Orbit control and FD operations optimisation for the repositioning of a satellite in the frame of a loose formation flying

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***Abstract* – An increasing number of flying missions are designed to use multiple spacecrafts and depend therefore on the reliability of all the spacecrafts involved. As soon as one of the satellites is no longer able to fulfil its mission, the formation it belongs to would be impinged and the objectives of the mission itself might have to be redefined to remain relevant.**

In the example of Sentinel-5P, which is the first mission of the European Union's Copernicus Programme dedicated to the Earth's atmosphere monitoring, an important feature of the mission is the synergistic exploitation of simultaneous measurements of imager data from the VIIRS instrument, embarked on the Suomi-NPP satellite of NASA/NOAA. Both satellites are consequently flying in loose formation, where Sentinel-5P orbit trails behind Suomi-NPP by 3.5 minutes along-track with a difference in Local Time of Ascending Node (LTAN) of 04:55 +/- 10s, allowing the Sentinel-5P observation swath to remain within the scene observed by Suomi-NPP. Both spacecrafts are following a near-polar, sun-synchronous orbit with an orbital cycle of 16 days and an ascending node equatorial crossing around 13:30 h. This repeat cycle depends upon the altitude of the orbit and is an essential criterion for the mission's definition.

Since S-NPP, launched in September 2011, is operating well beyond its nominal 5-year mission lifetime, a theoretical analysis has been performed as a risk mitigation on data unavailability. Alternative solutions have been studied to ensure the continuity of S5p mission data products. The prime motivation to redefine the mission definition is to provide a follow-on to the currently flying S-NPP mission and thereby ensure the necessary continuity of data and services to both the scientific research and operational application user communities. However, these expectations should be weighed against the technical feasibility and the resources involved by the different solutions.

The first and main constraint to be fulfilled is indeed to keep the scientific interest of the mission. This implies involving the scientific community into the definition of the new design of the mission. In the case of the example presented in the paper, LTAN difference and time separation are driving the tandem configuration, as they are the direct consequence of the scientific and safety requirements of the mission. However, the feedback from the years already flown in tandem and the on-going improvements on the post-processing of the data might make these initial requirements evolve.

Another crucial element of the redefinition of the mission is the optimization of the available and limiting resources. In particular, excessively fuel consuming manoeuvres should be avoided at the risk of reducing the remaining lifetime of the spacecraft too much.

On top of these technical considerations, one should not forget to consider the impact on the operations themselves. Among those, Flight Dynamics resources need to be part of the compromise since for obvious organizational and economic reasons, the new operational constraints must adapt to the workload of the team already in place. The paper will hence provide an overview of the different strategies considered, evaluating the advantages and disadvantages of each of them, to ultimately offer the best compromise.

ABBREVIATIONS AND ACRONYMS

ANX	Ascending Node Crossing
ESOC	European Space Operations Centre
da	Delta in semi-major axis
dv	Delta in velocity
FD	Flight Dynamics
IAM	Inclination Adjustment Manoeuvre
IP	In-Plane manoeuvre (IPP: IP Prograde, IPR: IP Retrograde)
JPSS	Joint Polar Satellite System
LTAN	Local Time of Ascending Node
LTDN	Local Time of Descending Node
MLSTAN	Mean Local Solar Time of Ascending Node
NAPEOS	Navigation Package for Earth Orbiting Satellites

NOAA	National Oceanic and Atmospheric Administration
NOAA-21	National Oceanic and Atmospheric Administration 21, designated JPSS-2 prior to launch
OCM	Orbit Control Manoeuvre
OOP	Out-Of-Plane manoeuvre
PSO	Position Sur Orbite
RAAN	Right Ascension of Ascending Node
S-5P	Sentinel-5P
S-NPP	Suomi National Polar-orbiting Partnership
SMA	Semi-Major Axis
TROPOMI	TROPOspheric Monitoring Instrument
VIIRS	Visible Infrared Imaging Radiometer Suite
YOL	Years Of Lifetime

I. INTRODUCTION

An increasing number of space missions are now reliant on multiple spacecrafts, emphasizing the importance of ensuring the reliability and continuity of all satellites involved. When one satellite fails, it can disrupt the entire mission, necessitating a re-evaluation of the mission's objectives. This paper serves the purpose of documenting the results of the trade-off studies carried out to investigate different options for a possible re-positioning of the Copernicus Sentinel-5 Precursor (S5P) satellite within a loose formation with NOAA-21, replacing its current formation with NASA's Suomi-NPP, which was launched in October 2011 and has a current end of life (*EOL*) of October 2026. The aim is to maintain the mission's scientific objectives while optimizing flight dynamics operations. Various strategies are evaluated, considering technical feasibility, resource optimization, and operational constraints.

