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Optimising Tandem Orbit Control for Sentinel-2 Satellites: Strategies and Outcomes

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Abstract

The Copernicus Sentinel-2 mission, part of the European Space Agency's Copernicus Programme, funded by the EU and ESA, includes identical satellites that capture high-resolution optical imagery of Earth's land and coastal areas. Operating in a sun-synchronous orbit with a 10-day repeat cycle, they provide data in 13 spectral bands with spatial resolutions from 10 to 60 meters.

On September 5, 2024, the Sentinel-2C satellite joined Sentinel-2A and Sentinel-2B in orbit, ensuring the continuity of Earth imagery services. After launch, Sentinel-2C drifted towards its tandem position with Sentinel-2A. A series of manoeuvres were performed to position it correctly behind Sentinel-2A, starting the tandem phase. Flying satellites in a tight tandem configuration reduces uncertainties from atmospheric variability, enabling more accurate cross-calibration and improving data reliability. This method, successfully used in other missions, was recommended for Sentinel-2C during its commissioning to enhance data quality and consistency. To maximize the benefits of the tandem phase, ideally lasting 40 days (four 10-day repeat cycles), several mission requirements were established. The most stringent pertain to orbit maintenance, where the along-track separation must remain within 25 to 30 seconds, and the cross-track separation must fall within ±200m to ±700m at all latitudes.

This paper outlines strategies for controlling the orbits of two Sentinel-2 spacecraft in a tight tandem configuration. It emphasizes maintaining strict along-track and cross-track requirements and examines the effects of contingency manoeuvres, such as anomaly responses or debris avoidance. Additionally, it addresses manoeuvre performance errors, differences in spacecraft eccentricity, and the orbit maintenance of the older satellite within the tandem constellation.

Two tandem orbit control strategies were identified. The first, the Drifting strategy, involves flying the satellites at slightly different altitudes with weekly manoeuvres to maintain separation. The second, the Same Ground Track strategy, involves flying the satellites at the same altitude most of the time, performing orbit maintenance manoeuvres as needed, including touch-up manoeuvres to correct any relative drift. Both strategies were evaluated through extensive simulations covering a 60-day period, assuming average solar activity conditions around the time of the launch of Sentinel-2C. Results indicated that both strategies are viable.

The advantages and disadvantages of the two strategies were analysed, and ultimately, the "Same Ground Track" strategy was selected for the tandem phase operations. This strategy offers tighter control of cross-track differences, reduces the workload on operators, and does not necessitate adjustments of the orbit maintenance of the leading satellite.

On October 31, 2024, Sentinel-2C reached its tandem position, exactly 27.5 seconds behind Sentinel-2A, following the same ground track. Despite differences in manoeuvre performances, collision avoidance manoeuvres, and an inclination orbit maintenance manoeuvre on Sentinel-2A, the cross-track separation remained well below 100 meters at all latitudes for the complete tandem phase. The along-track separation stayed almost constant at 27.5 seconds, adhering to the selected strategy.

Keywords: Copernicus Sentinel-2, Tandem Satellite Constellation, Orbit Control Strategies, Data Reliability

Acronyms/Abbreviations

Across track (XT)
Ascending Node Crossing (ANX)
Copernicus FOS Operations Support Service Contract (COP-2)
Collision Avoidance Team (CAT)
European Space Agency (ESA)
European Space Operations Centre (ESOC)
Flight Dynamics (FD)
Ground-Track (GT)
Inclination (i)
In Orbit Commissioning (IOC)
In Orbit Commissioning Review (IOCR)
In-Plane (IP)
In-Plane Prograde (IPP)
In-Plane Retrograde (IPR)
Launch and Early Orbit Phase (LEOP)
Mean Solar Local Time (MSLT)
Multi-Spectral Instrument (MSI)
Navigation Data Message (NDM)
Orbit Control Manoeuvre (OCM)
Out-Of-Plane (OOP)
Sentinel-2 (S2)
Sentinel-2A (S2A)
Sentinel-2C (S2C)

1. Introduction

The Sentinel-2 mission is a crucial part of the European Union's Copernicus Programme, designed to deliver comprehensive and precise data to enhance environmental management, understand and mitigate the impacts of climate change, and ensure civil security, while managing the technical and operational challenges associated with satellite operations. The mission consists of a pair of identical polar-orbiting satellites, positioned in the same sun-synchronous orbit with a 10-day repeat cycle, phased 180° apart. This configuration enables a high revisit frequency of 5 days all around the world, significantly enhancing the monitoring capabilities. Each satellite is equipped with a Multi-Spectral Instrument (MSI) that captures imagery across 13 spectral bands, ranging from visible and near-infrared to shortwave infrared, with spatial resolutions of 10 meters, 20 meters, and 60 meters.

On September 5, 2024, the Sentinel-2C satellite joined the Sentinel-2A and Sentinel-2B satellites already in orbit. This addition ensures the continuity of high-resolution optical imagery, which is crucial for long-term environmental monitoring and analysis. Sentinel-2C helps maintain the consistency and reliability of the data provided by the Sentinel-2 mission, replacing the oldest satellite, Sentinel-2A, in the constellation after its commissioning phase.

Although there is no mission requirement for a tandem flight at any time during the mission, it was strongly recommended to conduct a tandem phase during the commissioning of Sentinel-2C. This would enable cross-comparison and characterization between the series of Sentinel-2 MSI measurements, fundamentally supporting the Copernicus Climate Change Service [2]. The justification, requirements, considered concept, and assessment of impacts of a tandem flight phase during the Sentinel-2C in-orbit commissioning (IOC) on the mission (space and ground segments and operations) were collected in a technical note [3], which served as a starting point for the analysis reported in this paper on the operational concept of controlling the orbits of two Sentinel-2 spacecraft in a tandem constellation adhering to certain requirements. The considered tandem flight is between Sentinel-2C (the satellite in commissioning) and Sentinel-2A (the satellite that will be replaced by Sentinel-2C after the IOCR), but the concept could be applied to any combination of two Sentinel-2 satellites. Right after the Launch and Early Orbit Phase (LEOP), a manoeuvre campaign was conducted to acquire the tandem position with Sentinel-2A as soon as possible.

To provide consistent, high-quality data, the Sentinel-2 mission's orbit control ensures precise maintenance of sun-synchronous orbits through regular orbital manoeuvres. The next section addresses the orbit control, starting with the orbit control requirements for both routine and tandem operations.

2. Orbit Control

2.1. Orbit control requirements

The general orbit control requirements for the Sentinel missions are defined in [1]. For this analysis essential requirements concern (1) the reference orbit and ground track, (2) the ground track deviation, and (3) local time deviation during the commissioning and routine operations phases. To meet the Sentinel-2 mission requirements (e.g., revisit time, instrument coverage), a specific reference orbit is defined for each satellite. The Sentinel-2 satellites fly 180 degrees apart on the same reference orbit, resulting in different ground tracks due to the same local time of the ascending nodes (ANX). If two satellites are to fly the same ground track (GT), as in tandem flight, they will conversely have different orbits with different local times of the ANX. The GT deviation of each satellite must be maintained within ±2 km of their reference GT. Although the requirement for local time deviation is quite generous (within ±90 seconds of the reference orbit's local solar time of the ascending node), the local time is kept within 10 seconds of the reference orbit's local solar time of the ANX throughout the year to ease mission planning.

The orbit control requirements for the tandem phase have been defined in [3]. For this analysis, the essential requirements concern (1) the tandem phase duration, (2) the along-track separation, (3) the across-track separation, (4) Sentinel-2A operations, and (5) the safety along-track distance. To maximize the benefits of the tandem phase, it should ideally last 40 days (four 10-day repeat cycles) as a goal, but at least 20 days as a requirement. This limits the time available for the acquisition of the tandem position after the Sentinel-2C LEOP. The most stringent requirements pertain to the along-track separation, which must remain within 25 seconds (goal) to 30 seconds (requirement), and the across-track separation, which must fall within ±200 meters (goal) to ±700 meters (requirement) at all latitudes. The term "goal" denotes a non-mandatory but highly desirable requirement, and the term "requirement" denotes the requirement mandatory to be met. Strict separation over time is however not required. Since Sentinel-2A remains the on-duty satellite during the tandem phase, routine operations must be maintained without violating its ground-track control band, except for satellite safety. To accommodate worst-case safe mode conditions, a minimum along-track separation distance of 26.5 seconds is to be always maintained.

2.2. Tandem phase reference orbit

The stringent across-track separation requirement dictates that Sentinel-2C must fly close to the same reference ground track as Sentinel-2A. Consequently, it needs a reference orbit with a Mean Solar Local Time (MSLT) at the ascending node offset from the Sentinel-2 baseline value of 22:30 hours by the same amount as the required tandem along-track separation. The injection of Sentinel-2C at launch placed the spacecraft below the reference altitude, introducing a natural drift towards Sentinel-2A and positioning it behind Sentinel-2A for the tandem phase. A target offset of +28 seconds was chosen to provide sufficient margin for both the separation requirement of 30 seconds and the safety along-track distance requirement of 26.5 seconds. The target reference orbit of Sentinel-2C during the tandem phase is defined in Table 1.

