SENTINEL-1A REFERENCE ORBIT ACQUISITION MANOEUVRE CAMPAIGN

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***Abstract:** Sentinel-1 is a two satellite radar imaging mission, part of the European Copernicus Programme. Both satellites of the constellation, Sentinel-1A and Sentinel-1B, are operated in a sun-synchronous reference orbit, with a 12 day ground-track repeat cycle after 175 orbits and a Mean Solar Local Time of the Ascending Node of 18:00h. The first satellite of the constellation, Sentinel-1A, was launched on the 3rd of April 2014 by a Soyuz rocket from Europe's Spaceport in French Guiana. The Flight Dynamics Team at the European Space Operations Centre (ESOC) in Darmstadt, Germany, was in charge of designing a manoeuvre campaign to correct the injection errors and acquire the reference ground-track, to be started after the 3 day LEOP. The execution of a collision avoidance manoeuvre on the second day of LEOP revealed a non-nominal behaviour of the propulsion system. After characterizing the spacecraft thrust capabilities, a new approach to the reference orbit acquisition manoeuvre campaign was developed by the complete ESOC Mission Control Team. The reference orbit acquisition was successfully concluded in the beginning of August 2014, after more than 400 manoeuvres and 4 months since the start of the LEOP. This paper presents the strategies and tools developed by Flight Dynamics to tackle the acquisition problem as part of the preparation for the launch. It presents as well the re-adaptation of the strategy after LEOP and its operational implementation and execution.*

***Keywords:** Sentinels, Reference Acquisition, Copernicus, GMES, Earth Observation.*

1. Introduction

Copernicus is a programme of the European Commission to monitor the Earth using multi-source data to collect information related to environment and security on a global level. The Sentinel satellites, operated by the European Space Agency, are an integral part of this programme. Sentinel-1, the first of the five Sentinel missions, consists of a two LEO satellite constellation providing all-weather, day and night radar imaging for land and ocean services, performed by its C-Band Synthetic Aperture Radar (SAR) payload.

As for many other Earth Observation missions, the satellites of this constellation have an orbit control based on a reference orbit with a repeat ground-track pattern. The reference orbit of Sentinel-1 consists of a sun-synchronous dusk-dawn frozen orbit, with a 12 day ground-track repeat cycle after 175 orbits and a Mean Solar Local Time of the Ascending Node (MSLTAN) of 18:00h. The two satellites of the constellation, Sentinel-1A and Sentinel-1B, should be separated by 180 degrees in argument of latitude, which results in a repeat ground-track cycle of 6 days for the constellation as a whole.

For Sentinel-1A the Flight Dynamics Team at the European Space Operations Centre (ESOC) in Darmstadt (Germany), had the role of supporting the 3-day Launch and Early Operations Phase (LEOP) as part of the Mission Control Team, and to design a reference acquisition manoeuvre campaign strategy in the course of the same LEOP to correct the injection errors and acquire the reference orbit at one of the 175 reference nodes. This paper describes the acquisition problem and its analysis by Flight Dynamics in the months preceding the launch, as well as tools and techniques prepared beforehand to quickly produce a detailed manoeuvre campaign during the course of the LEOP. The two main drivers in the acquisition analysis were the relatively high dispersions specified by the launcher and the thrusting capability of the spacecraft, whose thrusters could at most perform 14 cm/s manoeuvres at beginning of life. As a result of the analysis Flight Dynamics recommended the allocation of 6 weeks for the acquisition campaign.

Sentinel-1A was launched on the 3th of April 2014 by a Soyuz rocket from Europe’s Spaceport in French Guiana. Even though no manoeuvres were planned for execution during LEOP, a collision avoidance manoeuvre had to be implemented on the second day of LEOP to mitigate the conjunction risk with the NASA satellite ACRIMSAT (see [1] for a detailed description of the Sentinel-1A LEOP operations). The non-nominal performance of Sentinel-1A’s propulsion system observed during the execution of this manoeuvre led to a re-definition of the reference orbit acquisition campaign during the weeks that followed the end of LEOP. The paper addresses the contribution of the Flight Dynamics Team to the re-definition and implementation of the manoeuvre campaign that was conduced from April to August 2014. Sentinel-1A started its first control cycle about its reference ground-track on the 7th of August 2014, after the execution of more than 400 manoeuvres to correct the semi-major axis injection error of approximately 8 kilometres.

2. Acquisition Campaign Analysis Prior to the LEOP

In the months preceding the Sentinel-1A LEOP, Flight Dynamics carried out an analysis of the acquisition problem, which included the development of a S/W tool to design an acquisition manoeuvre campaign depending on the injection achieved by Soyuz. The tool could be run in a parametric analysis mode or in an operational mode to generate a single manoeuvre strategy based on given injection conditions. The tool was used in its parametric analysis mode before LEOP to produce an estimation for the duration of the acquisition campaign. As an outcome of this analysis Flight Dynamics recommended the allocation of 6 weeks for acquisition operations as input to the Commissioning plan. In addition, the tool was intended to be used in its operational mode during LEOP to generate the acquisition strategy once the injection achieved by Soyuz was determined.

2.1 Acquisition Problem

The target of the acquisition manoeuvre campaign was to synchronize the spacecraft with its reference ground-track at any of the possible 175 reference nodes (apart by 229 kilometres), keeping a maximum difference in perpendicular distance to the reference ground track below 120 metres at the Equator and at the maximum latitude point in the orbit. Additionally the final MSLTAN had to be between 17:57 and 18:05 hours. In order to meet the ground-track synchronization target, both semi-major axis and inclination achieved at injection had to be corrected:

- The semi-major axis correction had to be performed to start a drift at the Equator crossings towards a reference orbit node. Once close to the reference node, the semi-major axis had to be brought to its reference value to stop the drift and achieve the ground-track synchronization.
- The inclination correction aimed at bringing the inclination to its reference value while inducing or correcting (if necessary) a drift in MSLTAN such that it was within the target interval at the end of the acquisition.

