Sentinel-1B Flight Dynamics Operations during LEOP and Acquisition of its Reference Orbit: Achieving the Sentinel-1 Constellation

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The satellite Sentinel-1B was launched on the 25th of April 2016 by a Russian Soyuz-ST launcher from Europe's Spaceport in French Guiana. The Sentinel-1 Mission is part of the Copernicus Programme, comprising two satellites carrying a C-band Synthetic Aperture Radar (SAR) each. Both satellites are controlled around Sun-synchronous reference orbits with a 12-day repeat cycle, frozen eccentricity and a 180 deg argument of latitude separation between the two satellites. During the three-day LEOP the Sentinel-1 Flight Dynamics (FD) Team working at ESOC was tasked with performing orbit determinations, monitoring AOCS, as well as designing a manoeuvre strategy to acquire the reference orbit, for which a mission analysis study was done during the Launch Preparation Phase. Similarly to Sentinel-1A, plume impingement was expected in the two thruster sets used for semi-major axis corrections of Sentinel-1B. As a result a new procedure was created to slew the spacecraft and use the non-affected third set of thrusters for this purpose. This paper provides a summary of the work performed by the Sentinel-1 FD Team during the Sentinel-1B LEOP as well as the preparation, design and implementation of the manoeuvre campaign culminating with the successful acquisition of the Sentinel-1 constellation on June the 16th 2016.

Key Words: Sentinels, Copernicus Programme, LEO, Earth Observation

Nomenclature

e	:	Eccentricity
SMA	:	Semi-Major Axis
RAAN	:	Right Ascension at Ascending Node
AoL	:	Argument of Latitude
MSLTAN	:	Mean Solar Local Time at Ascending Node
SAR	:	Synthetic Aperture Radar
SAW	:	Solar Array Wings
OCT	:	Orbit Control Thruster
NPM	:	Normal Pointing Mode
Subscripts		
X	:	X component
Y	:	Y component

1. Introduction

1.1. Overview

Approximately two years after the launch of Sentinel-1A, its twin satellite Sentinel-1B was launched on the 25th of April 2016 at 21:02:13 UTC by a Russian Soyuz-ST launcher equipped with a Fregat upper stage from Europe's space port in French Guiana. The Sentinel-1 Mission is a two-satellite system, with each satellite carrying a C-band SAR as well as a laser communication payload to transmit data to the geostationary European Data Relay System for continual data delivery. Sentinel-1 is the first in-orbit complete constellation from the Sentinels fleet that was developed for the European Earth observation Copernicus Programme. The Sentinel-1 constellation is operated from the European Space Operations Centre (ESOC) in Darmstadt, Germany.

The Sentinel-1 Flight Dynamics (FD) Team, as part of the Mission Control Team working at ESOC, was tasked with the following principal activities during the Sentinel-1B three-day LEOP: to perform the first orbit determination after separation and assess the injection achieved by the launcher vehicle, to monitor the Attitude and Orbit Control System (AOCS) telemetry during the deployment of the SAR and the SAW, to generate spacecraft AOCS commands for the on-board propagator configuration, and to design an optimal manoeuvre strategy to bring Sentinel-1B to its reference orbit, thus completing the Sentinel-1 constellation. This last activity required a mission analysis study during the Launch Preparation Phase. The initial phase offset between the two satellites depended on the launch date, while the initial phase drift rate depended on the injection state vector achieved by Soyuz. A parametric analysis accounting for the twelve possible initial phase offsets and various initial phase drift rates was carried out.

1.2. Reference Orbit

Sentinel-1A and B are controlled around dusk-dawn Sun-synchronous reference orbits with a 12-day repeat cycle after 175 orbits with frozen eccentricity and a MSLTAN of 18:00[1]. The two satellites share the same ground track while flying with a separation of 180 deg in argument of latitude, thus actually halving the revisit time of any particular node to six days.

The Sentinel-1A reference ground-track could be acquired at any of its 175 reference nodes, depending on the injection case. In this case the spacecraft was separated from the nearest node by at most 0.5 deg in phasing2). For Sentinel-1B the acquisition of the reference orbit was constrained to a specific reference node due to the required 180 deg angular separation with respect to Sentinel-1A. This additional constraint made the Sentinel-1B acquisition of the reference orbit more demanding than the original acquisition problem.

1.3. Spacecraft Description

Sentinel-1B is a three-axis stabilized spacecraft, and is in all respects identical to Sentinel-1A. The AOCS consists of the following sensors and actuators: fine sun sensors, magnetometers, gyroscopes, star trackers, GPS receivers, magnetic torquers, a reaction wheels assembly and a monopropellant (hydrazine) propulsion system. The propulsion system has 3 pairs of 1 N OCTs, each set made up of a prime and redundant unit, and 4 pairs of Reaction Control Thrusters for attitude correction. Sentinel-1 OCTs 1, 2, and 3 are respectively located on the spacecraft sides +X, -X and -Y, and the deployed SAR and SAW are aligned with the X-axis, as can be seen in Fig. 1. A detailed description of the deployment of the appendages of a Sentinel-1 spacecraft can be found in Ref 1).

