the launches up to and including L7, Galileo satellites were launched in pairs directly into the target orbital plane, but not into the target slots in the orbit. The generic mission analysis for this type of launches is described in detail in Ref 1). The coarse target acquisition of each spacecraft is achieved by performing three drift start manoeuvres, staying in free drift for approximately 21 days, and then performing three drift stop manoeuvres, using up to 35 m/s in Delta-V per spacecraft for a nominal launch. Afterwards, between six and eight fine positioning manoeuvre slots are available for correcting the remaining error and to acquire the target orbital slot precisely. The fine acquisition of the target slot ensures that a single corrective manoeuvre will be required for the first 12 years of operations[2)].

In the preparation of the launch, one of the main roles of the FD CNESOC Orbit and Manoeuvre Team is to design the manoeuvre strategy for the launch on the 24th of May, as well as the launches on the backup dates of the 25th and 26th of May. The manoeuvres cannot be freely optimized, but rather have to respect a multitude of constraints. In particular, a manoeuvre and corresponding slews have to be performed in station visibility, there are constraints on Earth Sensor inhibitions that have to be avoided, and operational constraints have to be taken into account. The approach is to define manoeuvre slots with a maximum duration of 4 hours. In the actual manoeuvre campaign maneouvres can be optimized inside the defined slots (the boost start time must be later than the beginning of the slot, and the boost end time must be earlier than the end of the slot). The main analysis work consists in selecting the manoeuvre slots for the Drift Start, Drift Stop, and Fine Positioning phases for each one of the launch dates. In this paper the procedure to derive target slots is described in detail.

The injection on the 24th of May and the subsequent LEOP and manoeuvre campaign were carried out nominally. The final target in SMA and AoL had to be acquired precisely, respectively by 5 meters and 0.002 degrees. The assessment of the acquisition was affected by the presence of a Y-bias of uncertain magnitude, which is nominally not modeled in operations. Only two fine positioning manoeuvres were necessary for the acquisition of the target A6 by GSAT0211, however the acquisition could only be confirmed four days after the execution of the last manoeuvre, due to a shallow drift in AoL towards the target. This resulted in a longer OD arc without perturbations than is usually available for other Galileo launches, providing the chance to assess the along-track effect of the Y-bias in the acquisition phase.

## 2. The Spacecraft

The Galileo spacecraft are manufactured by OHB Systems in Bremen, Germany. A Galileo spacecraft weighs approximately 733 kilograms. Its attitude is three-axis stabilized and is steered by reaction wheels. Magnetotorquers are used to dump the wheel momentum. The spacecraft has coarse and fine Sun sensors, infrared Earth sensors, and a gyro unit for determining the attitude.

Each spacecraft has a Hydrazine monopropellant propulsion system, and four 1-Newton thrusters mounted on the –X face of the spacecraft, tilted 16 degrees with respect to the X axis, used for the purpose of doing orbital manoeuvres. The four thrusters can be activated at the same time, with the attitude being kept stable by off-modulation, providing a maximum Delta-V of 20 m/s. They can also be activated one at a time, for smaller manoeuvres, providing a minimum Delta-V of 0.059 mm/s at Beginning of Life.

Shortly after the injection, the spacecraft is set to Sun Pointing Mode. At the end of the LEOP, the attitude is switched to Earth Pointing Mode, in which the spacecraft can manoeuvre. In this attitude the spacecraft can slew in yaw, which allows for the execution of manoeuvres with in-plane or out-of-plane Delta-V, or any combination thereof.

## 3. Launch and Acquisition Problem

### 3.1. Injection

The spacecraft are injected in the target orbital plane with a SMA approximately 300 kilometres higher than the target SMA. The spacecraft are separated such that they have a 25 kilometres SMA difference between them, thus acquiring along-track separation from injection onwards. For a perfectly nominal injection the necessary Delta-V to correct the SMA amounts to 18-19 m/s per spacecraft. The nominal injection inclination and RAAN are close to the target elements. The injection Keplerian elements are displayed on Table 1.

Table 1. Nominal injection state-vector in J2000 reference frame.

| Parameter (unit) | GSAT0210 | GSAT0211 |
|---|---|---|
| Epoch (UTC) | 2016/05/24-12:36:39.6 | |
| SMA (km) | 29912.3 | 29887.7 |
| Eccentricity | 0.00029 | 0.00056 |
| Inclination (deg) | 57.341 | 57.341 |
| RAAN (deg) | 322.216 | 322.216 |
| AoP (deg) | 259.0 | 49.6 |
| AoL (deg) | 239.37 | 239.38 |

During the first three days of LEOP the transition to the Normal Mode is performed, by activating the Earth Acquisition Mode (EAM). In EAM the spacecraft rotates starting from SAM until it finds the Earth with its Earth sensors. In order to avoid Earth sensor blindings, this operation can only be performed in restricted intervals. The windows of opportunity to activate the EAM are predicted by FD as part of the Specific Mission Analysis and a nominal slot to activate the EAM is defined in the LEOP schedule, together with the FCT.

### 3.2. Target Orbital Slots

The target orbital slots are denominated by A2 and A6, and are separated by 180 degrees in AoL. Each spacecraft is assigned one of the slots as a result of the analysis described in this paper. The choice depends on the launch date. The target orbital slots should be acquired fifty days after launch at the latest. Examples of target state vectors for the launch on the 24th of May are depicted in Table 2 and Table 3.

Table 2. Example A2 target slot in J2000 reference frame.

| Parameter (unit) | Value |
|---|---|
| Epoch (UTC) | 2016/07/09-07:15:10.711 |
| SMA (km) | 29601.9028 |
| Eccentricity | 0.0000839 |
| Inclination (deg) | 57.3419 |
| RAAN (deg) | 320.9759 |
| AoP (deg) | 310.4759 |
| AoL (deg) | 0.0 |

Table 3. Example A6 target slot in J2000 reference frame.

| Parameter (unit) | Value |
|---|---|
| Epoch (UTC) | 2016/07/08-10:08:10.728 |
| SMA (km) | 29601.9285 |
| Eccentricity | 0.0000710 |
| Inclination (deg) | 57.3430 |
| RAAN (deg) | 320.9983 |
| AoP (deg) | 54.0098 |
| AoL (deg) | 0.0 |

The relative position of the spacecraft with respect to the A2 and A6 slots depends on the launch date, as depicted in Fig. 1. The relative positions and the constraints described in 3.4. determine which slot is assigned to each spacecraft.

