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Sentinel-3 orbit control strategy

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Abstract

The Sentinel-3 satellites fly around the Earth on a Sun-synchronous orbit with a repeat cycle of 27 days and cycle length of 385 orbits with the requirements to maintain ground-track deviation at all latitudes within ±1 km of the reference ground track and the Mean Local Solar Time (MLST) deviation at the ascending nodes within ±90sec from 22:00. This paper describes the current strategy for the orbit control of the Sentinel-3 satellites at EUMETSAT including trade-off between minimization of number of out-of-plane (OOP) maneuvers and fuel consumption, how the number of in-plane (IP) maneuvers are minimized accounting for the observed orbit propagation uncertainties and addressing the controllability of the orbit eccentricity with the limitation that IP maneuvers are placed within eclipse.

Keywords: Sentinel-3, LEO, maneuver, station keeping, orbit control.

1. Introduction

The Sentinel-3 mission is part of the Copernicus programme of the European Commission and provides data continuity for the ERS and Envisat satellites. Its space segment consists currently of two identical satellites launched in 2016 and 2018 on a Rockot launcher from Plesetsk Cosmodrome.

The Sentinel-3 satellites fly around the Earth on a Sun-synchronous orbit with a repeat cycle of 27 days and cycle length of 385 orbits with the requirements to keep ground-track deviation at all latitudes within ±1 km of the reference ground track and the MLST deviation at the ascending nodes within ±90sec from 22:00. An OOP station keeping maneuver is performed every three or four months and an IP maneuver every two to ten weeks depending on the level of solar activity. For these station keeping maneuvers, Sentinel-3 satellites are equipped with two sets of four 1N monopropellant hydrazine thrusters.

The EUMETSAT orbit control strategy is driven by the following considerations:

- minimization of the number of maneuvers, especially OOP, as they have a higher impact on mission data availability, with the constraints that OOP maneuvers, including their pre- and post-maneuver slew, shall be performed within eclipse due to certain platform constraints while aiming at the same time to optimize fuel consumption;
- maintenance of the orbital eccentricity as close as possible to the reference frozen eccentricity, respecting at the same time the recommendation to implement IP maneuvers as well within eclipse, to reduce their impact on mission (no visible channels acquisition);
- maintenance of MLST is automatically controlled in the short term due to the tight ground-track control however strategies leading to long MLST drifts are to be avoided or monitored.

2. OOP maneuvers

The OOP maneuvers are needed to correct the inclination drift caused mainly by Sun and Moon attraction force. The minimum number of OOP maneuvers per year is slightly below three as the maximum orbit inclination change that can be implemented by a single maneuver is limited to around 2.3m/s due to the requirement that the satellite ground-track shall be maintained within a corridor of +/-1km. In practice, this limit is reduced when accounting for the operational constraints of implementing maneuvers during week days, typically in the middle of the week, and the short-term variations of the ground-track deviation evolution caused by the Moon attraction force.

Figure 1 shows the required thrust duration as a function of the velocity increment and the pressure in the tank during the satellite lifecycle, Figure 2 shows the available arc within eclipses along the year for thrusting accounting for the 90-degree platform rotation required before and after the maneuver as well as accounting for the margins defined by the satellite manufacturer and Figure 3 shows the evolution of equivalent maximum achievable impulsive velocity increment at the ascending nodes fulfilling the eclipse constraint.

Fig. 1: Thrust duration as a function of the velocity increment and the pressure in the tank