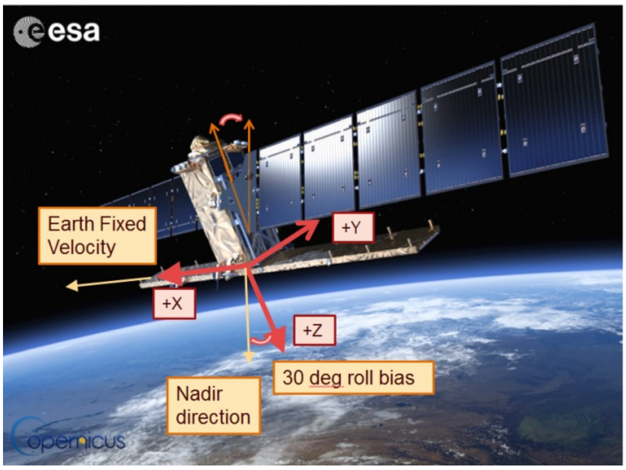

Fig. 1. Sentinel-1 spacecraft reference frame.

When flying in NPM +X matches the direction of the velocity, while +Z points towards nadir with a 30 deg roll bias. Given the fact that Sentinel-1 is in a dusk-dawn orbit, the X-axis (and therefore the solar panels) are perpendicular to the direction of the Sun. OCT 1, 2, and 3 are aligned with the flight direction, anti-flight direction and orbit normal direction respectively. Nominally the first two thruster sets are dedicated to the execution of in-plane corrections, while the third thruster set is dedicated to the execution of out-of-plane corrections. The flight operations of Sentinel-1A have revealed that the first two thruster sets are affected by plume impingement (plume interaction with the SAR and SAW), which implies a drastic limitation of their maximum activation time (35 seconds instead of 300 seconds) and performances2)3). The same behaviour was expected for Sentinel-1B.

In view of the more demanding acquisition problem a new procedure was derived by the spacecraft manufacturer Thales Alenia Space for Sentinel-1 spacecraft, in order to perform in-plane manoeuvres using OCT 3 for up to 600 seconds and using one or both branches at the same time. This is possible by slewing the spacecraft by +90 (respectively -90) degrees around the nadir direction, thus aligning OCT 3 with the positive (respectively negative) velocity direction. The slew to the firing attitude, the burn plus the slew back to the NOM attitude take about 160 minutes. As a consequence of the slew the SAW are brought almost parallel to the Sun direction, thus bringing the satellite into eclipse conditions. Furthermore, the -X (respectively +X) face of the satellite is exposed to the Sun. According to simulations performed by industry these conditions do not cause a violation of thermal or power constraints. After the slew end the spacecraft needs to remain six hours in NPM in order to restore the temperatures and allow the battery to recharge.

2. Mission Analysis

2.1. Summary

During the Launch Preparation Phase the FD Team performed a mission analysis study on the acquisition problem covering all possible launch dates and the expected dispersion of the injection orbital elements. For each derived strategy figures for the duration and Delta-V cost were provided. In the design of a manoeuvre strategy assumptions were made in order to ensure that it is operationally and technically feasible. The software used for the mission analysis was used as well during LEOP to design the operational manoeuvre acquisition.

2.2. Target Orbit

The target orbit of the Sentinel-1B spacecraft follows the same reference ground track as Sentinel-1A. The separation between the in-orbit reference positions of both spacecraft is of 180 deg in phase angle, which leads to a revisit time of the overflown areas every six days.

The MSLTAN has to be kept within 5 minutes with respect to its reference position at 18:00. However the Sentinel-1 spacecraft undergoes a MSLTAN increase of up to 2 min accumulated throughout the mission. As a result when the reference ground track is acquired, the MSLTAN should be inside the control interval [17:55 – 18:03].

2.3. Assumptions and Operational Constraints

The manoeuvre strategies were designed taking into account the following assumptions:

- The manoeuvring campaign shall start two days after the end of the three-day LEOP.
- OCT 3 is used to execute out-of-plane manoeuvres.
- OCT 3 is used as well to execute large in-plane manoeuvres using the procedure described in Section 1.3.
- During the acquisition campaign ten ground station passes are booked per day, approximately during normal working hours. Given the fact that four station passes are necessary prior to and past manoeuvre execution, it is assumed that a single in-plane manoeuvre can be executed per day at

approximately 12:00 UTC.

- Two in-plane manoeuvres are executed per week, scheduled on Tuesdays and Thursdays. This is assumed to be a realistic operational arrangement, providing sufficient time for orbit determination, manoeuvre calibration, re-optimization of the manoeuvre plan and space debris screening.
- The maximum in-plane manoeuvre duration is constrained to 600 seconds. This manoeuvre duration shall be reached after the execution of a test campaign where the manoeuvre duration is increased progressively from 300 s to 400 s, 500 s and 600 s.
- The Delta-V value for a 600 s burn using a single branch has been assumed to be of 0.28 m/s. This figure has been computed using the predicted thruster performance and assuming an average value for a manoeuvre campaign using 10 kg of propellant, starting from Beginning of Life conditions.
- It is possible to perform an in-plane manoeuvre with branches A and B simultaneously, thus doubling the delta-V per manoeuvre.
- Up to six out-of-plane manoeuvres with a maximum duration of 300 seconds can be executed in a single day, from Monday to Thursday. The constraint on the duration is related to the AOCS recovery time and Fridays are left manoeuvre-free to allow for calibration within normal working hours.