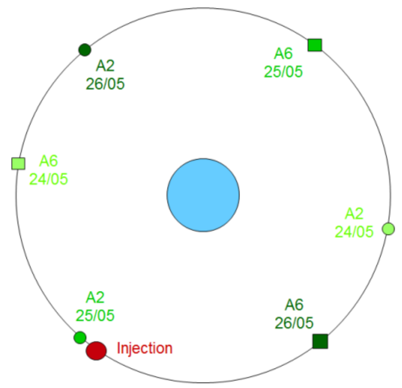


Fig. 1. Depiction of relative position of A2 and A6 slots with respect to injection slot for the nominal launch and the two backup dates.

The target has to be acquired in all Keplerian elements, with particularly demanding requirements in accuracy of the SMA and AoL[3], as detailed in Table 4.

Table 4. Slot acquisition accuracy requirements.

| Keplerian Element (unit) | Accuracy |
|---|---|
| SMA (m) | 5 |
| Eccentricity | 0.005 |
| Inclination (deg) | 0.01 |
| RAAN (deg) | 0.01 |
| AoL (deg) | 0.002 |

It should be remarked that the required accuracy of the eccentricity is much lower than the one specified for the SMA and the AoL. A deviation in eccentricity means that the target might be considered acquired when assessed at a particular AoL but not at others. Due to this reason, the assessment of the acquisition is always done at J2000 ascending nodes.

### 3.3. Manoeuvre Concept

The manoeuvre campaign to acquire the target slots is divided in four phases, as detailed in Table 5. The Drift Start phase starts from injection.

Table 5. Phases for Galileo satellites injected on a Soyuz launcher

| Phase | Duration (days) | Manoeuvres / Spacecraft |
|---|---|---|
| Drift Start (A) | 7 | 3 |
| Free Drift (B) | 21 | - |
| Drift Stop (C) | 4 | 3 |
| Fine Positioning (D) | 17 | 8 |

Manoeuvres are designated by the corresponding phase, i.e. A1, A2, A3 for the Drift Start phase, C1, C2, C3 for the Drift Stop phase, and D1, D2, etc. for the Fine Positioning phase.

In the Drift Start phase three manoeuvres are executed for each spacecraft alternately. In this phase the SMA is adjusted such that each spacecraft drifts towards its slot during the Free Drift phase. Orbital plane and eccentricity deviations might be corrected as well in the Drift Start phase. The manoeuvres have a nominal 10:10:1 distribution in change of SMA. This ensures on one side the repeatability of conditions for manoeuvres A1 and A2 (so that the calibrated A1 manoeuvre can be used to properly command A2), and the flexibility of doing a drift trim with manoeuvre A3.

During the Drift phase the spacecraft is handed over to the Galileo Control Centre (GCC) in Oberpfaffenhofen (Germany), in order to perform commissioning activities.

In the Drift Stop phase the along-track drift is stopped with three manoeuvres, again with a 10:10:1 distribution. At the end of this phase the acquisition of the target inclination and RAAN should be concluded.

In the Fine Positioning phase up to eight manoeuvres (for L7) can be executed to correct the remaining error in any component. Prior to each manoeuvre the acquisition of the target is assessed by performing an orbit determination with the latest tracking data, and if the target is not met, further manoeuvres are planned. In this phase only in-plane burns are done in order to correct the SMA and AoL.

### 3.4. Constraints

#### 3.4.1. Collision Avoidance

GSAT0210 is injected higher than GSAT0211 by 25 km. It should remain higher than GSAT0211 during the Drift Start phase, in order to avoid possible collisions while the spacecraft still have low separation in AoL. This does not play a role anymore in the Drift Stop and Fine Positioning phases, because the spacecraft will have drifted approximately 180 degrees apart in AoL by that time.

#### 3.4.2. Spacecraft Constraints

A high Solar Aspect Angle (SAA) limits the maximum duration of a manoeuvre, as specified in Table 6, because of power limitations.

Table 6. Limitations to manoeuvre duration. An SAA of zero means perpendicular incidence of the Sun in the Solar Panels.

| SAA Interval (deg) | Maximum Manoeuvre Duration (s) |
|---|---|
| $0 \leq \alpha < 60$ | - |
| $60 \leq \alpha < 70$ | 4130 |
| $70 \leq \alpha < 80$ | 470 |
| $80 \leq \alpha \leq 90$ | 200 |

Furthermore, Earth sensors can be blinded by the Moon, Sun or the appearance of the Antarctica. During the southern hemisphere winter, the Antarctica is also considered a blinding object due to the disturbances it creates in the Earth Sensors. A double event with one of these blindings disallows the execution of a manoeuvre. For L7 the southern hemisphere Winter begins between the Drift Start and Drift Stop phases, continuing until past the end of the Fine Positioning.

#### 3.4.3. Station Visibility Constraints

The Galileo station network for L7 comprises 6 stations during LEOP and Drift Start phase: Southpoint, Hartebeestoek, Dongara, Kiruna, Kourou, and Santiago. During the remaining phases it comprises 7 stations: Southpoint, Hartebeestoek, Dongara, Kiruna-TTCF, Kourou-TTCF, Noumea-TTCF, and Reunion-TTCF. This network ensures almost continuous single-station visibility, and the tracking data recorded from multiple stations ensures that there is sufficient geometrical information for a precise orbit determination.

For the A1 manoeuvre it was agreed to have station coverage from two stations 40 minutes before the start of boost and 15 minutes after end of boost to make sure that there is a backup station available in the critical phase of the first manoeuvre. During the Drift Stop and Fine Positioning phases each manoeuvre has be covered from the same station starting 3h39m before the start of the manoeuvre up to 1h39m after the end of the manoeuvre. This constraint comes from operational activities to be performed from the routine operators (GCC GfR).

#### 3.4.4. Orbit Determination Accuracy

The orbit determination during the acquisition campaign is based on range measurements from the available station network. During the first hours of acquisition angle measurements are used as well. One ranging sequence is recorded every two hours for each spacecraft. This frequency is increased towards the end of the acquisition campaign in order to precisely determine the SMA and AoL targets.

Time constraints are set in order to ensure good quality of the orbit determination at all stages[1)]. Prior to a manoeuvre optimization an orbit determination has to be performed based on an unperturbed arc comprising at least one full orbital revolution arc (14 hours). In the Fine Positioning phase this is increased to two full orbital revolutions.