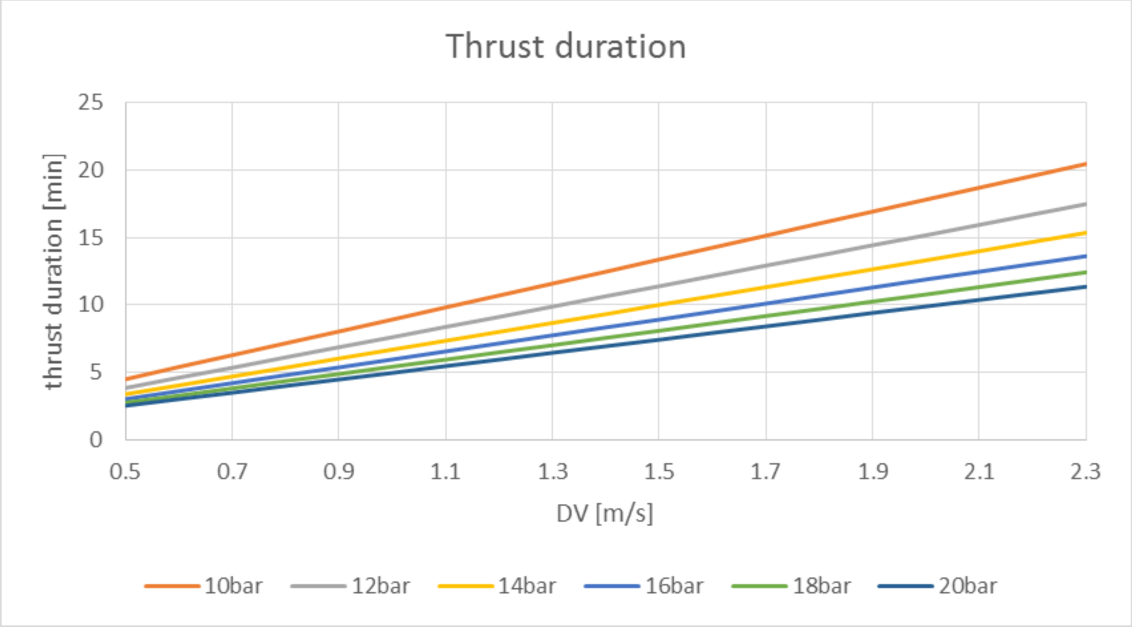


Fig. 2: Available time within eclipse for thrusting along the year

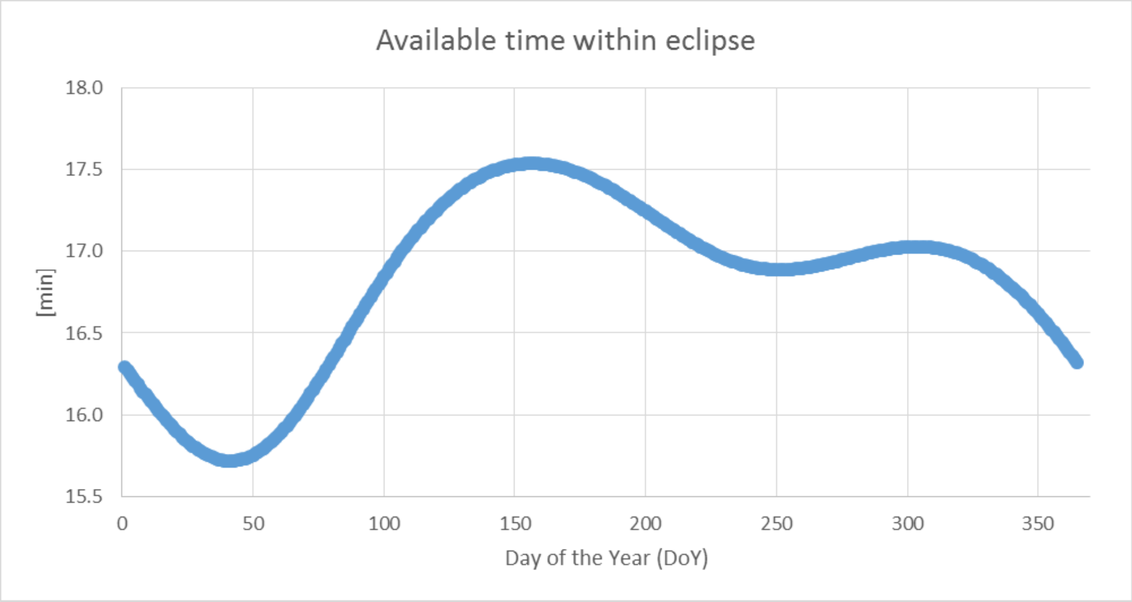
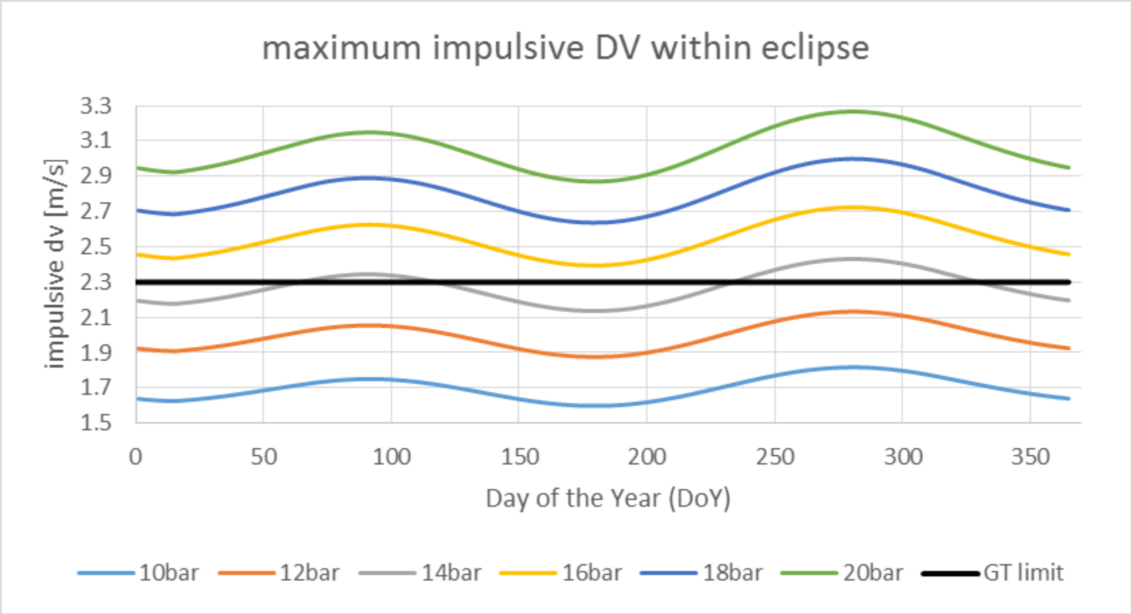


