SENTINEL-1A FLIGHT DYNAMICS LEOP OPERATIONAL EXPERIENCE

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Abstract: *Sentinel-1 is a two-satellite mission with each satellite carrying a C-Band Synthetic Aperture Radar. The Sentinel-1 satellites are part of the Sentinels fleet, which has been developed for the European Earth Observation Copernicus Programme. Sentinel-1A was launched on April 03 2014 by a Soyuz from Europe's Space port in French Guiana into a 700 km altitude, frozen eccentricity, dusk-dawn sun-synchronous orbit with a ground-track repeat cycle of 12 days. This paper presents a report of the most relevant Flight Dynamics operations that were conducted at the European Space Control Centre (ESOC) in Darmstadt, Germany during the Sentinel-1A three day LEOP. These activities included the assessment of the injection orbit achieved by the launcher using S-band radiometric measurements during the first hours of LEOP, the monitoring of the Spacecraft appendages deployment sequence, monitoring and supporting the Spacecraft mode transitions and the implementation and execution of the first collision avoidance manoeuvre for this mission during the second day of LEOP.*

Keywords: *Copernicus, Earth Observation, LEOP operations, LEO, Sentinels.*

1. Introduction

Sentinel-1A was launched by a Russian Soyuz-ST launcher equipped with a Fregat-M upper stage on April 03 2014 at 21:02:26 UTC from Europe's Space port in French Guiana. Sentinel-1A is the first in-orbit spacecraft (S/C) from the new ESA Sentinels fleet developed for the European Earth observation Copernicus Programme, previously known as GMES (Global Monitoring for Environment and Security). It is also the first of a two-satellite System (Sentinel-1B currently planned for launch in April 2016), each carrying a C-band Synthetic Aperture Radar (SAR) as well as a laser communication payload to transmit data to the geostationary European Data Relay System for continual data delivery. The Sentinel-1 mission provides continuity of crucial data for user services initiated with the ERS and Envisat missions. This data is already benefiting numerous services. For example, services that relate to the monitoring of Arctic sea-ice extent, routine sea-ice mapping, surveillance of the marine environment, including oil-spill monitoring and ship detection for maritime security, monitoring land-surface for motion risks, mapping for forest, water and soil management and mapping to support humanitarian aid and crisis situations.

Sentinel-1A is controlled around a sun-synchronous reference orbit with a ground-track repeat pattern of 175 orbital revolutions in 12 days and a Mean Solar Local Time of the Ascending Node (MSLTAN) of 18:00 h.

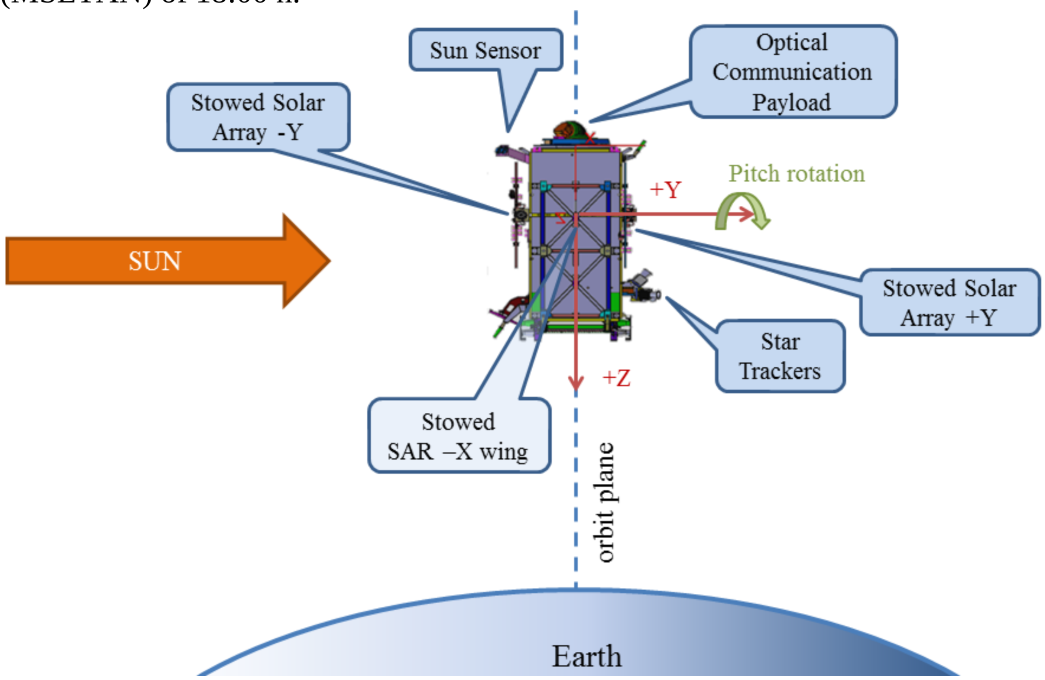

Figure 1. Sentinel-1A stowed representation (in RDM and SHM). +X S/C axis points towards the flight direction. S/C Y axis is aligned with the Sun direction. Solar Array –Y illuminated when stowed.

The S/C Attitude and Orbit Control System (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 Orbit Control Thrusters and 4 pairs of Reaction Control Thrusters for attitude correction. Every pair is made up of a prime and a redundant component. The attitude control thrusters are fired when the S/C enters Rate Damping Mode (RDM) after separation, damping any residual rotation left by the launcher upper stage and achieving a S/C pitch rotation of -8 times the orbital period. In the subsequent AOCS mode called Safe Hold Mode (SHM) magnetotorquers and reaction wheels maintain the attitude and reduce the pitch rotation rate to twice the orbital period. The periodic behavior of the Earth’s magnetic field in a polar orbit and the polarization of the angular momentum with the loading of the reaction wheels allow the magnetotorquers to maintain this pitch rate while aligning the S/C –Y axis with the orbit normal, which in a dusk-dawn orbit coincides with the direction to the Sun (see Figure 1). When the appendages deployment commences, the effect of the gravity gradient torque dominates over the magnetic torque, resulting in the alignment of the S/C X axis (appendages axis) with the nadir direction, maintaining thus a pitch rate equal to the orbital period. Upon ground telecommand a transition into the Normal Pointing Mode (NPM) occurs, where the S/C performs a fine attitude control based on the use of reaction wheels in close loop with star trackers, gyroscopes and GPS, and magnetotorquers for wheel unloading.