Table 1. Sentinel-2C Reference Orbit (Tandem Mission)

Repeat Cycle	10 days
Cycle Length	143 orbits
Sun synchronous, MSLT at ascending node	22:30:28.0 h
Eccentricity	Frozen eccentricity vector
Longitude of 1st ascending node	8.55644 deg
Phase difference with respect to Sentinel-2A reference	28 seconds

Since Sentinel-2A is not flying exactly on its reference ground track and reference MSLT, the orbit maintenance of the Sentinel-2C orbit should be based on the actual ground track of Sentinel-2A. This "reference" ground track can be generated by the GROUNDTRACK application of the NAPEOS SW [5], using the predicted Sentinel-2A orbit as input, including planned manoeuvres (orbit maintenance or collision avoidance manoeuvres). During the tandem phase, this "reference" should be used to optimize the manoeuvres of Sentinel-2C for maintaining the tandem constellation.

2.3 Orbit control considerations

Before identifying suitable orbit control strategies for the tandem phase, it is essential to identify what operational activities affect the along-track and across-track separation of the two satellites in tandem and to what extent. The following activities could be identified:

- Routine orbit maintenance manoeuvres on the operational satellite (Sentinel-2A)
- Collision avoidance manoeuvres on either of the two spacecrafts
- Eccentricity control of the trailing spacecraft (Sentinel-2C)

To quantify the effect of manoeuvres on the along-track and across-track ground track drift, it is important to consider observables such as ground track at equator $\Delta l_0(t)$ and at maximum latitude $\Delta l_L(t)$, and the local solar time $\Delta H(t)$. These observables are highly susceptible to perturbations, including atmospheric drag, third-body interactions, and higher-degree and order gravitational perturbations. Fortunately, for two identical satellites flying in tandem, the level of perturbations is very similar. Therefore, similar-sized manoeuvres will be required to counteract the effects of these perturbations on the orbit, keeping the satellites' ground tracks within the ±2 km control band. To keep the satellites on the same ground track, manoeuvres need to be executed simultaneously on both spacecraft. However, this is operationally impractical in terms of manoeuvre preparations and considering a manoeuvre execution failure on the trailing spacecraft, the satellites will drift towards each other.

To determine the effect of a difference in velocity between the two satellites on the relative across-track drift, formulas from [4] are used, where an equation is derived that links the change in ground track at equator $\Delta l_0(t)$ along the equator to the in-plane orbit maintenance manoeuvre size ΔV and delta time ΔT:

$$\Delta l_0 = -\frac{3}{2}\omega_{TE}\frac{a_e}{a}\Delta a\Delta T = -\frac{3\omega_{TE}a_e}{\sin(i)}\frac{\Delta V}{V}\Delta T, \tag{1}$$

where $\Delta T = T_{target} - t$ (T_{target} is the time of the next orbit maintenance slot, and t is the mid time of the manoeuvre), ω_{TE} is the rotation rate of the Earth ($2\pi/1\ day$), a_e is the Earth’s radius, V is the spacecraft velocity, and a is the orbits semi-major axis. The ground track drift perpendicular to the reference ground track or Sentinel-2A ground track is then defined as follows:

$$\Delta gt = \Delta l_0 \sin i, \tag{2}$$

where i is the satellite’s inclination. The next equation links the manoeuvre size (ΔV) to the change in semi-major axis (Δa) (3) and the change in along-track distance (Δd) to the change in semi-major axis (Δa) and the time to the next orbit maintenance slot (ΔT) (4).

$$\Delta a = 2a\frac{\Delta V}{V}, \tag{3}$$

$$\Delta d = 1.264\,\Delta a\frac{\Delta T}{P}, \tag{4}$$

where P is the orbital period of the S/C and the constant, 1.264, is the change in orbital period (s) per change in semi-major axis (km) for the nominal Sentinel-2 orbit. Taking equation (3), a prograde in-plane manoeuvre increases the semi-major axis, and this leads to a westward drift in ground track with respect to the original ground track.

Considering the across-track separation requirement, assuming the spacecrafts are flying at the same altitude and on the same ground track, a difference in velocity, induced by an IP prograde manoeuvre, will introduce a relative across-track (XT) drift in ground track. Equations (1) and (2) can be used to compute how long it takes, depending on the size of the manoeuvre, to reach a +200m, +400m, +700m and +1400m across track separation. The numbers are presented in Fig. 1. The 400m and 1400m across track separation cases are added to reflect going from -200m to +200m, and from -700m to +700m across track separation.

The figure illustrates that when manoeuvres are executed one day apart, the XT separation increases to 200 m, 400 m, 700 m, and 1400 m for delta-v sizes of 1.3, 2.5, 4.4, and 8.8 cm/s, respectively. To identify what manoeuvres can be expected for routine orbit maintenance and collision avoidance, and their impact on along-track and across-track drift, the manoeuvre history of Sentinel-2A was examined in terms of sizes and performance errors.

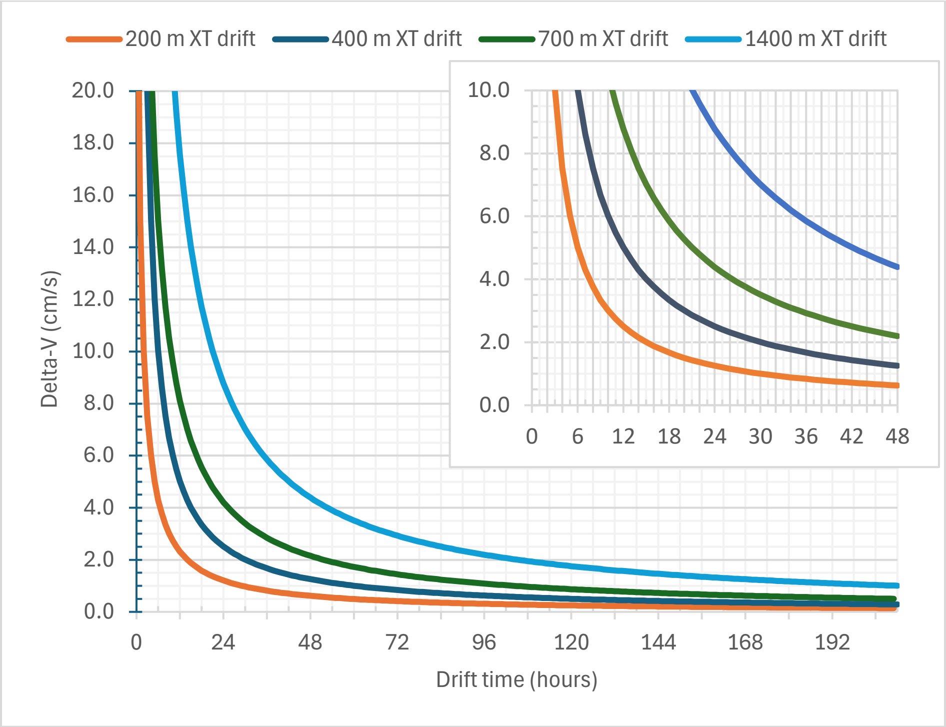

Fig. 1. Velocity difference (cm/s) as a function of drift duration (hours) of a across track (XT) ground track separation of 200m, 400m, 700m and 1400m.

2.3.1. Effect of orbit maintenance and collision avoidance manoeuvres on the tandem constellation

The ground track of Sentinel-2A has been maintained within its ±2km control band around its reference since 02 July 2015. Up to March 2024, 64 orbit control manoeuvres (OCMs) were executed for orbit maintenance. In addition, 24 pairs of collision avoidance manoeuvres (CAMs) were executed, where 10 CAMs were optimised to perform orbit maintenance on top of the collision avoidance.

The largest OCM executed so far has been 3.85 cm/s and the smallest 0.9 mm/s, where the largest under performance error observed was 1 mm/s and the largest over performance error observed was 0.8 mm/s. The average orbit maintenance manoeuvre size was 1.56 cm/s. Taking equations (1) and (2), a manoeuvre size of 3.85 cm/s introduces a ground track drift of 614 meter in 24 hours. An under-performance error of 1 mm/s reduces this drift by 16 meters. The opposite is true for an over performance. Smaller manoeuvres tended to have larger under-performances, but not more than 7% of the commanded delta-v.

The largest CAM executed up to now has been 19.0 cm/s and the smallest 0.75 mm/s. CAMs come in pairs and are executed at least 1 orbit revolution apart, but sometimes a bit more to execute the return manoeuvre inside eclipse. With a CAM size of 19 cm/s, the ground track drifts 210 meter and the along track separation grows with 0.4 seconds after one orbit revolution. Taking an average CAM size of 4 cm/s, the values are 45 meter and 0.1 seconds respectively. The largest overall under-performance error (pair of collision avoidance manoeuvres combined) observed on Sentinel-2A was 1.9 mm/s and the largest overall over-performance error observed was 1.1 mm/s. An overall performance error of 1.9 mm/s introduces a XT difference of 30 meter after 1 day. A 1 cm/s performance error results in an along-track drift of 0.342 seconds and a XT drift of 160 meter per day.