According to the dispersion values expected for the eccentricity (see Table 1), the eccentricity correction could for most part of the injection cases be absorbed by the semi-major axis correction. This is achieved by placing the in-plane manoeuvres at the right argument of latitude. In case the in-plane manoeuvres were not sufficient to correct the eccentricity, there would be dedicated manoeuvres to correct the eccentricity.

2.2. Assumptions and Constraints to the Analysis

The design of the manoeuvre campaign was driven by the following assumptions and constraints:

- Start of manoeuvring after the 3 day LEOP;
- Expected orbit dispersions at injection as specified by the launcher;
- A maximum delta-v of 14 cm/s per manoeuvre, corresponding to a maximum thruster on-time of 300 seconds for the 1 Newton thrusters at beginning of life;
- The execution of a maximum of one manoeuvre per orbital revolution, to ensure the recovery of the AOCS between manoeuvres;
- Execution of calibration/test manoeuvres at the beginning of the manoeuvre campaign;
- The allocation of sufficiently large calibration arcs between manoeuvre groups, in order to have a proper characterization of the propulsion system and allow for the screening of conjunction risks by the Space Debris Office (SDO) at ESOC before the implementation of subsequent manoeuvres;
- Manning constraints, conducting operations to the maximum extent possible within working hours.

Some of these assumptions and constraints are described in detail in the following subsections.

2.2.1. Nominal Separation State-Vector and Dispersions

The Sentinel-1A injection state vector was selected at the reference altitude and orbital plane. In terms of distance to the reference ground-track at the Equator, Sentinel-1A injection orbit was 34 kilometres eastwards from the nearest reference node. The assumed dispersion values for the analysis were the ones provided by Soyuz, listed in Table 1.

Table 1: Separation state-vector (True-of-Date) and launcher-specified dispersions.

Parameter	**Nominal Separation**	**Dispersion (1-sigma)**
Epoch (UTC)	2014/04/03-21:25:50.2	-
Semi-major axis (km)	7064.536	2.973
X-component of Eccentricity Vector	-0.000799	0.0004109
Y-component of Eccentricity Vector	0.000021	0.0001848
Inclination (deg)	98.1872	0.02894
Right Ascension of Ascending Node (deg)	102.12	0.006111
Argument of Latitude (deg)	248.89	0.006728

The 3-sigma dispersion in right ascension of ascending node (RAAN) translates into a 4 seconds dispersion in MSLTAN, which is well within the window of [17:57, 18:05] hours. Therefore the maximum expected error in this parameter did not play an important role in the analysis. Of more importance was the drift in MSLTAN during the acquisition phase introduced by the dispersion error in inclination and semi-major axis.

2.2.2. Sentinel-1A Propulsion System

Sentinel-1A is equipped with three pairs of 1 Newton thrusters, each pair consisting of a prime and a backup unit.

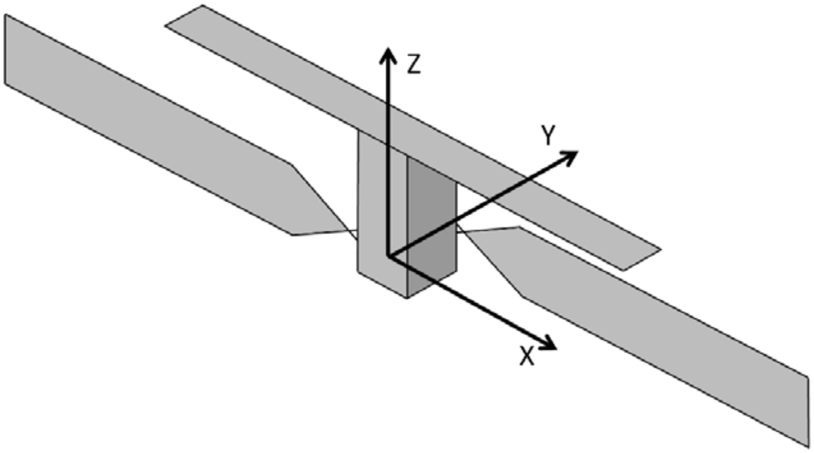

Figure 1: Sentinel-1A spacecraft-centered reference frame.

The spacecraft reference frame is depicted in Fig. 1. In its Normal Pointing Mode (NPM), without yaw and roll steering laws being enabled, the attitude of Sentinel-1A is such that +X is pointing in the direction of the inertial spacecraft velocity, and the +Z axis is pointing towards the Earth with a 30 degree roll angle. This was the mode selected before launch for the execution of the reference orbit acquisition manoeuvres.

Thrusters 1 and 2 are respectively used for in-plane (IP) manoeuvres against the flight direction and in the flight direction, being respectively mounted on the +X and the –X faces of the satellite. Thruster 3 is mounted on the –Y face of the satellite with a 30 degree tilt to account for the attitude law, such that in NPM without steering laws it provides a purely out-of-plane (OOP) thrust in the opposite direction to the orbit normal vector. It is used for inclination manoeuvres around the orbital node crossings. A manoeuvre executed at the descending node increases the inclination, while a manoeuvre executed at the ascending node has the opposite effect. IP and OOP corrections could be performed without any previous slew manoeuvre.

The maximum thrust duration recommended by the spacecraft manufacturer was set to 300 seconds, which corresponds to a delta-v of 13.9 cm/s at the end of LEOP tank conditions. This maximum duration was given by the limitation of the Reaction Wheels to keep the platform pointing during the thrust. A 100 minutes margin between burns was also foreseen to allow for the momentum dumping of the Reaction Wheels (achieved with magnetotorquers).

2.2.3. Space Debris Conjunction Monitoring and Manoeuvre Calibration

The ESOC SDO is responsible for monitoring conjunction risks affecting ESA satellites. This screening service relies on the debris catalogues delivered on best effort bases by the Joint Space Operations Centre (JSpOC). The design of the manoeuvre strategy had to account for sufficient margin between the execution of manoeuvres in order to:

- Assess the manoeuvre performance and determine the achieved orbital change.
- Provide SDO with sufficient time to submit the orbit with the next planned manoeuvres to JSpOC and process the results in time before the implementation of the next manoeuvre group.

The analyses were run assuming execution of manoeuvre batches of 6 subsequent orbital revolutions, leaving a period of 14 hours between batches.

