ISTS-2017-d-027／ISSFD-2017-027

Sentinel-3A Flight Dynamics LEOP Operational Experience

By Mikel CATANIA,[1] Claudia DIETZE,[2] and Jochen KLEIN[3]

[1] *LSE at European Space Operations Center, ESA, Darmstadt, Germany*
[2] *CS at European Space Operations Center, ESA, Darmstadt, Germany*
[3] *CGI at European Space Operations Center, ESA, Darmstadt, Germany*

Sentinel-3A is an Earth observation satellite, part of the European Commission's Copernicus Programme. Launched in 2016, it was operated from ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany during the Launch and Early Operations Phase (LEOP) and commissioning phase. This paper presents the most relevant events of these phases from a Flight Dynamics perspective. The LEOP was successfully concluded within the nominal timeline, but was not free from unexpected events. The most relevant was an anomaly with the Star Trackers, in which the attitude estimation yielded values that differed between 50 and 150 degrees from the correct attitude, depending on the Optical Head used. This paper presents the events that were triggered by this problem, from the discovery by Flight Dynamics to the on-board fix. During the first days of commissioning, manoeuvres were executed for thruster torque estimation and the observed torques were higher than expected. This paper also discusses the findings and the results, how further manoeuvres were required, and how the most likely cause was plume impingement. As a final comment, the negative value of the drag coefficient during the first weeks is discussed.

Key Words: Copernicus, Sentinels, LEOP, Sentinel-3

1. Introduction

The Sentinel-3 mission is part of the European Commission's Copernicus Programme, consisting of two satellites flying a near-polar, sun-synchronous orbit, separated in phase by ±140 degrees. Sentinel-3A is the first of the two satellites and was launched on February 16th, 2016 at 17:57 UTC from Plesetsk, Russia by a Rockot launcher. To cover the operational requirements of the mission, the Sentinel-3A satellite follows a reference orbit with an altitude of ca. 800 km, a Local Time of Descending Node (LTDN) of 10:00 and a repeat cycle of 385 orbits in 27 days.

The main objective of the Sentinel-3 mission is to measure sea surface topography, sea and land surface temperature, and ocean and land surface colour to support ocean forecasting systems, environmental monitoring and climate monitoring. The satellite carries four main instruments, including two radiometers, a spectrometer and a SAR, to perform these observations.

During the Launch and Early Operations Phase (LEOP) and the commissioning phase the satellite was operated from ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany. After six months of operations it was handed over to EUMETSAT, from where the satellite is operated now in its routine phase. This paper discusses the most relevant events during the LEOP and the beginning of the commissioning phase from a Flight Dynamics (FD) perspective including the cooperation with the Flight Control Team (FCT) and the spacecraft manufacturer team from Thales Alenia Space present at ESOC during this critical period. The three days long LEOP phase covered all the activities from separation up to the achievement of the nominal attitude and switch on of the main instruments.

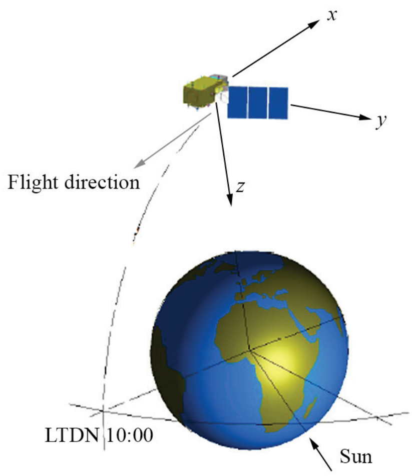

Fig. 1. Schematics of the Sentinel-3A nominal attitude, showing the spacecraft axes and the flight direction.

2. AOCS description

Sentinel-3A flies nominally in a nadir pointing attitude with yaw steering, such that the main instruments point towards the Earth and the cross-track component of the relative velocity of the Earth's surface is compensated for. Power supply is achieved by means of a rotating solar array, which is oriented towards the Sun at all times (see Fig. 1).

The Attitude and Orbit Control System (AOCS) is composed of the following sensors and actuators:

- Coarse Sun Sensors (CSS), providing a Sun direction vector.
- two Magnetometers (MAG), providing Earth's magnetic field vector.
- two Coarse Rate Sensors (CRS), to propagate satellite attitude during eclipses and other instruments' blinding peri-

ods.