Fig. 3: Equivalent maximum achievable impulsive delta-V within eclipse

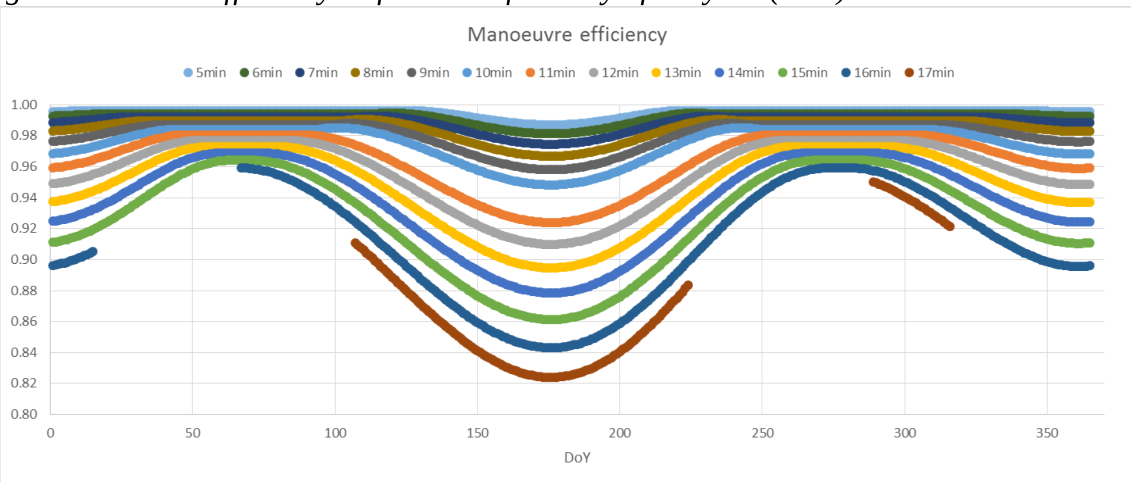


On top of the eclipse constraint, an additional constraint has been recently imposed by the satellite manufacturer to prevent the temperature of the fill-and-drain valve (FDV) from exiting safe conditions. From Figure 1, Figure 2, Figure 3 and this additional constraint, it is inferred that:

- during the first one or two years of operations, it is possible to have an average of around 2.6maneuvers per year although a fixed yearly pattern for the dates of the OOP maneuvers is deemed more beneficial for planning purposes and therefore 3 maneuvers per year were implemented for Sentinel-3A and is currently being implemented for Sentinel-3B;
- 3 OOP maneuvers-per-year strategy is possible until 2022 for both sentinel-3A and 3B satellites when tank pressure should be around 14bar;
- 4 OOP maneuvers-per-year strategy is possible until the end of the lifetime of 12.5years.

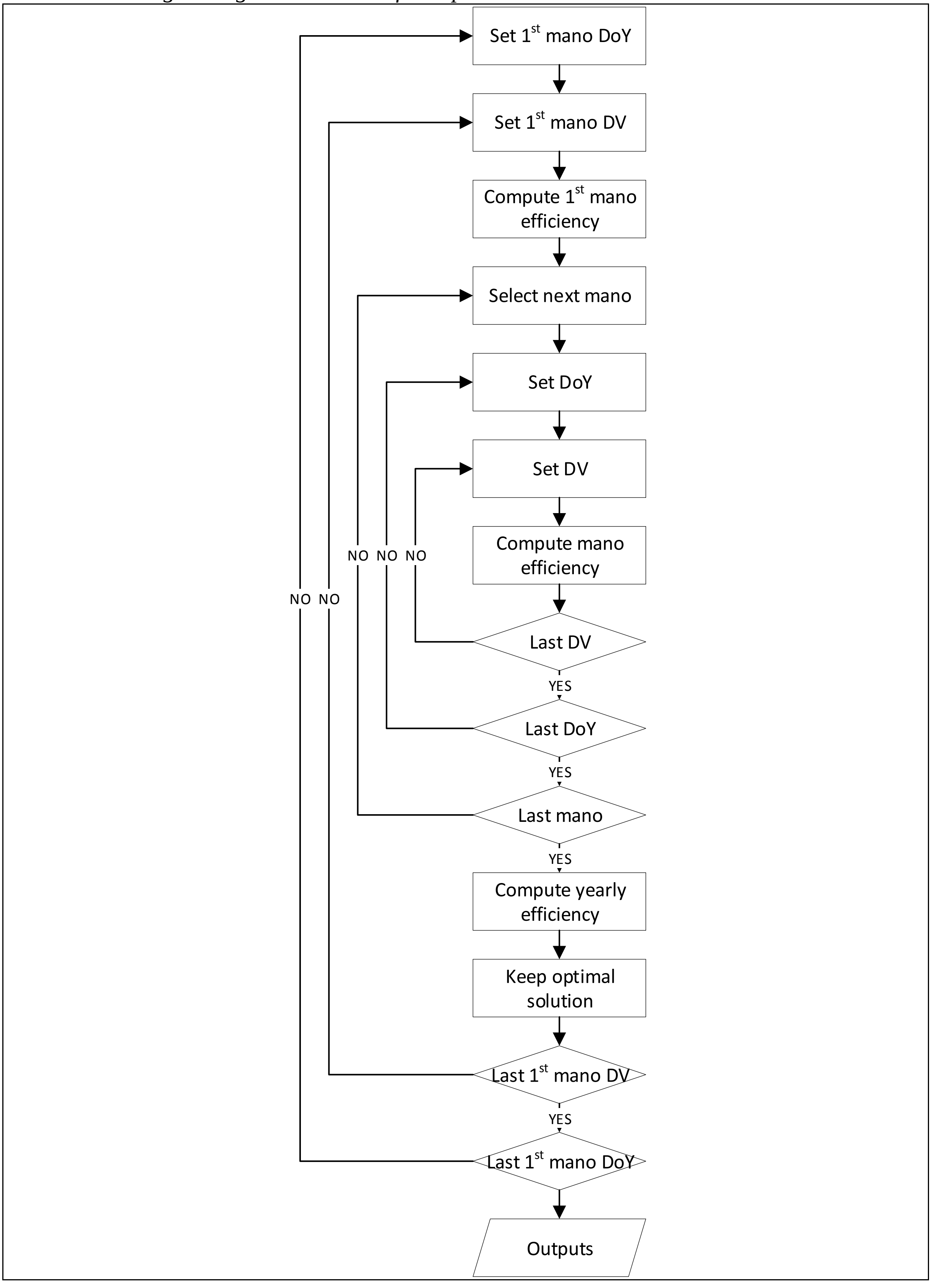
Figure 4 shows the maneuver efficiency for a single OOP maneuver accounting for spreading and off-node positioning required to meet the eclipse constraint as a function of the day of the year and the maneuver duration.