II. MISSION BACKGROUND

The Copernicus Sentinel-5 Precursor mission is the first Copernicus mission dedicated to monitoring our atmosphere. The main objective of the Sentinel-5P mission is to perform atmospheric measurements with high spatio-temporal resolution, to be used for air quality, ozone & UV radiation, and climate monitoring & forecasting. The satellite was successfully launched on 13th October 2017.

The satellite's local time of ascending node (LTAN) crossing of 13:30 h has been chosen to facilitate the so-called loose formation operation with NASA's Suomi-NPP spacecraft and make the most from the science data, 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. This 'loose formation' concept allows consequently the utilization of co-located, high resolution cloud mask data provided by the VIIRS instrument on-board Suomi-NPP during routine processing of the TROPOMI methane product on-board Sentinel-5P.

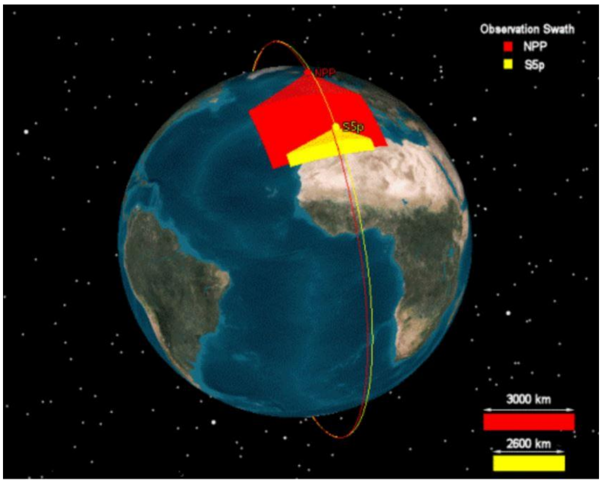

Fig. 1 Illustration of the swath overlap of the Sentinel-5P TROPOMI and the VIIRS instrument on Suomi-NPP

The loose formation 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 of 120 sec was agreed to guarantee, in case of a contingency on S-5P, it shall not enter the control box of S-NPP for at least 60 days.

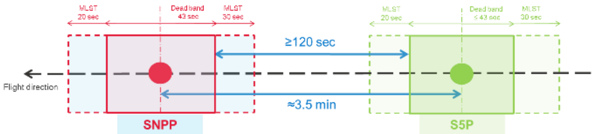

Fig. 2 'Loose formation' flying concept for S-5P and S-NPP and the adopted separations for the routine phase of the missions as described in [2]

In the frame of this loose formation, it is also required to keep the distance between the 2 satellites as constant as possible. This is why Sentinel-5P and S-NPP yearly IAM manoeuvres have to be coordinated, to keep the MSLTAN difference nearly constant. Ground track control manoeuvres of both satellites are however independent. This flying concept and its implementation are described in [2].

However, NOAA's Suomi-NPP satellite is now being operated beyond its initial nominal mission lifetime. On 10th November 2022, a new NOAA satellite called NOAA-21 (designated JPSS-2 prior to launch) was launched into the same orbit. Therefore, different options of re-positioning Sentinel-5p were taken in consideration to bring it from its current orbital position flying in a loose formation flight with S-NPP to another one where it could fly in loose formation with NOAA-21 and serves similar scientific objectives.

III. MISSION CONSTRAINTS AND REQUIREMENTS

The possible repositioning of Sentinel-5P is driven by both scientific and technical requirements. Scientifically, the mission aims to provide high-resolution measurements of various atmospheric components (including ozone, NO_2, SO_2, CH_4, CO, formaldehyde, aerosols, clouds...). These measurements require optimal spatial, temporal, and spectral resolutions to meet the needs of the scientific community for accurate monitoring and forecasting of atmospheric composition. This also necessitates an optimal satellite configuration to maximize data collection efficiency and accuracy. Moreover, the involvement of the scientific community is crucial in designing the mission to ensure that the repositioning process aligns with scientific objectives.