- Multiple Heads Star Tracker (MHSTR), with three Optical Heads, the main attitude sensors used in the higher control modes.
- GNSS system to provide position and velocity information.
- four Reaction Wheels (RWS), used to provide a certain angular momentum for gyroscopic stiffness in the initial AOCS modes and as attitude controllers in Normal Mode.
- three Magnetotorquers (MTB) used for wheel off-loading in Normal and Orbit Control Modes and to provide attitude control in the initial AOCS modes.
- Reaction Control System (RCS) with 2 sets of 4 thrusters, used to provide delta-v respectively along the spacecraft $+x$ and $-x$ axis. The RCS uses hydrazine as monopropellant, which is stored in a single tank, pressurized with nitrogen.

Upon separation, the AOCS system follows a sequence of modes, each of them using different sensors and actuators. The spacecraft also goes through a sequence of modes which are distinct from the AOCS ones. First the AOCS enters Initial Safe Attitude Mode (ISAM) and residual rates are damped with the MTB. The spacecraft deploys the solar array and speeds up two RWS to a constant speed, aligning the angular momentum vector with the spacecraft $-z$ axis. This axis is pointed towards the Sun for a power-positive state and the angular rate around this axis is set to 0.25 deg/s due to thermal requirements. Actuation in this phase is done with MTB. During eclipse, when the Sun direction cannot be estimated by the CSS, no attitude control is done by the AOCS and the Sun direction is maintained with gyroscopic stiffness.

The next AOCS mode is Transition Mode (at which point the spacecraft enters NOM mode), entered nominally at Mission Elapsed Time (MET) 27:00, in which the attitude changes from Sun pointing to the nominal Nadir pointing. In this mode the main attitude sensor is the MHSTR and the CRS. The RWS and MTB go from providing gyroscopic stiffness and attitude control respectively, to providing control torque with four RWS and angular momentum management with the MTB. After a damping phase in which the spacecraft rates are slowed down to zero, 3-axis control is done to achieve the Nadir pointing attitude. Some transitions within the mode are governed by the orbital position, which is given by the GNSS unit.

Upon completion of the Transition Mode activities, AOCS switches to Normal Mode at MET 31:00. The same sensors and actuators are used as the last phases of the previous mode to provide the precise attitude determination and control needed for the operation of the instruments.

3. Flight Dynamic tasks during LEOP

One of the main tasks of FD was to support the entry to the spacecraft NOM mode (AOCS Transition Mode). Since different, more precise sensors are used with respect to the previous phase, it was necessary to check the correct behaviour of these units. During the Initial Safe Attitude Mode, the MHSTR and GNSS are switched on by ground command and their performance is assessed by comparing against other sensors or ground

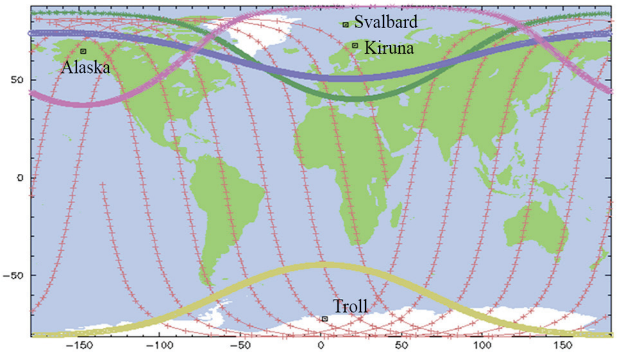

Fig. 2. Ground track of the first 7 orbits and visibility of the different ground stations used during LEOP.

models. Flight Dynamics was responsible for the corresponding checks to ensure the correct behaviour of those units before the switch to Transition Mode could be initiated.

The tasks of FD during LEOP also included the active monitoring of the AOCS behaviour during all phases. The telemetry (TM) of the sensors and actuators used in the different modes was analysed in real-time, and the data was used to estimate the rates and the attitude and to compare them with expected values. In case of any anomalous observation, FD would immediately inform the Flight Control Team.

Even though the nominal timeline did not foresee any command to be generated by FD, the team was ready for a possible Collision Avoidance Manoeuvre if a danger of collision was detected by ESA's Space Debris Office. In such a case, FD would compute the required manoeuvre to reduce the risk of collision to acceptable levels and generate the command to be uploaded to the spacecraft. No risk of collision was detected during the LEOP and no command generation was needed.

Apart from the monitoring of the AOCS behaviour, another task of FD during LEOP was to determine the injection orbit achieved by the launcher and support the ground station network in acquiring the spacecraft signal especially during the first orbits. To support the near-polar orbit four stations were used: Troll (Antarctica), Svalbard (Norway), Kiruna (Sweden) and Alaska (see Fig. 2). This configuration guaranteed spacecraft visibility both at the South and North Pole for the most critical parts of the LEOP, especially the first orbits, including sufficient margins of visibility in case of a non-nominal injection.