Fig. 4: Maneuver efficiency as function of the day of the year (DoY) and maneuver duration



With the information available in Figure 1, the constraint of 15minute duration per maneuver and the inclination rate evolution it is possible to estimate the best combination of maneuver days and sizes in the case of 3 and 4 maneuvers per year. Figure 5 depicts the algorithm used.

Fig. 5: Algorithm used to find optimal maneuver location and size



Here are some extra details on each of the steps shown in algorithm of Figure 5:

a) *Set 1st mano DoY*: day of year (DoY) for 1st maneuver within the year is defined within a loop. Holiday period around the beginning and the end of the year is skipped.
b) *Set 1st mano DV:* maneuver delta-V is defined within a loop accounting for the total number of maneuvers per year and the total delta-V required within a year.
c) *Compute 1st mano efficiency:* 1st maneuver efficiency is computed based on its size and its DoY that provides the information on the available arc within the eclipse.
d) *Select next mano:* next maneuver within the year is selected within a loop ranging from 2 until 3, in the case of 3 maneuvers per year, and until 4, in the case of 4 maneuvers per year.
e) *Set DoY:* maneuver DoY is selected within a loop ranging from a minimum separation of 1 month with respect to previous maneuver and maximum separation driven by the inclination rate evolution.
f) *Set DV:* maneuver delta-V is defined within a loop accounting for the total number of maneuvers per year and the total delta-V required within a year.
g) Compute maneuver efficiency: maneuver efficiency is computed based on its size and its DoY.
h) Compute yearly efficiency: as the product of the efficiency of all maneuvers.
i) Keep optimal solution: for each 1st manoeuvre DoY, keep the combination of maneuver sizes and DV which provides higher yearly efficiency.

Figure 6 and Figure 7 shows the most optimal location and sizes for 3 and 4 maneuvers per year as a function of the day of the year (DoY) of the first OOP maneuver within the year.

Fig. 6: Most efficient maneuver dates and sizes as function of the day of the year (DoY) of the 1st OOP maneuver with 3 OOP maneuvers per year

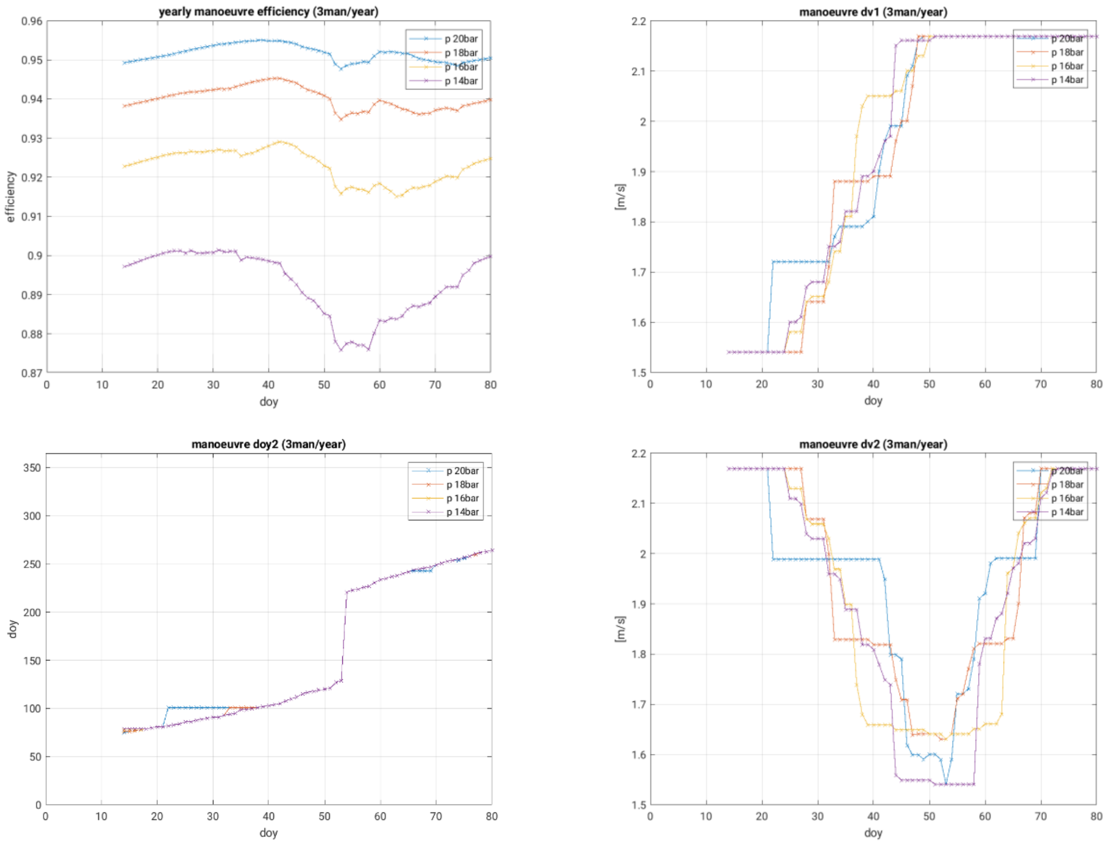


Fig. 6 (Cont.): Most efficient maneuver dates and sizes as function of the day of the year (DoY) of the 1st OOP maneuver with 3 OOP maneuvers per year