A relative drift of the two spacecrafts, reducing the separation, potentially results in the violation of the requirements defined in section 2.1. As seen in Fig. 2, the compliance with the ±200-meter ground track control band can be violated within a few hours in case of a large manoeuvre. Typical CAM sizes potentially lead to a drop below the defined safety limit of 26.5 seconds with respect to the nominal separation of 28 seconds in less than 24 hours.

Indicating, executing a "DOWN/UP" CAM on the trailing spacecraft could be riskier than an "UP/DOWN" CAM, even in case a collision risk assessment prescribes a "DOWN/UP" scenario.

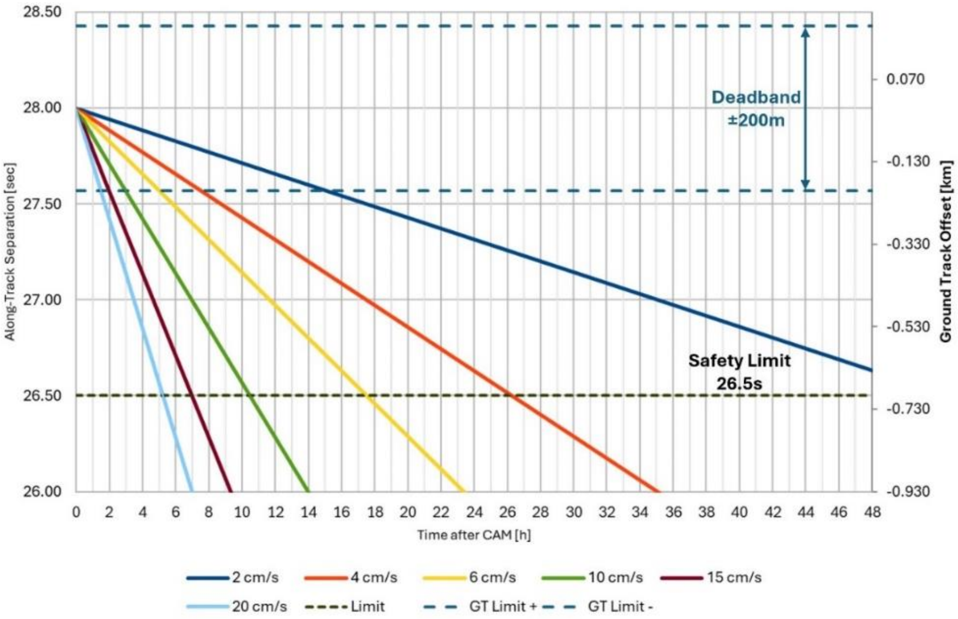

Fig. 2. Drift in along-track separation in relation to operational limits for different magnitudes of relative motion (e.g. following a CAM on the trailing spacecraft with a failed/aborted return "UP" burn).

The following two graphs represent two CAM scenarios applicable to both spacecraft. Fig. 3 illustrates a CAM scenario, where the first burn causes the two spacecraft to initially drift apart and a 5% over performance of the return burn results in a reduction in separation. In this case, the critical safety distance is reached after several days (e.g., 6 days for a CAM of 20 cm/s). Fig. 4, then illustrates the more critical situation of a reversed burn sequence with a 5% under performance of the return burn, where the critical safety distance is reached faster for the same size CAM burns (e.g., 3 days for a CAM of 20 cm/s)

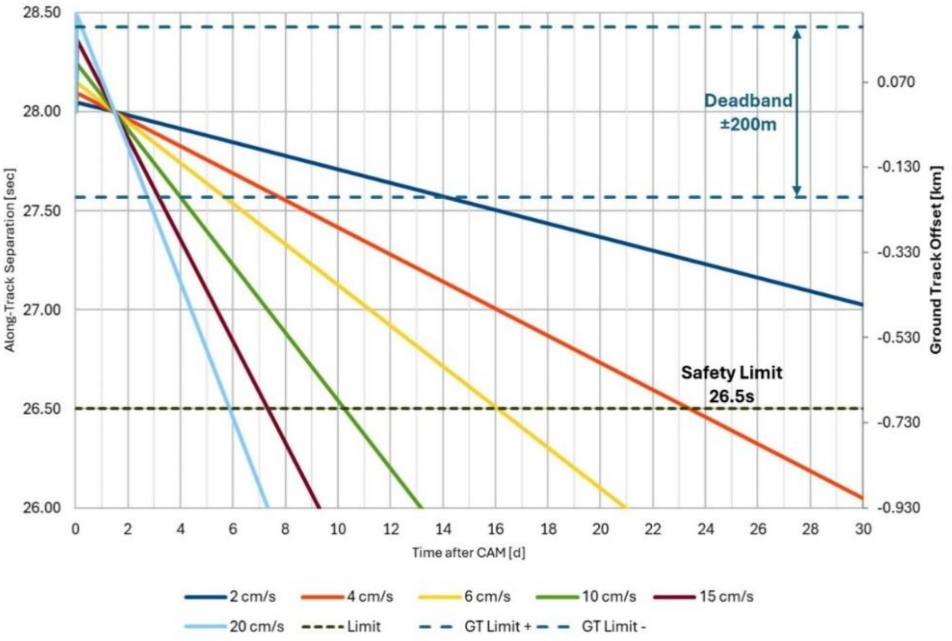

Fig. 3. Along-track and ground track drift due to a 5% over performance of the return burn that reduces separation.

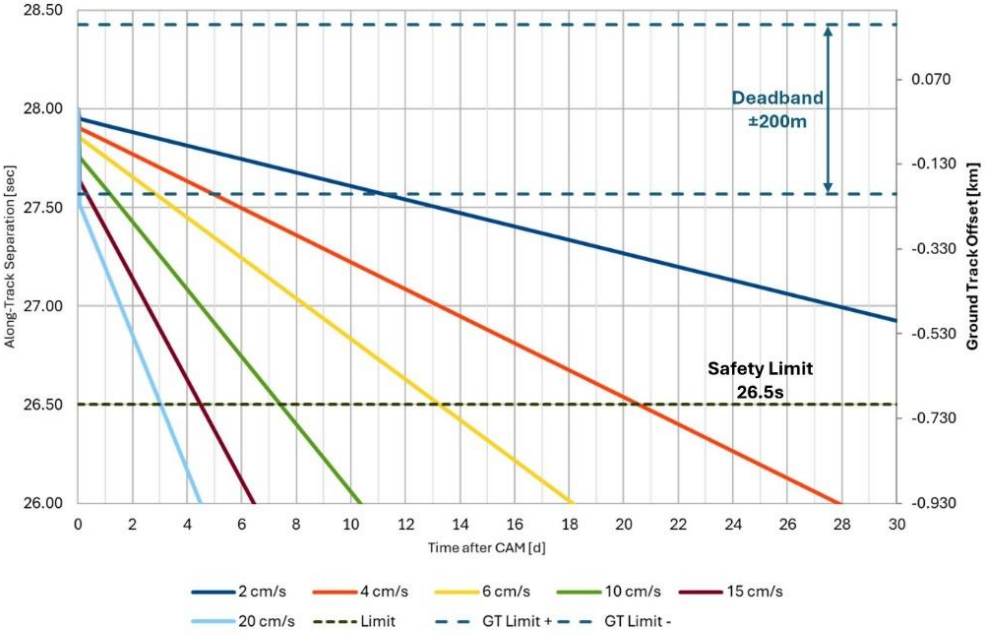

Fig. 4. Along-track and ground track drift due to a 5% under-performance of return burn that reduces separation.

The orbit maintenance manoeuvre frequency on Sentinel-2A has increased from an average of every 5 weeks at the start of the mission to every 2 to 3 weeks recently, due to heightened solar activity at this point in the solar cycle. This increase in solar activity necessitates larger and more frequent IP manoeuvres to maintain the ±2 km ground track dead-band requirement. With larger manoeuvres, there is a concern that the across-track drift could exceed the ±700m requirement.

2.3.2. Effect of differences in eccentricity on the tandem constellation

A difference in eccentricity between two spacecraft flying in tandem affects the across-track difference during an orbit due to the difference in velocity during the orbit. To quantify this effect at all latitudes, two extreme cases of differences in eccentricity were investigated to determine if the eccentricity of the two spacecraft should be aligned before starting the tandem phase.

To maintain the 500 m delta-altitude requirement, the eccentricity vector must remain within an eccentricity circle centred on the frozen eccentricity, with a radius of 5.56×10^{-5}. For the two cases, the eccentricity vectors were chosen at opposite sides of the eccentricity circle. In the first case, the e_y is the same (frozen eccentricity value), but e_x has opposite signs ($\pm5.56\times10^{-5}$), placing the perigees at 92.79 degrees and 87.23 degrees PSO, respectively. In the second case, e_x is zero and e_y is the frozen value $\pm$ 5.56×10^{-5}, placing the perigees at the same PSO (90 degrees).