At MET 07:00 FD was to provide the first Orbit Determination (OD), which also provides predictions on the spacecraft visibility at each station updated according to the actual injection orbit. The first orbit solutions were based on angular and ranging data. After switch on of coherency in pass 4 around MET 04:00 also Doppler data was available. After the switch-on of the GNSS units and the posterior transition of the transponder to a high bit rate mode around MET 31:00 there would be no more ranging data available and the OD would be based only on data from the GNSS units. Before this, it was necessary to make an assessment of the validity of the GNSS data by FD, which was done as part of the NOM mode entry activities. FD would then perform ODs every 12 hours up to completion of LEOP at MET 72:00.

Based on the injection orbit FD was also required to present a strategy for the acquisition of the reference orbit. This study was expected to be done after the second OD and to be presented for discussion with the FCT around MET 32:00.

4. Separation, first acquisition and first passes

The launch of Sentinel-3A happened at the nominal time, on February 16th, 2016 at 17:57:31 UTC. The Rockot vehicle lifted off the Plesetsk launch complex in Russia and performed a nominal ascending flight sequence. Separation happened over the coast of Kenya at 19:17:21 UTC followed by a successful acquisition of signal (AOS) at a time of 19:30:25 UTC over the Kiruna station. On first acquisition the spacecraft showed a nominal behaviour. The AOCS mode was ISAM and the rate damping mode brought the spacecraft to a state in which the solar array could be deployed already before the pass.

The first pass was a combined Kiruna, Svalbard and Alaska pass. The reported Time Offset Value (TOV) at Kiruna AOS was 3 seconds early and decreased down to 2 seconds early at Alaska loss of signal (LOS). The values indicated an injection well within the expected accuracy, as the spacecraft was seen with only a few seconds of difference with respect to the predictions based on the nominal injection orbit. Using the provided TOVs and radiometric tracking data, FD predicted a TOV of less than 1 second early at the next pass over Troll, which was confirmed by the observations. The ranging and angular tracking data retrieved during this Northern Pole pass allowed a coarse orbit determination, indicating an increase in semi-major axis of 1.6 km with respect to the nominal orbit and an inclination difference of 4 mdeg. This values were well within the expected ranges (standard deviations of 0.3 and 0.2, respectively). The found orbit solution was confirmed and refined by the following Southern and subsequent passes, whereby from pass no. 4 onwards also Doppler data was available as coherency was switched on.

After the 6th pass at Troll the first complete OD including generation of station predictions and further orbital products was performed. The values of the initial estimates were confirmed: The injection was close to nominal, with the error in all elements below 1 sigma. The parameters of the injection orbit are summarised in Table 1.

Table 1. Orbital parameters after the first Orbit Determination.

	OD	Reference	Difference
Semi-major axis (km)	7188.461	7186.792	1.669265
Eccentricity	0.001307	0.001118	0.000188
Inclination (deg)	98.6971	98.70135	−0.00424
Argument of Ascending Node (deg)	116.0105	116.0247	−0.01425
PSO (deg)	355.0424	354.9271	0.1153

One of the first activities to be performed by FD during the first three passes was the assessment of the MAG measurements. Given the estimated orbital position (based on the nominal injection orbit at this point) and the IGRF-12 model of the Earth's magnetic field, the MAG readings were compared to the expected values computed on ground. Since the attitude estimation uses the MAG readings, the only independent check is to compare the norm of the magnetic field. According to the satellite manufacturer's requirements the check was considered accepted if the difference was below 10 μT. The maximum observed difference was in the order of 4 μT (see Fig. 3), so it was considered that the MAG behaviour was as expected. Following the nominal timeline, this was reported to the FCT at pass 5 around MET 05:30.

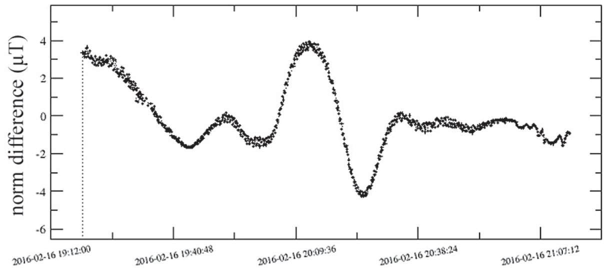

Fig. 3. Difference in norm of Earth's magnetic field vector as measured by the MAG and computed on-ground covering the first three passes.