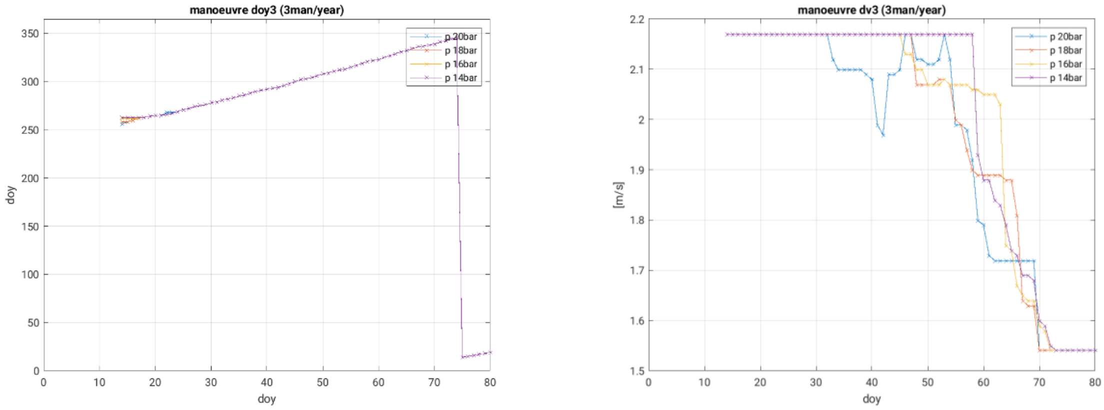


Fig. 7: Most efficient maneuver dates and sizes as function of the day of the year (DoY) of the 1st OOP maneuver with 4 OOP maneuvers per year

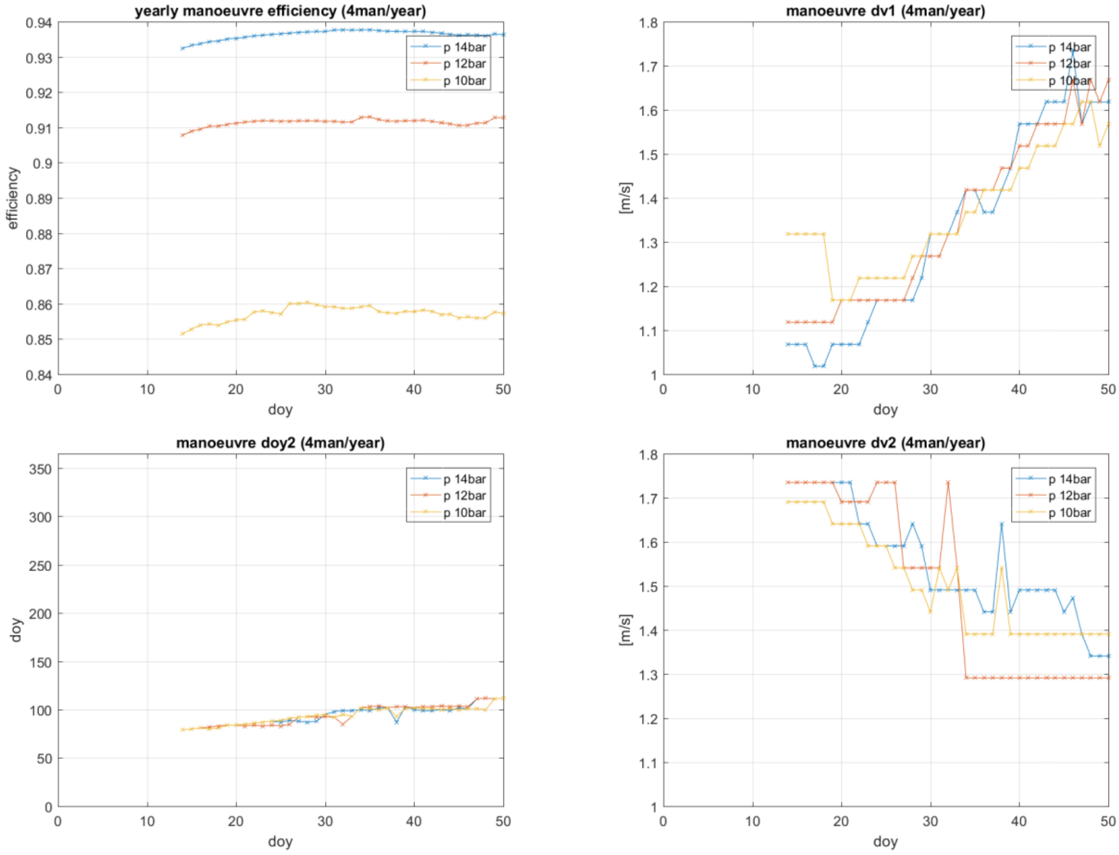
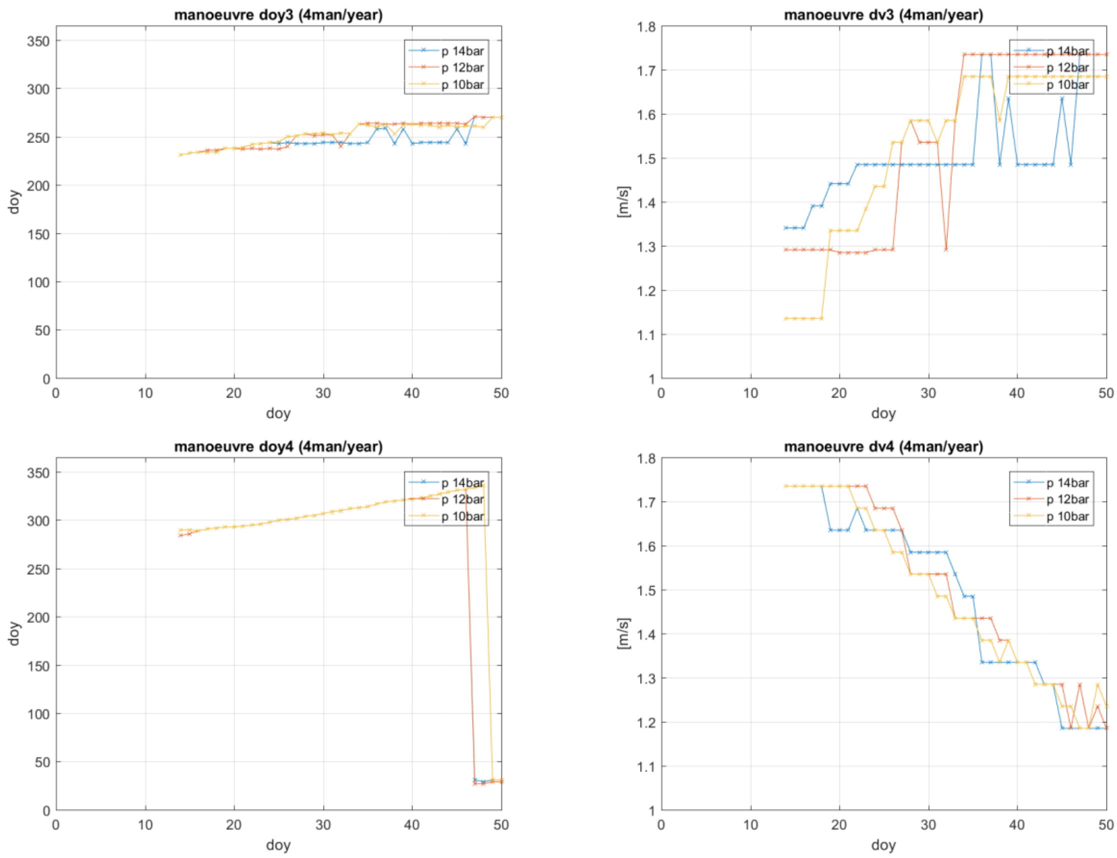


