# Sentinel-5P Loose Formation Flying with Suomi-NPP: LEOP, Orbit Acquisition and Orbit Maintenance

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## Abstract

The Sentinel-5 Precursor Copernicus mission is dedicated to monitoring our atmosphere. The satellite carries the TROPOMI payload mapping trace gases and aerosols affecting air quality and climate. It was launched on October 13, 2017 at 09:27:30.0 UTC from the Plesetsk Cosmodrome. To make the most from the science data Sentinel-SP is flying behind the Suomi-NPP within a time window of 2-5 minutes, while keeping the difference in Mean Solar Local Time of Ascending Node (MSLTAN) constant at 4:55 minutes ± 10 sec, i.e. in 'loose formation'. This paper describes the 'loose formation' flying concept and how it was implemented operationally for Sentinel-5P. It summarises part of the work that was performed by the Sentinel-5P Flight Dynamics team at ESOC during the launch preparation, LEOP, orbit acquisition and routine operation phases. How the orbit maintenance requirements could be met operationally and what the outcome has been so far following this approach is discussed in more detail.

**Keywords:** Sentinel-5P, Copernicus, LEOP, Orbit acquisition, Orbit maintenance, Loose formation

## Introduction

The Sentinel-5 Precursor mission, also known as Sentinel-5P (S5P), is the first Copernicus mission dedicated to monitoring our atmosphere in terms of air quality, ozone and surface UV, and climate. Its primary objective is to perform remote sensing of the atmosphere by means of the state-of-the-art TROPOspheric Monitoring Instrument (TROPOMI), an UV-VIS-NIR-SWIR push-broom grating spectrometer, that provides measurements of ozone, $NO_2$, $SO_2$, formaldehyde, methane, carbon monoxide, and aerosols at high temporal and spatial resolution.

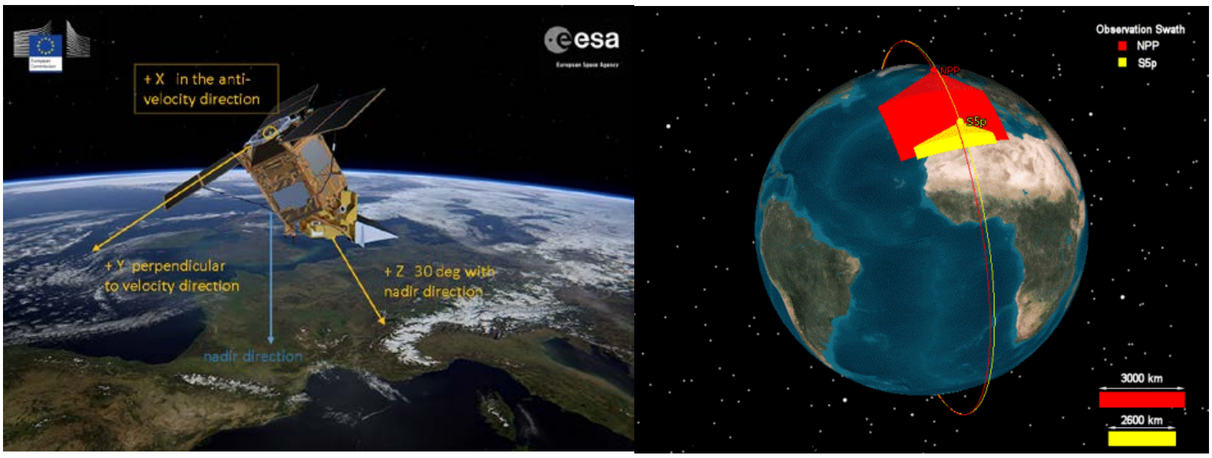


*Fig. 1: Impression of the Sentinel-5P SC in orbit (left) and the swath overlap of the Sentinel-5P TROPOMI and the VIIRS instrument on Suomi-NPP (right)*

In Fig. 1, S5P is depicted in its main sub mode used when taking the observations, called NM_AUTO/CAP (Normal Mode Automatic/Custom Accurate Pointing). In this sub mode the line of sight of TROPOMI is geodetic pointing and yaw steering is active. S5P is equipped with a mono-propellant hydrazine propulsion subsystem operated in blowdown mode, with a redundant set of four 1 N thrusters used for orbit control, all of them mounted on the –Z SC plate. When activated, this set of thrusters deliver a Δv mostly in the direction of the SC +Z axis. The execution of orbit control manoeuvres takes place in a mode called Orbit Control Mode (OCM), after the execution of a suitable SC slew to align the +Z SC direction with either the orbital inertial velocity (for in-plane corrections) or with the orbital angular momentum (for out-of-plane corrections). Other axes of the satellite body reference frame are also indicated in the illustration on the left, where the +X-axis is pointing in the anti-velocity direction and the Y-axis completes a right-handed body frame.

To improve the S5P science return, high resolution cloud information acquired close in space and time to that of the S5P observations is needed. These auxiliary data are provided by the NOAA/NASA Suomi-NPP (SNPP) spacecraft of the Joint Polar Satellite System (JPSS), which has a Visible/Infrared Imager Radiometer Suit (VIIRS) instrument on board. To keep the usability of the cloud mask data from SNPP at an acceptable level and ensure that overlap requirements associated with the instrument field of views on both satellites are satisfied, the two SC need to fly as close as possible without compromising the missions' safety. The ESA S5P mission and the NOAA/NASA SNPP & JPSS mission have therefore formulated an operational concept for the S5P mission to fly in 'loose formation' with the SNPP spacecraft.

## Loose Formation Flying Concept

To guarantee the safety of the missions in the constellation (highest priority) a similar concept as for the morning and afternoon constellations [1] needed to be adopted for S5P and SNPP. The proposed concept is based on control boxes, where each mission has its own reference orbit and by controlling the orbit around its reference (centre of the box) it is assured both satellites are kept within defined boundaries (see Fig. 2). A minimum safe separation between control boxes is defined to guarantee, in case of a contingency, the non-functioning trailing satellite shall not enter the other satellite's control box before a defined period of time. For the S5P/SNPP constellation a period of 60 days was agreed, corresponding to a minimum control box separation of 120 sec.

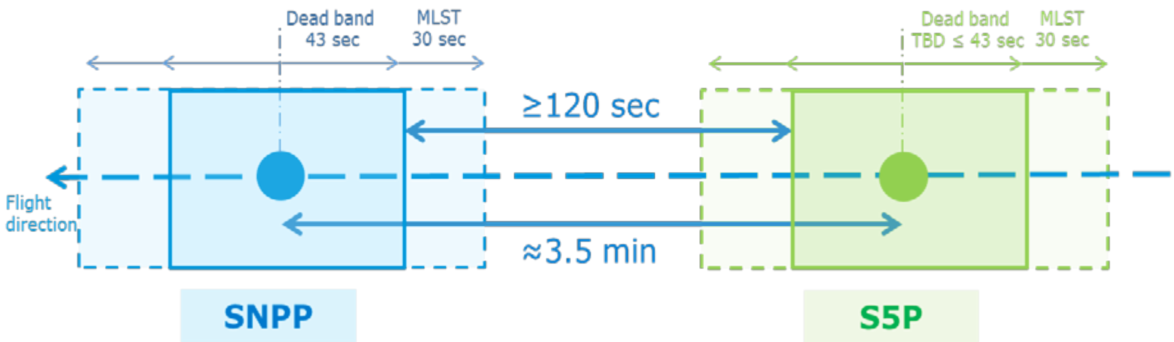


*Fig. 2: Depicting the 'loose formation' flying concept for S5P and SNPP and the adopted separations for the routine phase of the missions.*

Besides considering a minimum safe distance between both satellites for the definition of the constellation concept (quality of the cloud mask degrades sharply when acquisitions are more than 5 minutes apart), also a constant distance between the actual positions of both satellites and keeping the ground-tracks as adjacent as possible to observe the clouds from the same angle, were considered. These considerations resulted in a hybrid master-slave control box strategy, where the control is based on coordinating the Inclination Adjustment Manoeuvres (IAM), keeping the same local time profile, while the Drag Make Up (DMU) manoeuvres are independent of each other and are driven by the defined control box of each satellite. The concept will be described in more detail in future conferences publication by the System Analysis Office at ESTEC.