In the first case, the effect on the along-track and across-track differences at different latitudes shows a cyclic along-track separation over one orbit that can be up to 1.6 km, corresponding to 0.22 seconds. Propagating the state vectors for 10 days, the differences in ground track remain below the 100-meter level but drift during this time.

In the second case, the effect on the along-track and across-track differences at different latitudes shows a cyclic along-track separation over one orbit that can be up to 3.2 km, corresponding to 0.42 seconds in spacecraft along-track separation. Propagating the state vectors for 10 days, the differences in ground track reach the 200-meter level for some latitudes but does not exceed it.

The results of the two cases indicate that minimizing the difference in eccentricity reduces the overall across-track difference over an orbit revolution to a minimum when flying on the same ground track. Satellites with similar eccentricities will orbit the Earth at nearly the same speed and altitude, maintaining a stable distance between them.

2.4. Tandem orbit control strategies

In preparation of the Sentinel-2C mission, an initial assessment of the feasibility of a tandem flight between Sentinel-2A and Sentinel-2C was conducted [3]. This led to the proposal of one tandem orbit control strategy. However, upon further examination of operational constraints, the COP-2 FD team proposed an alternative strategy. The two proposed tandem orbit control strategies are:

Strategy A: The satellites fly at slightly different altitudes, with manoeuvres executed at fixed intervals (e.g., once a week). These manoeuvres are performed one day or less apart between the two satellites, causing them to continuously drift with respect to each other.

Strategy B: The satellites fly at the same altitude, following a manoeuvre sequence based on the routine orbit control of Sentinel-2A (e.g., every 2 to 4 weeks, depending on the solar activity). In this strategy, 90% of the required delta-v for the leading S/C is executed on the trailing S/C several orbits before, followed by a touch-up manoeuvre to raise the trailing S/C to the same altitude as the leading S/C.

2.4.1 General assumptions

Assumptions that apply to both strategies are listed below:

- Manoeuvres on a routine Sentinel-2 S/C are executed within a certain timeslot and within a PSO range:
  - Thrust start & end between 14:45 and 17:39 UTC
  - Prograde IP manoeuvre thrust phase between PSO 302.1 deg. and 52.7 deg.
- Two ground station passes are available for uplink of the manoeuvre command before execution of the manoeuvre -> Manoeuvre commands available ~5 hours before execution
- Planned manoeuvre is screened by the Collision Avoidance Team (CAT) for collision risks 1 day before implementing the OCM
- Re-screening of a slightly changed manoeuvre size takes ~1 hour
- Calibration of executed manoeuvre and orbit determination takes ~5 hours after execution of the manoeuvre, assuming sufficient GPSR/GNSS data after the manoeuvre is available for the calibration process
- Re-optimisation of manoeuvre and generation of Navigation Data Message (NDM) for collision risk screening takes ~3 hours
- One ground station pass is available for confirmation of manoeuvre execution
- The duration of the tandem phase is between 20 days (requirement) and 40 days (goal).

2.4.2. Orbit control strategy A: Drifting

The "Drifting" tandem orbit control strategy, as described in [3], involves executing IP manoeuvres at fixed intervals - weekly during periods of high solar activity - with a maximum of 24 hours between manoeuvres. This approach maintains a narrow ground track band, narrower than the ±2 km operational requirement, by avoiding excessively large manoeuvres and increased delays between manoeuvres. These two aspects (weekly manoeuvres and 24-hour intervals) directly affect the variation in the along-track distance, and consequently the across-track distance, between the two spacecraft.

A chief-deputy orbit control strategy, with the two satellites flying at slightly different altitudes (approximately 10 meters apart in altitude as shown in Fig. 5), results in the spacecraft flying at different speeds. This causes the along-track separation to decrease and the across-track distances to drift until the next IP manoeuvre, typically a week later.

With this strategy, the control of the leading/routine S/C needs to be adjusted from once every 2 to 3 weeks to once a week before the tandem phase can start. This means the S/C must be controlled within a smaller dead band around its reference. Depending on the ground track situation of the leading/routine S/C at the time of tandem acquisition, this adjustment may take several weeks. The acquisition phase, aimed at achieving the ideal configuration at the start of the tandem phase, will be as demanding as for strategy B (Same Ground Track). At the end of the acquisition phase, the trailing/commissioning S/C must be at the same altitude as the leading/routine S/C one day prior.

In this strategy, the OCM on the leading S/C must be optimized and executed so that the along-track separation reaches the 26.5 seconds safety threshold by the time of the OCM on the trailing S/C the following week. If the OCM on the leading S/C overperforms or the OCM on the trailing S/C underperforms, the separation will decrease more rapidly, potentially violating the safety distance before the next OCM on the trailing S/C (6 days later). A 5% relative over performance of a 4 cm/s OCM introduces an additional across-track drift of 200 meters and a further reduction in separation of 0.4 seconds.

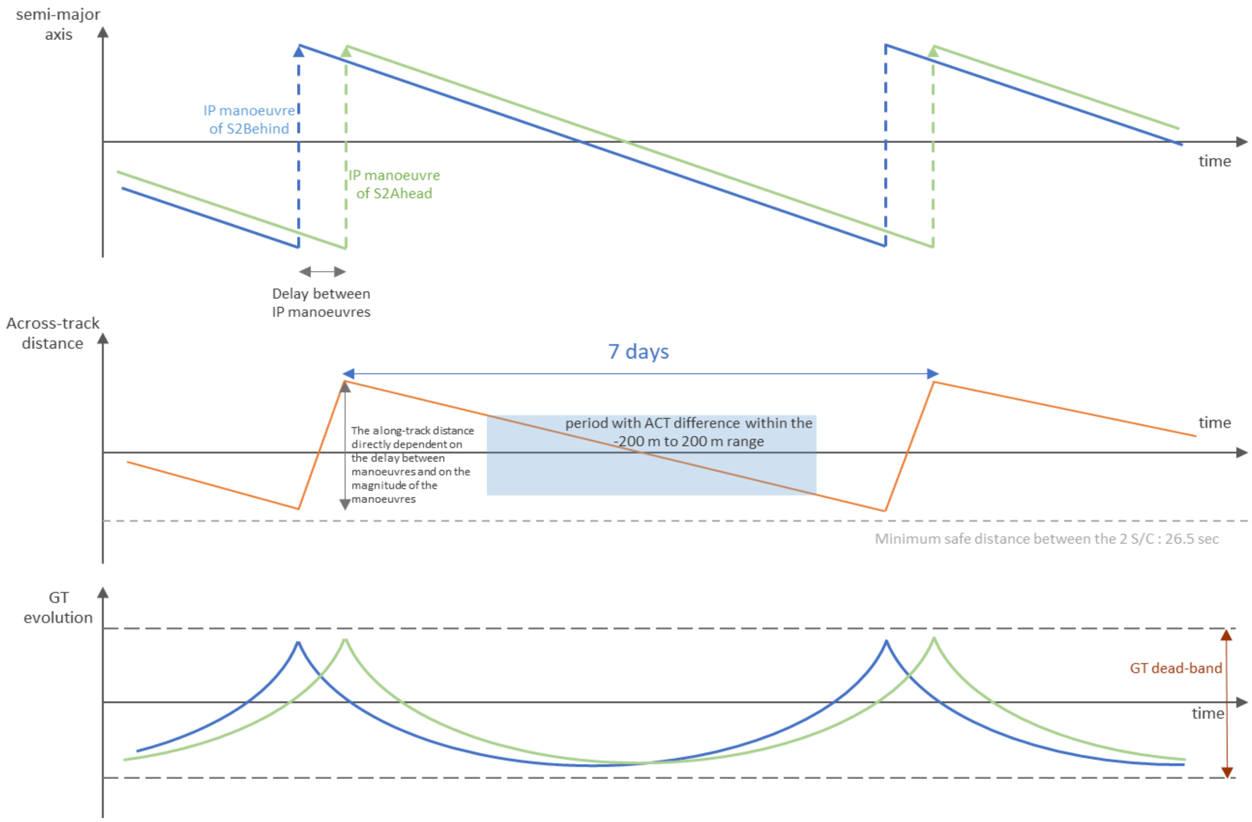

Fig. 5. Tandem phase orbit control strategy A: “Drifting”

Variations of the “Drifting” strategy were presented in [3]. The three scenarios identified were:

Scenario 1: OCM-2 of the "leading" spacecraft (S/C) is executed immediately after OCM-1 of the "trailing" S/C, without a full performance evaluation of OCM-1. Sanity checks ensure the AOCS status is nominal. This scenario requires a larger separation to ensure safety despite any performance deviations of the trailing satellite. The manoeuvres can be completed within a day during working hours. Variations in satellite separation due to OCM performance should be acceptable until the next manoeuvre opportunity (the following week).