Fig. 7 (Cont.): Most efficient maneuver dates and sizes as function of the day of the year (DoY) of the 1st OOP maneuver with 4 OOP maneuvers per year



In order to have a more homogeneous operational workload along the year Sentinel-3A and Sentinel-3B OOP maneuvers have been decoupled. Sentinel-3A maneuvers are currently performed around DoY 75, 250 and 350 and Sentinel-3B maneuvers are performed around DoY 40, 100 and 290 (the most efficient).

3. IP Maneuvers

The IP maneuvers are needed to correct the semi-major axis decay caused by the atmospheric drag. A prograde IP maneuver of 2mm/s to 4cm/s is needed every two to ten weeks depending on the level of the solar and geomagnetic activity governing the atmospheric density. In the ideal case of having no orbit prediction error, each prograde IP would be sized to hit the westernmost limit of the ground-track corridor. Figure 8 shows this ideal scenario without orbit prediction error.

Fig. 8: Ideal in-plane station-keeping cycle for different levels of solar activity: number of days between IP maneuvers (left), semi-major axis decay between IP maneuvers (center) and delta-V (right) vs semi-major axis decay rate.

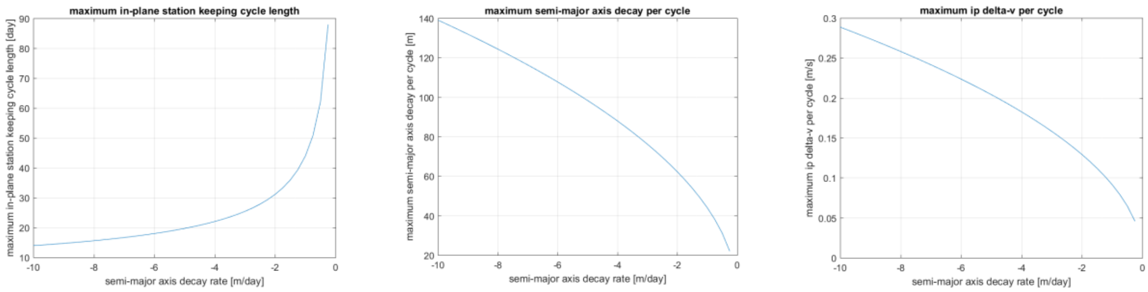
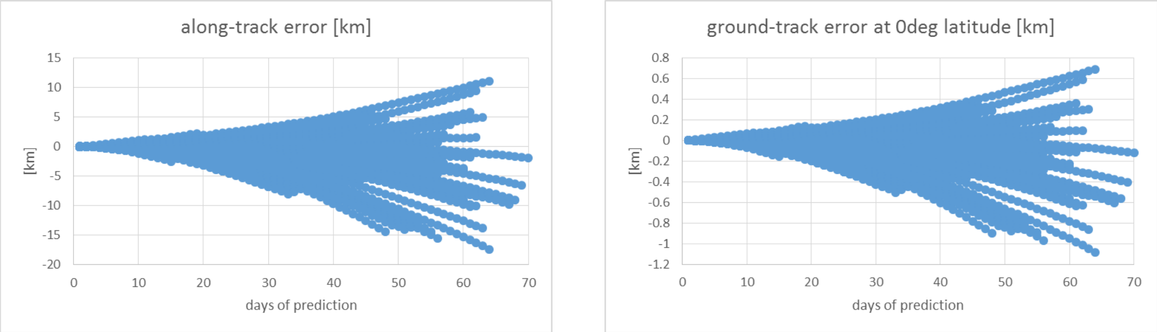