2.2.4. Manning Constraints

Operations should be conduced as far as possible within normal working time. Therefore the execution of manoeuvres on Friday or over the weekend was excluded.

2.3. Manoeuvre Campaign Optimization S/W Tool

A S/W tool was developed to run multiple manoeuvre sequence optimization cases. The core of this tool was the ESA Flight Dynamics Infrastructure S/W for manoeuvre optimization (MANTRA). For given injection dispersion values (semi-major axis, inclination and RAAN) and a given duration of the coarse acquisition phase in weeks, the optimization of the manoeuvre sequence was performed in four steps taking into account the various constraints mentioned in the previous chapter:

1) The necessary impulsive delta-V (IP and OOP) to correct the injection is calculated.

2) The total IP and OOP impulsive delta-v obtained in the previous step are divided in batches of manoeuvres executed every day, without targeting any specific reference node. After this step two candidate reference nodes for acquisition (one to the East and one to the West) are identified.
3) The manoeuvre sizes are optimized again constraining the final node longitude to achieve the ground-track acquisition at the Equator for the two candidate reference nodes.
4) One of the reference nodes is selected. The manoeuvre strategy is adapted to comply with the operational constraints mentioned in the previous section. In addition the IP manoeuvres are adjusted to correct the eccentricity vector.

The process is explained more in detail in the next subsections.

2.3.1. Step 1 – IP and OOP Delta-v

In the first step the total necessary IP and OOP delta-v's for correcting the injection error are computed, assuming that they are done respectively with a single IP manoeuvre and a single OOP manoeuvre.

2.3.2. Step 2 – Delta-v Split

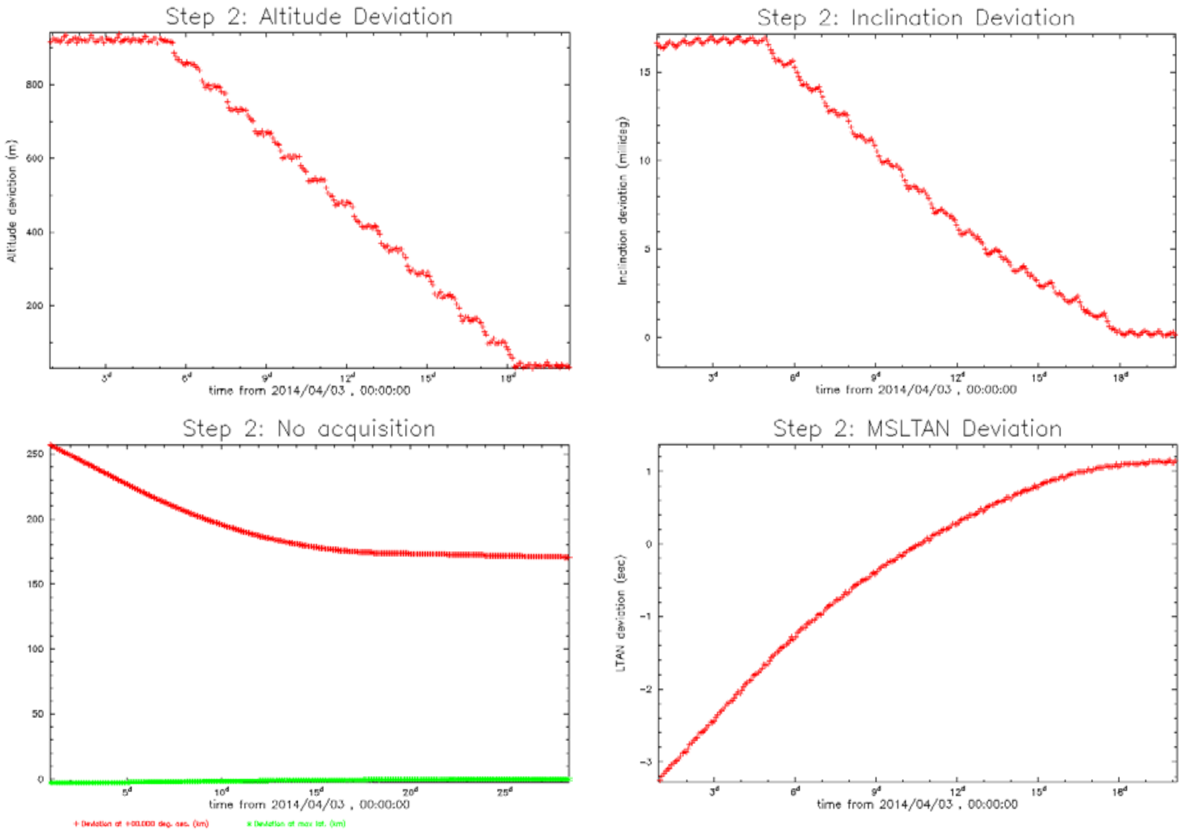

Figure 2: Example of optimization Step 2 results.

In the second optimization step, the estimated delta-v's get evenly split into daily batches of manoeuvres, for different durations of the acquisition phase, in 1 week steps. A constraint is also set on the final MSLTAN, to ensure that it is kept within 17:57 and 18:05 hours. In Fig. 2. the altitude, inclination, MSLTAN and ground-track deviation for a nominal injection case are depicted.

There are cases for which the split is not possible, due to the limitation in manoeuvre number and size. Those cases provide the required information about the minimum time window that should be allocated to the acquisition of the reference orbit after LEOP. For the cases in which a split is possible, no specific reference node was targeted, therefore at the end of the acquisition the spacecraft should lie between two nodes, one to the East, and one to the West (see bottom-left plot in Fig. 2). For those cases one proceeds to Step 3.

2.3.3. Step 3 – Acquisition of East and West Nodes

For each case from Step 2, the distribution of delta-v's is further refined to target the closest nodes, to the West and to the East, in two separate optimizations. The acquisition of the selected reference node might be achieved with a natural drift, or it might be necessary to increase or revert the drift (such as in Fig. 3), resulting in additional fuel consumption. Therefore the former case is in general preferable. The selected case is then refined in the fourth and final step.