#### 3.4.5. Operational Constraints

In order to avoid the overlap of critical activities on two spacecraft at the same time, it is ensured that there is a minimum separation of four hours between the end of the boost of one spacecraft and the beginning of the boost of the other spacecraft.

The manoeuvres are assigned orbital slots comprising several hours. Their orbital position can be reoptimized in short notice due to manoeuvre misperformances. In order to reduce variations in the manning plans, manoeuvre slots are limited to four hours.

## 4. Design of Acquisition

### 4.1. General Approach

The main aim of the acquisition design is to assign manoeuvre slots for each manoeuvre and spacecraft. These can be freely defined before LEOP provided that they are within the desired time span of each phase and fulfill the constraints described in 3.4. Furthermore the slots are distributed as spread out as possible in different AoL ranges, such that orbital plane deviations can be corrected as efficiently as possible fuel-wise.

The manoeuvre slots are optimized in the following sequence:

1) Drift Start Slots
2) Drift Stop Slots
3) Fine Positioning Slots

The optimizations and the generation of orbital events such as station visibilities were done with the aid of the NAPEOS and MANTRA software employed by the FD team at ESOC.

### 4.2. Drift Start Slots

The station visibility of the spacecraft during the Drift Start phase is well known and cannot dramatically change in a nominal injection. Double inhibitions do not occur because the southern hemisphere Winter has not begun and the angle between the Sun and the injected plane is above the visibility of the Earth Sensors, so the Moon is the only blinding object. It is thus possible to assign A1-A3 manoeuvre slots with respect to MET which are valid for any launch date. In Fig. 2 the GSAT0210 slots are depicted for a launch on the 24$^{th}$ of May, plotted together with the station passes. The Drift Start slots are selected in coordination with the FCT, considering their shift pattern in order to avoid a shift handover in the middle of a manoeuvre preparation or execution.

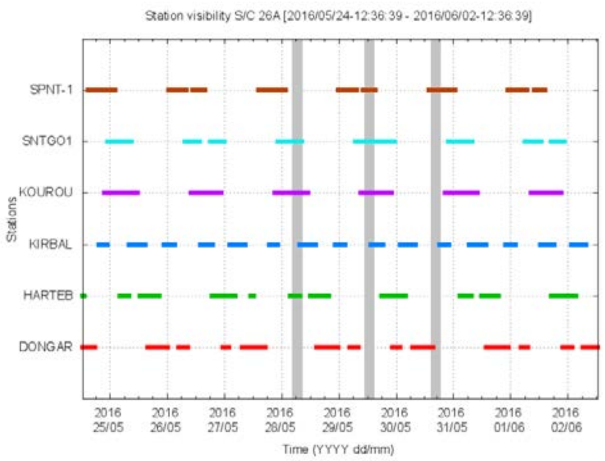


Fig. 2. GSAT0210 manoeuvre slots (in gray) for the 24$^{th}$ of May.

In order to fulfill the collision avoidance constraint described in 3.4.1., the lower spacecraft, GSAT0211, is the first one to be manoeuvred, nominally lowering the SMA and thus increasing the radial separation between spacecraft.

The Drift Start slots for the L7 launch are detailed in Table 7.

### 4.3. Drift Stop Slots

The Drift Stop slots depend on the selected target orbital slot for the spacecraft and on the specific acquisition case. The target slot defines the nominal station visibility, but the separation in AoL of the spacecraft with respect to the target slot at the start of the Drift Stop phase, which might be of several degrees, changes the expected station visibility.

Table 7. Drift Start manoeuvre slots.

| Manoeuvre | Satellite | MET (HH:MM) |
|---|---|---|
| A1 | GSAT0211 | 55:45 – 59:45 |
| A1 | GSAT0210 | 91:15 – 95:15 |
| A2 | GSAT0211 | 104:00 – 108:00 |
| A2 | GSAT0210 | 125:00 – 129:00 |
| A3 | GSAT0211 | 134:30 – 138:30 |
| A3 | GSAT0210 | 149:30 – 153:30 |

As a consequence the Drift Stop slots have to be designed individually for each launch date, by first selecting the target orbital slot, and then refining the station visibility based on the particular optimization.

### 4.3.1. Coarse Solution

On a first step the target slots A2 and A6 are assigned to each spacecraft, based on the in-plane problem of acquiring the SMA and the AoL targets, ignoring the other Keplerian elements. The slots are assigned such that any potential close conjunctions between the satellites are avoided during the Drift Start phase.

A coarse solution for the acquisition problem is derived by using MANTRA, assuming a single in-plane Drift Start manoeuvre and a single in-plane Drift Stop manoeuvre, only aiming for the target SMA and AoL. The assignment of slots is listed on Table 8, and the coarse solutions are depicted in Fig. 3. In these plots the relative position of the spacecraft with respect to the target slots is represented. The graph is periodic on the X-axis, starting and ending with slot A2. The Y-axis shows the delta-SMA of the spacecraft w.r.t. the target. The assigned slots for each date are described in Table 8.

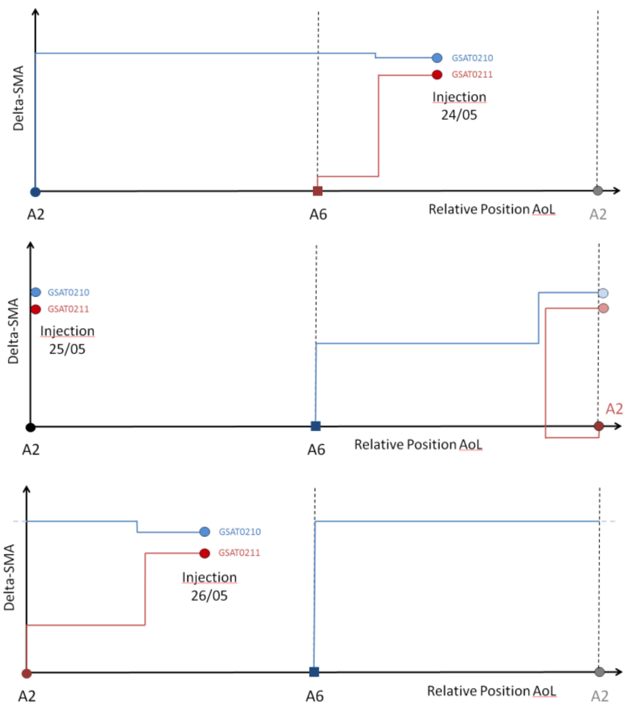


Fig. 3. Depiction of coarse optimizations for the 3 launch dates.