Additionally, the decision to transition from the current loose formation with SNPP to a similar formation with NOAA-21 necessitates careful consideration of technical feasibility and operational implications. Technical considerations such as efficient resource utilization are paramount, particularly for Flight Dynamics (FD). Optimizing fuel consumption and operational constraints, while adhering to strict manoeuvre campaign constraints, ensures minimal disruption to ongoing operations and timely data acquisition. Ultimately, involving the scientific community in mission design and optimizing resource utilization are essential to the success of the repositioning process and the continued delivery of high-quality atmospheric data.

While the decision to mimic S-NPP's yearly inclination manoeuvres until further notice prioritizes mission stability, alternative options for methane product processing, including transitioning to a loose formation with NOAA-21 but also another approach to minimize the dependencies with respect to other spacecrafts, highlight the ongoing evaluation of mission strategies to optimize scientific output and operational efficiency. Ultimately, a balance between scientific objectives and technical feasibility is essential to ensure the continued success of the Sentinel-5P mission.

IV. STRATEGIES FOR REPOSITIONING

Sentinel-5P, S-NPP and NOAA-21 are all flying (near poles) sun-synchronized orbits. The orbital precession is influenced by the perturbations caused by the Earth's oblateness, resulting in the rotation of the orbit plane in the direction of the Earth's revolution. The orbital precession, denoted as Ω, can be associated with parameters such as the orbital semi-major axis a, the eccentricity e, and inclination i as in (1)

$$\frac{d\Omega}{dt} = -\frac{3n.R_e^2 .J_2}{2a^2(1-e^2)^2}\cos(i) \quad (1)$$

with n the orbital angular speed, J_2 is the geopotential coefficient of second order, R_e the average radius of the Earth. For the numerical values of these variables, see [3].

A. *Current situation of Sentinel-5P wrt S-NPP*

Sentinel-5P is currently flying in formation with S-NPP with the reference orbit described in Table 1 and the ground-track is maintained within +/-20km of its reference ground track. The LTAN difference is controlled around 04:55 +/- 10s, while the along-track separation is controlled around 210s +/- 90s.

Table 1 S-NPP & S-5P Reference Orbit

S-NPP & S-5P Reference Orbit	
Repeat cycle	16 days, 227 orbits
Semi-major axis	7202176 meters
Eccentricity	0.001148
Inclination	98.73 deg
Arg. of perigee	90.00 deg
Asc. Node Crossing	13:25 (SNPP) 13:30 (S5P)

B. *Foreseen situation of Sentinel-5P wrt NOAA-21*

In the current JPSS constellation, S-NPP and NOAA-21 are located 90 deg apart as illustrated in Fig. 3

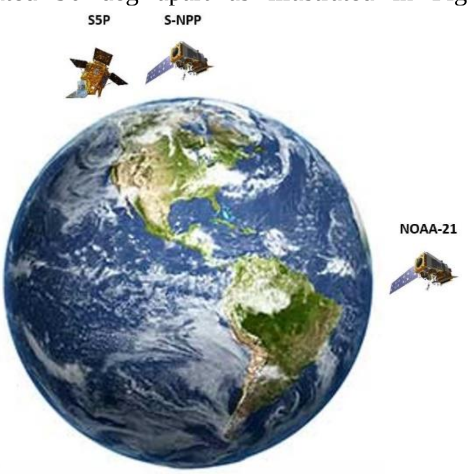

Fig. 3 Current position of Sentinel-5P with respect to the JPSS constellation (credit ESA / NASA)

The plan being to mimic the loose formation of S-5P/S-

NPP to fly the future S-5P/NOAA-21 loose formation, the same assumptions apply for the phasing between Sentinel-5P and NOAA-21 and the reference orbits as illustrated in Table 2.