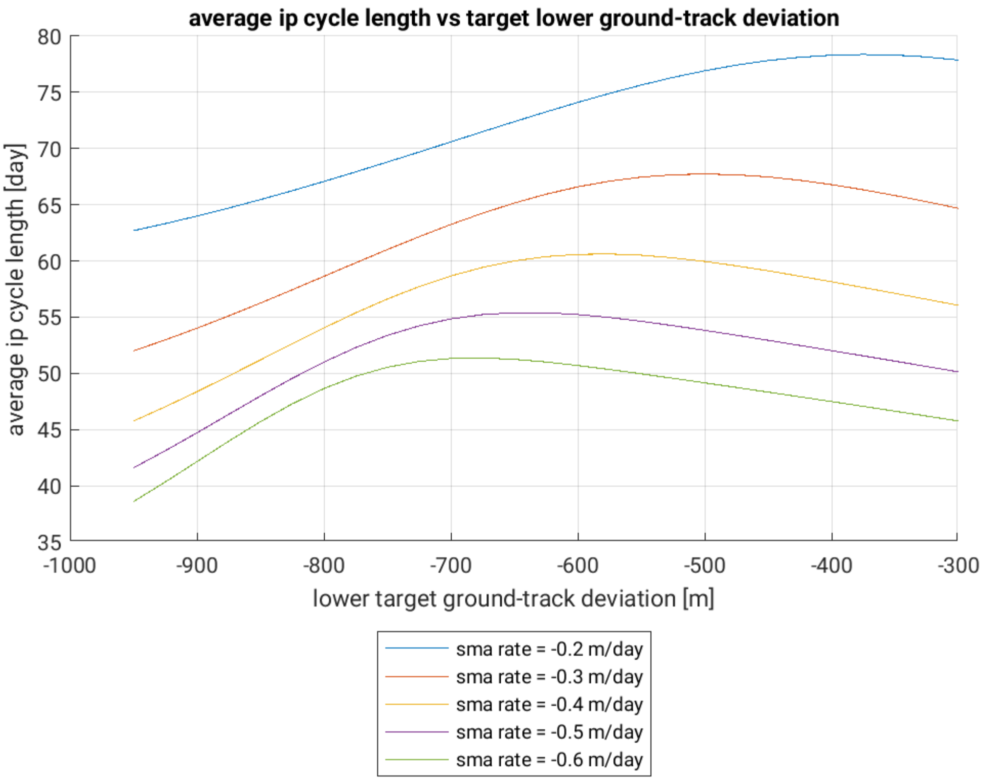
Figure 9 shows the orbit prediction error observed for the last two years of operations of the Sentinel-3A satellite.

Fig. 9: Sentinel-3A orbit prediction error



In order to minimize the number of IP maneuvers, the target westernmost point of the ground-track deviation is optimized accounting for this observed long-term propagation uncertainties modelled as a Gaussian distribution. Figure 10 show the optimal target for low solar and geomagnetic activity.

Fig. 10: Optimal target westernmost point



As it can be seen in Figure 10, the higher the atmospheric density, the higher semi-major axis decay rate, the shorter nominal IP station-keeping maneuver cycle and the smaller orbit propagation error (that grows with time) allowing a targeting of the of the westernmost point of the ground-track deviation closer to the limit of -1km.

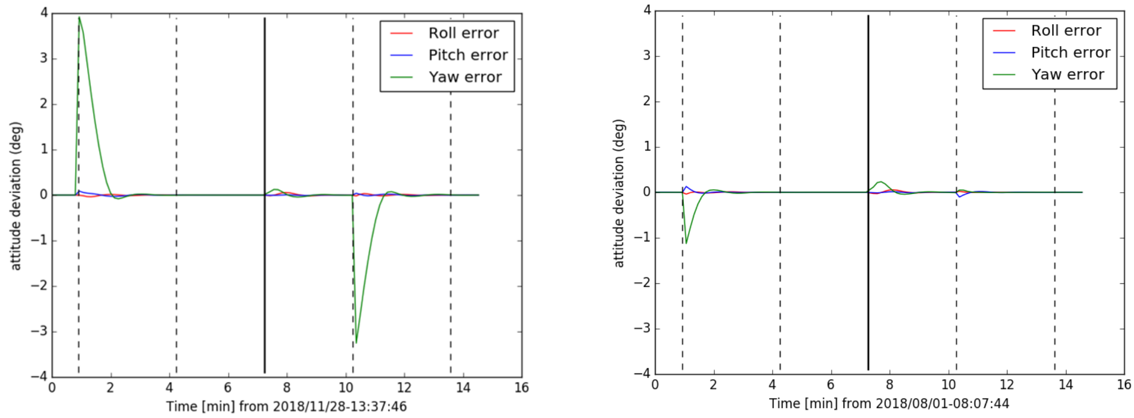
The presence of an OOP maneuver in the near future and before the end of the planned IP station-keeping cycle will modify this optimal target of the westernmost point of the ground-track corridor. In this case the objective is either to maximize chances to remain within the ground-track corridor or to target null ground-track deviation with respect to the nominal ground-track at the time the next OOP maneuver, if necessary to maximize OOP delta-V size.

A new IP station-keeping cycle is then initiated with the OOP maneuver thanks to the small yaw bias applied to the platform with respect to 90deg (pure OOP maneuver).