2.4. In-Plane Positioning Problem

The in-plane problem refers to finding feasible ways to correct the initial SMA in order to start and stop a drift, which leads to the acquisition of the target orbit, ignoring the rest of orbital parameters, in particular the inclination and the eccentricity. The problem is tackled with a linear approach and the resulting Delta-V cost and duration of the acquisition campaign are obtained for every strategy. First-order approximations of the equations of orbital motion are sufficiently accurate for estimating the duration and the Delta-V cost of a strategy and are as well computationally affordable and fast.

2.4.1. Initial Sentinel-1A/B In-Orbit Relative Position as a Function of the Launch Day

The injection state vector requested to the launcher vehicle was at the reference SMA, eccentricity, and inclination. The Sentinel-1B AoL at injection is independent of the launch date.

In the in-plane positioning problem a unique in-orbit position has to be acquired, 180 degrees apart from Sentinel-1A. Depending on the initial drift, the same target position can be acquired through increasing or decreasing the phasing. Four cases are considered:

- **Target T/2:** the target is acquired a half-orbit ahead of Sentinel-1A by drifting in the flight direction.
- **Target -T/2:** the target is acquired a half-orbit behind Sentinel-1A by drifting against the flight direction.
- **Target 3T/2:** the target is acquired one and a half-orbits ahead of Sentinel-1A by drifting in the flight direction.
- **Target -3T/2:** the target is acquired one and a half-orbits behind Sentinel-1A by drifting against the flight direction.

The phase difference with respect to the target depends on the launch date. Given the fact that the Sentinel-1 reference orbit has a twelve-day repeat cycle, there are twelve possible target locations. Sentinel-1A completes 14 + 7/12 orbital revolutions in one day. As a consequence the position of Sentinel-1A with respect to Sentinel-1B at the time of the Sentinel-1B injection moves forward by 210 deg every day of the repeat cycle, as depicted in Fig. 2.

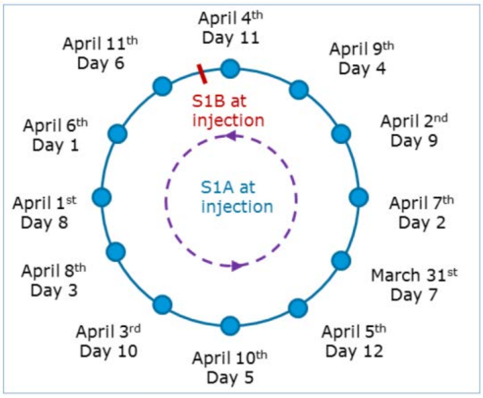

Fig. 2. Possible Sentinel-1A/B relative in orbit position as a function of the launch day.

2.4.2. Initial drift with respect to the Target Orbit due to Injection Dispersion

Depending on the initial SMA deviation a drift in relative orbit position with respect to Sentinel-1A reference orbit (or equivalently with respect to the target) is achieved. This initial drift determines to a large extent the choice of one of the targets listed in Section 2.4.1. In a nominal injection case there isn’t any initial drift in phasing. In this case a drift has to be started and stopped, and so in principle the closest target would be selected. On the other hand, if there is a SMA deviation at injection, the initial drift will impact the feasibility to achieve certain targets and will determine the target selection depending on the required Delta-V and/or time. The considered launch dispersions are listed in Table 1.

Table 1. Soyuz injection dispersion standard deviations.

Parameter	Unit	1σ Deviation	3σ Deviation
SMA	km	3.0	9.0
e_x (x1000)	-	0.482	1.446
e_y (x1000)	-	0.344	1.032
Inclination	deg	0.03	0.09
RAAN	deg	0.05	0.15
AoL	deg	0.122	0.366

2.4.3. Analysis Approach and FD Software

For every set of initial conditions two strategies can be automatically derived by the FD software used for the mission analysis:

- **Natural Drift Acquisition:** Sentinel-1B drifts with the injected SMA towards the target, stopping the drift at the latest possible time.
- **Fast Acquisition:** the initial drift rate is increased and decreased in order to acquire the target as fast as possible.

The Natural Drift strategy ensures that the minimum Delta-V is consumed. For certain initial conditions it might not be possible to start a natural drift towards a certain target in the frame of the assumptions described in Section 2.3. The Fast strategy ensures that the target is acquired as fast as possible, but with the biggest expenditure of Delta-V. The final operational strategy is in principle a compromise between the two strategies.

Examples of the SMA evolution during a Natural Drift and a Fast Acquisition strategy for the same initial conditions and target can be seen in Fig. 3.

In addition, the software supports the generation of a scenario in which the SMA injection error is corrected as fast as possible under the assumptions detailed in Section 2.3 without attempting an acquisition of the target. This information is useful to assess which targets might be feasible.