Scenario 2: OCM-2 of the "leading" spacecraft (S/C) is executed only if OCM-1 of the "trailing" S/C performs within acceptable limits; otherwise, OCM-2 is aborted. This scenario is like Scenario 1 in preparation and criticality, with OCM-2 planned independently from OCM-1. The GO/NOGO decision for OCM-2 depends on preliminary checks of OCM-1's performance. This introduces timing constraints but is manageable within working hours. Satellite separation may vary, requiring a smaller safety margin compared to Scenario 1.

Scenario 3: OCM-2 of the "leading" spacecraft (S/C) is adjusted based on OCM-1's performance of the "trailing" S/C. This requires more time between manoeuvres for GPS data collection, orbit determination, and optimization, delaying OCM-2 preparation and upload.

Scenario 2 seemed the most promising of the 3 scenarios and was analysed further. A summary of that analysis is presented in section 2.5.

2.4.3. Orbit control strategy B: Same Ground-Track

This strategy aims at keeping both satellites on the same ground track as much as possible. In this strategy, the orbit control of the leading/routine S/C is not changed. Its ground track is kept within the ±2 km dead band as has been done so far, but with OCMs planned on Wednesdays instead of Thursdays. To minimize the relative drift in ground track between the two S/C, the trailing S/C is manoeuvred 3 orbits before the leading S/C (to guarantee 3 ground station passes are available for a positive confirmation of the OCM on the trailing S/C and uplink of the OCM on the leading S/C), but with a manoeuvre size 90% of the manoeuvre size required for the orbit control of the leading/routine S/C. Consequently, a touch-up manoeuvre needs to be executed to stop/reduce the relative along-track and across-track drift to the minimum. The touch-up manoeuvre is optimized on Thursday considering the calibration of both manoeuvres, correcting any performance errors of the two larger OCMs, and targeting the ground track of the leading/routine S/C at the time of the next OCM in 2 to 4 weeks, depending on the level of the solar activity at the time of the tandem phase. The touch-up OCM is to be executed on Friday at an epoch that leaves enough time for a first calibration of the manoeuvre on that day.

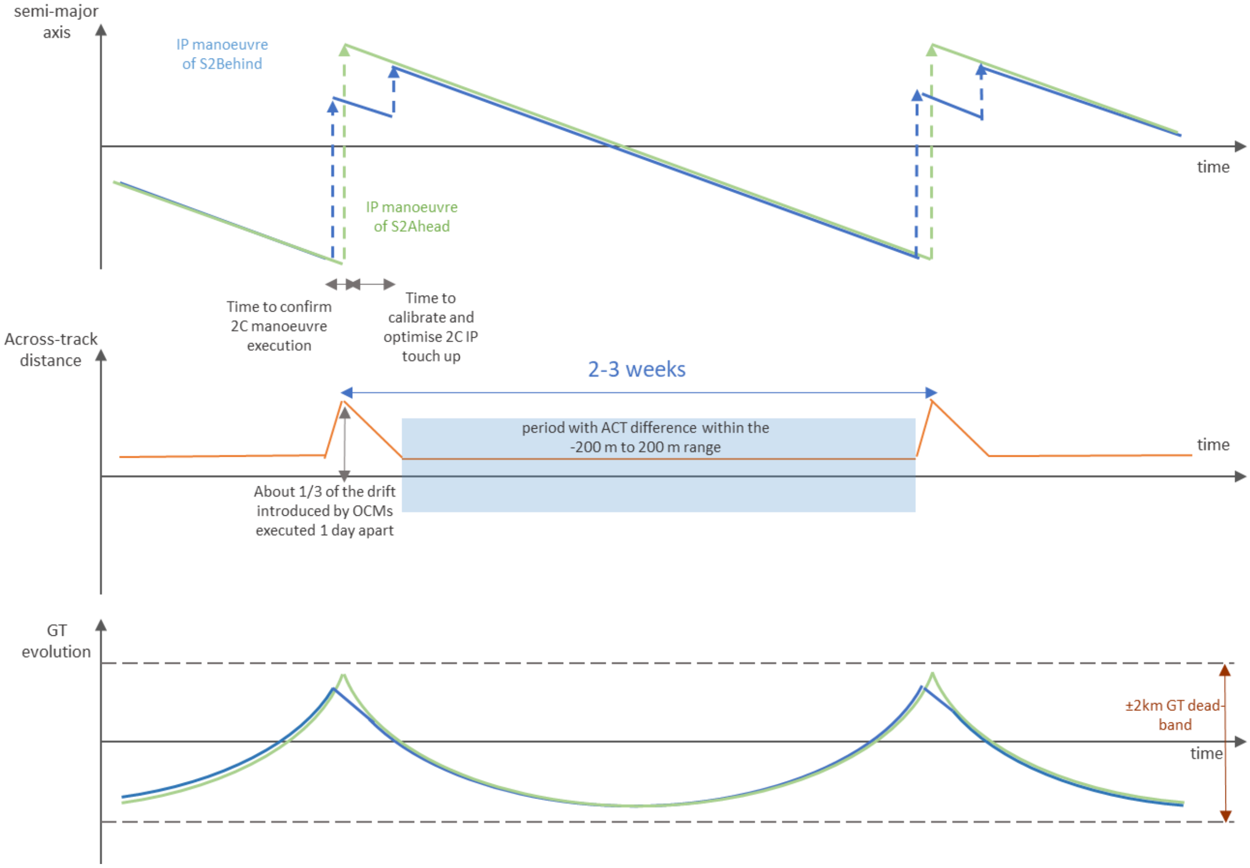

Fig. 6. Tandem orbit control strategy B: “Same Gound Track”

This chief-deputy orbit control strategy with the two satellites flying at nearly the same altitude after the touch-up manoeuvre, as shown in Fig. 6, leads to the two spacecrafts flying at almost the same speed, causing the along-track separation to stay constant or with a very small drift, and across-track distances to stay small/reducing until the next IP OCM required on the leading/routine S/C for orbit maintenance.

The 10% difference in delta-V between the two satellites was chosen to avoid requiring a retrograde touch-up manoeuvre on the trailing S/C in case the manoeuvre on the trailing S/C has a 5% overperformance and the manoeuvre on the leading S/C has a 5% underperformance. In this scenario, the ground track of the trailing S/C would drift away. Additionally, the touch-up manoeuvre should not be too small, as smaller manoeuvres tend to exhibit larger performance errors.

2.5. Evaluation of the tandem orbit control strategies

To evaluate the viability of the two strategies before the launch of Sentinel-2C, simulations were conducted covering a 60-day period, assuming average solar activity conditions expected around the time of the tandem phase. The results for the two strategies are summarized below. For the "Drifting" strategy, a normal manoeuvre sequence on the leading S/C was also simulated, with OCMs executed upon reaching the ±2 km dead band.

The effects of performance errors of the manoeuvres on the evolution of the along-track and across-track differences were also simulated and the results are reported below.

2.5.1. Drifting strategy (one week between OCMs)

For this simulation, the orbit control of Sentinel-2A was adjusted from once every 2 to 4 weeks to once a week. An OCM was introduced weekly to maintain the ground track within the dead band, with no performance errors included. The orbit control of Sentinel-2C was synchronized with Sentinel-2A, executing OCMs one day prior to those of Sentinel-2A. The resulting evolution of Sentinel-2C's ground track relative to Sentinel-2A is shown in Fig. *7*. The inclination of Sentinel-2C was aligned with Sentinel-2A before the start of the tandem phase.

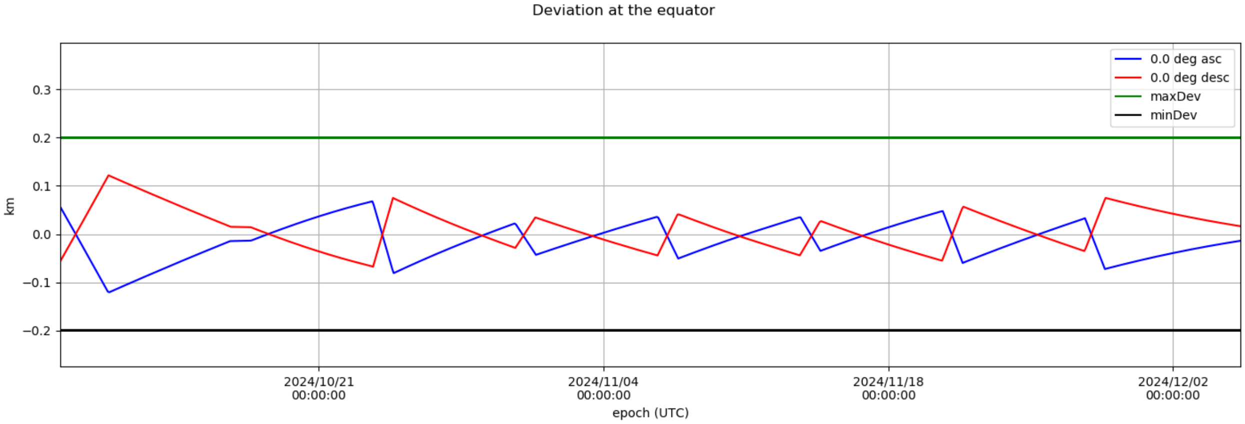

Fig. 7. Evolution of the Sentinel-2C ground track with respect to that of Sentinel-2A, applying the "drifting" strategy, executing OCMs once a week, one day apart, assuming nominal OCM execution on both S/C.