## Reference orbits

The SNPP mission is controlled around a Sun-synchronous frozen eccentricity reference orbit with a 16 day, 227 orbit repeat cycle, and a MSLTAN of 13:25. Following the concept, the S5P mission needs to be controlled around a Sun-synchronous reference orbit with a ground-track repeat cycle identical to that of SNPP, but with a MSLTAN close to 13:30. In addition, the longitudes of the ascending nodes of the S5P reference need to be within ±200 km of those of SNPP.

*Table 1: S5P and SNPP Mean Keplerian parameters (True of Date) of the reference orbits*

| SNPP & S-5P Reference Orbit (Mean elements ToD) | |
|---|---|
| Repeat cycle | 16 days, 227 orbits |
| Semi-major axis | 7202176 meters |
| Eccentricity | 0.001148 |
| Inclination | 98.730 deg |
| Arg. of perigee | 90.00 deg |
| MSLT ANX | 13:25 (SNPP) / >13:30 (S5P) |

## Orbit maintenance requirements

The control box of SNPP is defined such that the ground-track of SNPP is kept within ±20 km of its reference and the MSLTAN is kept between 13:24:40 and 13:25:30. The desired phasing of S5P with SNPP has been analysed before launch and the original limits for the ground-track and MSLTAN control of S5P were adjusted. The relevant requirements for orbit maintenance resulting from this analysis are:

1. The absolute MSLTAN shall be kept above 13:29:30 due to Sun calibration constraints. Note that this requirement is not related to the constellation but to the instrument.
2. The difference in MSLTAN w.r.t. SNPP shall be kept constant to 5 minutes ± 5 seconds, as long as there are no conflicts with the previous requirement, in which case the previous requirement takes priority, subject to mission manager decision.
3. The ground-track shall be kept within a control band of ±20 km or less around the reference, ensuring the absolute along-track distance between S5P and SNPP shall be maintained between 2 to 5 minutes.

To fulfil the 2$^{nd}$ requirement, S5P will need to follow the same control as SNPP, mimicking the IAMs for SNPP, which are currently executed once a year towards the end of September.

Note that if the MSLTAN difference is kept constant within the proposed tolerance, the 3$^{rd}$ requirement is met at all times provided the ground-track is kept within the ±20 km control band. If the MSLTAN difference cannot be maintained with the required tolerance, the ground-track needs to be controlled more actively to meet the 3$^{rd}$ requirement.

An initial separation of the control box centres of around 5 minutes was advised for the commissioning phase, reducing it to the proposed 3.5 minutes once confidence in the proposed formation flying concept and coordination between missions was gained. With the 3.5 minute along-track separation and the approximate 5 minute difference in MSLTAN, the reference ground-track of S5P at equator would be shifted ~42km to the east w.r.t. SNPP. Since both satellites are controlling their respective ground-tracks within a ±20 km control band (equivalent to about 43 seconds along-track), the actual distance between ground-tracks at equator varies between 2 and 82 km, well within the requirement of the S5P swath (~2600km) to be inside the SNPP swath (~3000km), depicted on the right side of Fig. 1.

## Mission Preparation

In preparation of the mission, the S5P FD team at ESOC investigated among others if and how the updated S5P orbit maintenance requirements could be met, in particular the requirement on keeping the MSLTAN constant with a tolerance of ±5 seconds, considering the orbit information of SNPP is provided by NOAA on a daily basis through Two Line Elements (TLE) only, which are generated from 5-day SNPP orbit predictions using the associated simplified Standard General Perturbation 4 (SGP4) model.

The updated requirement, to control the MSLTAN difference with respect to SNPP more tightly, dictates accurate knowledge of both the S5P and SNPP orbits and accurate modelling of the perturbations on these satellites are required to predict the evolution of the MSLTAN with sufficient accuracy over one year (SNPP IAMs are only executed once a year).

It was clear that just propagating the SNPP TLE, using the SGP4 perturbation model, would not provide the sought after accuracy on the MLTAN prediction after one year. To improve the accuracy of the long term SNPP orbit predictions, a more accurate initial state and a more accurate propagation model was required.

A straight forward approach investigated first, was to simply take the TLE, convert it to a state vector, and propagate it using a high precision propagator (instead of the SGP4 model) to determine the MSLTAN at the time of the next SNPP IAM. The FD infrastructure software, in particular the NAPEOS (NAvigation Package for Earth Orbiting Satellites) software package, was used for the propagations. The NAPEOS software package is a general purpose navigation software system for Earth orbiting satellite missions, providing orbit determination and prediction, manoeuvre planning and parameter estimation capabilities.

To determine if this approach was good enough to determine the MSLTAN of SNPP at the time of its next IAM with sufficient accuracy, the daily SNPP TLEs for about 7 months were collected from the NOAA server, converted to state vectors, and propagated with NAPEOS, using the best perturbation models available, introducing future DMUs where needed. Comparing the propagations against the reference orbit of SNPP, the propagation model was refined, in particular the drag coefficient used for the propagations and the DMUs introduced were adjusted. For each propagation the Local Time of Descending Node (LTDN) deviation w.r.t. the reference LTDN (01:25) was computed at the time of the next SNPP IAM. In this investigation the next IAM was planned for the end of September 2017. The exact date was not known at the time, so October 1, 2017 was chosen. The resulting variation and mean in LTDN deviation at the selected IAM date are depicted in Fig. *3*.