Table 2 NOAA-21 & S-5P Reference Orbit

NOAA-21 & S-5P Reference Orbit	
Repeat cycle	16 days, 227 orbits
Semi-major axis	7202176 meters
Eccentricity	0.001148
Inclination	98.73 deg
Arg. of perigee	90.00 deg
Asc. Node Crossing	13:25 (NOAA-21) 13:30 (S5P)

Having Sentinel-5P fly in loose formation with NOAA-21 instead of S-NPP would hence imply to move Sentinel-5P by 90 deg while targeting a similar LTAN (Local Time of Ascending Node) difference. This would therefore require a twofold repositioning campaign, to correct first the PSO (Position Sur Orbite) of the spacecraft, and then its LTAN to adapt to the LTAN of its new partner.

The PSO and LTAN corrections are indeed essential for moving a satellite on its orbit for several reasons. Firstly, the PSO correction adjusts the position of the satellite on its orbit, ensuring the desired observation geometry and maintaining optimal conditions for data collection. This PSO repositioning requires in-plane manoeuvres and would be the first step of a repositioning campaign.
Secondly, a LTAN correction is required to synchronize the satellite's orbital plane with the desired local time, enabling consistent and systematic observations of the Earth's surface features as per mission requirements. This LTAN correction requires out-of-plane manoeuvres and would be optimised towards the end of a repositioning campaign to enable a fine correction.
Such adjustments are necessary to fulfil the specific mission requirements of updating the loose formation flying configuration with respect to another JPSS spacecraft, while maintaining the satellite's utility for Earth observation and scientific research purposes. Together, these PSO and LTAN corrections enable precise alignment with the target area of interest and enhance the satellite's operational effectiveness. They also play a crucial role in orchestrating the satellite's repositioning to maintain its observational capabilities and mission objectives effectively.

V. Detailed Repositioning Analysis

This section will now cover the details of the required in-plane re-positioning manoeuvre analysis, together with the details of the optimisation of the local time correction manoeuvre that would be required to move Sentinel-5P towards NOAA-21.

A. PSO re-positioning analysis

For this the in-plane re-positioning analysis, several key aspects are considered to optimize the performance and longevity of the mission.

Assumptions regarding the PSO repositioning

Assumptions were made regarding the spacecrafts' capabilities manoeuvrability constraints and environmental factors. These include fuel limitations, orbital stability requirements and payload operational constraints. Among these constraints, one should mention:
- The duration of the repositioning campaign should ideally not last more than 2 weeks to limit data loss.
- Manoeuvres are only possible 2 (fixed) days per week
- Manoeuvres must not exceed 2 m/s so as not to require more demanding operations for ground stations and thus avoid carrying out a search or booking extra passes to download GNSS data as soon as possible after the maneuver.

Studied strategies for the PSO repositioning

Various studies were then conducted to evaluate different re-positioning strategies and are summed up in Table 3. This includes analysing delta-v requirements for manoeuvring, optimal timing of manoeuvres, and determining the ideal number of manoeuvres to achieve the desired orbit adjustments while optimising the fuel consumption and the workload on the teams.
For some of the cases, different implementations were studied for the start and end of drift maneuvers, with the division of large burns into several small ones (<2m/s) and the possibility of implementing if necessary 2 burns in 1 day to reduce the global duration of the drift (this is illustrated in Table 4 where some dv are larger than the maximum 2m/s, whereas the use of '+' is meant to represent 2 burns on 2 different days).

Table 3 Sum-up of different strategies for the PSO correction

Strategy	**1**	**2**	**3**	**4**	**5**
dv (m/s)	2	4	8	12	16
duration (days)	44	22	11/13	10/14	6
number of MAN	2	2	4	5	6
Workload Impact	low	mid	high	high	high

The selection of the re-positioning timeline is also meticulously examined within the broader context of ongoing mission activities, available resources, and the resultant impact on the overall mission lifetime. Factors such as ground station coverage, data collection schedules, and satellite health assessments are taken into account.
The analysis culminates in a comprehensive summary of different re-positioning options and associated trade-offs. Strategies derived from the in-plane re-positioning analysis are compared based on their effectiveness in achieving desired orbit adjustments, minimizing fuel usage, and prolonging mission lifespan. Each option's pros and cons are evaluated, highlighting the trade-offs between operational efficiency and resource conservation. Trade-offs may ultimately involve balancing between maximizing data collection opportunities and minimizing fuel consumption.