The across-track difference between the two S/C remains well within the ±200 m dead band for the entire tandem period under the assumed average solar activity conditions. The simulation assumes that all planned OCMs execute nominally. Performance errors change the picture.

The along-track separation during the simulated tandem phase is depicted in Fig. *8*.

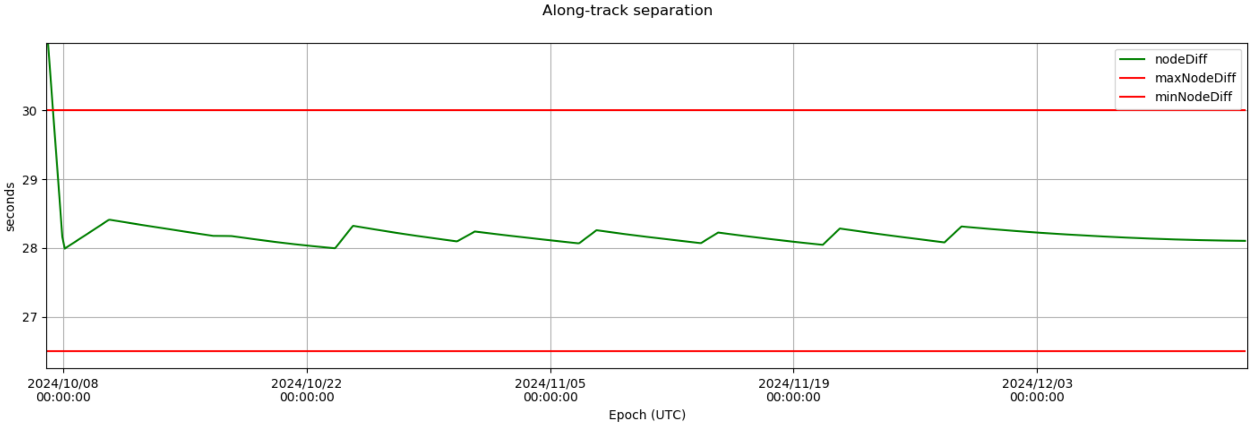

Fig. 8. Evolution of the along-track separation applying the "Drifting" strategy, executing OCMs once a week, one day apart, assuming nominal OCM execution on both S/C.

2.5.2. Drifting strategy (several weeks between OCMs)

Since the across-track difference remained well within the ±200 m dead-band with the drifting strategy executing the OCMs once a week, a normal orbit control of the Sentinel-2A S/C within the ±2 km dead-band was also simulated.

The orbit control of Sentinel-2A was not adjusted, and usual OCMs were simulated to keep its ground track within the ±2 km dead band, with no manoeuvre performance errors introduced. The orbit control of Sentinel-2C was synchronized with Sentinel-2A, executing the OCMs one day prior to those of Sentinel-2A. The resulting evolution of Sentinel-2C's ground track relative to Sentinel-2A is shown in Fig. *9*. No manoeuvre performance errors were introduced.

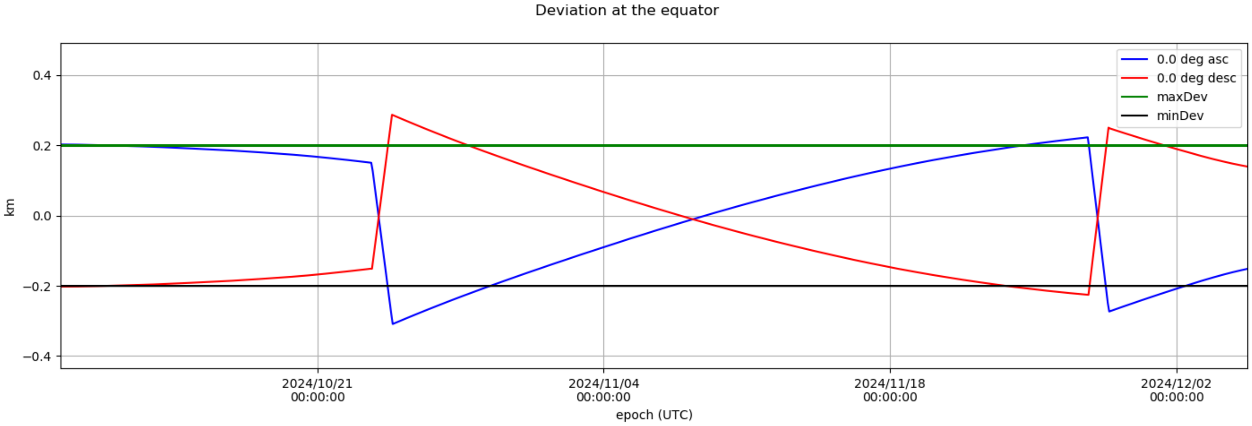

Fig. 9. Evolution of the Sentinel-2C GT w.r.t. that of Sentinel-2A, applying the "drifting" strategy, executing OCMs required for orbit maintenance within the ±2 km dead-band, one day apart, assuming nominal OCM execution on both S/C.

The along-track separation during the tandem phase is depicted in Fig. *10*.

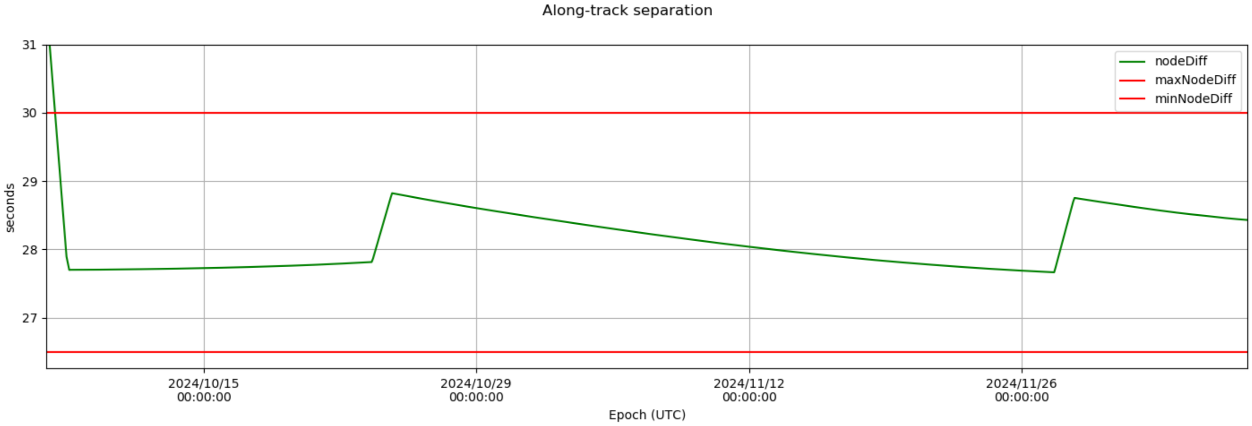

Fig. 10. Evolution of the along-track separation applying the "Drifting" strategy, executing OCMs required for orbit maintenance within the ±2 km dead-band, one day apart, assuming nominal OCM execution on both S/C.

The across-track difference between the two S/C only exits the ±200 m dead band briefly during the tandem period under the assumed average solar activity conditions. The simulation assumes that all planned OCMs execute nominally. However, performance errors have a larger impact compared to the weekly OCM case, and the along-track separation can change significantly due to these errors.

2.5.3. Same Ground Track strategy

The orbit control of Sentinel-2A is slightly adjusted, with usual OCMs planned to keep its GT within the ±2 km dead band, shifting the execution day from Thursday to Wednesday. No manoeuvre performance errors were introduced in this simulation. The orbit control of Sentinel-2C is synchronized with that of Sentinel-2A, executing 90% of the required OCM for orbit maintenance 3 orbits earlier, followed by a touch-up OCM approximately 2 days later. The resulting evolution of Sentinel-2C's ground track relative to Sentinel-2A is shown in Fig. 11.