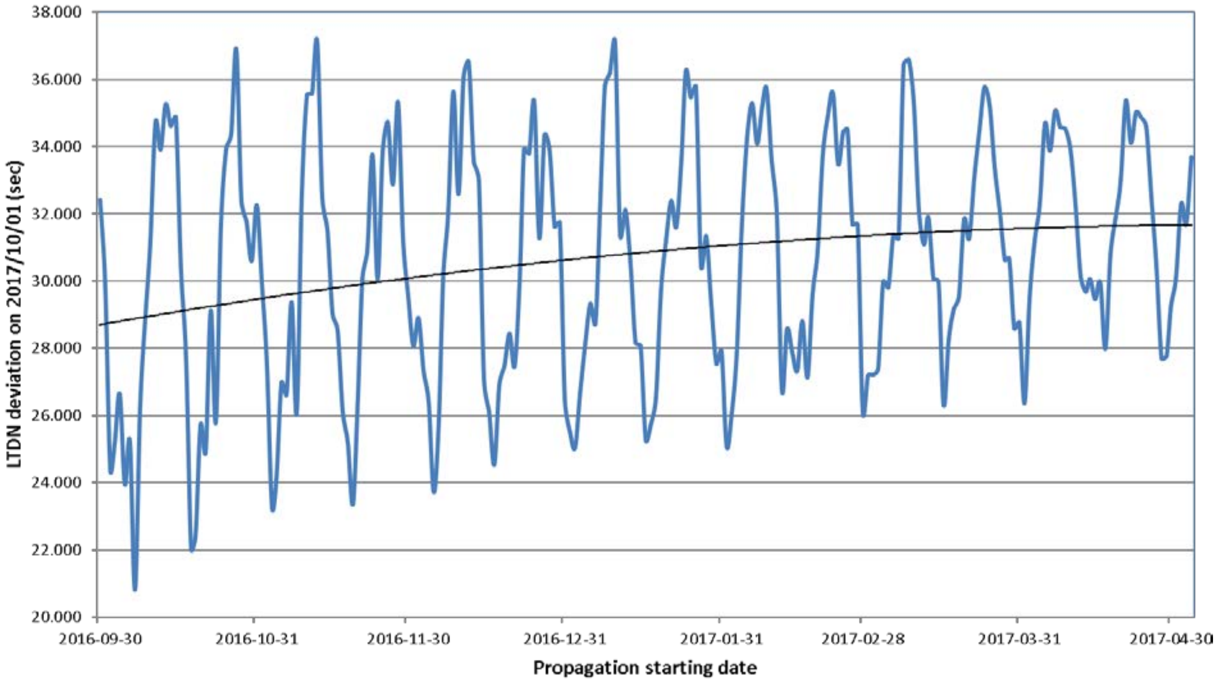


*Fig. 3: LTDN deviation on 2017/10/01 after propagating the from the daily SNPP TLE reconstructed SNPP orbits using the high precision propagator of NAPEOS.*

Propagation starting dates cover 7 months starting right after the SNPP IAM executed at the end of September 2016. Note, the mean LTDN deviation using this approach drifts with time going from 28.7 to 31.8 seconds. A variance of about 14 seconds for propagations of about one year are found. Even with a perfect one-year S5P orbit prediction, the required accuracy of ±5 seconds cannot be met following this approach.

The first approach already significantly improved the predictions over TLEs being propagated with SGP4, but not sufficiently. A second approach to improve the accuracy of the SNPP MSLTAN prediction even further was investigated, with the idea of getting a better propagation starting state by constructing 1-day orbits from the daily SNPP TLEs and consecutively treating the state vectors (at 1 minute time step) of these orbits as "pseudo-observations" in a Bayesian batch least-squares differential correction method, fitting an orbit through these observations making use of the orbit determination and propagation component of NAPEOS. The fitting period was set to 3 days, propagating again up to the time of the next SNPP IAM. In addition to the state vector at an epoch 1 day in the past of the determination arc, a daily drag coefficient was estimated. A mean drag coefficient could be determined from the middle day estimates and this was used in the end for the final long term propagations. The same set of TLEs was used as in the first approach, so the resulting variation and mean in LTDN deviation w.r.t. the reference LTDN (01:25) at the selected IAM execution date (see Fig. 4) could be compared.

Note the mean LTDN deviation using the second approach is quite constant at an average of 34.3 seconds. The variance improves a bit to about 8 seconds for propagations of about one year. The results of both approaches are combined in Fig. 5.

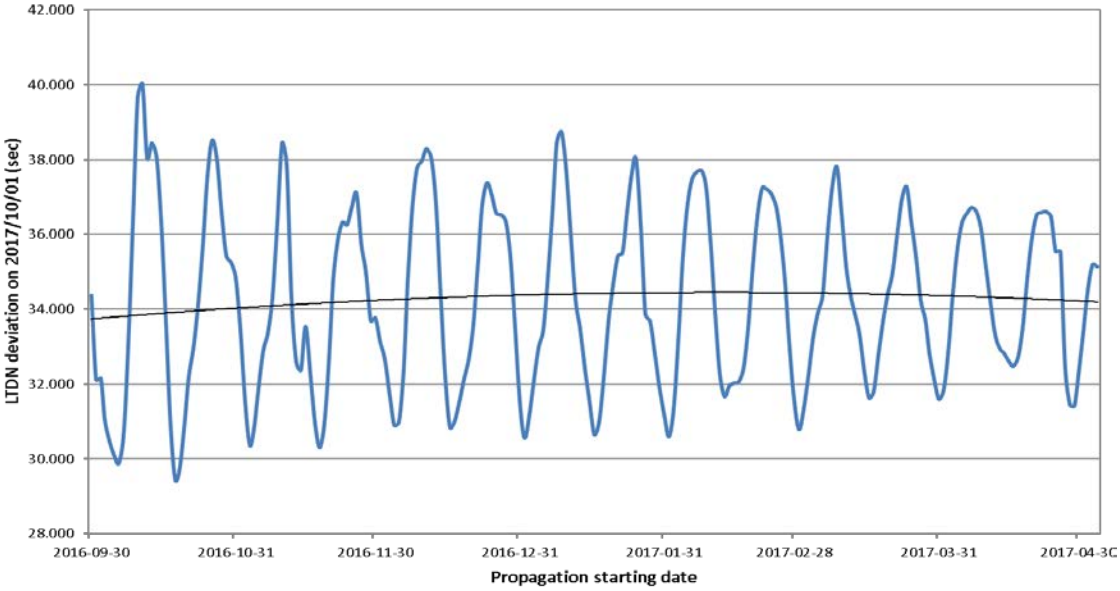


*Fig. 4: LTDN deviation on 2017/10/01 propagating the determined SNPP orbits up to the next SNPP IAM.*

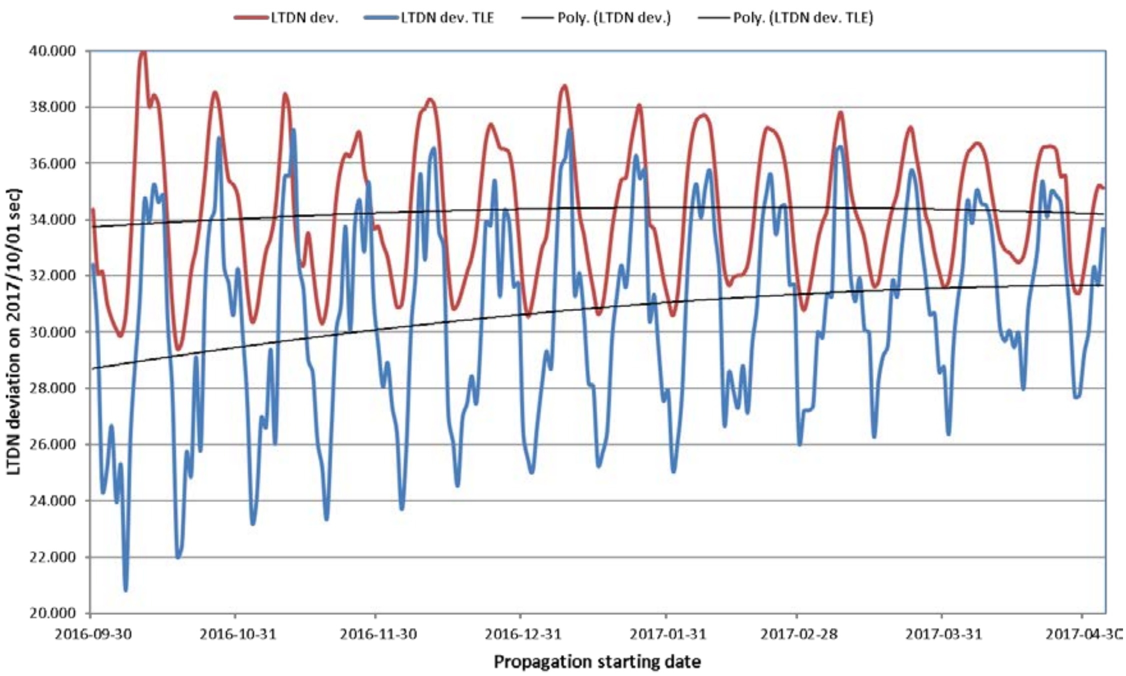


*Fig. 5: LTDN deviation on 2017/10/01 after propagating the determined SNPP orbit (red line) and the reconstructed SNPP TLE orbit (blue line).*