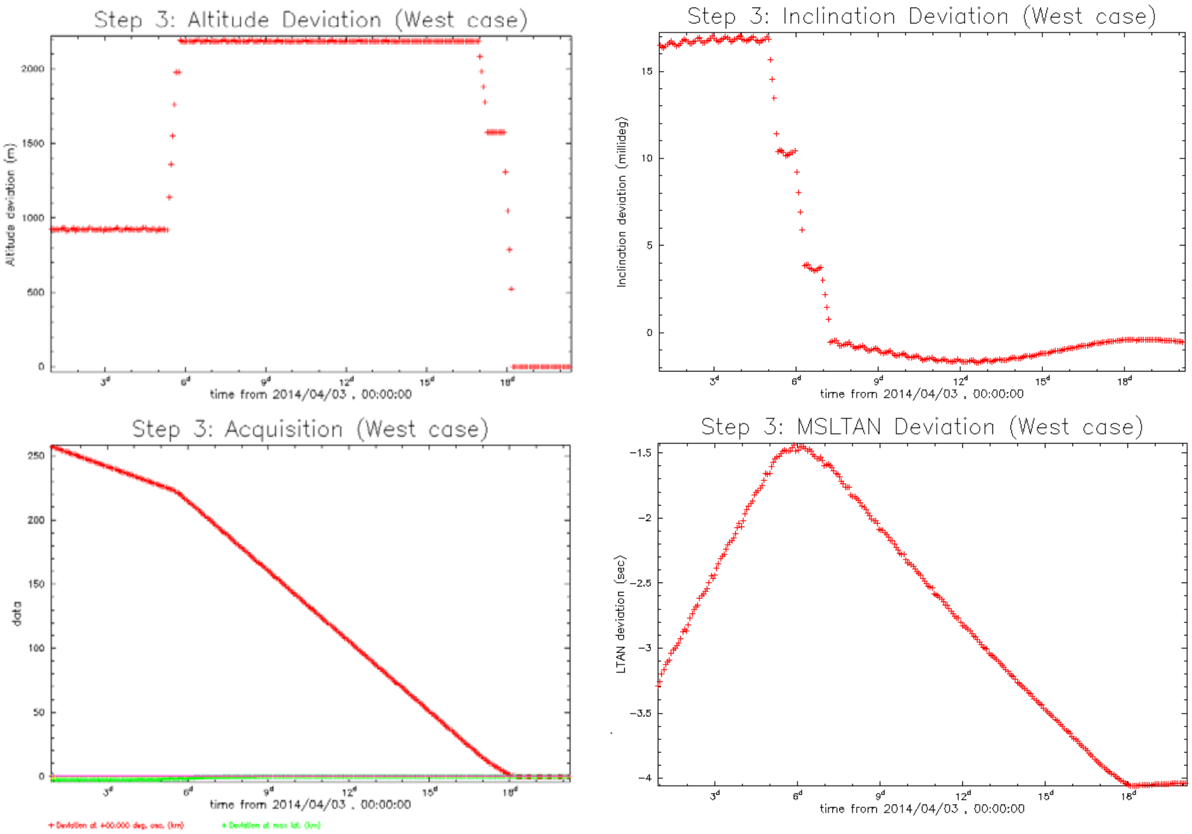

Figure 3: Optimization Step 3 results for a nominal case (western node). The drift has to be increased to acquire the selected reference node at the Equator.

2.3.4. Step 4 – Fine Optimization

The selected case is refined to take into account:

- The placing of calibration/test manoeuvres before the start of the campaign;
- The operational constraints. Manoeuvre batches are placed only from Monday to Thursday;
- The correction of the eccentricity. The eccentricity is corrected with the optimized IP manoeuvres if possible, otherwise dedicated manoeuvres are added to the strategy;
- The evolution of the MLSTAN. The IP and OOP corrections could be reshuffled to yield a more advantageous evolution of the MLSTAN.

These changes have as a likely consequence the extension of the acquisition by some days when compared with Step 3. In the LEOP the fine optimization results were to be used as the main input for a discussion with the complete Missions Control Team to agree on a final strategy.

3. Actual Acquisition Manoeuvre Campaign prepared after LEOP

Within a few hours after separation the Flight Dynamics Orbit Determination Team provided a consolidated orbit injection assessment based on S-band radiometric tracking data. The injection parameters errors relevant to the reference orbit acquisition are summarised in Table 2. Even though no manoeuvres were planned for execution during LEOP, a 40 seconds duration collision avoidance manoeuvre against the flight direction had to be implemented on the second day of LEOP. The assessment of the manoeuvre performance showed an unexpected behaviour of thruster 1 prime unit: an along-track performance error of -21 % and torques approximately ten times larger than expected were observed. The execution of test manoeuvres after LEOP, consisting of the activation of thrusters 2 and 3 prime units (for IP thrust in the flight direction and OOP thrust respectively), led to the conclusion that the observed issues were caused by plume impingement affecting thrusters 1 and 2. For more details about the propulsion system issue investigation see [1].

Table 2: Injection errors and required delta-v for correction.

Parameter	Injection Error	Necessary Correction (delta-v)
Semi-major axis	-7.8 km	4.1 m/s
Inclination	-16 mdeg	2.2 m/s
MSLTAN	4 s	N/A

The resulting new assumption for the generation of the manoeuvre acquisition strategy concerning the thrusters for IP correction was a maximum manoeuvre duration of 30 seconds. At the end of LEOP tank conditions, and taking into account the observed performance degradation for these thrusters (-30% approximately), this burn duration translated into a total delta-v per burn of 1 cm/s, instead of the almost 14 cm/s assumed before LEOP. Thruster 3, used for OOP manoeuvres, was not affected by the same issues.

The almost 8 kilometres lower semi-major axis achieved at injection implied a strong ground-track drift at the Equator with respect to the target reference orbit of 65 kilometres/day.

In other words Sentinel-1A was passing through two reference nodes per week (see Fig. 4). The MSLTAN drift was not a relevant constraint to the preparation of the manoeuvre plan. It was drifting by less than 1 second/day due to the combined effect of the semi-major axis and inclination deviations.