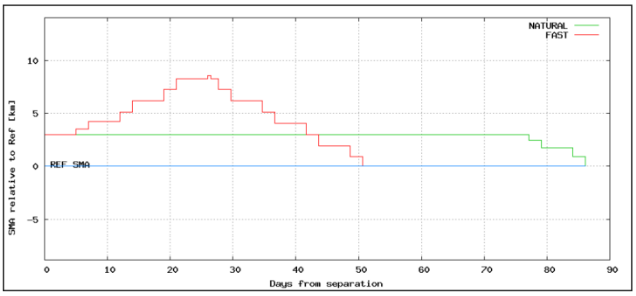

Fig. 3. SMA evolution of a Natural Drift strategy (green) and of a Fast Acquisition strategy (red) to acquire a –T/2 target.

2.4.4. Parametric Analysis

Figure 4 depicts the twelve launch cases for seven SMA dispersion cases (nominal injection and -3, -2, -1, +1, +2, and +3 sigma). The phasing with respect to Sentinel-1A is plotted on the Y-axis against the launch day, numbered from 1 to 12. The blue horizontal lines correspond to the four possible targets 3T/2, T/2, -T/2, -3T/2. For each day and every dispersion case the final relative in-orbit position after stopping the drift as fast as possible is shown (red triangles). In this case it has been assumed that the SMA is corrected by firing OCT 3 with a single branch. The launch on the 25th of April corresponds to day of cycle 8. This plot provides simple visual information on the most adequate target for every launch day and dispersion case, particularly taking into account that a drift reversal is usually slower than increasing the drift to reach the next target.

For each day and dispersion case a Fast Acquisition is derived by the software, targeting each one of the possible four targets. The target with the shortest acquisition duration is selected by the software as baseline for that case. The results for a launch on the 25th of April are listed in Table 2.

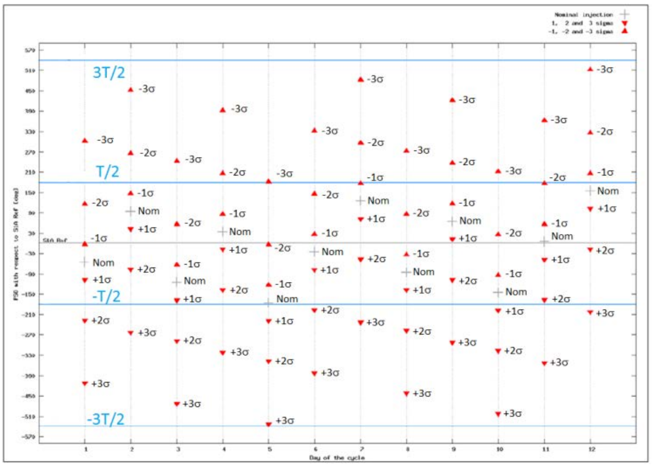

Fig. 4. Final phasing after fastest drift stop for one branch.

Table 2. Fast Acquisition for launch on the 25th of April (one branch).

Dispersion	Target	Duration (weeks)	Delta-V (m/s)
-3σ	3T/2	14	6.7
-2σ	T/2	9	4.2
-1σ	T/2	10	4.9
Nominal	-T/2	8	3.8
+1σ	-T/2	6	2.4
+2σ	-3T/2	12	5.9
+3σ	-3T/2	11	5.5

The same analysis was run assuming that the two branches of OCT 3 are fired at the same time, thus doubling the potential Delta-V in the same time span. The final phasing for this case can be seen in Fig. 5, where it is noticeable that there is a bigger concentration around the T/2 and –T/2 targets.

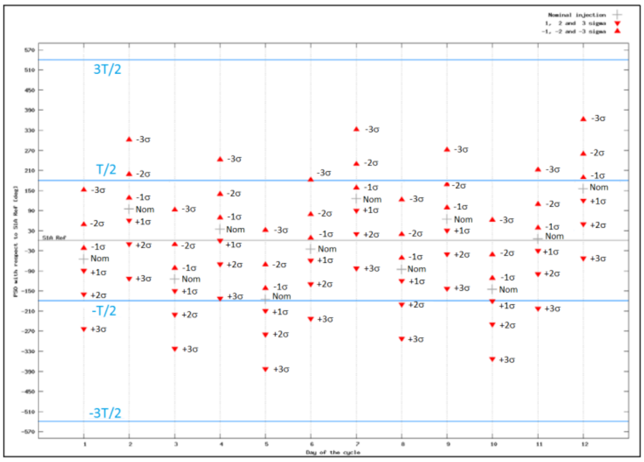

Fig. 5. Final phasing after fastest drift stop for two branches.

In Table 3 the dispersion cases are listed for two branches. Firing the two branches can save at least one week in the acquisition phase for all SMA dispersion cases, and several weeks in the case of larger dispersions, usually at a higher expenditure of Delta-V (but not always). This is the case for any launch date.

Table 3. Fast Acquisition for launch on the 25th of April (two branches).

Dispersion	Target	Duration (weeks)	Delta-V (m/s)
-3σ	T/2	7	5.7
-2σ	T/2	7	6.2
-1σ	T/2	8	7.3
Nominal	-T/2	6	5.3
+1σ	-T/2	5	3.6
+2σ	-T/2	6	4.7
+3σ	-3T/2	8	8.1

The option of using the two branches of OCT 3 for in-plane manoeuvres was considered beneficial for shortening the duration of the acquisition campaign and was used operationally.