Combining the results of the two approaches in one graph, the resulting mean using the first approach, one year before the next IAM, shows a difference of about 5 seconds with the resulting mean of the second approach. The actual SNPP LTDN deviation at the time of the IAM at the end of September 2017, 34.1 seconds, was quite close to the mean found using the second approach. This approach was adopted for planning the Out-Of-Plane (OOP) manoeuvres on S5P.

To plan the OOP manoeuvres for S5P, the following procedure was proposed: Determine the target MSLTAN for S5P at the time of the next IAM in one years' time following the second approach, by determining and propagating the SNPP orbit for 20 consecutive propagation starting dates in advance of the planned SNPP IAM, taking into account the planned SNPP IAM, which is provided by NOAA in great detail well in advance of the IAM manoeuvre. The investigations showed that 20 consecutive propagation days are enough to determine the mean SNPP LTDN deviation at the time of the next IAM (see Fig. 4) and get a first estimate of the S5P MSLTAN target. The procedure is repeated after the SNPP IAM has been evaluated and a detailed IAM manoeuvre report has been provided by NOAA. Slight changes in the target are to be expected due to IAM manoeuvre performance errors. Whether the target MSLTAN will actually be achieved depends on the performance of the OOP manoeuvre on S5P. Due to manoeuvre constraints on S5P, the total $\Delta v$ required for an inclination change needs to be split in several manoeuvres which accommodate the fine tuning of the last OOP, limiting the effect of performance errors on the achieved target MSLTAN. It is anticipated that even though the second approach improves the variance in SNPP LTDN deviation even more, the new requirement on the MLTAN difference between S5P and SNPP may still not be achievable. It was therefore decided to downgrade the requirement on the maintenance of the S5P MSLTAN to keeping the difference in MSLTAN with SNPP constant within ±10 seconds.

Note that the MSLTAN difference can in some cases be steered to a certain extent by careful planning of the S5P In-Plane (IP) manoeuvres required for keeping the ground-track within the 20 km control band. An offset of the semi-major axis w.r.t. the reference introduces a drift in MSLTAN. An average offset of +10 m causes an additional drift in MSLTAN of -0.4 seconds/year.

## Launch and Early Orbit Phase

The S5P satellite was launched on October 13, 2017 at 09:27:30.0 UTC from the Plesetsk Cosmodrome aboard a Rockot launcher. It was separated from the upper stage at 10:46:35 UTC followed by an automatic acquisition of TM at 11:01:00 UTC over the Kiruna station. Status at AOS was nominal with the Solar Arrays already fully deployed. Telecommand link was established at Kiruna accordingly and first commanding activities executed. From this point onwards, all nominal commanding activities on the satellite were performed following the LEOP timeline. The LEOP just lasted a little over 2 days and ended one day ahead of schedule on Sunday, October 15, 2017.

The injection achieved by the Rockot launcher was very close to nominal, with a semi-major axis 1.06 km larger and an inclination 6.6 mdeg smaller than nominal. The nominal injection state vector that was requested of the launcher was 9.96 km lower in semi-major axis than the reference to initiate a drift approaching SNPP from behind. At injection the difference in semi-major axis and inclination with SNPP were -8.9 km and -16.2 mdeg respectively. At this time S5P was trailing SNPP by 173.1 degrees drifting towards SNPP with 9.5 degrees/day due to its lower altitude.

The S5P FD team at ESOC was in charge of designing the manoeuvre campaign to acquire the reference, where initially S5P is to fly 5 minutes behind SNPP and the difference in MSLTAN is 5 minutes, essentially flying the same ground-track as SNPP. When designing the manoeuvre campaign the following constraints were taken into consideration:

- A test IP manoeuvre is to be executed at MET +99:37:30 h, the 4$^{th}$ Kiruna pass on L + 4 days, with a fixed duration of 60 seconds to commission the propulsion system and associated AOCS modes. The slew to manoeuvre attitude and the manoeuvre burn are to be executed within ground station visibility
- The maximum allowed manoeuvre duration depends on the number of thrusters used. With all 4 thrusters (X-, X+, Y-, and Y+) in use, the duration at beginning of life is limited to 600

seconds. With 2 thrusters (either X or Y) this reduces to 328 seconds. The thruster duration is independent of the number of reaction wheels (4 or 3) used during the manoeuvre

- The $\Delta v$ for the IP manoeuvres is limited to 2.1 m/s to avoid station acquisition problems in case of complete manoeuvre failure
- The IPs can be executed all around the orbit, but execution (including slews) above the Svalbard and Inuvik X-band stations shall be avoided to limit X-band outage
- An OOP manoeuvre can be executed around the ascending or descending node, but preferably inside eclipse (both burn and slews) at the descending node, to avoid possible solar entrance in the instrument during the thrust and/or during the attitude manoeuvres from Nominal Mode (NM) to OCM and back to NM. When in sunlight during the manoeuvre, the solar illumination of the instrument is avoided by rotating the SC around the flight direction axis. If possible, we avoided starting the slew above the Svalbard and Inuvik X-band stations to limit X-band outage.
- A maximum of one manoeuvre per orbital revolution can be executed to ensure the recovery of the attitude control system between manoeuvres
- A sufficiently large calibration arc is allocated between manoeuvres, to properly characterize the propulsion system and allow for the screening of conjunction risks by the Space Debris Office at ESOC before implementing subsequent manoeuvres
- Conduct operations during working hours by planning manoeuvre Tuesdays and/or Thursdays. If considered beneficial this can be extended to 3 days a week (Monday, Wednesday and Friday), but requires working on weekends and potentially holidays
- Perform a final IP manoeuvre on the order of 25 cm/s to target an altitude 27 meters below the reference to initiate a drift from a 5 minute to a 3.5 minute along-track separation with SNPP during the 6 month commissioning phase.
- The final MSLTAN must be between 13:29:30 and 13:40:00 UTC

During the LEOP the FD team proposed two manoeuvre strategies, where one strategy would acquire the target 4 days earlier than the other, but would require 0.62 m/s more $\Delta v$, would leave less room for recovery in case of contingencies, and would require working on weekends and holidays. The selected second strategy consisted of executing 2 IP manoeuvres in addition to the mandatory 60 second test manoeuvre, 1 OOP manoeuvre to target the same inclination as SNPP, and the final IP manoeuvre to acquire the target position behind SNPP 24 days after the end of LEOP on November 7, 2017.