Sentinel-1A operations are conducted at the European Space Operations Centre (ESOC) in Darmstadt, Germany. During the three-day LEOP the main activities of the Flight Dynamics (FD) team as part of the ESOC Mission Control Team were:

- Determine the injection orbit achieved by Soyuz/Fregat and support the Ground Station Network in acquiring the S/C signal at every scheduled visibility. Antennas were located in Svalbard (Norway), Alaska, Kiruna (Sweden) and Troll (Antarctica).
- Monitor the AOCS telemetry during the deployment of the SAR wings and the Solar arrays as well as the S/C mode transitions ranging from Rate Damping Mode to its final Normal Pointing Mode required for operating the S/C during the Commissioning and Routine Phases.
- Generate the AOCS commands required to re-initialise the on-board orbit propagation throughout its different accuracy modes to allow the S/C mode transitions.
- Start the preparation of a manoeuvre sequence to acquire the Mission Reference Orbit. The manoeuvre sequence selection was driven by the overall duration of the acquisition period and the fuel consumption.

This paper presents the FD operational activities conducted during the three-day LEOP.

2. Separation and first acquisition

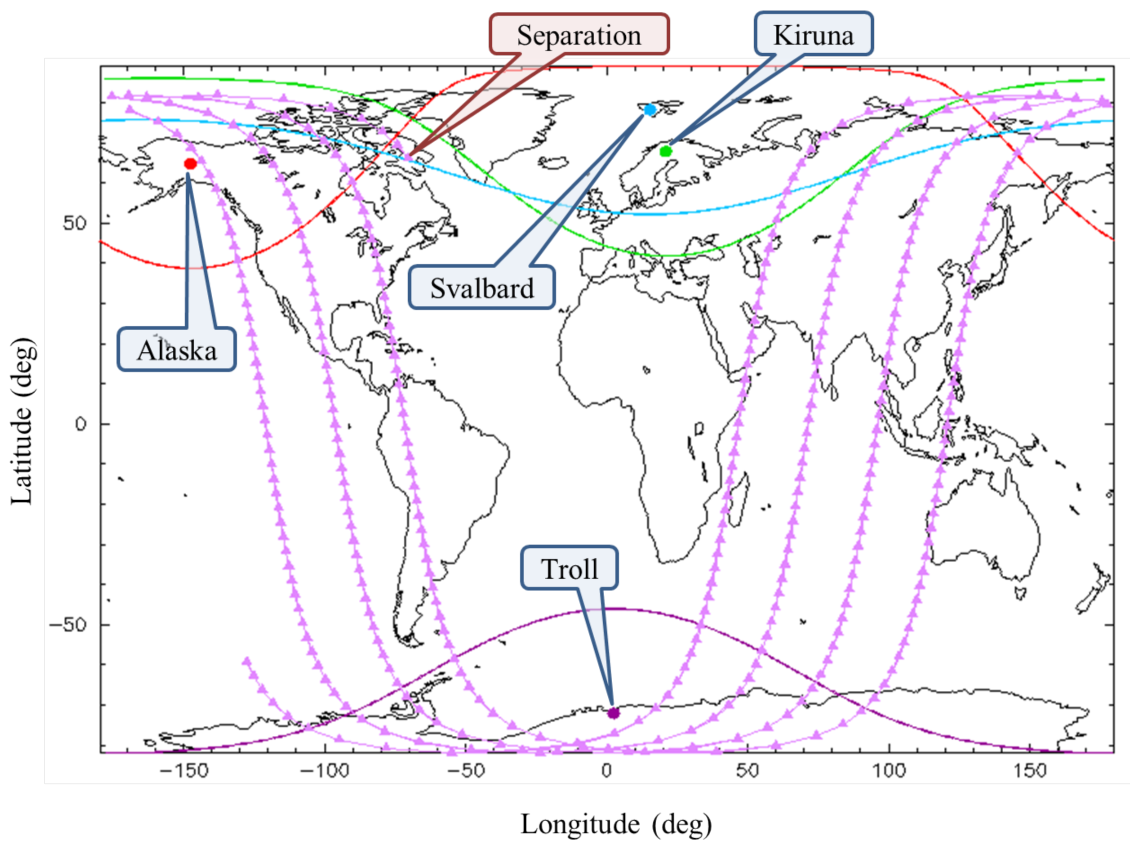

Figure 2. Sentinel-1A LEOP Ground Stations Network and S/C ground-track evolution during the first 4 hours after separation.

The Russian Soyuz launch vehicle was released from its launch pad at the Europe's Space Port in French Guyana on April 03 2014 at 21:02:26 UTC. Sentinel-1A separation from the Fregat-M upper stage took place 1404 seconds after lift-off, following a nominal ascending flight sequence which included separation of the Soyuz two main stages, payload fairing jettisoning, third stage boost, nose module separation and Fregat-M main burn. Separation occurred within visibility of KSAT ground station at Svalbard (see Figure 2) and three minutes before entering visibility from the SSC/USN antenna in Alaska. Approximately one minute after physical separation, the on-board automatic sequence started, switching on the S-band transponder and setting the S/C mode to RDM. The first TM frames were successfully received at Svalbard station and forwarded to ESOC at 21:27:15 UTC. At the end of the first Svalbard-Alaska combined ground pass the S/C rates had been damped as expected (see Figure 3) and auto-convergence to the next AOCS mode SHM had occurred. The received TM indicated a fully nominal S/C behavior and all commanding activities could be completed as planned.