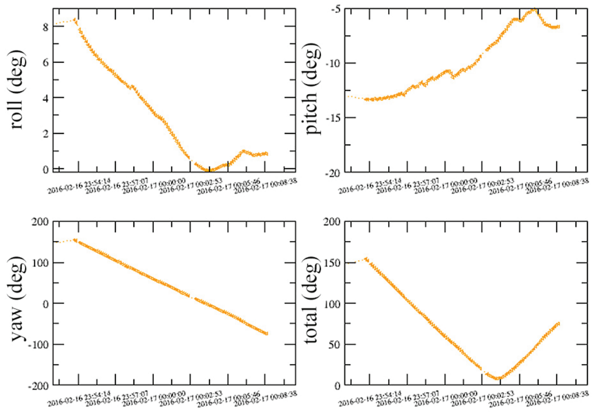

Fig. 4. Observed attitude with respect to the reference attitude during pass 6. The constant slope of the yaw angle indicated an angular rate of −0.25 deg/s, as was expected. The variations in roll and pitch are within the acceptable levels during the intial phase.

The spacecraft successfully entered the Sun pointing attitude with a −0.25 deg/s rate around the z axis (yaw). The attitude monitoring was based on the comparison against an expected nominal attitude. In principle the nominal attitude would have the $-z$ axis pointing towards the Sun, with the nominal yaw rate. However, as the initial yaw angle is unknown, any comparison would be biased by an initial phase offset, and any non-nominal yaw rate would add to the initial offset. Therefore, it was decided to have a null yaw rate in the reference attitude: this way the monitoring could readily tell the angular rate in yaw, without needing to take into account any phase difference. The comparison of the observed attitude with the reference is shown in Fig. 4. Note how the yaw angle has a constant slope indicating a constant rate. The roll and pitch angles show certain deviation but they are inside the expected levels: Attitude control done with the MTB is not as accurate as with the RWS. In addition, at this stage the attitude was estimated by FD using a least-squares method[1)] with the measurements of the Sun direction by the CSS and the magnetic field by the MAG. Because of the accuracy of the measurements, this estimation has an uncertainty of up to 25 degrees.

The rest of the FD activities up to pass 9 over Alaska and Svalbard at MET 08:24 focused on the monitoring of the AOCS behaviour. All active AOCS units showed nominal performance. The reaction wheels were spinning with constant predetermined speed depending on the AOCS submode, the attitude clearly showed stable Sun pointing with a constant yaw rate and the RCS system showed a slightly decreasing temperature of the hydrazine tank, also inside the normal expectations.

5. Star Trackers anomaly

Once in the steady state of ISAM, the Star Trackers were switched on to assess the correctness of the measurements before transitioning to the higher AOCS mode. This section summarizes the events of this activity.

5.1. Background on the Star Trackers

The Sodern Hydra Multiple Heads Star Tracker (MHSTR) assembly consists of three Optical Heads (OH) pointing towards the spacecraft $-y$ side, which in the nominal attitude faces deep space. The heads have a relative alignment of between 50 and 90 degrees between each other in order to provide a robust and accurate attitude determination when using information of the different OHs. The MHSTR contains two Electronic Units (EU), which compute the attitude quaternion of the spacecraft with respect to the inertial reference frame using the alignment information of the individual OHs. The data of several OHs is fused into a single attitude quaternion, which is used by the AOCS software for the attitude control. Usually a single EU is active, but both of them can be active upon demand.

The information available in telemetry is the attitude quaternion from inertial to spacecraft frame as computed by the EU, both the fused quaternion from several OHs and based on the readings of the individual OHs. No information of the quaternion from inertial to the unit frame of each individual OH is available.

5.2. Switch-on of the MHSTR

The MHSTR EU1 was switched on during pass 9 over Alaska and Svalbard at MET 08:30 and OH1 converged to a valid attitude estimation. FD could check its validity by comparing the retrieved attitude quaternion with the quaternion derived by FD based on the CSS measured Sun vector and MAG measured Earth magnetic field (note that this comparison could only be made outside of eclipse). As explained in the previous sections, this attitude estimation is coarse – a difference of up to 25 degrees would be considered acceptable.

The comparison using the readings of OH1 led to a surprising result: the observed deviation was in the order of 50 degrees, above the acceptable threshold. The next pass confirmed the unexpected behaviour: On pass 10 over Troll OH1 showed the same 50 degrees difference. After a gap in validity during the pass, OH3 became the only active head and the discrepancy with respect to the CSS and MAG measurements grew to 150 degrees. Not only did the MHSTR values not match the measurements of the other sensors, but there was a discrepancy between the OHs themselves (see Fig. 5). During pass 11, a jump in the fused quaternion could be more clearly observed when the validity changed from OH3 to OH1 without any gap.