2.5. Correction of Inclination and Drift of MSLTAN

Besides reaching a specific in-orbit position the reference orbit acquisition requires correcting the orbit inclination to its reference value. Table 4 provides an estimate of the Delta-V necessary to perform the inclination correction for each dispersion case.

At a rate of six manoeuvres per day the inclination correction can take up to eight days for a 3-sigma error in inclination. This does not automatically translate into a longer acquisition phase. Depending on the in-plane manoeuvre plan, it might be possible to insert inclination manoeuvres during a free drift period, when no in-plane manoeuvre is necessary.

Table 4. Correction of inclination.

Inclination Dispersion	Delta-V (m/s)	# Manoeuvres (one branch)
1σ	3.932	15
2σ	7.864	29
3σ	11.796	43

A deviation in inclination causes a drift in MSLTAN. It can be seen in Fig. 6 that the accrued deviation in MSLTAN for cases within the 3-sigma does not result in a violation of the target MSLTAN within 70 days, even when assuming that no inclination correction is performed during that period.

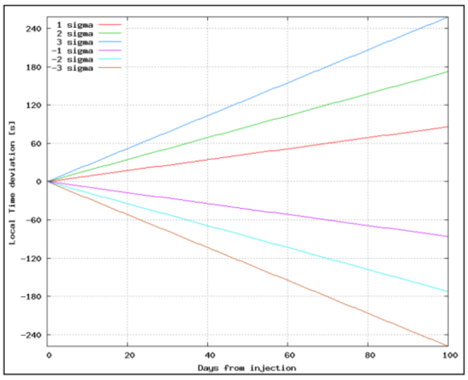

Fig. 6. MSLTAN deviation for various injection cases.

2.6. Correction of Eccentricity

The eccentricity for 1-, 2- and 3-sigma dispersions can be corrected with a budget of 1.78 m/s, 3.60 m/s and 5.43 m/s respectively. If this figure is below the necessary Delta-V to correct the SMA and acquire the target slot, for which there are examples listed in Tables 2 and 3, then the eccentricity can be corrected without any extra Delta-V by placing the existing manoeuvres at the optimal orbit location.

Statistics were compiled for all launch dates and dispersion cases to ascertain how likely it is that additional Delta-V is necessary to correct the eccentricity. As can be seen in Table 5, for 1- and 2-sigma dispersions it is unlikely that dedicated eccentricity corrections are necessary.

Table 5. Statistics for necessary dedicated eccentricity corrections.

Eccentricity Sigma Dispersion	Dedicated Eccentricity Correction (% Cases)
1σ	2.4
2σ	21.4
3σ	70.2

3. LEOP

3.1. Launch

Originally the spacecraft should have been launched on the 22nd of April at 21:02 UTC. However, the launch was twice delayed by one day due to bad weather in Kourou. On the 24th of April a further one-day delay was declared due to a technical issue in the third stage of the Soyuz launcher. On the 25th of April the launch took place at nominal lift-off time.

3.2. Injection and First Acquisition

Separation took place nominally on the 25th of April at 21:25:47.4 UTC, 1413 seconds after lift-off. Shortly after separation there was acquisition of signal over Svalbard (KSAT) and then Alaska (USN) as nominally expected, with indication of no initial time offset in the spacecraft orbit. The initial orbit determinations using ranging passes from Svalbard, Alaska, Troll (KSAT), and Kiruna (ESTRACK) already indicated that the injection was nominal.

An orbit determination was performed within Mission Elapsed Time (MET) +06:00 using range and Doppler tracking data from the four stations, and the corresponding update of antenna pointing elements was provided to the ground stations. The injection was confirmed to be nominal. The injection elements for the separation epoch are detailed in Table 6, and the orbit determination residuals are depicted in Fig. 7.

Table 6. Sentinel-1B injection elements in J2000 at separation epoch.

Keplerian Element	Unit	Nominal	Deviation (absolute)	Deviation (sigma)
SMA	km	7064.474	1.854	+0.6
e_x	-	-0.000807	0.000116	+0.2
e_y	-	0.000003	0.000220	+0.6
Inclination	deg	98.2606	0.0046	+0.2
RAAN	deg	124.1166	0.0037	+0.1
AoL	deg	67.9426	0.0451	+0.4

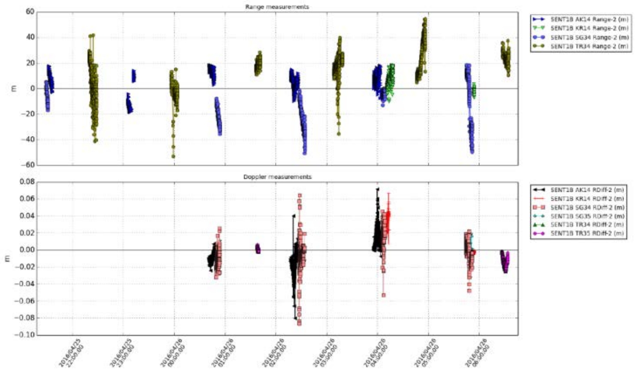

Fig. 7. Range and Doppler residuals of refined orbit determination.