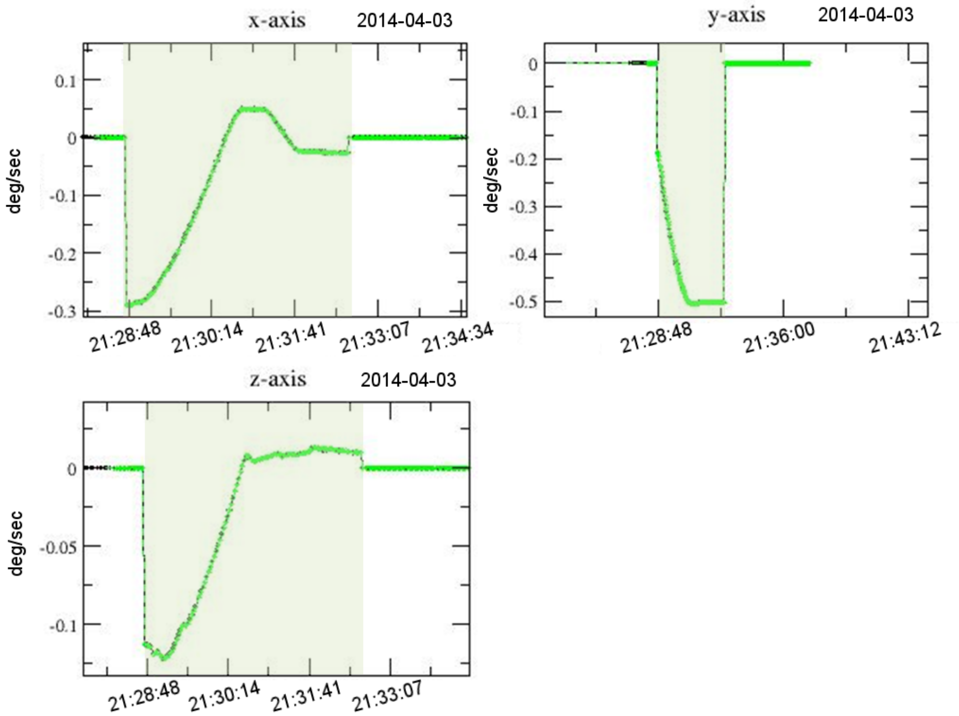

Figure 3. First pass (shaded region) S/C rates measured by the gyroscopes. The S/C follows the planned damping in X and Z axes and achieves a rate equal to -8 times the orbital period in Y axis.

The S-band transponder was set to incoherent mode to avoid noisy signal at initial acquisition. This implies that no 2-way Doppler measurements were performed during the first pass. Both ground stations acquired the S/C signal and remained in auto-track during the whole pass duration; the carrier uplink was performed first at Svalbard and it was passed to Alaska before the end of the combined pass. Svalbard station reported time offset values (TOV) of 0.3 seconds and 1 second S/C late at the start and end of the pass respectively. Alaska reported 1.5 seconds S/C early at the beginning of the pass. The FD Orbit Determination Team performed an injection orbit assessment at the end of the first ground pass using angular and ranging data retrieved from both stations.

A coarse orbit determination employing this set of tracking data did not lead to a conclusive state vector determination. Solutions with a semi-major axis difference with respect to the nominal injection varying from -4.0 to -8.0 km were obtained with similar goodness-of-fit. The reported TOVs by the two stations were contradicting and therefore could not be trusted to decide which orbit solution could be used to generate TOV predictions for the upcoming pass. Consequently FD did not provide a TOV for the subsequent Troll pass but only an indication to expect AOS earlier than predicted. Troll station acquired the Sentinel-1A signal without difficulties, reporting a 1 second early TOV at the beginning of the pass, evolving to 2 seconds early before LOS. At the end of the pass a new assessment of the orbit injection was performed using the ranging and angular tracking data retrieved after the Troll pass. With this set of data a good orbit determination was possible. The result of this orbit determination was confirmed and consolidated as more tracking data were retrieved in subsequent passes. The launcher injection performance is summarised in Table 1.

Table 1. Launcher injection performance

Element (osculating J2000)	Achieved	Nominal	Difference	Required (1-sigma)
Semi-major axis (km)	7056.7096	7064.5360	-7.8264	3.0
Eccentricity	0.000743475	0.000798999	-0.000055524	0.0002
Inclination (deg)	98.248994	98.265243	-0.016250	0.03
RAAN (deg)	101.957822	101.939637	0.018185	0.05
Argument of latitude (deg)	67.480749	67.38899	0.091759	n/a

The FD Orbit Determination Team continued providing TOV values to the stations during the six hours that followed separation. Due to the semi-major axis injection error the TOV grew at a rate of 9 seconds per orbit approximately, reaching a maximum of 37 seconds S/C early at the fourth pass over Troll. At this point new station predictions were generated and delivered. After the delivery of new station predictions, which were updated with subsequent orbit determination results every 12 hours, ground stations did report 0 seconds TOV throughout the remainder of the three day LEOP.

3. Appendages deployment sequence

As mentioned in the previous chapter, after separation the AOCS went autonomously to RDM and achieved the target spin rate of -8 times the orbital period in the Y axis (see Figure 3). The damping took less than 4 minutes with a total fuel consumption of 26 grams. The AOCS transitioned then to SHM, activating the reaction wheels to a fixed value of 1165 rpm. The TM monitoring during the second ground pass at Troll confirmed the expected S/C rates being -2 times the orbital period around the S/C Y axis.

Once the AOCS achieved SHM the deployment of the two Solar Arrays and the two SAR wings began at the fourth ground pass over Troll (MET 02:52 h). A primary target of the sequence was to achieve a S/C Power Positive state, which is the state when the power budget can guarantee a permanent survival and the remaining deployments can go ahead with no risk related to the S/C power consumption.

The two appendages are aligned along the S/C X-axis when extended. Each SAR wing deployed in two steps called partial and full deployment. As it can be observed in Figure 4 steps 1 and 2, it was important to perform the partial deployment of each SAR wing before deploying the Solar Arrays in order to avoid possible interference during the deployment and rotation of the Solar Array.