The rates derived from the MHSTR measurements were compared to the CRS readings. They did not match in direction, but the norm differed in less than 10%, indicating some constant bias in the MHSTR attitude measurements.

While this situation was developing, a too low temperature in the SARL instrument (outside the scope of interest of FD)

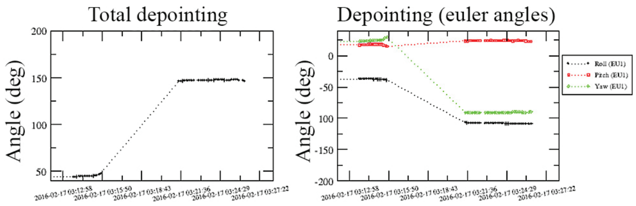

Fig. 5. Comparison between the attitude computed by the MHSTR and the attitude from CSS and MAG measurements during pass 10. At the beginning of the pass OH1 was active and the discrepancy was about 50 degrees. After a blinding period, OH3 became active and the discrepancy was close to 150 degrees.

caused the manufacturer's team to advice a transition to NOM mode as soon as possible. However, at this point the MHSTR was considered not safe for usage by the AOCS controller in the next mode, preventing any transition. A quick understanding of the problem was needed.

After pass 11 and coincident with the handover from FCT shift A to B, a meeting between FCT, FD and satellite manufacturer representatives was held at MET 10:30 to discuss the issue of the MHSTR discrepancy. The observations, especially the instant jump during pass 11, made the most reasonable explanation at the moment to be an error in the parameters used by the MHSTR software. As the next steps, the industry experts would download and inspect the on-board parameters of the MHSTR to look for any anomaly and the FCT would proceed to switch on EU2 assigning OH3 to it, while maintaining OH1 and OH2 assigned to EU1. This would allow to compare the behaviour to the observed one from EU1 in order to discard the possibility of a malfunctioning electronic unit.

During passes 12 and 13 the same behaviour in the MHSTR attitude determination was observed. Only one OH was valid at any given time. OH2 had not been valid so far. From pass 14 at MET 12:30 until pass 16 at MET 14:10 the switch of Electronic Units was performed as decided in the meeting and it was observed that the attitude provided by EU2 using OH3 data resulted in the same off-pointing of 150 degrees as before. OH1 and OH2 were active in EU1 at different intervals. The discrepancy with respect to the CSS and MAG measurements when using OH2 data was observed for the first time and showed a discrepancy of 90 degrees. This confirmed the wrong behaviour of the MHSTR. During all this time no more than a single OH had been valid for a given EU, which was also unexpected and thought to be part of the anomaly. During pass 16 all OHs were assigned back to EU1, and EU2 was switched off.

5.3. Reason found and analysis of solution

The situation did not improve during the next few passes. The spacecraft state was stable, but the issue with the MHSTR prevented any transition to NOM mode. It was imperative to understand the problem and find a solution, as this transition was now promptly wanted due to the low temperature of the payload as reported above.

By MET 17:00 after pass 19 the satellite manufacturer detected the root cause of the MHSTR problem and a meeting was held to discuss the issue. The MHSTR EUs had the alignment quaternions of each OH stored in memory in order to compute the final attitude quaternion from the inertial to spacecraft reference frame based on the OH readings. The root problem was an inconsistency between the values used by the MHSTR and the actual alignments of the OHs. There had been a wrong interpretation of the meaning of the quaternions uploaded on-board. The uploaded alignments corresponded to a reference frame which was rotated around the line of sight, with a different magnitude depending on the OH. The direction of the line of sight for the OHs was thus correctly given by the alignment quaternions, but when computing the rotation from inertial to spacecraft frame based on the OH readings the result was incorrect.