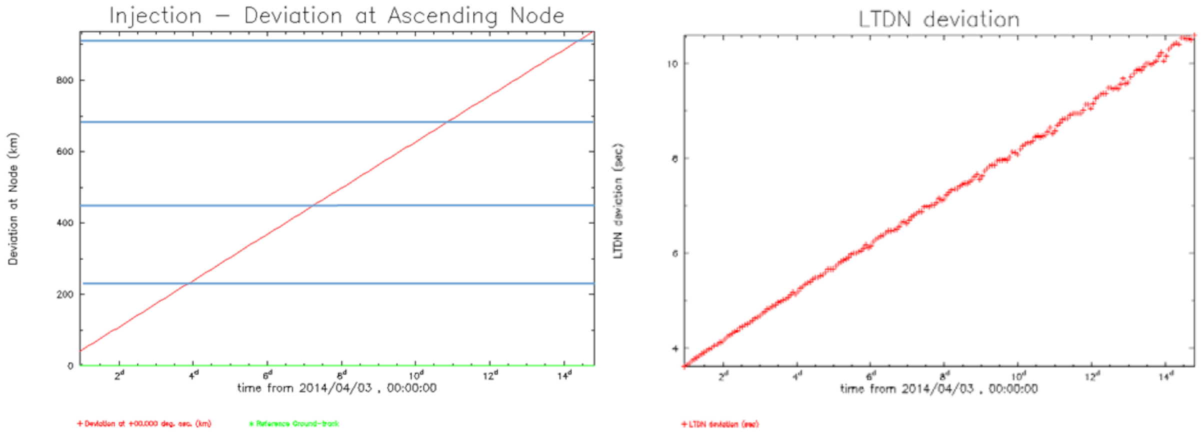

Figure 4: Ground-track at the Equator and MSLTAN deviation evolution after injection.

With these initial conditions, there was no immediate need for starting the acquisition campaign other than the schedule constraints regarding the commissioning activities, some of which could only start once the reference ground-track had been acquired.

The proposed approach by the Flight Dynamics Team was a two phase campaign. It was quite clear that the campaign should start with an initial orbit rise phase (Phase 1), where the semi-major axis would be increased as fast as operationally possible. The target for the semi-major axis at the end of Phase 1 was set 4 kilometres below the reference one, which corresponds to a semi-major axis increase of 4 kilometres. At that point the longitude drift at the Equator would be 32 kilometres/day, or 1 reference node crossing per day. That drift rate gave the opportunity to start Phase 2 of the reference orbit acquisition at the Equator targeting a reference node, with repeating initial conditions every week.

The Flight Dynamics Team worked together with SDO and FCT to develop a safe operational concept for the implementation of such a long manoeuvre campaign. From the figures mentioned above it was clear that ESOC was facing a campaign lasting several months and comprising more than 400 manoeuvres. The agreed concept was essentially based on the execution of manoeuvre batches avoiding weekends, with one manoeuvre planning exercise per week. This manoeuvre planning was twofold, including the planning of the coming week manoeuvre batches and the overall strategy re-planning. The result of this planning was used to perform collisions risk screening and Mission Planning activities (station booking, commissioning operations, etc) for the following week. The manoeuvering window was set to [19:00 – 08:00] UTC and the number of manoeuvres per batch was increased gradually as more confidence on the platform behaviour was built up. The concept is graphically described in Fig. 5.

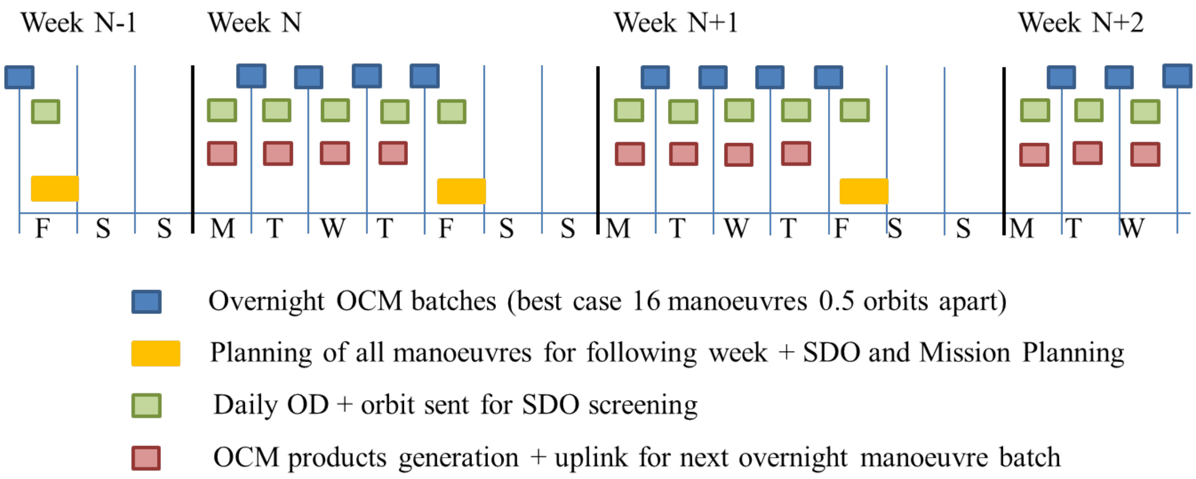

Figure 5: Manoeuvre strategy operational concept.

3.1. Execution of the Manoeuvre Campaign Phase 1: Orbit Rise

A pre-condition to start the acquisition campaign applying the operational concept described in the previous subsection was to perform a proof-of-concept manoeuvre batch. A 6-manoeuvre test batch took place on the 23d of April during working hours and with ground station passes after every manoeuvre execution. This station coverage allowed the monitoring of the AOCS recovery between burns, with the possibility of cancelling the remainder of the manoeuvre sequence in case of non-nominal behaviour. Following the successful execution of this test batch, Phase 1 of the acquisition campaign started on the 30th of April 2014 with the execution of the first 8-manoeuvre batch. For some of the batches in Phase 1 eccentricity vector corrections were performed (see Fig. 7). These were achieved by placing all manoeuvres on the same orbit location, in opposition to distributing them in two groups executed at opposite arguments of latitude when no eccentricity correction was desired. The AOCS response throughout the first weeks of Phase 1 was satisfactory. Stable pointing was provided during the thrust actuation and the reaction wheels dumping in between burns was achieved. In view of the observed behaviour, on the 17th of June 2014 it was decided to reduce the time interval between manoeuvres from one to half an orbit period. Keeping the same manoeuvre window ([19:00 – 08:00] UTC), this change implied the possibility to perform 14 manoeuvres per batch, leaving an orbit of pause in the centre of the window (8 manoeuvres + pause + 6 manoeuvres). This manoeuvre setup did not permit eccentricity corrections. Whenever an eccentricity correction was needed, a 8-manoeuvre batch was selected instead.