4. Orbital eccentricity

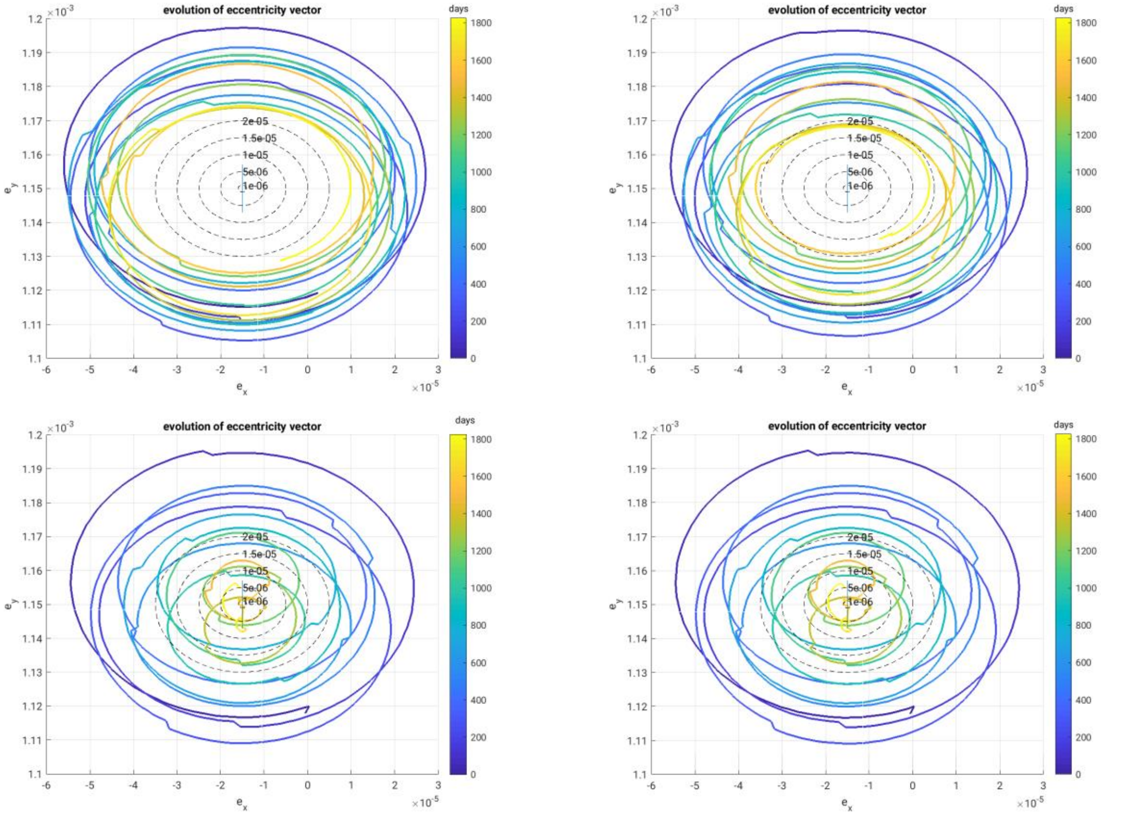
The IP maneuvers including their short, but required by the platform, pre- and post-maneuver slews are executed within eclipse in order to reduce their impact on the instrument visible channels data acquisition. This constraint reduces the controllability of the orbital eccentricity. The pre- and post-maneuver slews are needed to pause and resume the satellite yaw steering attitude law as the platform is designed to implement IP maneuver in geocentric pointing mode without yaw steering. This operation consumes time and reduces the available arc within the eclipse for the actual execution of the IP maneuver. The shorter the available arc within the eclipse the less control there is on the orbital eccentricity. It is, however, possible to mitigate this reduction on controllability of eccentricity notably by commanding a yaw bias that coincides with the rotation angle of the nominal platform yaw steering at the predicted start time of either the pre- or post-maneuver slew as this shortens the angular rotation and the time required for it. Figure 11 shows an indication of how much time can be gained by following this approach by reducing the rotation required after the maneuver.

Fig. 11: Attitude error (commanded vs actual angle) for two IP maneuvers with delta-V aligned with the along-track direction (on the left) and aligned with the nominal yaw steering law at the time of the post-maneuver slew (on the right). Vertical straight line represents the maneuver time and dashed vertical lines the pre- and post-maneuver slew start and theoretical end times including tranquilization times



The IP manoeuvers are then placed at the most optimal or less suboptimal point within the eclipse and are normally executed shortly before ground-track dead-band is violated at low latitudes, however, at times, they can be performed a few days or weeks in advance, in order to select a more favorable position of the eccentricity circle. Figure 12 shows three different simulations of the evolution of the eccentricity making use of 50% and 75% of the eclipse and allowing maneuver dates to be advanced up to a week.

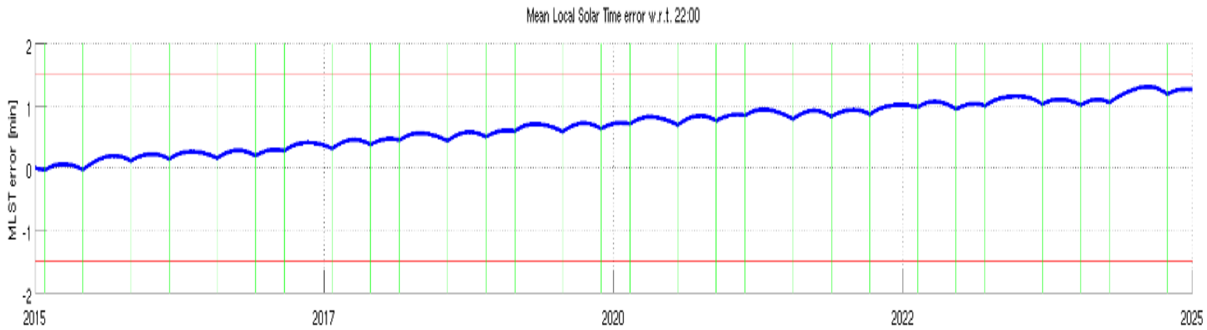
Fig. 12: Eccentricity evolution with IP maneuver placed within 50% of the eclipse arc (left) and 75% of the eclipse arc (right) and allowing in addition maneuver dates to be advanced up to a week (bottom plots)



5. MLST

The MLST control requirement of ±90sec will be fulfilled automatically for many years by respecting the ground track requirement of ±1 km with the OOP maneuver strategy described in section 2. Figure 13 shows a simulation of the MLST deviation evolution.

Fig. 13: MLST deviation evolution



If necessary, it will be possible to reduce this MLST drift by tweaking OOP maneuvers in size and date thus deviating slightly from the optimal strategy described in section 2.

References

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