The manufacturer's team proposed new values to be uploaded on-board based on the review of documentation. Before the upload, it was agreed to assess the correctness of the new values in an analysis by FD. The quaternions of each OH from telemetry represent the rotation from inertial to spacecraft frame. Since there was no direct information on the inertial attitude of each OH in unit frame, it was necessary to reprocess the telemetry quaternions, applying first the inverse of the alignments used on-board and applying afterwards the new alignments. Using the usual quaternion nomenclature in which q_{BA} represents the quaternion of the rotation from frame A to B and the quaternion multiplication is given by $q_{CA} = q_{CB}q_{BA}$, the quaternion from inertial frame to spacecraft frame seen in telemetry computed with the values of an Optical Head OHi can be decomposed into:

$$q_{\mathrm{SJ}}^{\mathrm{TM}} = q_{\mathrm{SOH}i}^{\mathrm{onb}} q_{\mathrm{OH}i\mathrm{J}}, \tag{1}$$

where $q_{\mathrm{SOH}i}^{\mathrm{onb}}$ is the on-board value of the alignment from OHi to spacecraft and $q_{\mathrm{OH}i\mathrm{J}}$ is the quaternion from inertial to OHi frame as measured by the unit. The quaternion multiplication above shows what the MHSTR was doing. FD was interested in getting $q_{\mathrm{SJ}}^{\mathrm{new}} = q_{\mathrm{SOH}i}^{\mathrm{new}} q_{\mathrm{OH}i\mathrm{J}}$, where $q_{\mathrm{SOH}i}^{\mathrm{new}}$ is the new alignment of OHi proposed by industry. There is no direct knowledge of $q_{\mathrm{OH}i\mathrm{J}}$, but with the TM data the value could be computed as:

$$q_{\mathrm{SJ}}^{\mathrm{new}} = q_{\mathrm{SOH}i}^{\mathrm{new}} \left(q_{\mathrm{SOH}i}^{\mathrm{onb}}\right)^{-1} q_{\mathrm{SJ}}^{\mathrm{TM}}. \tag{2}$$

The telemetry containing the MHSTR data was retrieved and the relevant parameters were extracted and reprocessed applying the described conversion. The comparison of the results with the attitude derived by CSS and MAG measurements showed a significant improvement: the angular difference was now below 20 degrees. Moreover, there was a clear continuity in the values when the switch of OHs happened (see Fig. 6). This indicated that the new alignments corresponded to realistic values.

5.4. On-board patch

After the new values were deemed valid by FD and the manufacturer, the FCT uploaded the new values to the on-board software on pass 29 at MET 26:50. When the MHSTR EU1 was switched on, all OHs went into tracking mode (unlike before when only one was valid at a time) and the agreement between the attitude measurements of all OHs and the CSS and MAG estimation improved dramatically, as expected from the analysis done before the patch. The offset between the different OHs was also consistent and low, meaning that the new values agreed with the actual alignments of the OHs.

The situation was monitored for the next passes and the results showed that the MHSTR was now in a good condition for the transition to NOM mode.

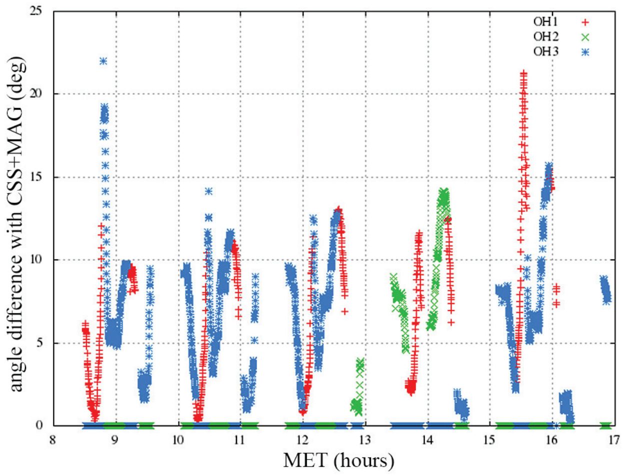

Fig. 6. Comparison between the attitude from CSS and MAG estimates and MHSTR measurements reprocessed applying the corrections, with TM up to pass 19. The discrepancy was now within the thresholds. It can also clearly be seen that when the active OH changed, the computed attitude maintained continuity, indicating that the new alignments were realistic.

6. Transition to NOM and rest of LEOP activities

As explained in section 3, FD was in charge of assessing the performance of the GNSS unit before a transition to NOM. The primary unit was switched on during pass 11 at MET 10:00. The monitoring activities took place in parallel to the MHSTR issues and consisted of comparing the state vector returned by the unit with the orbital position and velocity predicted by FD. The results showed a good agreement, with a deviation in the order of 50 m and 0.08 m/s. The GNSS was considered in good condition for the transition to NOM.

By pass 33 at MET 30:30 all conditions for the transition to NOM were met and the transition was commanded by the FCT. In total the MHSTR anomaly caused a delay of 4 passes – around 4 hours– in the nominal LEOP timeline. The spacecraft then followed the expected process and the final spacecraft attitude was achieved. AOCS entered Normal Mode at MET 33:30 and all activities of the LEOP timeline were completed for a timely finish. FD continued to monitor the behaviour of the AOCS system and to perform ODs during this time with no major upset happening.