Phase 1 was successfully completed on the 26th of June after achieving the planned semi-major axis rise by 4 kilometres and the eccentricity vector corrections towards the frozen value (see Fig. 6 and 7). A total of 23 batches of in-plane manoeuvres were planned and executed over 10 weeks. During these 10 weeks the detection of high collision risks by the Space Debris Office forced the cancellation of one manoeuvre batch on the 15th of May, and to the implementation of additional collision avoidance manoeuvres.

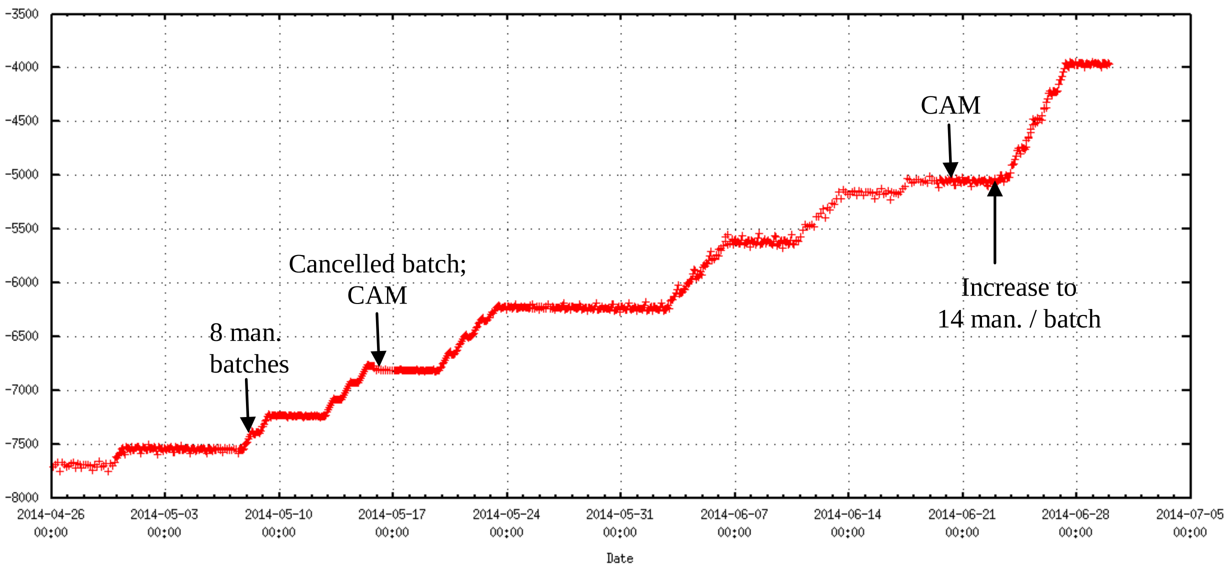

Figure 6: Altitude deviation (m) with respect to the Reference Orbit during Phase 1.

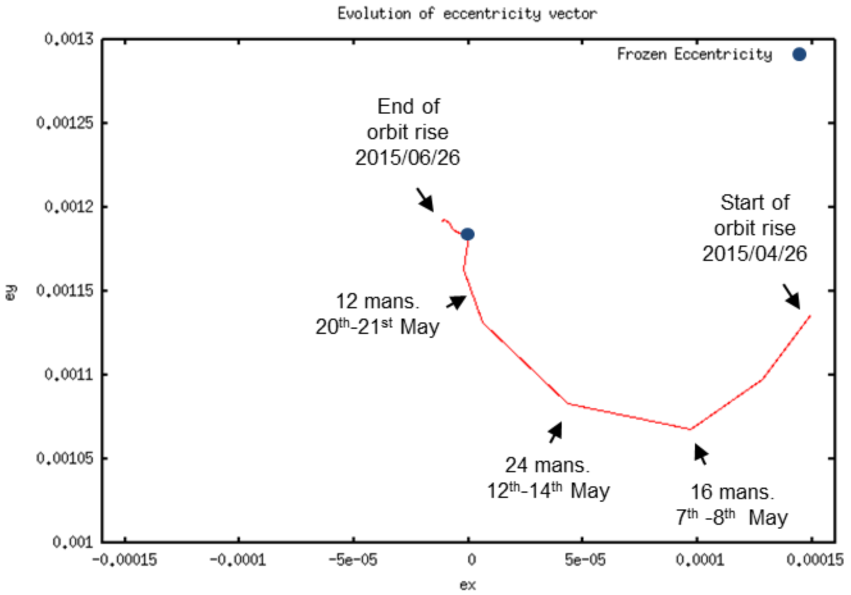

Figure 7: Evolution of the averaged eccentricity vector during Phase 1.

3.2. Execution of the Manoeuvre Campaign Phase 2: Final Ground-track Acquisition

During the execution of Phase 1 of the plan several options for Phase 2 were analysed. On the 26th of June, upon completion of Phase 1, the way to proceed with the acquisition had already been agreed. The targets for Phase 2 were to start a final ground-track drift at the Equator crossings towards a reference node, correct the inclination injection dispersion, and deliver an eccentricity vector close to the frozen value at the time of the acquisition.

The operational concept validated during Phase 1 was continued for the semi-major axis correction in Phase 2. In these conditions, the minimum achievable duration for Phase 2 was 6 weeks.