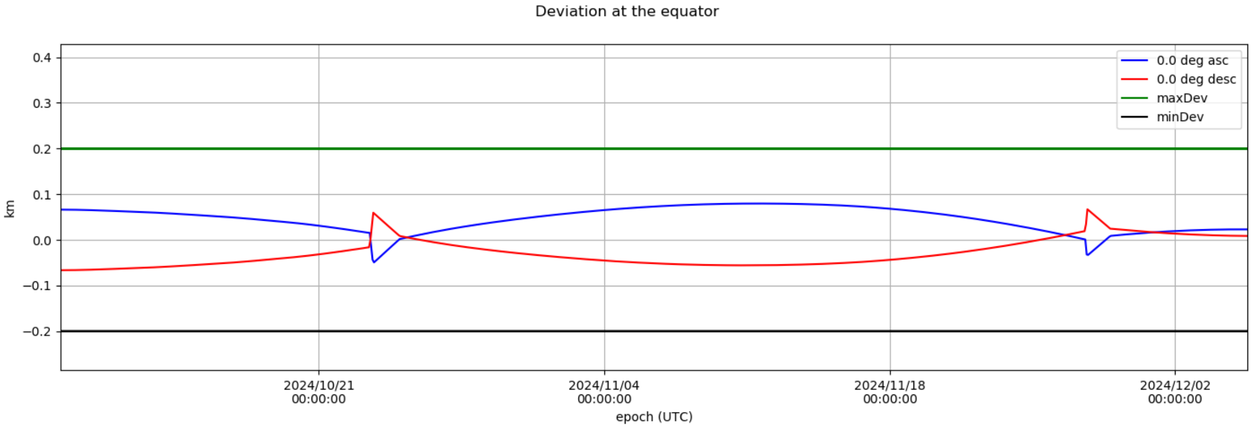

Fig. 11. Evolution of the Sentinel-2C GT with respect to that of Sentinel-2A, applying the "Same Ground Track" strategy, executing 90% of the required OCM on Sentinel-2A for orbit maintenance, 3 orbits before, with a touch up OCM about 2 days later, assuming nominal OCM execution on both S/C.

The across-track difference between the two S/C remains well within the ±200 m dead band throughout the entire tandem phase under the assumed average solar activity conditions. Notably, the across-track drift after the first OCM on Sentinel-2C is about one-third of that observed in the once-a-week OCM drifting case. This reduction is due to the shorter interval between the OCM and the one on Sentinel-2A, as well as the smaller size of the OCM on Sentinel-2C.

The along-track separation during the tandem phase is depicted in Fig. 12. Note the along-track separation hardly changes during the tandem phase. It stays almost constant at 28 seconds.

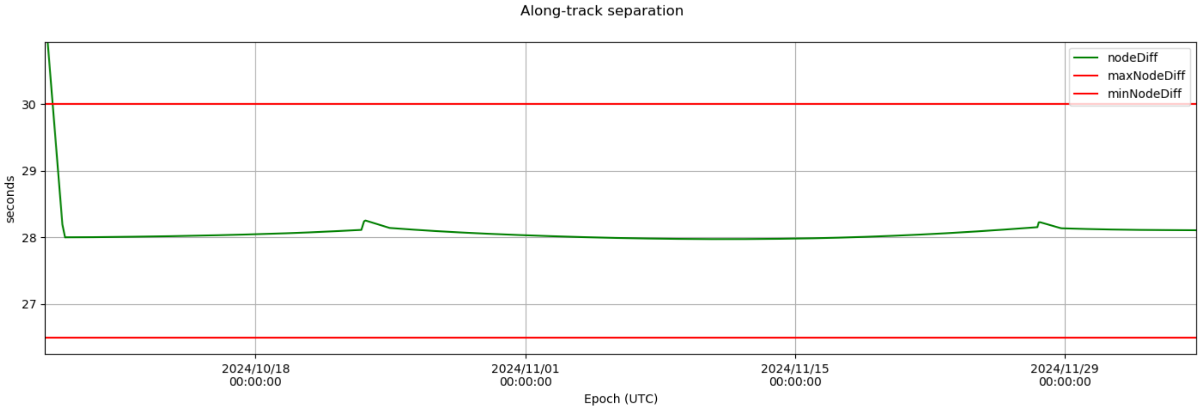

Fig. 12. Evolution of the along-track separation applying the "Same Ground Track" strategy, executing OCMs required for orbit maintenance within the ±2 km dead-band, executing 90% of the required OCM on Sentinel-2A for orbit maintenance, 3 orbits before, with a touch up OCM 2 about 2 days later, assuming nominal OCM execution on both S/C.

To evaluate the effect of a S2A manoeuvre performance error on the across-track difference and along-track separation, simulations were conducted with a 5% over-performance and a 5% under-performance, with the touch-up manoeuvre optimized to correct the error. The resulting across-track differences and along-track separations are very similar to those in Fig. 11 and Fig. 12. In the 5% over-performance case, the GT of Sentinel-2C drifts slightly more to the west (minDev) but remains within 100 m of Sentinel-2A's GT. In the 5% under-performance case, the opposite occurs, but the GT still stays within 100 m of Sentinel-2A's GT. Performance errors have minimal impact on the along-track separation, as the relative drift is immediately corrected by the touch-up manoeuvre.

Simulations also indicated that an over-performance of the OCM on the leading S/C requires a slight advancement of the touch-up manoeuvre to stop the drift on the S2A GT, while an under-performance requires a slight delay. However, this adjustment is not necessary. The touch-up can be executed on Friday morning, targeting the S2A GT at the time of the next orbit maintenance OCM.

Moving the touch-up OCM about 11 hours later for the over-performance case and about 10 hours earlier for the under-performance case only slightly changes the scenario. According to the formulas in paragraph 2.3, a 12-hour delay or advance of the touch-up OCM after a 5% error on a 3 cm/s burn (i.e., 1.5 mm/s) introduces an additional drift of only 12 meters.

The across-track difference results below show the effect of a 5% over-performance (see Fig. 13) and a 5% under-performance (see Fig. 14) of the touch-up OCM on Sentinel-2C. An error of 5% on a 1.9 mm/s touch-up OCM (i.e., 0.09 mm/s) has a larger effect on the across-track difference due to the time until the next orbit maintenance OCM. In these cases, after 35 days, the across-track difference changes by about 50 m.

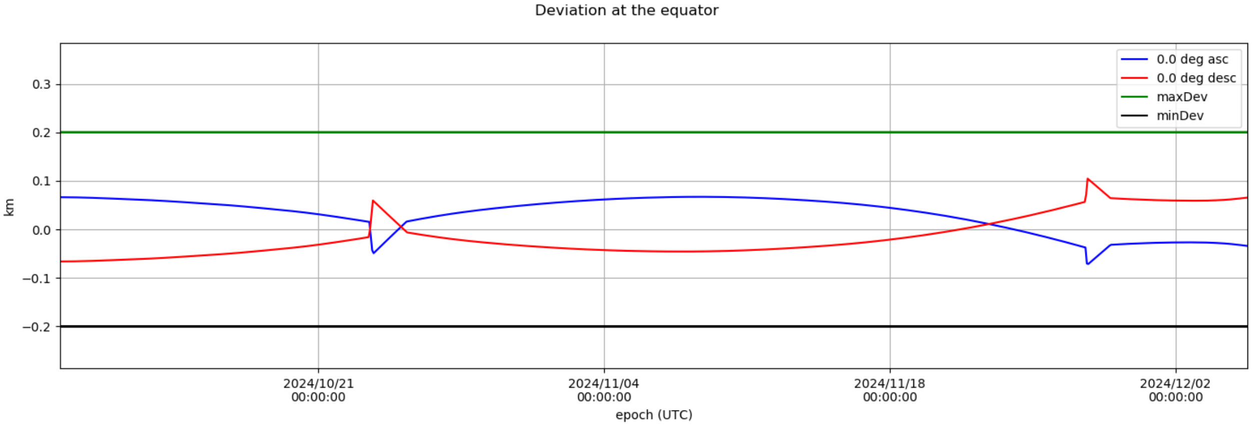

Fig. 13. Evolution of the Sentinel-2C GT with respect to that of Sentinel-2A, applying the "Same Ground Track" strategy, executing 90% of the required OCM on Sentinel-2A for orbit maintenance, 3 orbits before, with a touch up OCM about 2 days later, assuming a 5% over-performance of the touch up OCM.

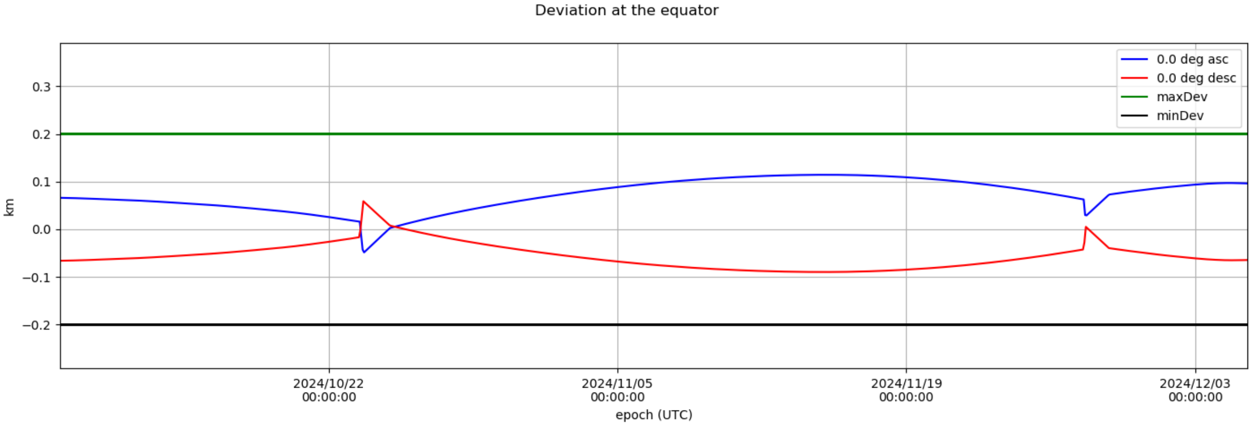

Fig. 14. Evolution of the Sentinel-2C GT with respect to that of Sentinel-2A, applying the "Same Ground Track" strategy, executing 90% of the required OCM on Sentinel-2A for orbit maintenance, 3 orbits before, with a touch up OCM about 2 days later, assuming a 5% under-performance of the touch up OCM.