Table 8. Assignment of slots.

| Launch Date | GSAT0210 | GSAT0211 | Comments |
|---|---|---|---|
| 2016/05/24 | A2 | A6 | Slight adjustment of drift for GSAT0210. |
| 2016/05/25 | A6 | A2 | GSAT0211 reverts drift. |
| 2016/05/26 | A6 | A2 | GSAT0210 increases drift. |

### 4.3.2. Definition of Slots

Station visibilities and Earth sensor inhibitions can be calculated with the NAPEOS software by using the corresponding coarse optimization orbits as inputs. The results are post-processed to derive valid manoeuvre slots based on the constraints listed in 3.4, as shown on Table 9. As additional info the beginning and ending AoLs.

Table 9. Examples of slots for GSAT0210 for a launch on the 24th of May.

| Station | Start | End | Dur. | AoL Range (deg) |
|---|---|---|---|---|
| SPNT-1 | 06/20-05:25 | 06/20-05:26 | 00:01 | 182-182 |
| NOTTCF | 06/20-06:31 | 06/20-09:28 | 02:57 | 209-284 |
| DONGAR | 06/20-07:16 | 06/20-08:10 | 00:53 | 228-251 |
| NOTTCF | 06/20-11:19 | 06/20-11:53 | 00:33 | 331-346 |

### 4.3.3. Selection of Drift Stop Slots and Refinement

The Drift Stop slots are manually selected such that the constraints are fulfilled. Slots are selected to be as long as possible (up to four hours), such that there is as much flexibility as possible when correcting eccentricity and orbital plane errors. For the same reason the slots are selected such that the manoeuvre slots cover a wide range of AoL. GSAT0210 is the first spacecraft manoeuvring, because it has the biggest Drift Stop manoeuvres for all analysed cases (as it can be seen in Fig. 3), and is expected to require more Fine Positioning manoeuvres to acquire the target. Placing it first is expected to shorten the acquisition campaign.

Once a preliminary selection of the manoeuvre slots is done, a full optimization is performed using MANTRA. Three Drift Start manoeuvres and three Drift Stop manoeuvres are optimized inside the respective slots in order to correct all the dispersion errors. In principle the manoeuvres should have a 10:10:1 distribution of SMA change in each phase, but this is a soft constraint and can be relaxed if necessary for convergence of the solution.

After a valid solution is obtained, the station visibilities are recomputed using NAPEOS for the obtained orbital solution. The manoeuvre slots are adjusted according to the recomputed visibilities and inhibitions. A reoptimization is performed if necessary, for example if an optimized manoeuvre is now outside a recomputed maneouvre slot.

The selected Drift Stop slots for GSAT0210 and GSAT0211 are listed in Table 10, and their placement in the orbit is shown in Fig. 4. Some slots are longer than the mandated four hours but are shortened at the end of the Drift Start phase. This is done more than twenty days in advance, once the A3 manoeuvre has been executed and the visibility at the start of the Drift Stop phase is better determined. The evolution of the SMA and relative AoL is depicted in Fig 5.

Table 10. Chosen Drift Stop Slots for the launch on 24th of May.

| Manoeuvre | Station | Start (UTC) | End (UTC) | Duration |
|---|---|---|---|---|
| C1-210 | NOTTCF | 06/20-06:31 | 06/20-09:28 | 2h57m |
| C1-211 | RETTCF | 06/20-13:49 | 06/20-16:44 | 2h55m |
| C2-210 | SPNT-1 | 06/21-18:37 | 06/22-00:33 | 5h56m |
| C2-211 | SPNT-1 | 06/22-14:57 | 06/22-19:38 | 4h41m |
| C3-210 | HARTEB | 06/24-00:22 | 06/24-01:39 | 1h16m |
| C3-211 | RETTCF | 06/24-21:33 | 06/24-23:05 | 1h32m |

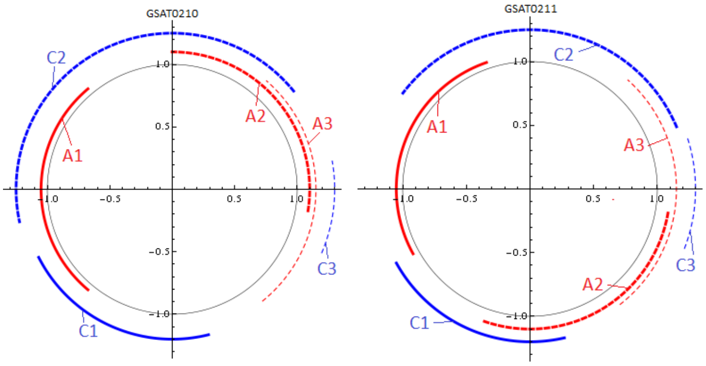

Fig. 4. AoL range for Drift Start and Drift Stop slots for a launch on the 24th of May. With a 4 hour slot about 100 degrees in AoL can be covered. A perfect coverage is not possible due to constraints in the total time of the LEOP and the presence of double inhibitions.

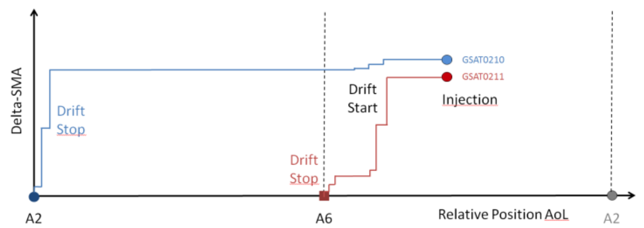

Fig. 5. Fine optimization SMA and drift w.r.t. the target slots.

#### 4.3.4. Robustness of Solution

As a final step the robustness of the selected slots is tested against various dispersion cases. Worst-case scenarios of 3-sigma dispersions in every orbital element are considered. The same slots as for the nominal case are taken, but the manoeuvres are reoptimized in order to compensate for the increased error in the orbital components. The selected slots for the three launch dates were validated against worst-case injection scenarios. In all cases it was possible to derive a manoeuvre optimization that successfully acquired the target orbit using under 35 m/s Delta-V per spacecraft. In the cases with difficult convergence, the 10:10:1 proportion between manoeuvres had to be severely relaxed.