7. Thruster torque calibration manoeuvres

7.1. Sentinel-3A thrusters system

The spacecraft has eight thrusters arranged in two sets of four thrusters. Set 2 exerts the thrust in the flight direction, whereas the set 1 does it against the flight direction (see Fig. 7). Each thruster provides a force level of 1 N at beginning of mission. Manoeuvres are executed with either of the sets depending on the type of manoeuvre (in-plane prograde or retrograde). For out-of-plane manoeuvres, the spacecraft performs a slew to align the thrust direction with the required delta-v vector.

For large manoeuvres all four thrusters of a given set are fired together. Attitude is controlled by modulating the thruster pulses in order to cope with the induced torques. It is also pos-

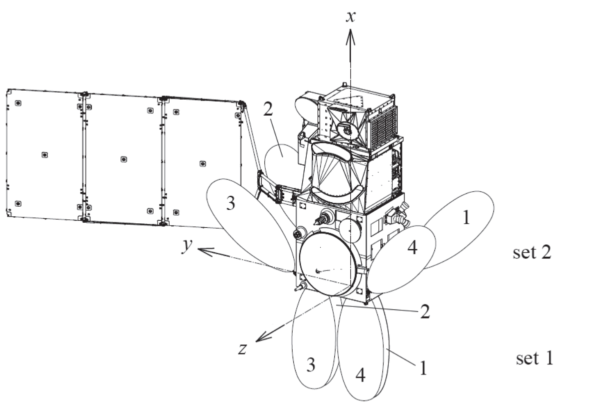

Fig. 7. Configuration of thrusters for Sentinel-3A. Note that the spacecraft x axis points opposite to the flight direction. Set 1 provides thrust against the flight direction, whereas set 2 does it in the flight direction. The thrusters of set 2 are angled to minimize the risk of plume contamination of other spacecraft components.

sible to perform a manoeuvre using a diagonal pair of thrusters of a set. This is done for manoeuvres requiring a small delta-v or in the case of thruster failure, in order to avoid the need of a slew to use the other set. In this case the attitude is controlled by the RWS. The torque induced by the thruster pair imposes a limit on the achievable delta-v, as the attitude controller may not be able to cope with a too high angular momentum transfer. The activities envisaged for the first two commissioning days aimed at characterizing the torque level of each thruster pair.

7.2. Calibration manoeuvres

Four manoeuvres were prepared. On the first day of commissioning thruster set 1 would be tested using thrusters 1 and 3 for the first manoeuvre and then thrusters 2 and 4 for the second. For both, the delta-v specified by the procedures of the spacecraft manufacturer was 18 mm/s. Similarly, on the second day thruster set 2 was tested, with a manoeuvre of 7 mm/s for each pair of thrusters. Thruster set 2 required a smaller delta-v and thus a shorter firing time, because of the higher torques expected.

7.3. Monitoring of the manoeuvres

On February 22$^{\text{nd}}$ the two manoeuvres of thruster set 1 were executed and monitored. Both manoeuvres performed as expected. The number of pulses and fuel consumption matched FD predictions. The main interest was to check the spacecraft rates during the burn for any misbehaviour due to higher than expected torques. The only significant increase in spacecraft angular rate was in the x axis (roll) up to a value of -0.01 deg/s for pair 1-3, and 0.01 deg/s for pair 2-4. The torques induced by the thruster firing were inside the expected levels (see Table 2).

Table 2. Observed and limit torque components (in spacecraft frame and Nm) for the thruster torque calibration manoeuvres executed on February 22$^{\text{nd}}$ with thruster set 1. The limits are in absolute value.

	x	y	z
Pair 1-3	0.1031	−0.0054	−0.0220
Pair 2-4	−0.1134	−0.0118	−0.0238
Limit	0.1578	0.2367	0.2621

The monitoring of the manoeuvres using set 2 on February 23$^{\text{rd}}$ yielded some unexpected results. The RCS system behaved as expected, but for thruster pair 1-3 high angular rates were observed around the x and z axes, with the attitude de-pointing in yaw growing to 0.5 degrees during the firing. The torque in the roll axis was inside the limit, but in yaw it was outside the threshold. For pair 2-4 the rate increased mostly around the x axis, resulting in a de-pointing in roll of almost 1 degree and an excess of the torque limit (see Table 3). Also, the orbital performance assessment showed that for set 2 the performance of the manoeuvres was around 75% and 86% respectively for each thruster pair.