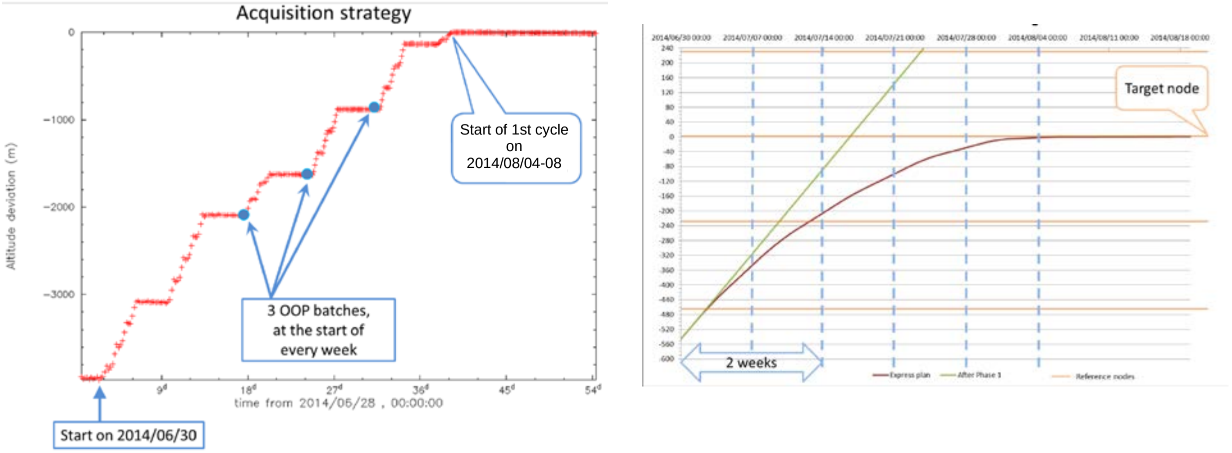

Figure 8: Phase 2 strategy with altitude and ground-track deviation.

The inclination correction was planned in a sequence of three OOP manoeuvre batches to be executed on Mondays on three consecutive weeks, starting on the 7th of July. The rationale behind this was to allocate enough time during the remainder of the week for the calibration and correction of any IP parasitic component, which would affect the ground-track drift at the Equator crossings. The manoeuvre durations were planned in a ramp-up fashion to safely characterize the platform reaction to longer thrust durations. OOP corrections were performed with thruster 3, which was not affected by the problems described at the beginning of this section. The three batches were performed with a fully nominal AOCS response and the estimation of an averaged IP parasitic component of 1.4% against the flight direction. The effect of the OOP corrections on the inclination and the MSLTAN evolution are shown in Fig. 9.

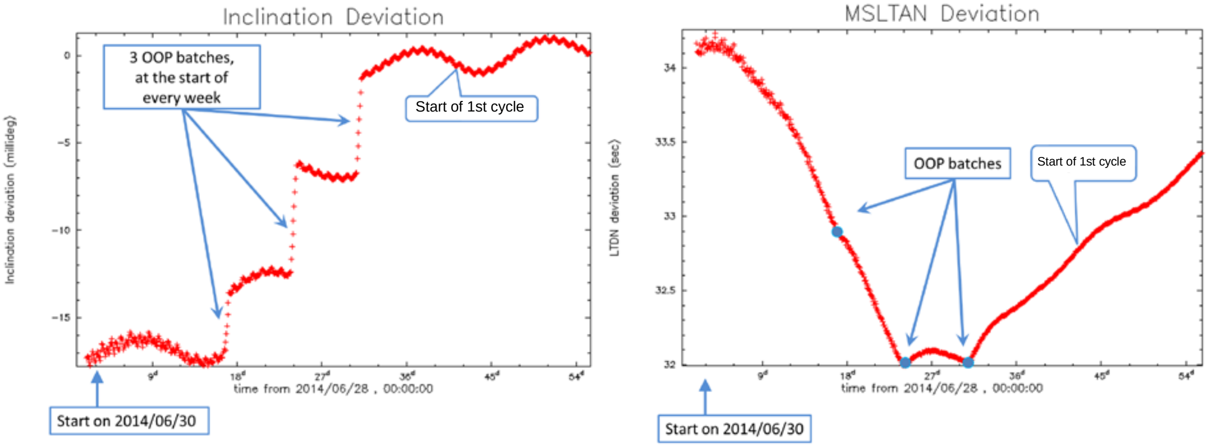

Figure 9: Inclination and MSLTAN deviations during Phase 2.

During this Phase a manoeuvre batch cancellation or modification, for instance due to a collision avoidance event, had a much larger impact than during Phase 1. Not reducing the drift rate as planned would lead to a drift of Sentinel-1A past the targeted reference node. This would demand either a drift reversion (with the corresponding fuel penalty) or an additional drift period to acquire the next reference node towards East, which would have extended the duration of Phase 2. The acquisition of the reference ground-track was essential for the continuation of Commissioning activities, therefore the 6 week duration constraint for Phase 2 was to be fulfilled with high priority. Consequently a Flight Dynamics Team on-call service had to be arranged during the 6 weeks of Phase 2 in order to have the capability to re-plan and implement manoeuvre batches during the weekends (see Fig. 10) in case of missed batches.

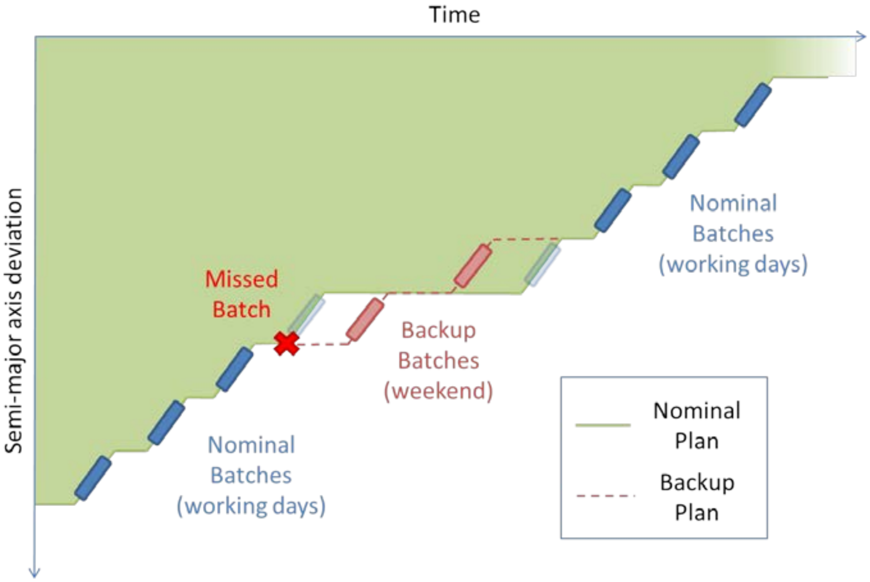

Figure 10: Depiction of a recovery after a batch cancellation. The area above either line is a constant that depends on the required drift in longitude.