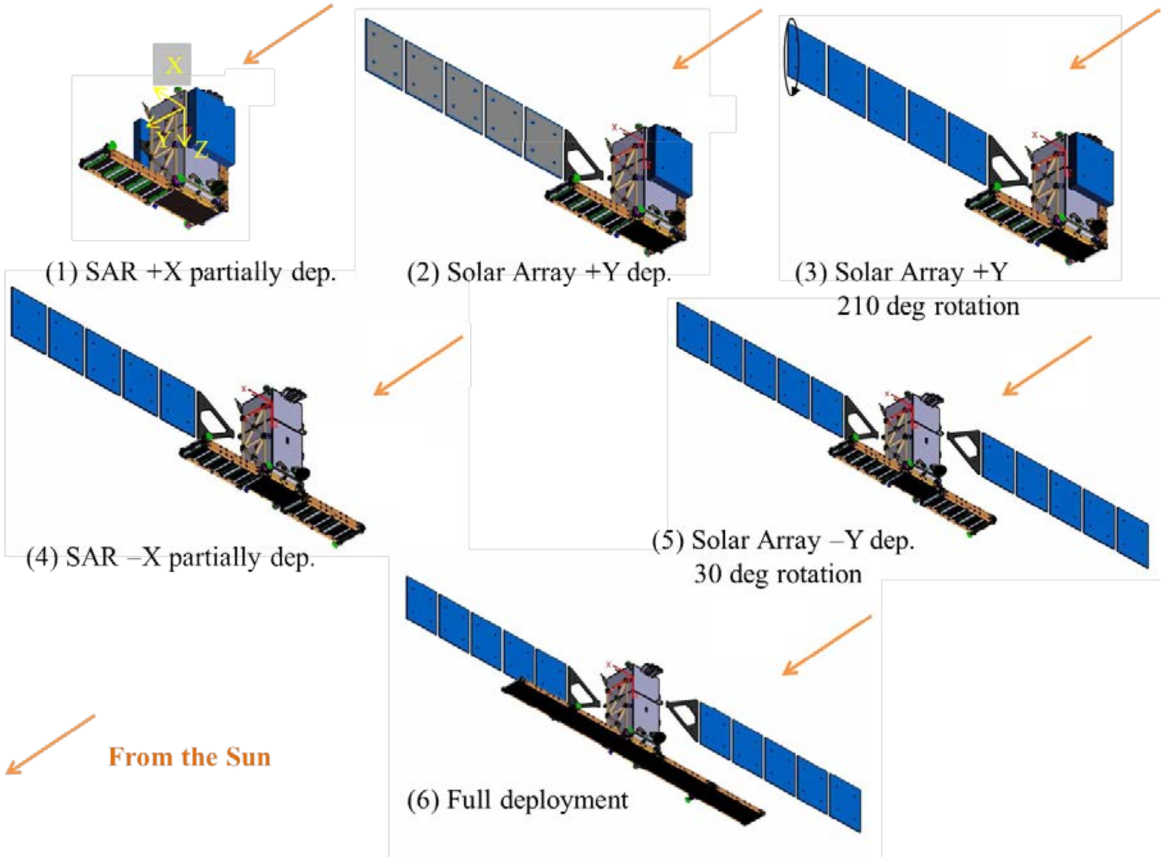

Figure 4. Sentinel-1A SAR and Solar Array deployment sequence.

The first step in the sequence was the SAR +X wing release by means of a pyrotechnic actuator. This event was noticeable in TM as a small oscillation in the S/C rates. The partial deployment was not commanded until the following ground pass over Svalbard-Alaska at MET 03:36 h (see Figure 4 step 1). The deployment was successfully completed by the time the S/C entered visibility from Troll at MET 04:28 h. During this pass the SAR –X wing release (not partial deployment yet) was commanded. The +Y Solar Array deployment was telecommanded at the next contact with the S/C from Kiruna-Svalbard-Alaska at MET 05:13 h (see Figure 4 step 2). The 210 deg +Y Array rotation required to get Sun incidence was nominally planned for this pass but was actually commanded and monitored at the next ground pass over Troll at MET 06:04 h, at which point Power Positive Status was achieved (Figure 4 step 3). The deployment of the +Y Solar Array was noticeable in the monitored S/C rates, which experience disturbances of up to 0.5 deg/s in roll and 2 deg/s in yaw (see Figure 5). These were followed by periodic oscillations in the rates of an amplitude of about 0.2 deg/s, that were damped within one orbital revolution before the next deployment sequence step. Further deployment monitoring and commanding activities continued nominally until S/C full deployed status was achieved at MET

11:00 h (Figure 4 step 6). Sentinel-1A slowly converged to gravity gradient stabilized attitude with the S/C –X axis pointing towards the nadir direction. At MET 11:55 h the reaction wheels were commanded back to no rotation since the initial gyroscopic stiffness required at separation was no longer needed for the attitude control. The angular momentum transfer was clearly observed in the S/C rates followed by the gravity gradient stabilization.

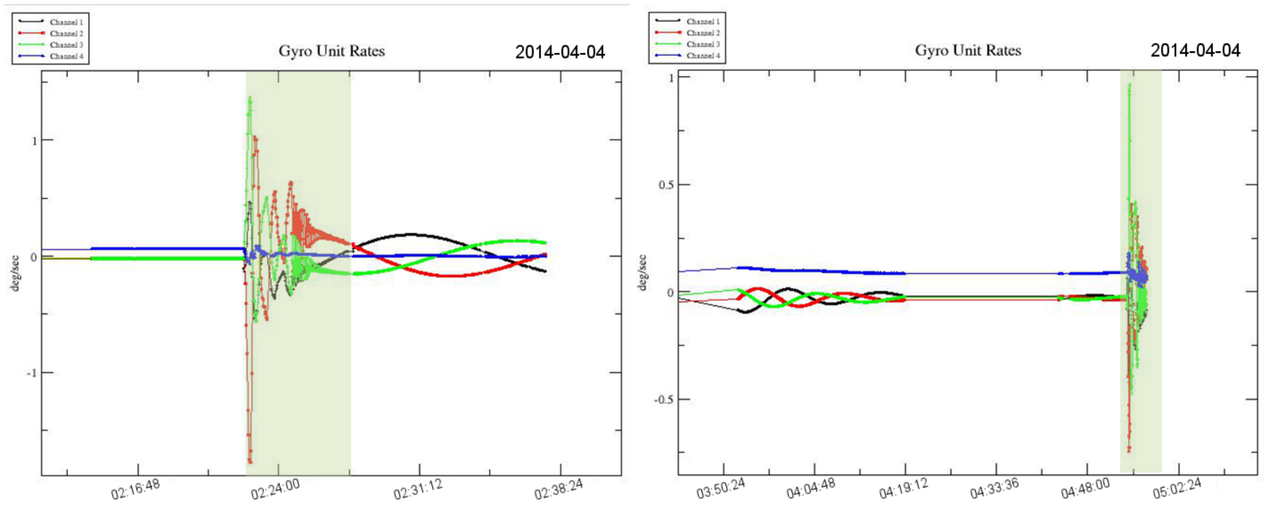

Figure 5. Gyro rates during the deployment of the Solar Arrays (shaded regions). +Y Solar Array (left) and –Y Solar Array (right)

4. Collision avoidance manoeuvre during LEOP

4.1. Manoeuvre preparation and operational implementation

At MET 11:00 h after having completed the deployment sequence, LEOP operations aimed at commanding from ground the S/C mode transitions to reach NPM, the nominal operating mode during the Mission phase. The most relevant operational steps to reach NPM were the on-board update of the input state vectors used by the on-board coarse orbit propagation, switching on and performing checkouts of the hardware required in NPM, namely the GPS receivers and the STTs and enabling the on-board precise orbit determination based on the converged least square solution provided by the GPS receivers. Nominally the transition to NPM was planned to be commanded from Kiruna ground station at MET 31:30 h.