MSLT deviation caused by the In-Plane positioning problem, which is intrinsic to the phase change given to the spacecraft, due to the fact that the semi-major axis is different than the reference for a certain time.

## Orbit Acquisition

At the start of the acquisition phase the MSLTAN of S5P and SNPP were 13:29:59.9 UTC and 13:25:25.0 UTC respectively. S5P was drifting towards SNPP and to reach its target, 17.7 degrees (5 minutes) behind SNPP, it needed to drift 155.8 degrees, which in turn increased its local time by 16.8 seconds. The injection error in inclination was slowly decreasing the local time by a negligible -0.093 seconds/day. At the same time the MSLTAN of SNPP was actually drifting in the other direction, because an IAM had just been performed on the 29th of September, decreasing its inclination and reverting its drift in local time. An OOP manoeuvre with a size of 2.089 m/s was needed to reduce the inclination of S5P to that of SNPP, reducing the total drift in local time during the drift phase. The time of the OOP manoeuvre was selected to achieve the desired difference in local time of 5 minutes with SNPP at the time of orbit acquisition. A slight over performance of the manoeuvre lead to a final difference of 4:55 minutes, which was not corrected any further, since the requirement on the MSLTAN was still met. To correct the semi-major axis of S5P, a total Δv of 4.57 m/s was required. An overview of the manoeuvres executed during the acquisition phase, including timing, duration, thruster off-modulation, and calibration results, and the average off-pointing angle from the planned Δv direction are presented in Table 2.

*Table 2: Performance of the orbit acquisition manoeuvres*

| **Burn mid time** | **Type** | **Duration (s)** | | **Off modulation** | | **Δv (m/s)** | | | **Pointing error (º)** |
|---|---|---|---|---|---|---|---|---|---|
| | | Pred. | Actual | Pred. | Actual | Pred. | Actual | Perform. | |
| 2017-10-17 13:05:00 | IP | 61.458 | 66.188 | 0 % | 7.1 % | 0.308 | 0.304 | -1.4 % | 0.2 |
| 2017-10-24 10:11:26 | OOP | 452.121 | 454.000 | 7.1 % | 7.5 % | 2.089 | 2.113 | +1.2 % | 0.5 |
| 2017-10-26 09:05:29 | IP | 444.309 | 442.875 | 7.5 % | 7.2 % | 2.021 | 2.034 | +0.7 % | 0.5 |
| 2017-11-02 09:17:22 | IP | 440.511 | 439.750 | 7.2 % | 7.0 % | 1.968 | 1.992 | +1.2 % | 0.6 |
| 2017-11-07 07:10:23 | IP | 60.250 | 60.375 | 7.0 % | 7.2 % | 0.262 | 0.262 | -0.2 % | 0.3 |

When executing the test IP manoeuvre, the Y+ thruster did not perform as expected. It executed approximately 25% less pulses than the other three thrusters. As a consequence the off-modulation increased by about 7% and the manoeuvre thus took longer to execute than expected. All the commanded pulses were executed nevertheless. The change in off-modulation was considered when preparing the next manoeuvres, which showed the same discrepancy in Y+ thruster pulses. The increase in off-modulation didn't affect the manoeuvre plan, since the duration of the manoeuvres was still well below the 600 seconds limit.

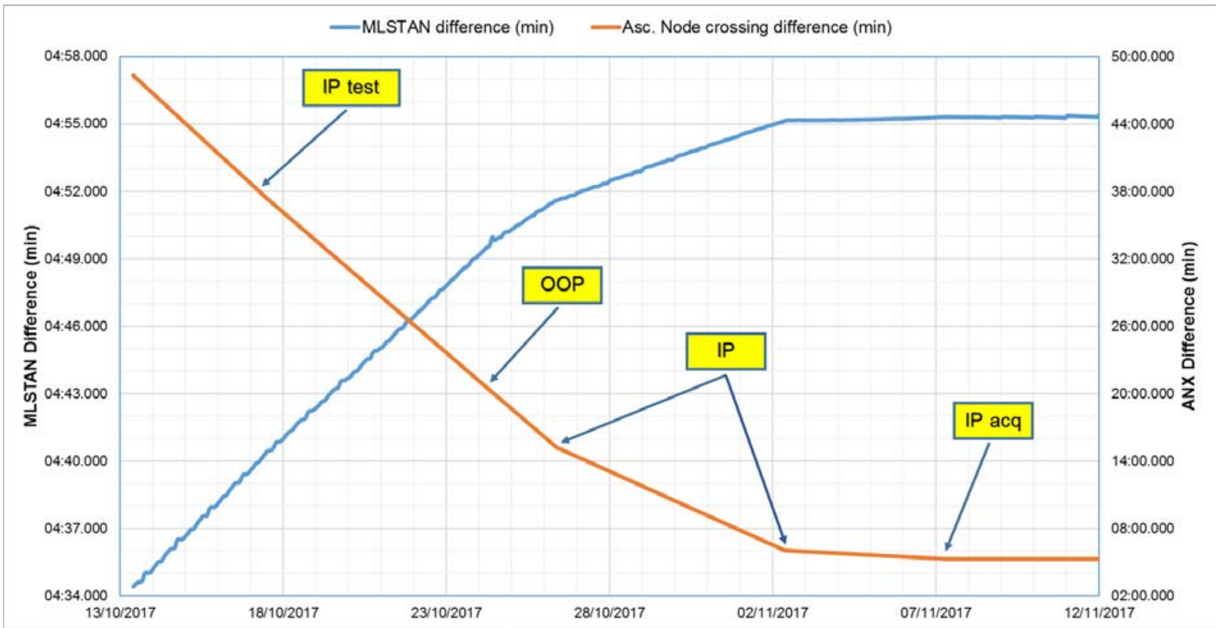


*Fig. 6: The along-track and MSLTAN separation with SNPP during the orbit acquisition phase. The achieved separation at acquisition on 7 November 2017 were 5:19 and 4:55 minutes respectively. Indicated are the times the 5 acquisition manoeuvers were executed.*

The larger manoeuvres (around 2 m/s) of the campaign showed a not insignificant off-pointing angle, which introduced a Δv of about +18 mm/s in the along-track and cross-track direction for the OOP and IP manoeuvres respectively. The in-plane effect of the OOP manoeuvre was compensated for by adjusting the remaining manoeuvres of the plan. After each manoeuvre the manoeuvre plan was adjusted and the calibration results were taken into account when preparing the following manoeuvre.

The results of the reference orbit acquisition campaign in terms of along-track and MSLTAN separation between S5P and SNPP are presented in Fig. 6.

## Orbit Control in Phase E1

The S5P reference orbit for the commissioning phase (E1) was defined relative to the SNPP reference orbit as 5 minutes behind along-track, and a 4:55 minutes difference in MSLTAN. The final IP acquisition manoeuvre was executed when the ground-track of S5P was just inside the 20 km control band around this reference. The size was selected such that S5P would drift towards the 3.5 minute separation position w.r.t. the SNPP reference in 6 months' time. Staying inside the 20 km control band during this time would have required an IP orbit maintenance manoeuvre by April 11 (see Fig. 7), but since S5P was already drifting towards the reference to be used in the routine phase (E2), the orbit maintenance was switched to control S5P around the new reference orbit instead.