Table 4 Sum-up of the valid strategies

Strategy	2.2	3.4	4.1	4.2
dv (m/s) DOWN	2.1	3.8	4+2	2+2+2
dv (m/s) UP	2.1	1.9+1.9	4+2	4+2
dv (m/s)	4.2	7.6	12	12
duration (days)	21	14	9	14
number of MAN	2	4	5	5

In the light of these considerations, two cases were excluded very quickly for different reasons: the projected duration of the strategy 1 exceeds acceptable limits, rendering it not feasible; strategy 5 demands two manoeuvres per day, but scheduled for the wrong weekdays, rendering it impractical. The other 3 cases however revealed different possibilities : initially encountering issues with manoeuvring on inappropriate weekdays, adjustments in burn reduction and timing of drift stop manoeuvres for the strategy 3 yield an acceptable solution; Stressing the importance of the constellation safety, strategy 4 advocates for a gradual approach to drift stop manoeuvres and advises against finishing the repositioning with a large burn, meeting successfully the primary requirements; despite lasting longer than the required two weeks, the strategy 2 only necessitates two manoeuvres (see Table 4), making it the easiest to execute among the options covered by this analysis.

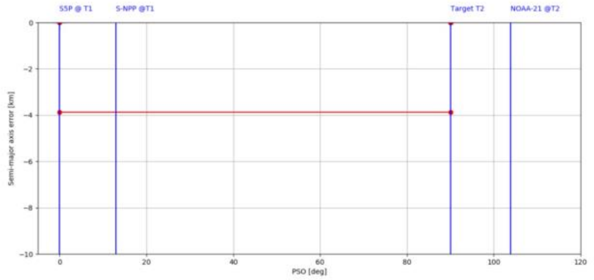

Fig. 4 Scheme of the timeline of the PSO repositioning of Sentinel-5P for the strategy 2.2

Conclusion wrt PSO repositioning

This comparative analysis informed decision-making regarding the optimal course of action for PSO re-positioning and made it possible to select strategy 2.2 for this first phase of the global repositioning.

B. LTAN correction analysis

The angular velocity of a perfectly Sun-synchronized orbit plane would orbit the Earth in alignment with the Earth's rotational axis and match exactly the Earth's revolution angular velocity. Thus, its Local Time of Ascending Node (LTAN) would remain fixed. However, various factors, including satellite orbit injection error, Earth's gravity, atmospheric drag, and solar perturbation, cause the LTAN to drift.
As detailed in [1], LTAN drift doesn't depend on the satellite characteristics, but on the orbit parameters. It will therefore be very similar for both satellites flying in loose formation. Furthermore, this LTAN drift can be predicted with a very small error for a long time period, using the classic result of the RAAN rate caused by the J_2 perturbation. Equation (1) yields the following result for the LTAN error as derived in [4]:

$$\delta LTAN\ (t) = \frac{3n.R_e^2.J_2}{4a^2} \sin\left(i_0\right) \frac{di}{dt} t^2 \qquad (2)$$

where i_0 is the average inclination.

Assuming the foreseen strategy for the in-plane repositioning, different options were then considered for the LTAN correction, starting from the situation described in Fig. 5 which illustrates the predicted LTAN evolution for the 3 missions considered in this study, after propagating the orbits using ESOC infrastructure (NAPEOS).

The forthcoming analysis aims to evaluate five distinct scenarios regarding orbital adjustments for the satellite, considering various factors such as delta-v requirements, timing of manoeuvres, and the number of manoeuvres involved.

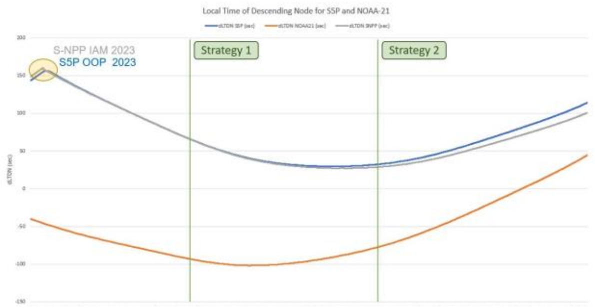

Fig. 5 Initial relative situation of the predicted LTAN evolution for the 3 missions after propagating the orbits using the high precision propagator of NAPEOS (based on the daily SNPP and NOAA-21 TLE).