On April 04 at 14:45 UTC (MET 17:45 h) the Space Debris Office at ESOC communicated to the Mission Control Team the results of the determined injection orbit screening against the NORAD TLEs catalogue. A series of high risk conjunctions with the NASA operational satellite ACRIMSAT were detected, the first one on April 05 at 06:04 UTC (MET 33:00 h). These results were confirmed within a few hours by the Joint Space Operations Centre (JSpOC). Table 2 summarises the screening results provided by JSpOC.

Table 2. Summary of Sentinel-1A conjuction risks with ACRIMSAT confirmed by JSpOC. ACRIMSAT 1-sigma uncertainty: radial 10m, along-track 50m and cross-track 10 m. D is the relative position vector of ACRIMSAT with respect to Sentinel-1A.

Epoch (UTC)	D-Radial (km)	D-Along track (km)	D-Cross track (km)	D (km)
2014/04/05 04:25:53	0.129	0.286	1.912	1.937
2014/04/05 06:04:28	0.077	0.150	1.001	1.015
2014/04/05 07:43:04	0.023	0.042	0.283	0.287
2014/04/05 09:21:39	0.034	-0.059	-0.393	0.399
2014/04/05 11:00:14	0.123	-0.177	-1.187	1.207

At MET 19:00 h, after getting confirmation from the ACRIMSAT operators that no manoeuvering was possible on their side, the ESOC Flight Control Team started working on a new operations timeline which would allow Sentinel-1A to reach NPM and perform a manoeuvre to mitigate the conjunction risk half a revolution before the first predicted potential conjunction at the latest. In parallel the FD Team and the ESOC Space Debris Office started preparing possible evasion manoeuvre scenarios. The analysis performed by the ESOC Space Debris Office was showing a series of head-on conjunctions at the same orbit location, namely at 20.082 deg argument of latitude with ACRIMSAT flying above Sentinel-1A in all close approaches. The ACRIMSAT orbit uncertainty in radial component provided by JSpOC was 10 m. With this uncertainty and looking at the fly-by radial distances reported in Table 2, it was clear that the potential conjunctions predicted for 2014/04/05-07:43:04 UTC and 2014/04/05-09:21:39 UTC (red shaded in Table 2) were posing a real danger to the Sentinel-1A Mission. Mitigating the risk for these two predicted conjunctions was the target of the collision avoidance manoeuvre. This risk mitigation had to be achieved by increasing the radial separation at the point of closest approach. The optimal way to achieve this radial separation was to preform an in-plane manoeuvre 180 deg away from the argument of latitude of the predicted closest approach. In this case an in-plane manoeuvre had to be executed at an argument of latitude of 200.082 deg and before 2014/04/05 07:43:04 UTC (MET 34:46 h), as depicted in Figure 6. The change in radial component introduced by an in-plane manoeuvre at the Sentinel-1A altitude can be expressed as:

delta-radial (m) = 2 x delta-semi-major axis (m) = 2 x 1885 sec x delta-v (m/s)

Sentinel-1A Orbit Control Thrusters are located on the S/C sides +X, -X and –Y. When flying in NPM these directions are aligned with the flight direction, anti-flight direction and orbit normal direction respectively. The maximum burn duration specified before launch was 300 seconds due to AOCS constraints. However the S/C manufacturer team present at ESOC during LEOP recommended a maximum avoidance manoeuvre duration of 100 seconds, since it was the first manoeuvre performed in-flight. A 100 seconds duration at the tank conditions in LEOP translated into a total delta-v of 0.048 m/s, which according to the expression provided above would increase the radial separation by 180 m. This change in radial component was enough to mitigate the risk when performing the manoeuvre in either direction, in or against the flight direction. Since the launcher injection had been 7.8 km lower than expected, a manoeuvre in the flight direction would have contributed to the operational altitude acquisition. On the other hand, it was operationally safer to perform the manoeuvre against the flight direction, given the fact that ACRIMSAT was flying above Sentinel-1A in the two close approaches. In case of a S/C reconfiguration during the manoeuvre execution, a manoeuvre in the flight direction could have brought Sentinel-1A closer to ACRIMSAT. The Mission Control Team joint decision was therefore to perform the collision avoidance manoeuvre against the flight direction, activating the thrusters located on the +X S/C face. Three manoeuvre cases were prepared by the FD Orbit Control Team corresponding to manoeuvre durations of 30, 60 and 100 seconds which translated into radial separation increase of 54, 108 and 180 m. respectively. The three cases were provided to the ESOC Space Debris Office, which determined that a 40 second burn was sufficient to bring the collision risk probability down to an acceptable level, accounting for some manoeuvre performance error. Similarly three different manoeuvre execution times were considered: the latest opportunity to perform the manoeuvre at 06:53:00 UTC (MET 33:55 h), which corresponds to half an orbital revolution before the first close approach, and two more opportunities one and two revolutions earlier at 05:13 UTC (MET 32:15 h) and 03:33 UTC (MET 30:35 h) respectively.

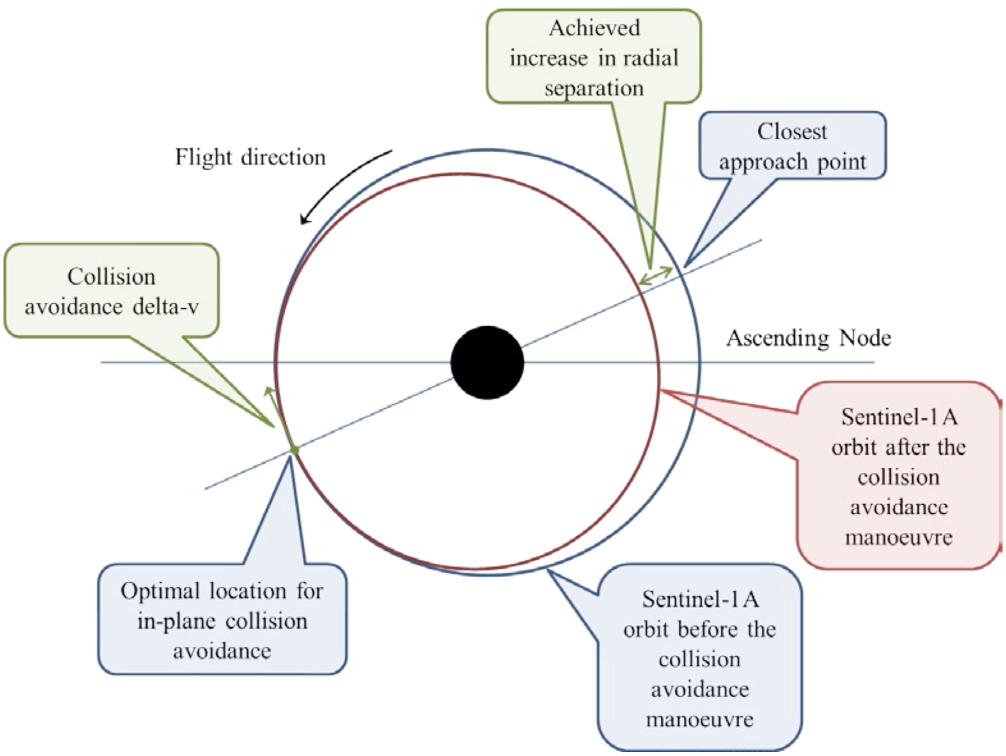

Figure 6. Collision avoidance scenario for a maximum radial separation increase.