### 4.4. Fine Positioning Slots

The derivation of Fine Positioning slots follows an approach similar to the one of the Drift Stop slots, but with simplifications. After the Drift Stop manoeuvres are over it is assumed that the target orbit has nearly been acquired. Using this fact, Fine Positioning slots are defined based on the target orbits, which means that a slot can be used independently of the launch date, provided that the minimum separation between manoeuvres described in 3.4.4. and 3.4.5. is respected. This severely reduced the effort in planning eight manoeuvre slots for each spacecraft for three possible launch dates. The majority of the Fine Positioning Slots used for the launch on the 24th of May were reused for the one on the 25th of May with switched spacecraft. The Fine Positioning slots for the 25th of May are reused wholesale for the launch on the 26th. The Fine Positioning slots for the launch on the 24th of May are listed in Table 11.

Table 11. Fine Positioning Slots for the launch on 24th of May.

| Manoeuvre | Station | Start (UTC) | End (UTC) | Duration |
|---|---|---|---|---|
| D1-210 | KITTCF | 06/25-09:15 | 06/25-10:55 | 1h40m |
| D1-211 | DONGAR | 06/26-11:25 | 06/26-13:34 | 2h08m |
| D2-210 | DONGAR | 06/27-08:09 | 06/27-10:41 | 2h31m |
| D2-211 | KOTTCF | 06/28-12:54 | 06/28-16:54 | 4h00m |
| D3-210 | KOTTCF | 06/29-08:32 | 06/29-12:32 | 4h00m |
| D3-211 | SPNT-1 | 07/01-00:55 | 07/01-03:21 | 2h26m |
| D4-210 | SPNT-1 | 07/01-19:56 | 07/01-23:56 | 4h00m |
| D4-211 | NOTTCF | 07/02-13:00 | 07/02-13:44 | 0h43m |
| D5-210 | SPNT-1 | 07/03-11:36 | 07/03-12:42 | 1h06m |
| D5-211 | SPNT-1 | 07/03-20:55 | 07/04-00:55 | 4h00m |
| D6-210 | KOTTCF | 07/04-22:37 | 07/05-01:47 | 3h09m |
| D6-211 | SPNT-1 | 07/05-12:32 | 07/05-14:51 | 2h19m |
| D7-210 | KOTTCF | 07/06-12:11 | 07/06-16:11 | 4h00m |
| D7-211 | HARTEB | 07/07-14:36 | 07/07-17:10 | 2h33m |
| D8-210 | KOTTCF | 07/08-03:39 | 07/08-04:35 | 0h56m |
| D8-211 | SPNT-1 | 07/08-16:00 | 07/09-20:00 | 4h00m |

## 5. LEOP and Acquisition Campaign

### 5.1. Injection

The L7 launch took place on the nominal launch date, on the 24th of May at 2016/05/24-08:48:43 UTC. The separation took place at 12:36:40 UTC. The GSAT0210 and GSAT0211 satellites were injected nominally into orbit, as can be seen in the dispersions on Table 12.

Table 12. Injection dispersions (values and deviations).

| Parameter (unit) | GSAT0210 | GSAT0211 |
|---|---|---|
| SMA (km) | +49.5 (+1.8 σ) | +46.3 (+1.7 σ) |
| Inclination (deg) | -0.0033 (-0.1 σ) | -0.0026 (-0.1 σ) |
| RAAN (deg) | -0.0126 (-0.5 σ) | -0.0136 (-0.6 σ) |
| AoL (deg) | -0.0562 (-0.8 σ) | -0.0615 (-0.8 σ) |

No major spacecraft anomalies occurred during the LEOP. GSAT0210 and GSAT0211 deployed the solar panels and entered the Sun Acquisition Mode within 30 minutes after the separation.

The EAM transition successfully took place for both spacecraft. It was commanded on the 25th of May at 14:30 UTC for GSAT0211, and on the 26th of May at 05:08 UTC for GSAT0210.

## 5.2. Manoeuvre Strategy

The low dispersion in the injection meant that a manoeuvre strategy similar to the one depicted in Fig. 5 could be followed, in which GSAT0210 adjusts the drift with small manoeuvres and then stops it with bigger manoeuvres, while GSAT0211 reduces the drift with big manoeuvres and stops it with smaller manoeuvres. Manoeuvre performances were nominal. Table 13 lists the entirety of manoeuvres executed during the manoeuvre acquisition campaign. Four and two Fine Positioning manoeuvres were necessary for GSAT0210 and GSAT0211 respectively.

Table 13. Manoeuvres performed during acquisition campaign.

| Manoeuvre | Beg Time (UTC) | End Time (UTC) | DV (m/s) |
|---|---|---|---|
| A1-0211 | 2016/05/26-16:33 | 2016/05/26-17:03 | 8.3 |
| A1-0210 | 2016/05/28-05:00 | 2016/05/28-05:08 | 2.3 |
| A2-0211 | 2016/05/28-17:57 | 2016/05/28-18:29 | 8.4 |
| A2-0210 | 2016/05/29-17:40 | 2016/05/29-17:48 | 2.2 |
| A3-0211 | 2016/05/30-02:42 | 2016/05/30-02:45 | 1.0 |
| A3-0210 | 2016/05/30-16:51 | 2016/05/30-16:53 | 0.4 |
| C1-0210 | 2016/06/20-08:34 | 2016/06/20-09:05 | 8.3 |
| C1-0211 | 2016/06/20-14:43 | 2016/06/20-14:48 | 1.4 |
| C2-0210 | 2016/06/21-20:39 | 2016/06/21-21:12 | 8.4 |
| C2-0211 | 2016/06/22-16:46 | 2016/06/22-16:52 | 1.6 |
| C3-0210 | 2016/06/24-00:38 | 2016/06/24-00:44 | 1.4 |
| C3-0211 | 2016/06/24-22:53 | 2016/06/24-22:54 | 0.2 |
| D1-0210 | 2016/06/25-09:45 | 2016/06/25-09:46 | 0.3 |
| D1-0211 | 2016/06/26-12:05 | 2016/06/26-12:05 | 0.03 |
| D2-0210 | 2016/06/27-09:15 | 2016/06/27-09:15 | 0.03 |
| D2-0211 | 2016/06/28-13:10 | 2016/06/28-13:10 | 0.0006 |
| D3-0210 | 2016/06/29-12:25 | 2016/06/29-12:25 | 0.004 |
| D4-0210 | 2016/07/01-20:00 | 2016/07/01-20:00 | 0.001 |

## 5.3. Manoeuvres in the Drift Start and Drift Stop Phases

The manoeuvres during Drift Start and Drift Stop had nominal performances, as can be seen on Tables 14 and 15. For both spacecraft the inclination, RAAN, and eccentricity targets were acquired with C3. The evolution of the elements with respect to the target is depicted for each spacecraft on Figures 6 and 7.