Once the Sentinel-1B injection orbit was determined the next operational step was to check any close proximities with the CNES satellite Microscope that was a co-passenger in the Soyuz launch. An orbit update of the Microscope satellite was provided by CNES following a previously agreed interface. There was no close proximity of the two spacecraft within 100 km in the along-track component or 1 km in the radial and cross-track components for the remainder of the LEOP.

4. Reference Acquisition Manoeuvre Campaign

4.1. Analysis During LEOP

4.1.1. Correction of Injection Errors

The Delta-V necessary for correcting the SMA, eccentricity, and inclination injection errors were respectively of 1.0, 0.94, and 0.6 m/s. As a consequence the eccentricity could be corrected as part of the in-plane manoeuvres, and the inclination could be corrected by executing four 250 s out-of-plane manoeuvres, which could be executed in a single day.

The initial MSLTAN deviation was of 1 s, and had an initial drift of -0.1 s / day, thus being well within the target independently of the acquisition plan.

4.1.2. Acquisition Problem

The positive injection error in SMA was inferior to 1-sigma. As expectable per Table 3, the most favourable target both in Delta-V and time was target –T/2. In these conditions manoeuvres could be performed to increase the drift and accelerate the acquisition.

During LEOP the same software that had been used for the mission analysis was run to derive a Fast Acquisition plan. The basic assumption was that OCT 3 would be used with both thruster branches. Two options were considered:

1) Perform one or two drift rate increase manoeuvres;
2) Perform up to 300s manoeuvres only or gradually increase the manoeuvre duration up to 600s.

Figure 8 depicts the optimization results for the four considered scenarios.

It can be seen that performing two drift rate increase manoeuvres (blue lines above) advances the acquisition by two days at most, while increasing the operational load and augmenting the Delta-V budget. This option was thus dropped.

The plan using the ramp-up of manoeuvres is almost a week faster than the plan using 300s manoeuvres, but it was considered operationally unsafe, because the ramp-up took place during the drift stop phase; if during this phase it were not possible to increase the duration of the manoeuvres as expected, then the drift rate would be too high and Sentinel-1B would drift past the target, which would imply a drift reversal. This would translate into a longer acquisition campaign and into waste of fuel, both of which are highly undesirable. The 300s manoeuvre plan was considered safer because the exact same duration was used multiple times, reducing the chances of failure which would result on re-planning.

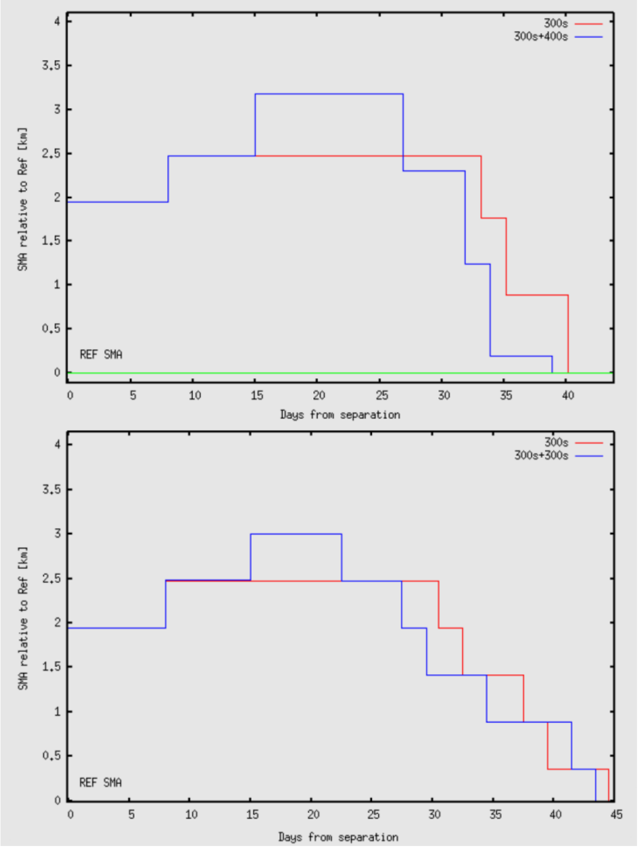

Fig. 8. SMA deviation versus time since separation. The plot on top depicts the ramp-up cases, the one below 300s manoeuvres only.

As a result the plan using 300s manoeuvres with a single drift increase manoeuvre was taken as a first approach for the baseline acquisition plan.

4.2. Test Manoeuvres

Before the acquisition campaign could be started, it was necessary to commission the propulsion system and confirm that in-plane manoeuvres using OCT 3 with both branches could be safely executed, ruling out problems due to thruster misalignments or unexpected issues in keeping the spacecraft pointing during the thrust. To this effect first each one of the branches had to be tested, and then a test slew manoeuvre had to be implemented.

It was decided to perform two test out-of-plane manoeuvres with OCT 3, one with each branch, on the 29th of April. These manoeuvres were planned with a duration of 100s, and were placed on the ascending node in order to correct the inclination by decreasing it. The manoeuvres performed nominally, with no unexpected behavior in the AOCS and respective performances of -0.1% and -2.1%.