Assumptions regarding the LTAN correction

The LTAN correction analysis for Sentinel-5P involves several critical considerations, among which:
- it is aimed to initiate the LTAN correction for Sentinel-5P as early as possible
- Sentinel-5P's manoeuvre planning must accommodate the operational continuity of S-NPP until at least the summer of 2024.
- yearly inclination corrections are scheduled around March 21, for S-NPP and September 21, for NOAA-21. These corrections necessitate corresponding Orbital Out-of-Plane (OOP) adjustments for Sentinel-5P to maintain synchronization.
- the analysis must reconcile conflicting requirements: minimizing the duration of the LTAN correction to limit data loss while also minimizing the required delta-v to preserve Sentinel-5P's operational lifespan. Achieving the dual objective involves careful planning to optimize the trade-off between minimizing data gaps and preserving fuel efficiency. Strategies for LTAN correction must hence prioritize efficiency, ensuring that the manoeuvre duration is minimized to limit the impact on data collection. Simultaneously, the analysis must strive to minimize the delta-v required for LTAN correction to prevent premature degradation of Sentinel-5P's operational lifespan.

Ultimately, the LTAN correction analysis aims to develop an optimized manoeuvre plan that addresses all requirements while ensuring the continued functionality and effectiveness of the Sentinel-5P mission.

Studied strategies for the LTAN correction

Considering the relative position of the LTAN of Sentinel-5P and NOAA-21, initiating the correction as early as possible would substantially increase the cost of the manoeuvre and therefore considerably impinge the lifetime of the mission. It follows that waiting and benefiting from the natural drift of Sentinel-5P LTAN towards NOAA-21 as long as possible would be the best approach. Nonetheless, given an average advantageous yearly drift of approx. 80 seconds, it would necessitate close to two years to attain the ultimate target, a timeframe deemed excessively distant to ensure the sustained operability of the Sentinel-5P mission. Moreover, a concluding touch-up manoeuvre remains inevitable to stop the drift of Sentinel-5P and align it with NOAA-21.

Different starting times were then simulated, whose results are shown in *Table 5.*

Table 5 Sum-up of different strategies for the LTAN correction

Strategy	**1 (*)**	**2 (*)**	**3**	**4**
Start time	09/23	03/24	03/24	03/24
dLTAN (s)	156	106	106	106
dv (m/s)	39.275	22.430	22.460	10.815
dv (YOL)	4.37	2.49	2.50	1.20
duration (days)	56	56	60	132
Data loss (days)	56	56	60	22
Number of MAN	17(+2)	9(+2)	9+2	4+2
Workload impact	high	mid	mid	low

For cases #1 and #2, the PSO correction has not been taken into account. 2 additional IP should then be added for the global repositioning, which might lead to an increased duration of the global repositioning.

As expected, the strategy 1 which would initiate the LTAN correction as soon as possible is the most expensive one from a fuel consumption point of view and has a significant impact on the data availability. It should therefore be disregarded as long as the mission can benefit from the data from S-NPP.

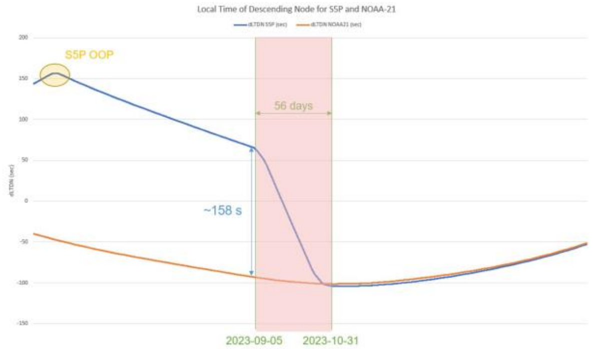

Fig. 6 Estimation of the 'cost' of an LTAN correction starting in Sept 2023, based on the propagation of the different orbits using the high precision propagator of NAPEOS.

From an operational point of view, the preferred option would be the strategy 4, prioritizing a 'low-cost' repositioning with minimal operational effort and is illustrated in *Fig. 7*. Alternatively, strategy 3 suggests moving Sentinel-5P more quickly, awaiting at least until the following spring to decrease delta-v costs and operational efforts.