Table 14. GSAT0210 planned manoeuvres and performance at execution.

| Mano. | Along-track Delta-V (m/s) | Cross-track Delta-V (m/s) | ΔSMA (km) | Performance (%) | Off-pointing (deg) |
|---|---|---|---|---|---|
| A1 | -2.27 | 0.26 | -37.0 | -3.7 | 1.8 |
| A2 | -2.16 | 0.04 | -34.8 | +1.0 | 1.0 |
| A3 | -0.41 | -0.02 | -6.7 | -0.2 | 1.0 |
| C1 | -8.33 | 0.12 | -135.6 | -1.2 | 0.8 |
| C2 | -8.36 | -0.13 | -135.2 | -1.4 | 1.2 |
| C3 | -1.39 | 0.01 | -22.3 | -1.5 | 1.3 |

Table 15. GSAT0211 planned manoeuvres and performance at execution.

| Mano. | Along-track Delta-V (m/s) | Cross-track Delta-V (m/s) | ΔSMA (km) | Performance (%) | Off-pointing (deg) |
|---|---|---|---|---|---|
| A1 | -8.30 | 0.20 | -134.8 | -0.7 | 1.7 |
| A2 | -8.38 | -0.08 | -135.9 | +0.9 | 1.3 |
| A3 | -0.78 | 0.56 | -12.6 | -0.5 | 0.8 |
| C1 | -1.39 | -0.09 | -22.7 | -0.4 | 0.8 |
| C2 | -1.59 | 0.28 | -25.7 | -1.5 | 0.9 |
| C3 | -0.21 | 0.02 | -3.4 | -1.6 | 0.9 |

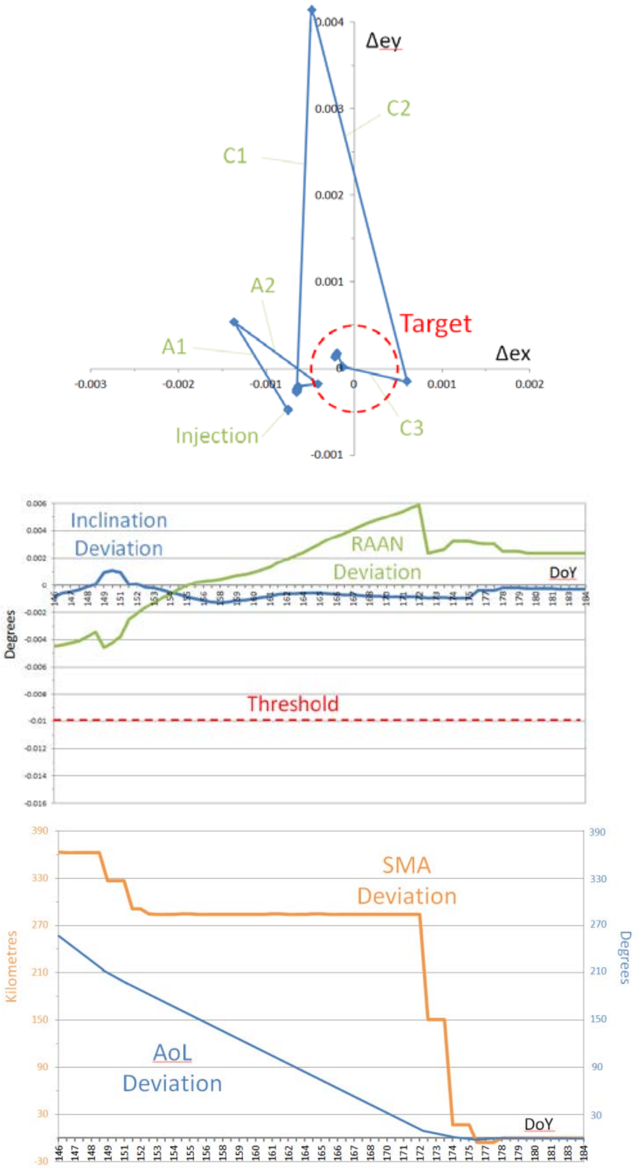


Fig. 6. Evolution of orbital parameters of GSAT0210 (eccentricity vector, inclination and RAAN, SMA and AoL).

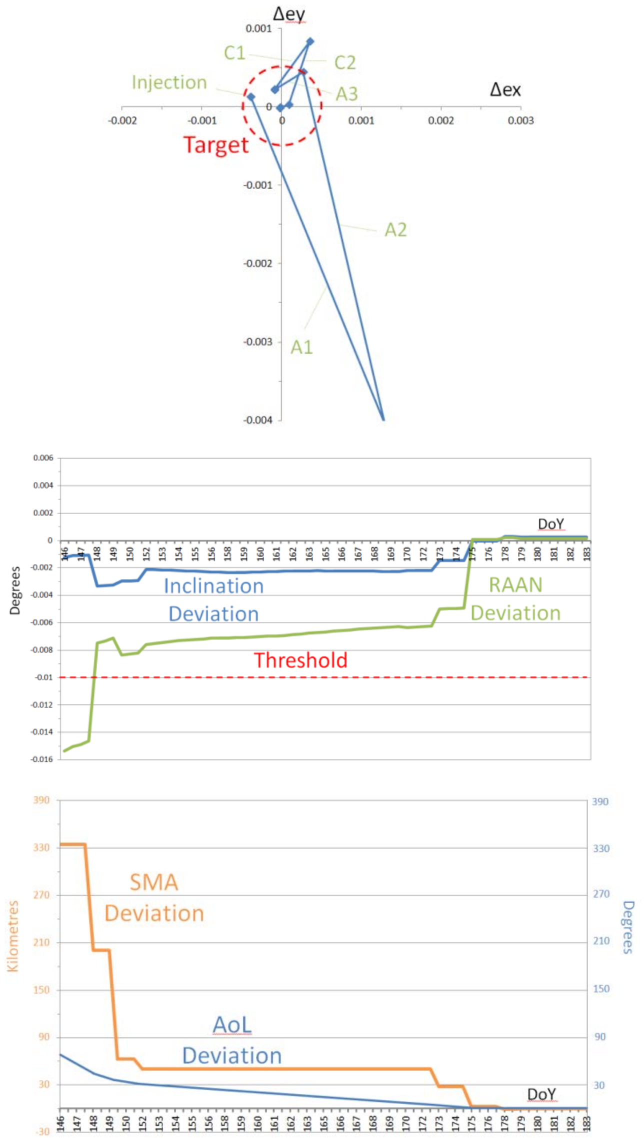

Fig. 7. Evolution of orbital parameters of GSAT0211 (eccentricity vector, inclination and RAAN, SMA and AoL).