The first attempt to enter NPM was commanded on April 04 at 20:36 UTC (MET 23:38 h). Following the entry in NPM a Gyro FDIR monitoring triggered a switch to all redundant equipment and the S/C went to Intermediate Safe Mode. A second attempt to enter NPM on April 05 at 03:00 UTC (MET 30:00 h) was successful, allowing the execution of the collision avoidance burn on April 05 at 05:14:45 UTC (MET 32:15 h).

4.2 Manoeuvre performance

The first orbit determination attempts after the execution of the burn showed a large performance error in the along-track component in the order of -20%. This figure was confirmed after collecting sufficient ranging, Doppler and GPS measurements in the hours that followed the manoeuvre. After retrieving a complete day of almost continuous GPS data a manoeuvre performance analysis was conducted, aiming at ruling out the possibility of thruster misalignment issues. Two orbit determinations were performed over a determination arc covering from 2014/04/04-05:00 UTC (one day before the manoeuvre execution) to 2014/04/06-06:00 UTC (one day after the manoeuvre execution) with different manoeuvre parameter estimation setups:

Orbit Determination Setup 1

- Estimated manoeuvre parameters: Along-track component performance error
- Orbit determination results:
    - Quality of the orbit determination: Good fit
    - Estimated along-track performance error: -20.5%

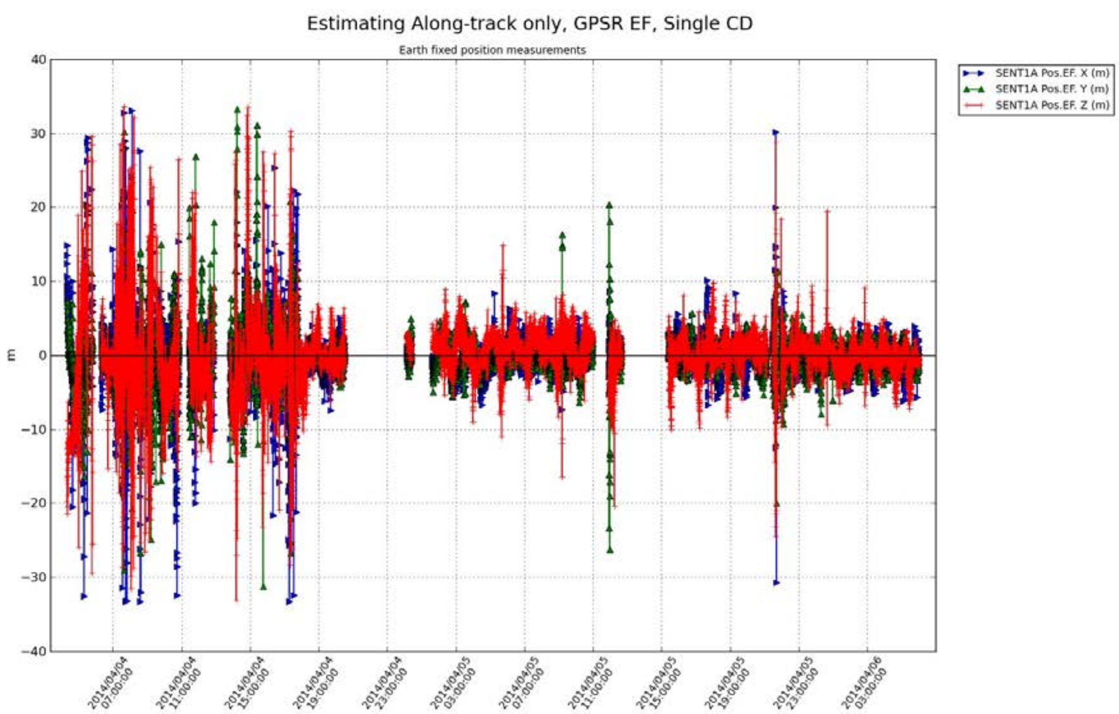

Figure 7. Orbit determination GPS residuals. Estimation of collision avoidance manoeuvre along-track component error.

Orbit Determination Setup 2

- Estimated manoeuvre parameters: Delta-v direction
- Fixed manoeuvre parameters: -10 % Delta-v module performance error.
- Orbit determination results:

- o Quality of the orbit determination: Bad fit, with an RMS one order of magnitude larger than in Setup 1.
- o Estimated Delta-v direction error: 2.5 deg