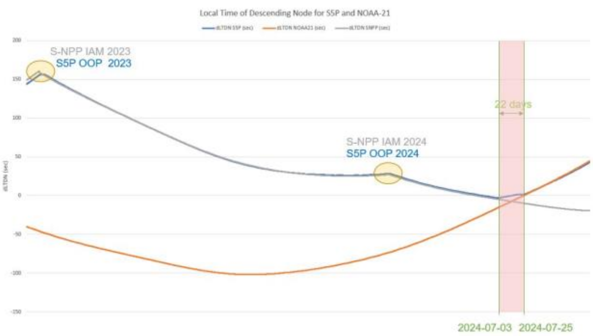

Fig. 7 Estimated LTAN evolution for the preferred option for the LTAN correction of Sentinel-5P wrt NOAA-21, based on the propagation of the different orbits using the high precision propagator of NAPEOS

Another option could though be considered. To further decrease fuel usage, one could indeed consider firstly, flying alongside S-NPP until Sentinel-5P's LTAN aligns with NOAA-21's post-inclination correction. Secondly, initiating the OOP correction right after S-NPP's yearly IAM while gradually drifting towards NOAA-21's LTAN. The rationale behind this strategy is to minimize downtime for Sentinel-5P's scientific data by adopting a hybrid position between S-NPP and NOAA-21's LTAN, while conserving fuel. The LTAN of the 3 spacecrafts would then evolve as plotted in *Fig. 8* which shows than the predicted LTAN difference between Sentinel-5P and the NOAA spacecrafts would be less than 10 s, hence fulfilling the scientific requirements of the mission.

Fig. 8 Estimated LTAN evolution for the hybrid solution for the LTAN correction of Sentinel-5P wrt NOAA-2121, based on the propagation of the different orbits using the high precision propagator of NAPEOS

Although the latter solution promises the lowest delta-v consumption, its feasibility heavily relies on NOAA's strategies for both satellites' yearly OOP corrections in 2024, posing challenges in refining the analysis for such future events.

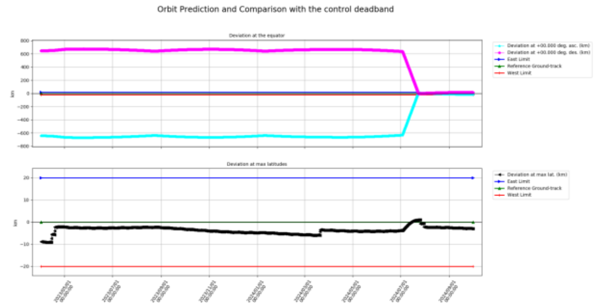

Fig. 9 Predicted ground track evolution, using the high precision propagator of NAPEOS, in the case of the preferred option for the LTAN correction.

VI. RESULTS AND RECOMMENDATIONS

In conclusion, the current operational constraints dictate that the LTAN correction cannot be accommodated within the two-week timeframe allocated for the PSO correction. However, our global strategy delineates distinct approaches for a 2-step repositioning campaign. Regarding the PSO repositioning, an agreed-upon three-week campaign employing a 2.1m/s DOWN/UP strategy has been established. This strategy aims to optimize the PSO's orbital parameters efficiently.
For the LTAN correction, the proposed strategy involves flying in tandem with S-NPP until Sentinel-5P's LTAN aligns with NOAA-21's LTAN. Although a potentially cost-effective hybrid solution has been initially considered, uncertainties surrounding this approach posed significant challenges and the perceived benefits might not outweigh the complexities and risks associated with its implementation.
Eventually, when the time of this repositioning comes, one should not overlook that the repositioning campaign must also be planned in the frame of other operational constraints (the FD team is also in charge of other flying missions that require maneuvering each week). Another element that should be taken into consideration when refining the final strategy is the natural drift in LTAN brought by the drift in PSO, which has been deliberately neglected in this study at this was not decisive at this stage.

VII. CONCLUSION

In conclusion, in the case it would be decided in the months to come to proceed with Sentinel-5P repositioning, a strategy has been proposed that aims to minimize delta-v costs, reduce data unavailability, and optimize additional operational workload for both PSO and LTAN correction. Pros and cons have been thoroughly elucidated to facilitate informed decision-making, ensuring a delicate balance between scientific objectives and technical feasibility for the ongoing success of the Sentinel-5P mission.

VIII. REFERENCES

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