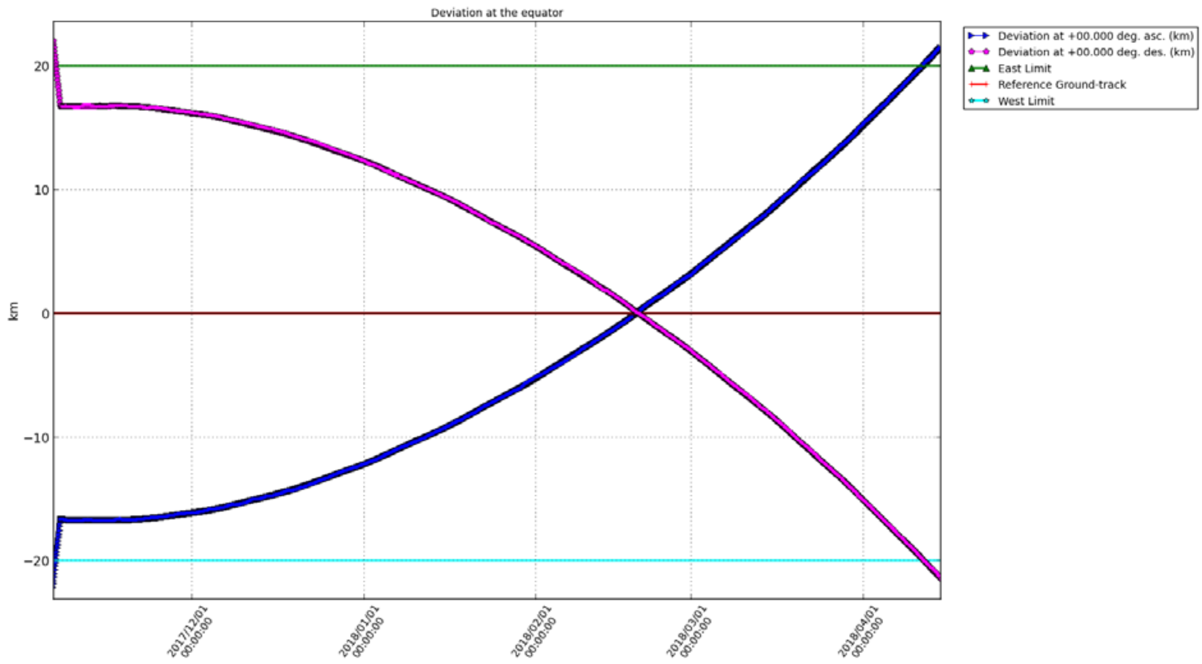


*Fig. 7: S5P ground-track deviation at ascending (magenta line) and descending (blue line) node crossing with respect to the phase E1 reference.*

The evolution of the along-track separation and MSLTAN difference with SNPP during this phase is presented in Fig. 8. Up to February 28, when a DMU manoeuvre was executed on SNPP, the along-track separation during this phase was quite constant as both SC were flying more or less at the same altitude. The evolution of the S5P local time was following that of SNPP quite closely during this phase, the difference staying constant at 4:55 minutes.

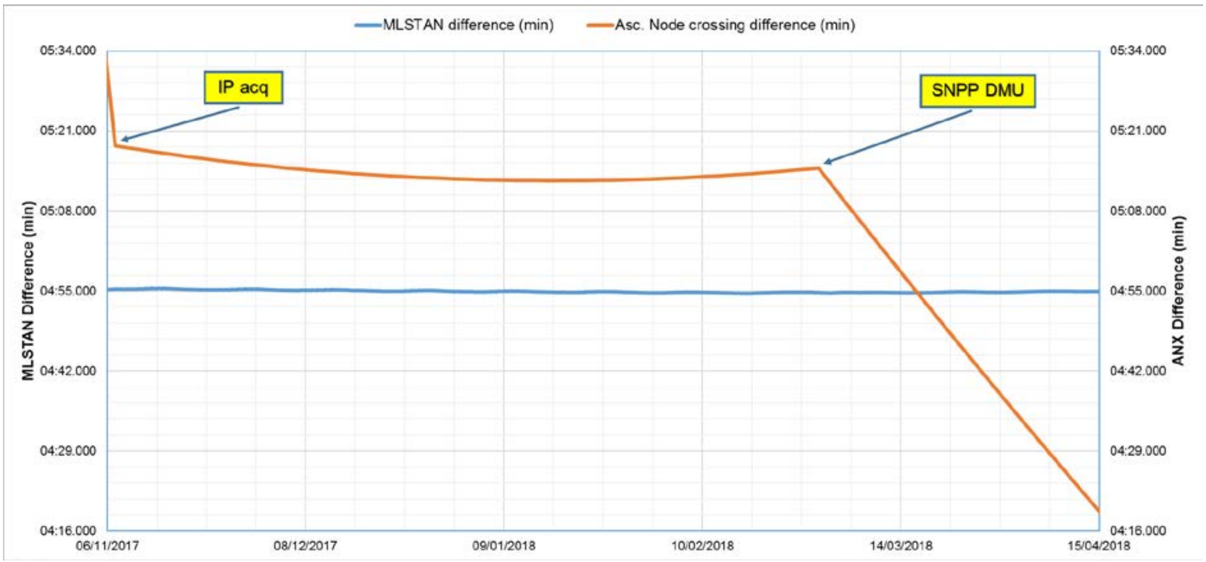


*Fig. 8: The along-track (orange line) and MSLTAN (light blue line) separation with SNPP during phase E1 until April 15.*

## Orbit Control in Phase E2

The S5P reference orbit for the routine phase (E2) was defined relative to the SNPP reference orbit as 3.5 minutes behind along-track, and a 4:55 minute difference in MSLTAN. After switching to the new reference orbit on April 11, S5P kept drifting towards the eastern boundary of the 20 km control band (and towards SNPP). To avoid exiting the control band, reverting the drift, an in-plane manoeuvre needed to be executed around mid-June (see Fig. 9). This IP manoeuvre actually consisted of 2 burns, the first one with thruster pair X-/X+ only and the second with thruster pair Y-/Y+ only. It was decided to split this manoeuvre in two to potentially identify the origin of the off-pointing in $\Delta v$, whether it be a misperformance issue, a misalignment issue or a bit of both.