The test in-plane manoeuvre using OCT 3 was planned for the 3rd of May using both branches and with a 100s duration as in the previous test manoeuvres. The maneouvre contributed to the selected acquisition strategy, i.e. it was a positive in-plane manoeuvre placed at the right orbit location to correct the eccentricity towards its frozen value. The test manoeuvre was successful, with a performance of -0.2%. It was thus confirmed that the coarse acquisition plan detailed in Section 4.1.2 could be carried out.

OCT 1 and OCT 2 were also tested during the acquisition campaign. The commissioning of these thrusters was relevant for two reasons: firstly, these thrusters are the ones that are activated nominally for the execution of collision avoidance manoeuvres in case a high risk of conjunction is detected during the space debris screening. Secondly, OCT 1 and OCT 2 are the thrusters used to perform the final touch-up manoeuvres for the final acquisition and to do orbit control during routine operations.

4.3. Baseline Plan

After the successful execution of the test manoeuvres a further refinement of the baseline plan was carried out. A 300s in-plane manoeuvre was planned on the 10th of May to increase the drift rate towards the in-orbit target. The SMA deviations and inclination corrections of this plan are depicted in Figures 9 and 10. The final acquisition was planned for the 15th of June by performing touch-up negative in-plane manoeuvres using OCT 1.

The drift phase, after the drift increase and before the drift stop manoeuvres, was used to place the remaining test manoeuvres with the OCT 1 and OCT 2 as well as the inclination correction. The test manoeuvres of OCT 1 and OCT 2 using branch A were placed on the 12th of May, with a duration of 30 s each. The four inclination manoeuvres, with approximate durations of 245 seconds, were planned on the evening from the 17th to the 18th of May.

4.4. Operational Execution

The in-plane manoeuvres using OCT 3 and the test in-plane manoeuvres were planned and executed following the baseline with minor modifications. As expected the performance of thrusters OCT 1 and OCT 2 was degraded due to plume impingement (around -30% performance error) and the overall behavior of the AOCS during the test manoeuvres was in line with the behavior observed for the twin satellite Sentinel-1A.

The out-of-plane corrections were postponed twice. The reason for first postponement was purely an internal decision from the Mission Control Team and the manoeuvre sequence was moved to the evening of the 30th to the 31st of May.

On the 28th of May the Space Debris Office in ESOC based on the inputs from JSpOC detected the risk of a conjunction of Sentinel-1B with Shi-Jian 11-02, an operational spacecraft operated by the Chinese Aerospace Science and Technology Corporation (CASTS). If no action were taken the two spacecraft would have a close approach on the 1st of June at 11:50 UTC with a radial distance of 25 meters, with Shi-Jian 11-02 above Sentinel-1B, which was considered a situation of high risk. It was agreed between agencies that Sentinel-1B would manoeuvre while Shi-Jian 11-02 would not.

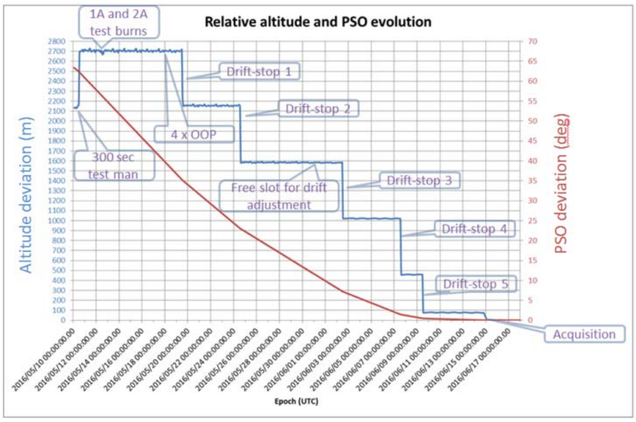

Fig. 9. SMA deviation and phasing of baseline plan.

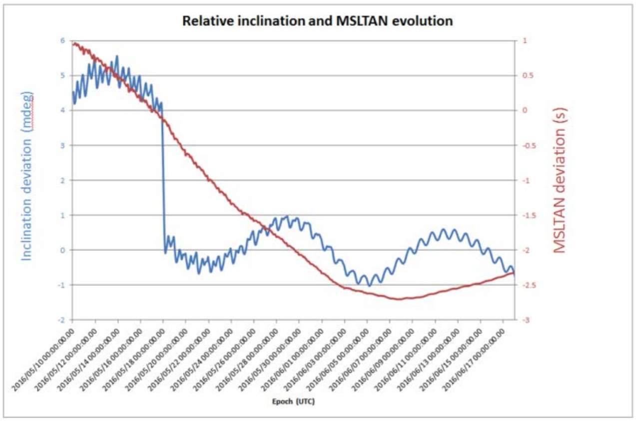

Fig. 10. Inclination and MSLTAN deviation of baseline plan.

The planned out-of-plane manoeuvres were cancelled, and two negative in-plane manoeuvres using OCT 1 with a duration of 30s were implemented in their stead. The cancelled out-of-plane manoeuvres were subsequently moved to the 13th of June.

The difference in the inclination correction between the baseline and the operational plan is depicted in Figure 11.