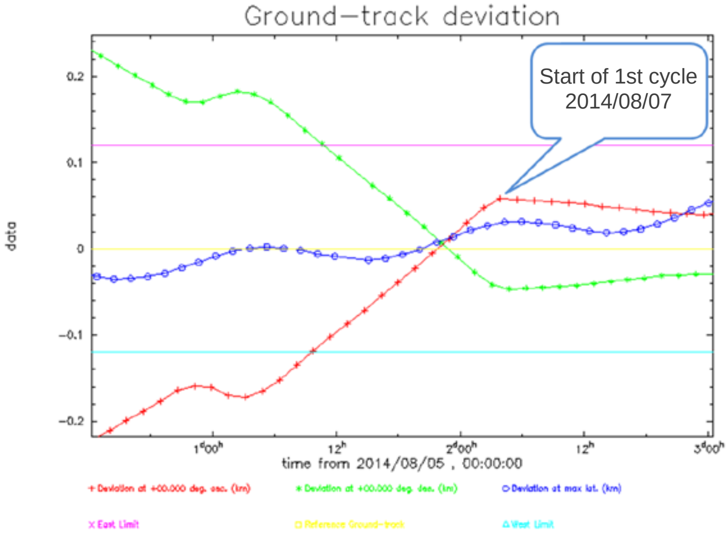

Figure 11: Ground-track deviation, with start of the first orbit control cycle.

The implementation and execution of Phase 2 of the acquisition strategy started on the 30th of June. No re-planning was required and the planned strategy could be followed, culminating in the acquisition of the reference ground-track at all latitudes on the 4th of August (see Fig. 11), after the execution of nearly 500 manoeuvres and a fuel consumption of 8.4 kg.

4. Routine Orbit Control Operations

Following the acquisition of the reference ground-track at all latitudes, the Sentinel-1A orbit maintenance operations have been progressively automated. The Sentinel-1 orbit control operational S/W is based on pre-scheduled optimization cycles with fixed manoeuvre execution slots per cycle. At the current levels of solar and geomagnetic activity this control cycle duration is set to one week with one manoeuvre slot per cycle. This 5 hour slot is on Wednesday and it is used for semi-major axis and inclination corrections. For more details on the Sentinel-1 orbit control concept see [2].

The orbit control has been successfully achieved until the present day, with a reduced number of excursions out of the control-band at the Equator crossings due to the uncertainty in the solar activity prediction and spacecraft safe mode occurrences. Figure 12 shows the evolution of the Sentinel-1A ground-track deviation at the Equator and at the point of maximum latitude from the moment of acquisition on the 7th of August 2014 until the end of 2014.

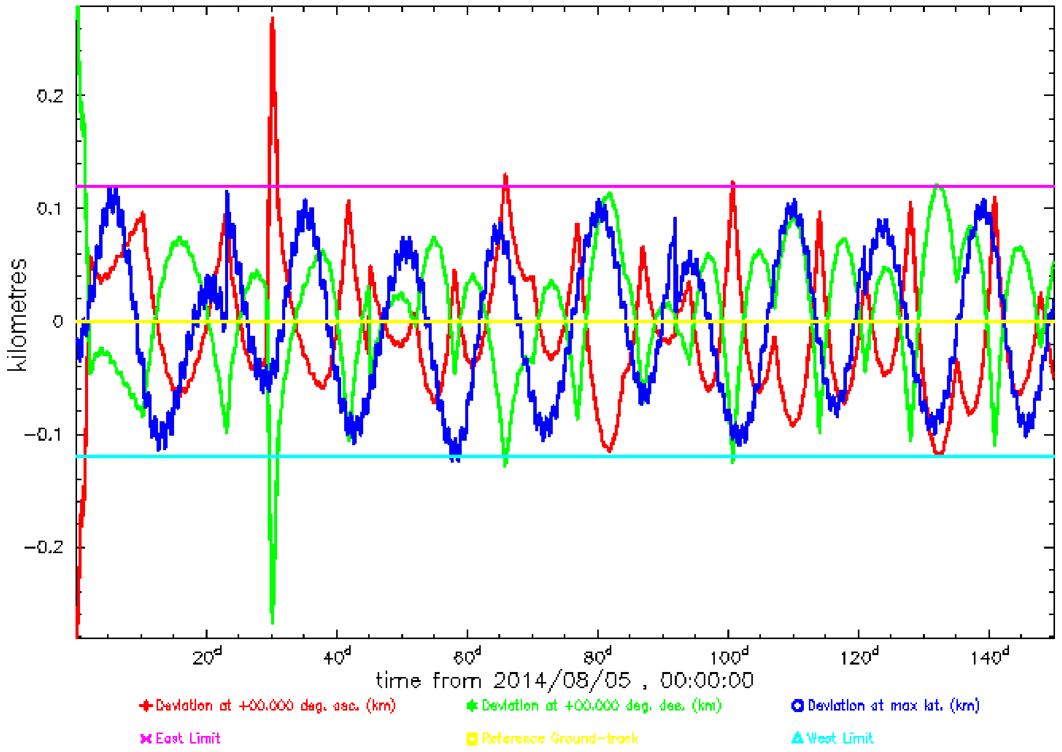

Figure 12: Sentinel-1A ground-track deviation at Equator crossings and maximum latitude from August to December 2014.

5. References

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