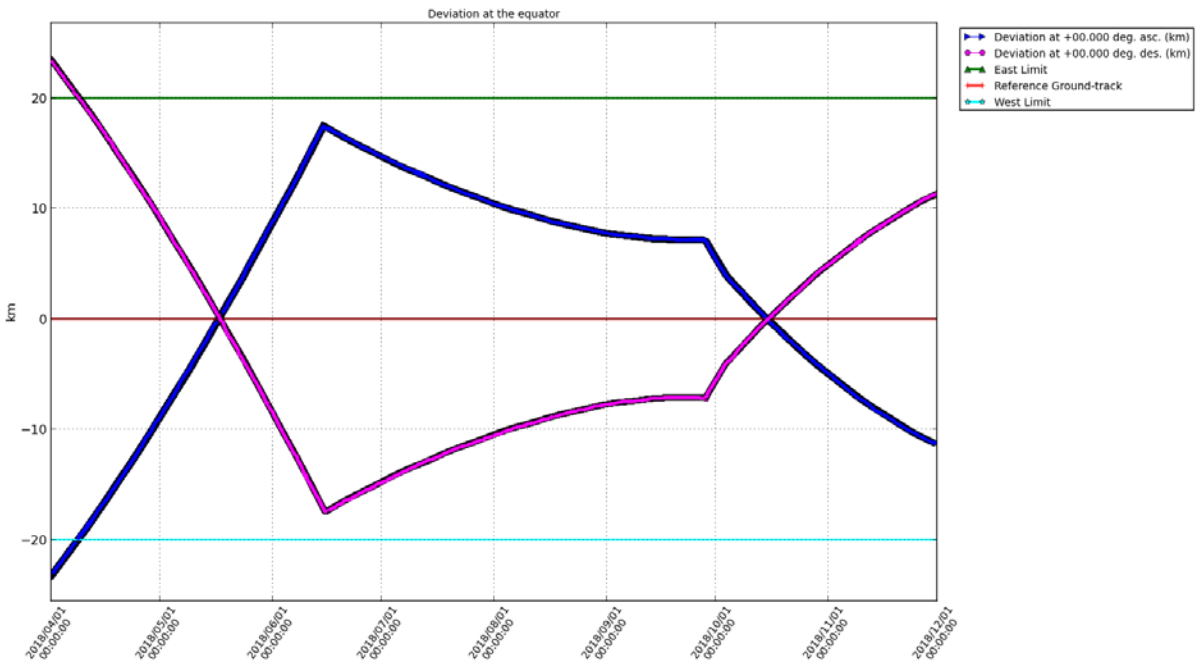


*Fig. 9: S5P ground-track deviation at ascending and descending node crossing with respect to the phase E2 reference*

In the first burn, a total of 376 pulses were commanded and executed on thrusters X-/X+, distributed equally over the two thrusters. The measured de-pointing during the thrust segment was about 0.02 degrees. In the second burn, a total of 372 pulses were commanded and executed on thrusters Y-/Y+, but thruster Y+ executed less pulses than Y- (176 vs 196). The measured de-pointing during the thrust segment was about 0.2 degrees - an order of magnitude larger than found for the first manoeuvre with the X-/X+ thrusters.

The overall performance of the manoeuvres were of the same order of magnitude as previous manoeuvres (+0.5% and -0.6% respectively, see Table 3), which seems to point to thruster misalignment rather than thruster misperformance. By analysing all manoeuvres in more detail, comparing the Δv directions with the expected thrust vector, larger misalignments in SC X-axis and SC Y-axis were found (0.1 degrees and 0.85 degrees respectively). Industry confirmed the computed thruster alignments were also compatible with the torques reconstructed from the off-modulation and reaction wheel measurements.

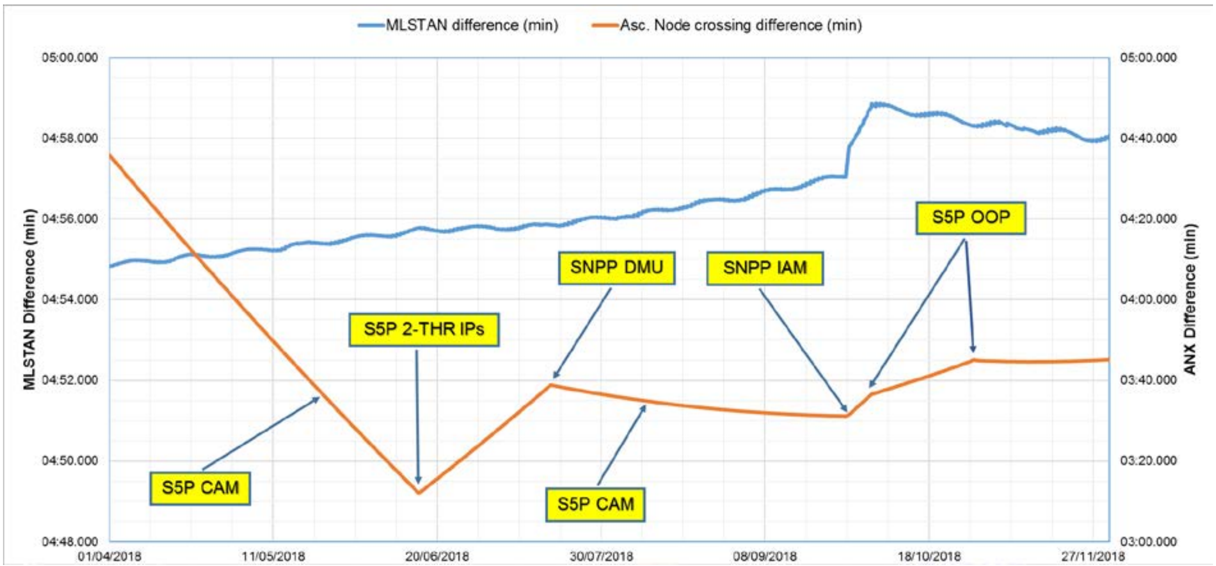


*Fig. 10: The along-track and MSLTAN separation with SNPP during phase E2 until December 1, 2018. Indicated are the points where manoeuvers were executed for orbit maintenance (both IP and OOP) and for collision avoidance.*

The evolution of the along-track separation and MSLTAN difference with SNPP during this phase is presented in Fig. 10. Apart from the IP manoeuvres, the graph also shows the Collision Avoidance Manoeuvres (CAM) that were executed during this time to avoid two high collision risk events, and the OOP manoeuvres that were executed to synchronise the local time evolution of S5P with that of SNPP after its yearly IAM at the end of September. A DMU was executed on SNPP mid-July, which reverted the drift in along-track separation again after the execution of the IP manoeuvres on S5P. The IP manoeuvres executed mid-June were not used to maximise the orbit maintenance control cycle, but reduced in size to compensate the effect of the OOP manoeuvre on the ground-track deviation at the node crossing planned for the end of September.

The yearly IAM was executed by SNPP on September 27, which needed to be followed by the OOP manoeuvres for S5P to re-synchronise the inclination and the MSLTAN evolution. Right after an IAM, the local time difference starts drifting away fast, so 2 OOP manoeuvres of around 2 m/s each, were planned and executed already the next day after nominal execution of the IAM was confirmed, followed by the final OOP manoeuvre on 3 October of around 1 m/s.