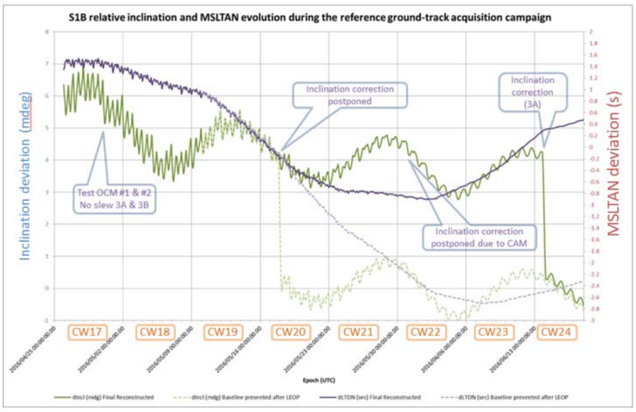

Fig. 11. Groundtrack deviation at acquisition of reference.

In the acquisition campaign the in-plane manoeuvres were placed in the orbit such that the eccentricity was progressively corrected until the frozen eccentricity was achieved within the operational bounds. The final eccentricity evolution during the acquisition campaign is depicted in Fig. 12.

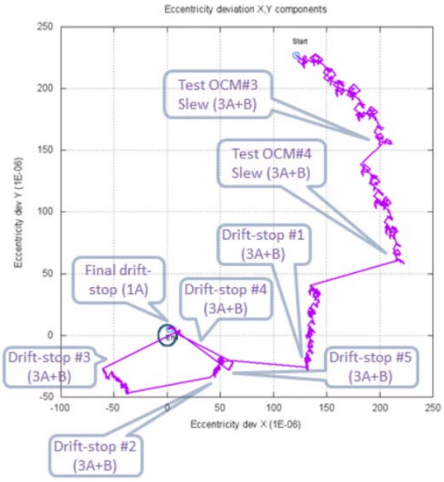

Fig. 12. Eccentricity deviation during acquisition campaign.

4.5. Final Acquisition

The Sentinel-1B reference orbit was acquired on the evening from the 15th to the 16th of June with the execution of five in-plane manoeuvres against the flight direction using OCT 2, each with a duration of 23s. The perpendicular distance with respect to the Sentinel-1B reference ground-track (at the Equator crossings and the maximum latitude) after the execution of the last acquisition manoeuvre sequence is portrayed in Figure 13.

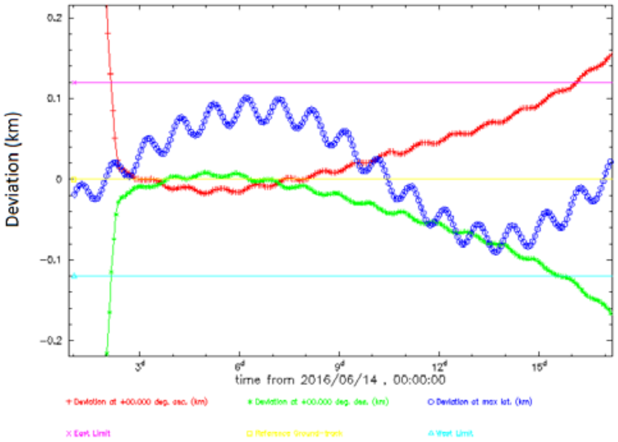

Fig. 13. Groundtrack deviation at acquisition of reference.

The acquisition manoeuvres were used to optimize the eccentricity as well, as is represented in Figure 14. The value at acquisition was chosen to minimize the Delta-V necessary for eccentricity control during the first routine orbit control cycles, taking into account the solar radiation pressure perturbation to the eccentricity expected in summer4).

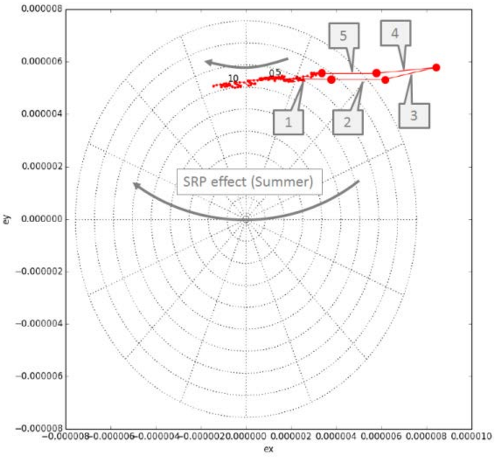

Fig. 14. Eccentricity correction of acquisition manoeuvres.

5. Conclusions

Sentinel-1B was launched on the 25th of April 2016 by a Russian Soyuz-ST launcher from Europe's Spaceport in French Guiana. After a seven week long manoeuvre campaign it acquired the reference orbit on the 16th of June 2016.

The procedure to execute large in-plane manoeuvres using OCT 3 in Sentinel-1B was successfully tested and carried out during the reference acquisition campaign of the satellite. The acquisition campaign was completed within a time frame commensurate with what was expected in the mission analysis. The acquisition plan was proven to be robust in the face of unexpected replannings.

In routine operations the spacecraft is currently being controlled around the reference orbit with an identical operational concept as is used for Sentinel-1A1).

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