### 5.4. Manoeuvres in the Fine Positioning Phase

#### 5.4.1. Manoeuvre Strategy

At the end of the Drift Stop phase the SMA and the AoL needed to be corrected for both spacecraft. The Fine Positioning manoeuvres were used to correct the SMA and AoL, with the exception of the D1 manoeuvre, which was used to correct inclination and RAAN in addition. Due to the strict accuracy of the targets and the misperformance of the manoeuvres that might exceed 10%, it is only possible to plan future Fine Positioning manoeuvres after the last executed manoeuvre has been assessed by an orbit determination.

The possible scenarios after an orbit determination are as follows:

1) The SMA and AoL targets already are or will be acquired without intervention.
2) The AoL target was acquired, but not the SMA target.
3) The AoL target was not acquired nor will be acquired without intervention.

In case 1) no manoeuvres are implemented. The acquisition is declared only after performing an orbit determination using four full revolutions of ranging data covering the acquisition epoch.

In case 2) a single manoeuvre is implemented to acquire the SMA target and stop the drift.

In case 3) two manoeuvres are implemented: the first adjusts the drift, while the second manoeuvre stops the drift.

During manoeuvre implementation, assumptions about the future manoeuvre calibration are skewed in order to prevent an overshoot of the AoL target, i.e. to avoid that the AoL drift is excessive in case of misperformance.

#### 5.4.2. Executed Manoeuvres

For the acquisition of the target of GSAT0210 four Fine Positioning manoeuvres had to be executed. In the case of GSAT0211 only two Fine Positioning manoeuvres were necessary, which stems from the fact that the C3 manoeuvre was one order of magnitude smaller than the one of GSAT0210, thus leading to smaller deviations at the start of the Fine Positioning phase.

For manoeuvres with a magnitude below 5 cm/s the off-pointing was not assessed anymore, due to the difficulty in calibrating the cross-track component, and only the magnitude was calibrated. Results are summarized on Tables 16 and 17.

Table 16. GSAT0210 planned manoeuvres and performance at execution.

| Mano. | Along-track DV (cm/s) | Cross-track DV (cm/s) | ΔSMA (m) | Performance (%) | Off-pointing (deg) |
|---|---|---|---|---|---|
| D1 | 32.26 | -4.16 | 5204 | -2.3 | 1.4 |
| D2 | 2.52 | 0.77 | 405 | -8.4 | - |
| D3 | -0.40 | 0.0 | -71 | +5.4 | - |
| D4 | -0.11 | 0.0 | -18 | +3.7 | - |

Table 17. GSAT0211 planned manoeuvres and performance at execution.

| Mano. | Along-track DV (cm/s) | Cross-track DV (cm/s) | ΔSMA (m) | Performance (%) | Off-pointing (deg) |
|---|---|---|---|---|---|
| D1 | 2.84 | 0.0 | 456 | +7.9 | - |
| D2 | 0.06 | 0.0 | 10 | +13.0 | - |

#### 5.4.3. Assessment of Acquisition

The acquisition of the target could be declared if the deviations of the determined state-vector with respect to the target orbit were inside the thresholds specified in Table 4. A 3-sigma margin had to be considered in addition, using the estimated variances of the elements in the OD.

The OD was set up such that each ranging pass was smoothed into a single point of data. The sigma of each station was set with base on the mission analysis assumptions[1)], such that the most realistic covariance results could be obtained. An example of the residuals of such an orbit determination is depicted on Figure 8.

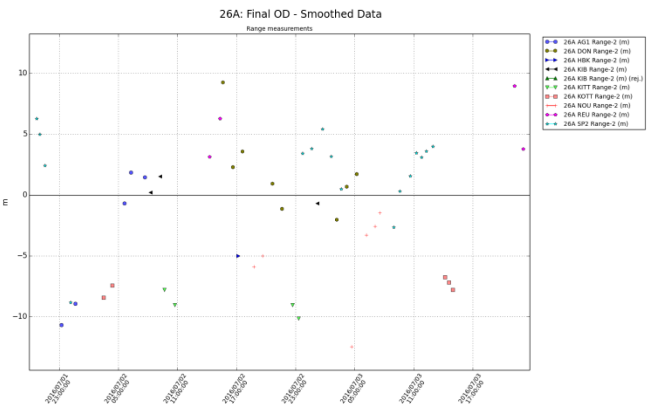

Fig. 8. Residuals of an OD using smoothed range measurements. Each point represents a ranging pass of ca. 5 minutes.

In the OD the Earth Potential Field was considered until the 12th degree and order. Sun and Moon perturbations, solid tides, and solar radiation pressure were considered as well.

The acquisition of target A2 by GSAT0210 was confirmed by FD and by the Galileo Control Centre on the 3rd of July, two days after the execution of the D4 manoeuvre. The acquisition elements are displayed on Table 18.

Table 18. Determined state vector at acquisition of A2 target.

| Parameter | Value | Deviation | 3σ | Threshold |
|---|---|---|---|---|
| Epoch (UTC) | 2016/07/02-20:23:35.656 | | | |
| SMA (km) | 29601.6301 | 0.0021 | 8.78e-4 | 0.005 |
| Eccentricity | 0.000174 | 8.62e-5 | 6.56e-8 | 5e-4 |
| Inclination (deg) | 57.3384 | 2.79e-4 | 3.12e-5 | 0.01 |
| RAAN (deg) | 321.1460 | 2.36e-3 | 3.26e-5 | 0.01 |
| AoL (mdeg) | 0.693 | 0.693 | 2.85e-2 | 2.0 |

Even though the last manoeuvre of GSAT0211 was executed on the 28th of June, it was only possible to declare the acquisition on the 2nd of July, four days after the execution of D2. When an OD was performed during the preparation of manoeuvre D3, at ca. 2016/6/30-19:00 UTC, the target had not been acquired in AoL in the determined orbit arc, as can be seen on Table 19. The drift in SMA is owed to the fact that the target orbit specified in Ref 3) is propagated with a Y-bias, while this effect is not modeled in operations.