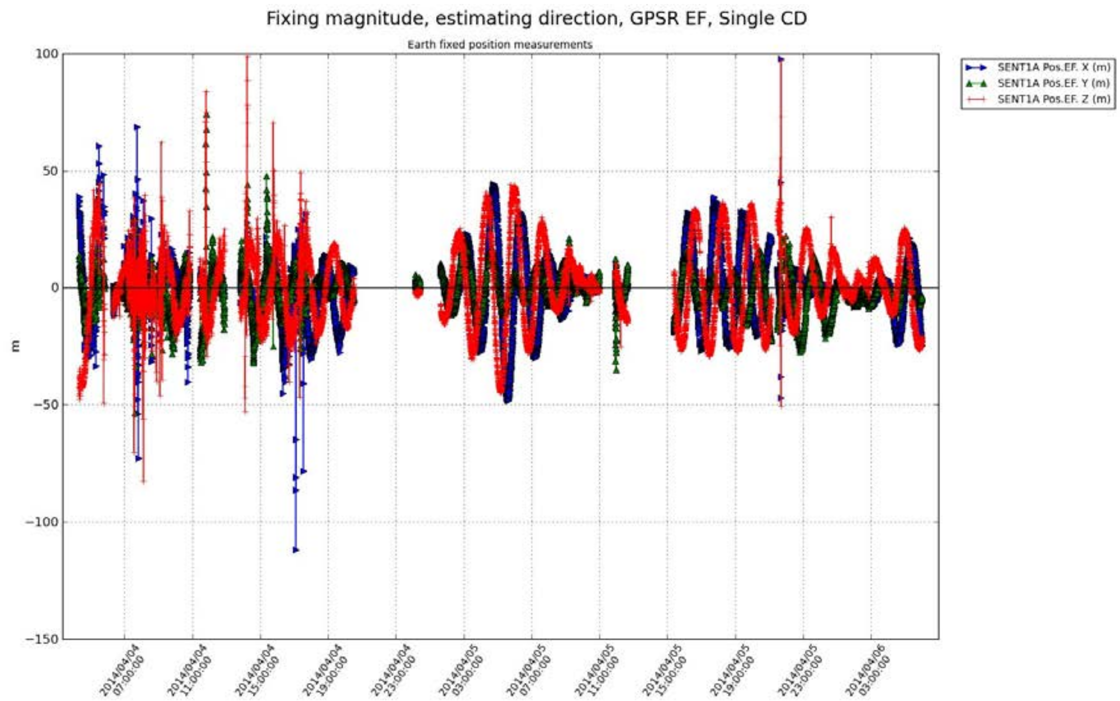

Figure 8. Orbit determination GPS residuals. Estimation of collision avoidance manoeuvre direction error assuming a -10% magnitude error.

These results led to the conclusion that the observed performance error could not be explained by a +X thruster misalignment.

The inspection of the S/C dynamics during the execution of the collision avoidance burn also revealed a non nominal behaviour. The AOCS TM retrieved during the first ground visibility after the manoeuvre execution (MET 34:55 h) showed that the S/C was in a healthy state and back to NPM. After the ground processing of the TM recorded during the burn the response of the AOCS to the thrust actuation could be inspected. The fuel consumption (19 grams) measured by means of pulse counting was in good agreement with the FD Team predictions. The evolution of the S/C rates and reaction wheels speed showed however large deviations with respect to the expected nominal behaviour. Upon thrust start the reaction wheels responded to the exerted torque on the S/C reaching their torque saturation. Consequently the S/C rates, which should have remained constant throughout the burn, increased. The torque exerted by the thrust was clearly higher than what the reaction wheels were able to absorb. The mentioned change in S/C rates was most noticeable in the S/C Y and Z axes, where it reached -0.016 and 0.012 deg/s respectively (see Figure 9). At the end of the thrust the reaction wheels remained at their maximum torque regime to achieve the platform stabilization and to correct the S/C attitude deviation accumulated during manoeuvre execution as can be observed in Figure 10. The reaction wheels operated for over two minutes, experiencing a more than 1000 rpm speed change (wheels 2 and 4) but staying well within their speed range of +/- 3500 rpm.

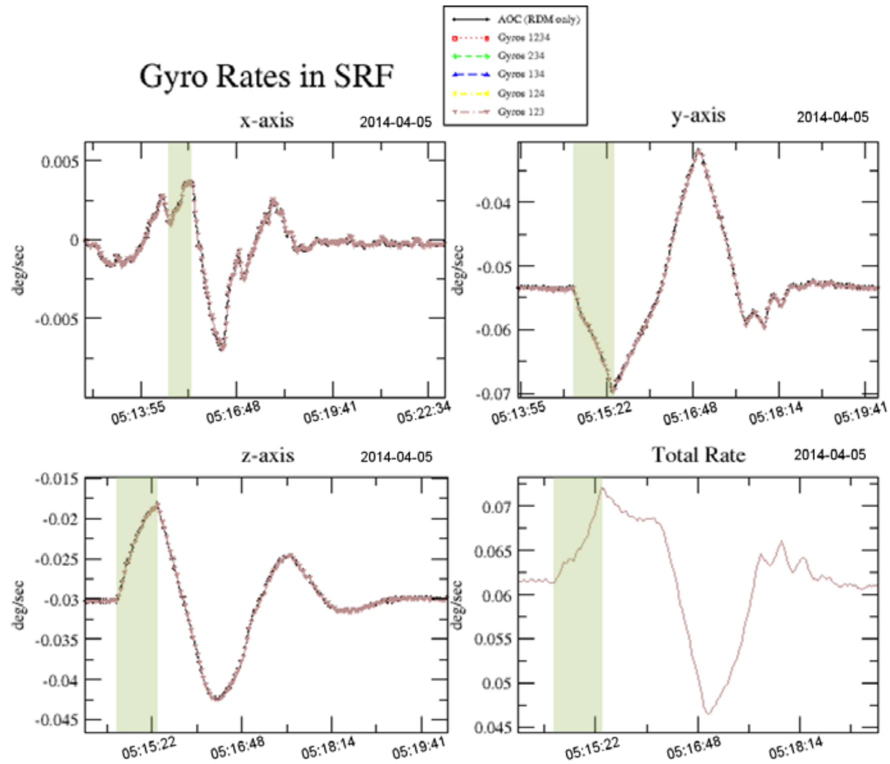

Figure 9 Sentinel-1A rates in S/C frame. Manoeuvre execution interval highlighted.

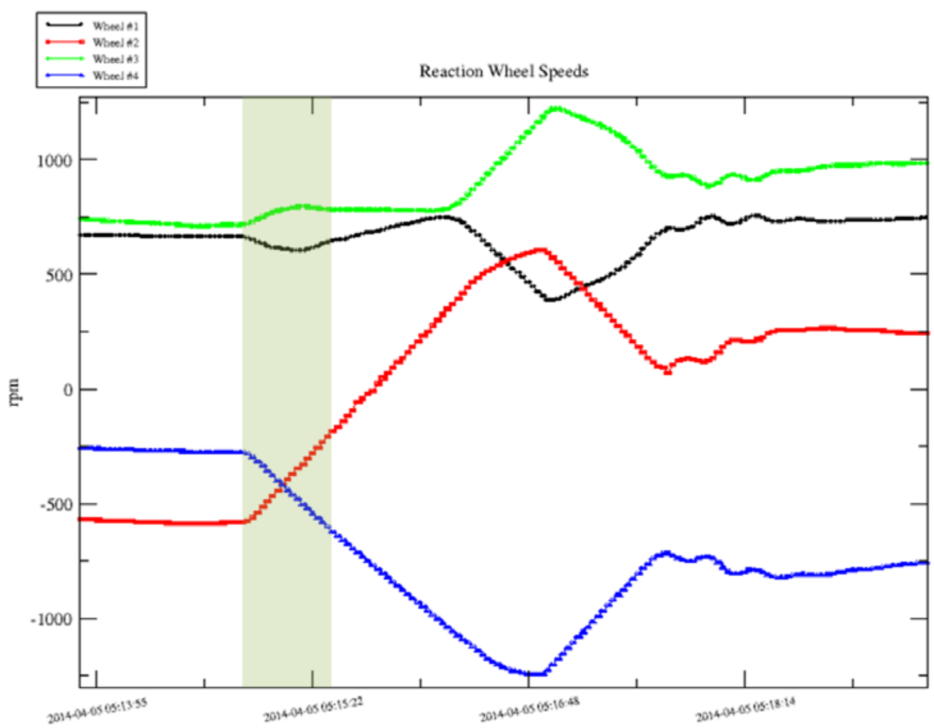

Figure 10 Reaction Wheels speed (shadowed region corresponds to manoeuvre execution period). The maximum slope indicates wheel saturation.