Table 3. Observed and limit torque components (in spacecraft frame and Nm) for the thruster torque calibration manoeuvres executed on February 23$^{\text{rd}}$ with thruster set 2. The limits are in absolute value.

	x	y	z
Pair 1-3	0.3656	−0.0079	−0.7670
Pair 2-4	−0.6712	0.1102	−0.1806
Limit	0.6519	0.3932	0.4903

The issue was discussed with the FCT and manufacturer representatives. Given the geometry of the spacecraft a possible explanation was plume impingement on the solar array, an issue observed already before on other spacecraft.[2)] In view of the results, it was decided to test again thruster pair 1-3 of set 2 (which had the highest disturbance torques) on two different orbital positions. The solar array has a different incidence angle depending on the orbital position and this could show whether plume impingement was a factor in the observed misbehaviour or not.

7.4. Second test manoeuvres and final results

Two manoeuvres were executed on February 26$^{\text{th}}$ for thruster pair 1-3 of set 2: one close to the South Pole and the second close to the North Pole. The first, performed at roughly the same orbital position as the manoeuvre done three days before, replicated the observed results. The observed torques had roughly the same values. The second manoeuvre, done with the same thruster pair one and a half orbits later close to the North Pole, showed different results. The torque had different components and the threshold was exceeded in the x direction (see summary in Table 4). This confirmed the plume impingement in the solar array as the most probable explanation.

Table 4. Observed torque components (in spacecraft frame and Nm) for the manoeuvres executed with thruster pair 1-3 of set 2 on February 26$^{\text{th}}$. The difference in the components led to the conclusion that plume impingement was the cause of the high torques.

	x	y	z
South Pole	0.3619	−0.0330	−0.8377
North Pole	0.6811	−0.1094	−0.1938

The higher than expected torque values resulted in new constraints in the maximum manoeuvre size when using thruster set 2 around the South Pole, both for a pair of thrusters and for all four thrusters. The maximum allowable delta-v was between 60 mm/s and 26 mm/s, depending on the number of operational reaction wheels. This new constraint, however, did not have any operational impact in the acquisition and maintenance of the reference orbit, as the control manoeuvres were either done outside of the South Pole zone or did not exceed the delta-v limit.

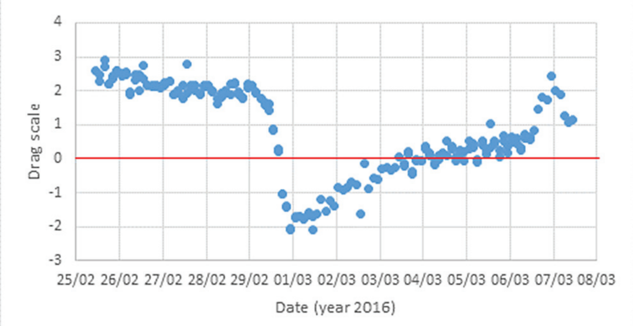

Fig. 8. Observed non-dimensional drag during the first days of commissioning. The nominal value is 2.5. The peak around March 7th is caused by exceptionally high solar activity.

8. Negative drag

Another interesting event was observed after the first week of flight when the estimated drag coefficients of the daily orbit determination suddenly dropped from being nominal (ca. 2.5) to negative on 29th of February and only slowly turned back to nominal within two weeks, see Fig. 8. The reason for the observed negative CD values was traced back to out-gassing caused by the heating of the instruments, which has been observed for other satellites in the initial weeks of the mission.

The resulting effect on the orbit was a positive acceleration in the flight direction. As the injected orbit was above the reference orbit, one or more manoeuvres were needed to reduce the semi-major axis to the reference value. The atmospheric drag would lead to a natural decay of the semi-major axis and therefore reduce the size of the acquisition manoeuvre. The observed negative drag value represented a small acceleration acting on the spacecraft in flight direction, maintaining or even increasing the semi-major axis. Fortunately, a high solar activity around the 7th of March led to a sudden raise in drag and corresponding decrease in semi-major axis such that in the end a smaller manoeuvre was sufficient for the final orbit acquisition.

9. Conclusions

The Sentinel-3A LEOP and first days of commissioning included some interesting unexpected events. All the parties involved worked efficiently to quickly understand and solve the encountered problems. All tasks were completed successfully and Sentinel-3A was made ready to fulfil its mission.

Acknowledgments

The authors would like to thank all the Flight Dynamics team for the support with Sentinel-3A. The authors would also like to thank Jaime Fernández from GMV for providing the plot of Fig. 8.

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