The Y-bias has a magnitude of 7.97e-13 km/s$^2$ when the payload is turned on[3)]. In the conditions of the acquisition phase of L7 the along-track effect corresponds to a constant acceleration of 3.82e-13 km/s$^2$ against the direction of velocity. This roughly translates into a change of -0.3 meters in SMA per revolution. During the manoeuvre campaign, during which the payload is in Keep Alive Mode, it is expected to be about half as high[3)].

Table 19. Evolution of SMA and AoL targets of determined orbit prior to D3 w.r.t. to target orbit. Italicized entries are included in the orbit determination arc.

| Epoch (UTC) | Delta-SMA (m) | Delta-AoL (mdeg) |
|---|---|---|
| *2016/06/29-14:58* | *-4.356* | *-2.193* |
| *2016/06/30-05:02* | *-4.018* | *-2.114* |
| 2016/06/30-19:07 | -3.704 | -2.043 |
| 2016/07/01-09:12 | -3.388 | -1.976 |
| 2016/07/01-23:17 | -3.061 | -1.861 |
| 2016/07/02-13:21 | -2.764 | -1.812 |

Using the D3 manoeuvre to increase the SMA would further reduce the drift. Due to the presence of the Y-bias in the target orbit, the SMA of the actual orbit was expected to increase w.r.t. the target orbit, which would further reduce the drift or even stop it. This could prevent a AoL acquisition, which would require the planning of two further manoeuvres to reintroduce a drift and another one to stop it. On the other hand using D3 to decrease the SMA would increase the drift but require bigger subsequent maneouvres to correct the SMA. The final decision was not to execute any D3 manoeuvre.

On the 2nd of July the acquisition of target by GSAT0211 was declared. The results of a post-acquisition OD can be seen on Table 20.

Table 20. Determined state vector at acquisition of A6 target.

| Parameter | Value | Deviation | 3σ | Threshold |
|---|---|---|---|---|
| Epoch (UTC) | 2016/07/01-23:16:36.212 | | | |
| SMA (km) | 29601.5795 | -0.0035 | 2.42e-4 | 0.005 |
| Eccentricity | 0.0000409 | 3.11e-5 | 4.14e-8 | 5e-4 |
| Inclination (deg) | 57.3375 | 2.56e-4 | 1.72e-5 | 0.01 |
| RAAN (deg) | 321.1689 | 1.5e-4 | 1.97e-5 | 0.01 |
| AoL (mdeg) | -1.92 | -1.92 | 1.77e-2 | 2.0 |

### 5.4.4. Assessment of Y-bias

Tracking data was available from after the execution of the D2 manoeuvre up to the end of the 4th of July, two days after the declaration of acquisition, although the data starting from the 3rd of July at 15h00 was sparser. With more than 6 days of tracking data, it was feasible to assess the constant along-track acceleration corresponding to the Y-bias.

The SMA was estimated at each target ascending node after the end of the D2 manoeuvre. Each OD arc was centered in the target node, and the arc was chosen such that it was as long as possible provided it was not perturbed by a manoeuvre. No constant acceleration was modeled.

It was possible to estimate the SMA for five different arcs and to compare them against the target values for the target orbit at ascending node. The arcs are listed in Table 21, and the estimated SMA values are depicted on Fig. 9.

Table 21.  Considered OD arcs.

| OD Arc | S/V Epoch | Arc Start | Arc End |
|---|---|---|---|
| 1 | 06/30-05:02 | 06/28-13:50 | 07/01-19:50 |
| 2 | 06/30-19:07 | 06/28-13:50 | 07/02-23:50 |
| 3 | 07/01-09:11 | 06/28-13:50 | 07/03-15:45 |
| 4 | 07/01-23:17 | 06/28-22:20 | 07/04-22:40 |
| 5 | 07/02-13:21 | 06/30-02:40 | 07/04-22:40 |

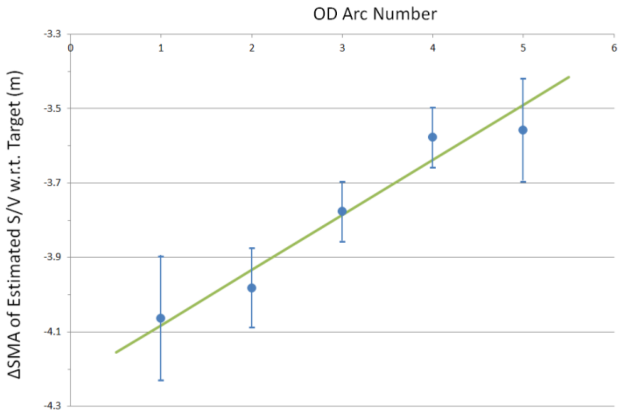


Figure 9.  Determined SMA values, 1-sigma dispersion, and linear fit.

The drift of the SMA w.r.t. the target orbit was linearly fit using weighted least squares. The weights were based on the estimated variances of the determined SMA. The fitted line corresponds to an along-track acceleration of 1.88e-13 km/s$^2$ against the direction of the velocity on the orbit during the acquisition phase, determined with a 1-sigma dispersion of 2.73e-14 km/s$^2$. This confirms the fact that the Y-bias during acquisition is approximately half as high as the Y-bias in operations. The estimate of the Y-bias effect with the payload on Keep Alive mode could be improved with a longer OD arc.

## Conclusions

The L7 LEOP and manoeuvre acquisition campaign were successfully planned and carried out by the CNESOC team at ESOC. In the preparation process, tools were developed that allow for the quick and systematic analysis of multiple acquisition scenarios. The target orbit acquisition was achieved without using all of the allocated manoeuvre slots.

The particular conditions of acquisition in AoL of the A6 slot by GSAT0211 gave FD the possibility of assessing the effect of the Y-bias on Galileo spacecraft during the orbital acquisition phase, in which the payload is set to Keep Alive.

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## References

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## Considerations

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