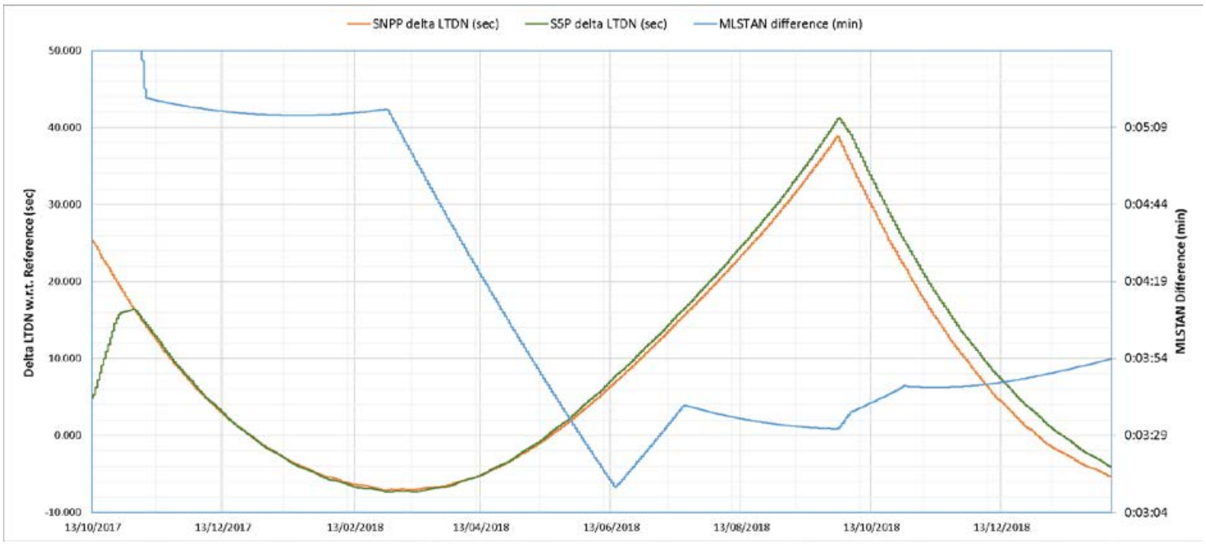


*Fig. 11: The delta LTDN w.r.t. reference for S5P (green line) and SNPP (orange line) and the MSLTAN separation of S5P with SNPP (blue line) during phase E2 up to 1 December 2018*

The procedure to determine the target local time for S5P at the time of the next IAM, described in the mission preparation section, was first used during the orbit acquisition phase when preparing the first OOP manoeuvre. Following the procedure, a target local time difference of 42.0 seconds was found. Since orbit acquisition, the local time of the missions stayed in-sync until around May when they slowly started drifting apart (see Fig. 11). The difference in local time at the time of the IAM on September 27, 2018, turned out to be 4:57 minutes, where SNPP showed a difference of 39.0 seconds w.r.t. the SNPP reference and S5P a difference of 41.0 seconds w.r.t. the S5P reference. The delta in target and actually achieved local time difference of 1 seconds can be explained by the over performance of that first OOP manoeuvre on S5P (see Table 2). These results, a delta of 3 seconds between expected and actual SNPP local time difference, indicate the procedure doesn't provide a perfect local time difference target but a couple of seconds uncertainty are to be expected.

The same procedure was followed again when preparing the OOP manoeuvre for the end of September 2018. With the nominal IAM, a local time difference of SNPP with its reference at the time of the next IAM (September 21, 2019) of 29.0 seconds was found, and after its execution, again with the calibrated manoeuvre (IAM showed a 0.7 % under performance), a value of 32.8 seconds was found. After the first two OOP manoeuvres were evaluated, the final OOP manoeuvre was optimised to achieve a difference in local time w.r.t. the S5P reference at the time of the next IAM of not 32.8 seconds but 31.0 seconds to recover the quick increase in local time difference whenever an IAM is executed, inherent to having to execute the OOP manoeuvre a couple of days later. With the IAM in September 2018 the local times drifted apart 1.8 seconds before the 3$^{rd}$ OOP was executed on S5P.

The $\Delta$v off-pointing found for the first two OOP manoeuvres was taken into account when the final OOP manoeuvre was prepared. An additional 7 mm/s against the flight direction needed to be added to maintain the ground-track requirements. This was achieved by reducing the yaw during the burn by 1.249 degrees, so instead of a 90 degree yaw a 88.749 degree yaw was commanded. A 21 mm/s in-plane $\Delta$v component of the OOP manoeuvre (against the flight direction) was expected. Achieved was an in-plane component of 18 mm/s against the flight direction, which postponed the need for the next IP manoeuvre to mid-July 2019. The performance results of the 2-thruster burns in mid-June and the OOP manoeuvres performed at the end of September / beginning of October are summarised in Table 3.

*Table 3: Performance of the first OOP orbit maintenance manoeuvres for S5P*

| Burn mid time | Type | Duration (s) | | Off modulation | | Δv (m/s) | | | Pointing error (°) |
|---|---|---|---|---|---|---|---|---|---|
| | | Pred. | Actual | Pred. | Actual | Pred. | Actual | Perform. | |
| 2018-06-15 10:19:57 | IP X | 11.740 | 11.750 | 2.1 % | 0 % | 0.260 | 0.261 | +0.5 % | 1.2 |
| 2018-06-15 15:24:26 | IP Y | 11.629 | 12.250 | 12.4 % | 5.1 % | 0.260 | 0.259 | -0.5 % | 1.7 |
| 2018-09-28 09:47:50 | OOP | 475.766 | 478.188 | 7.2 % | 7.7 % | 2.080 | 2.086 | +0.3 % | 0.5 |
| 2018-09-28 11:29:20 | OOP | 476.501 | 478.875 | 7.2 % | 7.7 % | 2.040 | 2.064 | +1.2 % | 0.5 |
| 2018-10-03 23:28:16 | OOP | 231.317 | 232.688 | 7.2 % | 7.8 % | 0.974 | 0.971 | -0.3 % | 0.5 |

At the time of writing, the predicted difference in local time w.r.t. their references at the time of the next IAM (September 21, 2019) is 29.7 seconds for S5P and 28.8 seconds for SNPP, indicating the requirement on the local time difference between missions is very likely to be met, at least until the next SNPP IAM.

## Conclusions

The Sentinel-5P (S5P) satellite, monitoring our atmosphere in terms of air quality and climate, was launched on October 13, 2017 at 09:27:30.0 UTC from the Plesetsk Cosmodrome. To improve the S5P science return, the ESA S5P mission and the NOAA/NASA Suomi-NPP & JPSS mission had formulated an operational concept for the S5P mission to fly in 'loose formation' with the Suomi-NPP (SNPP) spacecraft. The concept of loose formation flying has been summarised in this paper. Following this concept the S5P and SNPP satellites need to be controlled around a Sun-synchronous frozen reference orbit with a 16 day, 227 orbit repeat cycle, where S5P is flying behind SNPP within a time window of 2-5 minutes and S5P needs to keep the MSLTAN difference constant at 5 minutes ± 10 seconds during routine operations.

In preparation of the S5P mission, the Flight Dynamics team at ESOC investigated whether the requirements on orbit maintenance resulting from this concept could be met and how this would be achievable operationally. The investigation has been summarized in this paper and the selected approach has been presented, describing a procedure how to best achieve the requirement on the MSLTAN difference between the two missions.

Initially a MSLTAN difference of 5 minutes and an along-track separation of 5 minutes between missions was targeted after LEOP. At the end of a smooth orbit acquisition phase, a MSLTAN difference of 4:55 minutes and an along-track separation of 5:27 minutes were achieved, with S5P slowly drifting toward a slightly shifted reference with the same MSLTAN difference of 4:55 minutes, but separated along-track by 3.5 minutes with the SNPP reference. Following the described procedure during the acquisition phase, the MSLTAN difference with SNPP was kept within 2 seconds of the adopted 4:55 minute constant MSLTAN difference. The procedure was applied a second time when the MSLTAN evolution needed to be synchronised with that of SNPP after its yearly Inclination Adjustment Manoeuvre (IAM) executed at the end of September 2018. Three months thereafter, the difference in MSLTAN is still within a couple seconds of the defined constant value and predictions up to the next IAM (end of September 2019) indicate this will still be the case. Having used the procedure twice, it seems the requirement on the MSLTAN difference can be met following the described procedure.

# References

1. Schoeberl, M.R., "The Afternoon Constellation: a Formation of Earth Observing Systems for the Atmosphere and Hydrosphere", IGARSS, 2002.