As a quick assessment of the torque exerted by the thrust, the S/C total angular momentum was computed by adding the reaction wheels angular momentum and the S/C angular momentum derived from the S/C rates before and after the burn. This simplified approach ignores the fact that the S/C reference frame is not inertial, however given the small attitude change and low rates during the 40 second burn the error was deemed acceptable for a quick assessment. The resulting torque computed in that way was [0.00, -0.22, 0.15] Nm, which was one order of magnitude larger that the expected one as per S/C manufacturer [0.0003, 0.0283, -0.0054] Nm based on the measured S/C mass properties and thruster alignments before launch.

As explained in subsection 4.1, the analysis of the manoeuvre performance by the FD Orbit Determination Team did not reveal a +X thruster alignment issue as the reason for the performance error. With this in mind, other feasible explanations for the observed high torques could be:

- a possible displacement of the S/C Centre of Mass (CoM).
- a possible displacement of the +X thruster location.
- plume impingement.

Assuming a correct alignment and position of the +X thruster, the observed torques would have matched a S/C CoM displacement of -0.15 m in Y component and 0.22 m in Z component. These values were way too large compared with the expected S/C mass properties measurement campaign accuracy. A CoM displacement was considered a very unlikely explanation. In order to narrow down the possible root causes for the observed issues during the collision avoidance manoeuvre the execution of test manoeuvres was unavoidable. The preparation of a manoeuvre strategy for the reference-ground track acquisition, which was one the tasks for the FD Team during LEOP was postponed until more information on the propulsion system was collected and analysed.

5. End of LEOP and start of reference ground-track acquisition

After the three day LEOP Sentinel-1A was stable in NPM and the FD team proceeded with automated operational tasks including:

- A daily orbit determination based on S-band radiometric tracking data retrieved from ground stations and GPS measurements. The daily orbit determination was input to the generation of the agreed FD routine products used for station booking, antenna pointing and Space Debris screening amongst others.
- Monitoring and archiving of the AOCS relevant TM and generation of routine commands for on-board coarse and fine propagation.

In order to further understand the issues related to the execution of the first manoeuvre described in the previous chapter (performance error and high torques) two test manoeuvres were planned and executed on April 10 and April 15. These manoeuvres activated the prime Orbit Control Thrusters that had not been fired for the collision avoidance manoeuvre executed on the second day of LEOP, namely the thruster located on the –X S/C face (delivering a thrust in the flight direction) and the thruster located on the –Y S/C face (delivering a thrust out of the orbital plane, opposite to the orbit normal direction). The duration of the burns was selected according to the S/C manufacturer team’s recommendations. This recommendation was taking into consideration the torques observed during the first manoeuvre and the maximum capacity of the reaction wheels to maintain the S/C attitude when experiencing these high torque levels. The results of the test manoeuvres are summarized in Table 3. The collision avoidance manoeuvre is also included for completeness.

Table 3. Collisions avoidance and test manoeuvres performance

Thruster	Duration (sec)	Performance error	Observed torque (Nm)	Expected torque (Nm)
+X	40	-20.5 %	[0.00, -0.22, 0.15]	[0.0003, 0.0283, -0.0054]
-X	30	-34.0 %	[0.00, -0.06, 0.33]	[-0.0001, 0.0202, -0.0045]
-Y	60	+4.0 %	[0.04, 0.01, -0.02]	[0.0346, 0.0121, -0.0202]

These results, in particular the out of plane test manoeuvre (-Y thruster) helped to definitely discard a CoM displacement. The thrusters showing the unexpected behaviour were the ones located on the S/C –X and +X faces. Those deliver the thrust along the S/C X-axis, which is the axis along which the SAR and the Solar Arrays are deployed. This clearly pointed at plume impingement as the most likely cause for the observed S/C behaviour. The mass ejected by the thrusters, once in space is able to expand not only along the thrust axis but also laterally, hitting the S/C appendages and producing the observed torques. It is also known that plume impingement is linked to observed thruster performance degradation. The FD Attitude Team verified that the ratio between the observed torques around the S/C Y and Z axis could be explained by the different thrust axis to Solar array orientation for the two thrusters +X and –X.

The Sentinel-1 orbit control S/W (described in [2]) was consequently adapted to the new propulsion system features, namely the reduction of burn duration for in-plane orbit correction manoeuvres from 300 to 30 seconds. With this maximum in-plane burn duration (providing a delta-v of 0.009 m/s at the end of LEOP tank conditions) and the injection semi-major axis achieved by the launcher it was clear the reference ground-track acquisition campaign had to be re-engineered based on the execution of in-plane correction batches. On April 23 2014 a manoeuvre batch approach proof of concept was conducted, performing a sequence of six in-plane corrections in consecutive orbit revolutions. The AOCS response was satisfactory in terms of platform pointing and wheels recovery time. This marked the beginning of a long reference ground-track acquisition campaign which was successfully completed by August 06 2014. On this day and after the execution of more than four hundred manoeuvres Sentinel-1A started the first control cycle around its reference ground-track. This manoeuvre campaign is described in detail in [1].

6. References

[1] Vasconcelos A. et All. “Sentinel-1A Reference Orbit Acquisition Manoeuvre Campaign.” Proceedings 25th International Symposium on Space Flight Dynamics – 25th ISSFD. Munich, Germany, October 2015.

[2] Martin Serrano, M. A, Marc, X and Shurmer, I. “Sentinel-1: Operational approach to the orbit control strategy.” Proceedings 23th International Symposium on Space Flight Dynamics – 23th ISSFD. Pasadena, USA, November 2012.