In case of an under-performance of the touch-up manoeuvre, this can be corrected at the time of the next OCM by executing the OCM on S2C more than 3 orbits before the one on S2A, thereby extending the drift slightly longer. Conversely, an over-performance cannot be corrected in the same manner but could be accommodated by introducing a small retrograde touch-up manoeuvre between the OCM slots.

2.6. Selection of the tandem orbit control strategy

The simulations conducted indicate that both the "Drifting" strategy, which involves executing OCMs once a week, one day apart, and the "Same Ground Track" strategy are viable. The pros and cons of these two strategies are summarized in Table 2.

Table 2. Pros and cons of the analysed orbit control strategies for the tandem phase

Strategy	PROs	CONs
“Drifting” (once a week)	• No touch up OCM is foreseen to be executed on the trailing S/C	• Manoeuvre performance errors may violate the across-track difference / safety requirement until the next OCM slot • Under nominal conditions, OCMs required every week during the complete tandem phase • Depending on level of solar activity the across-track difference goal of ±200 m dead-band may only be partially met between the weekly OCMs • The orbit control of the leading S/C needs to be adjusted to once every week
“Same Ground Track”	• Under nominal conditions, OCMs only required once or twice during the complete tandem phase • Manoeuvre performance errors do not violate the across-track difference requirement until the next OCM slot • Between OCM slots the across-track difference is less than the ±200 m dead-band goal. • The orbit control of the leading S/C does not need to be adjusted	• A touch up OCM on the trailing S/C needs to be executed

Considering the pros and cons listed in the table above, it is evident that the Same Ground Track strategy is the optimal choice for the tandem phase of the two Sentinel-2 satellites. This strategy not only minimizes the impact on the operational routine mission but also reduces the number of interruptions to the planned commissioning activities, despite the need for a touch-up OCM each time a manoeuvre is required. It provides the best conditions for a successful tandem phase, meeting all requirements. Therefore, the decision was made to use this strategy for the tandem phase of Sentinel-2C with Sentinel-2A.

3. Tandem operational phases

There are three distinct operational phases associated with the tandem mission:
(1) acquisition of the tandem configuration,
(2) maintenance of the formation for a particular period, and
(3) relaxing the satellite constellation after the tandem phase.

3.1. Acquisition of the tandem configuration

The S2C spacecraft was successfully injected 10.6 km below the nominal mission altitude, allowing it to naturally drift towards its tandem position behind S2A. A total of four large IP prograde manoeuvres (total delta-v of about 6.33 m/s) were required to slow down the drift to a level where only two small IP fine acquisition OCMs of 1.2 cm/s and

1.5 cm/s respectively were required to acquire the tandem position. The large IP OCMs were timed such to align the eccentricity with that of S2A. Additionally, a small OOP OCM was planned shortly after LEOP and another one month later (total delta-v of 0.57 m/s) to align the inclination of S2C with that of S2A and to target the correct MSLT at the start of the tandem phase.

3.2. Maintenance of the tandem configuration

With the first IP fine acquisition OCM executed on October 29, the ground track of S2C was already within 700 meters of the S2A GT. The second IP fine acquisition OCM, executed on October 31, minimized the relative drift. One week after the start of the tandem phase, an inclination correction manoeuvre was required on S2A. A small bias in the yaw angle of the OOP OCM was introduced to create an IP component for the in-plane orbit maintenance of S2A. The same approach used for IP tandem control was applied to the OOP OCMs. An OOP manoeuvre of almost the same size as for S2A was executed on S2C, about three orbits before the one on S2A. A slightly smaller yaw angle bias was introduced to reduce the IP component to 95% of that for S2A. A small touch-up manoeuvre of 2.4 mm/s was executed two days later.

Table 3. Manoeuvres executed on Sentinel-2C during the tandem phase with Sentinel-2A

#	Mid time OCM (UTC)	OCM type	Duration (s)	Commanded delta-v (m/s)	Calibrated delta-v (m/s)	Perf. Error (%)
1	2024/10/31-14:32:37.650	IPP	5.3	0.0150	0.0146	-3.1
2	2024/11/06-09:51:18.898	OOP/IPP	314.1	0.9325/0.0530	0.9344/0.0537	+0.2
3	2024/11/08-12:00:00.440	IPP	0.9	0.0024	0.0025	+3.2
4	2024/11/23-03:21:56.081	IPR (CAM)	7.3	-0.0200	-0.0207	+3.2
5	2024/11/23-05:02:38.069	IPP (CAM)	7.3	0.0200	0.0206	+3.2
6	2024/11/27-10:52:04.896	IPP	11.0	0.0300	0.0309	+3.0
7	2024/11/29-11:32:17.614	IPP	1.0	0.0028	0.0029	+3.0
8	2024/12/18-10:48:25.601	IPP	10.0	0.0280	0.0283	+0.9

Almost two weeks later, a relatively large CAM of 12 cm/s was executed on S2A. Only three days later, a small CAM of 2 cm/s was needed on S2C. Both CAMs were executed nominally and had minimal effect on the tandem configuration (see Fig. 15). A few days later, an orbit maintenance manoeuvre was required and executed on S2A. The tandem control approach was applied to S2C, nicely aligning the ground tracks again.

Table 4. Manoeuvres executed on Sentinel-2A during the tandem phase with Sentinel-2C

#	Mid time OCM (UTC)	OCM type	Duration (s)	Commanded delta-v (m/s)	Calibrated delta-v (m/s)	Perf. Error (%)
1	2024/11/06-16:33:36.702	OOP/IPP	422.5	0.9203/0.0563	0.9225/0.0567	+0.2
2	2024/11/19-23:03:08.056	IPR (CAM)	55.2	-0.1200	-0.1184	-1.4
3	2024/11/20-00:43:49.963	IPP (CAM)	55.2	0.1200	0.1188	-1.0
4	2024/11/27-16:16:58.379	IPP	16.5	0.0340	0.0345	+1.5
5	2024/12/18-15:33:19.704	IPP	13.2	0.0273	0.0279	+2.2

Fig. 15 shows the comparison of the S2C GT with that of S2A for the complete tandem phase of 50 days. Note, the across-track difference remained below the 100 m level all the time. During this time also the eccentricity and inclination of S2C were kept very close to that of S2A. Consequently, the across-track difference at all latitudes remained well below the 100 m level.

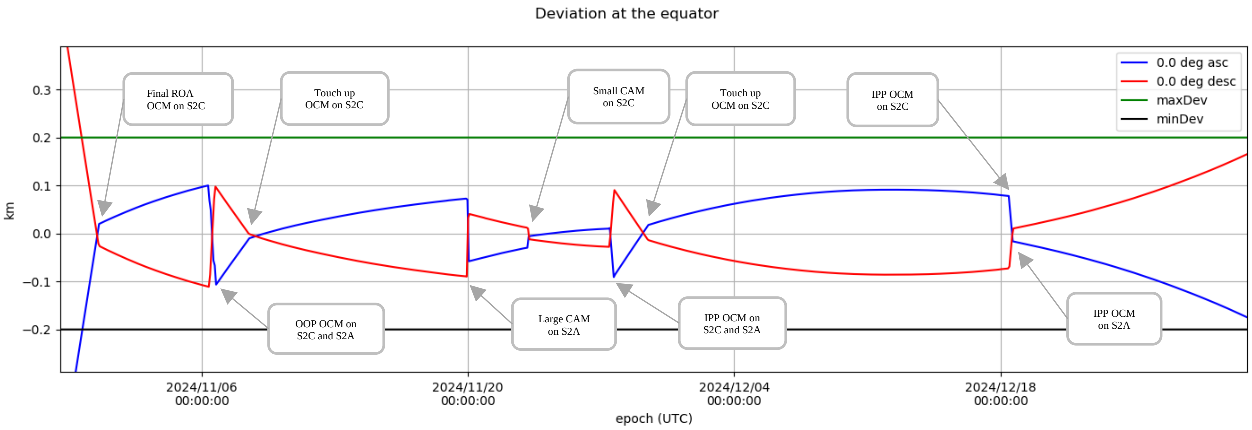

Fig. 15. Comparison of Sentinel-2C ground track with that of Sentinel-2A during the tandem phase

The along-track separation between S2C and S2A during the complete tandem phase is presented in Fig. 16. Note the along-track separation remained constant at 27.50 ± 0.25 seconds the entire tandem phase. The MSLT remained even more constant.

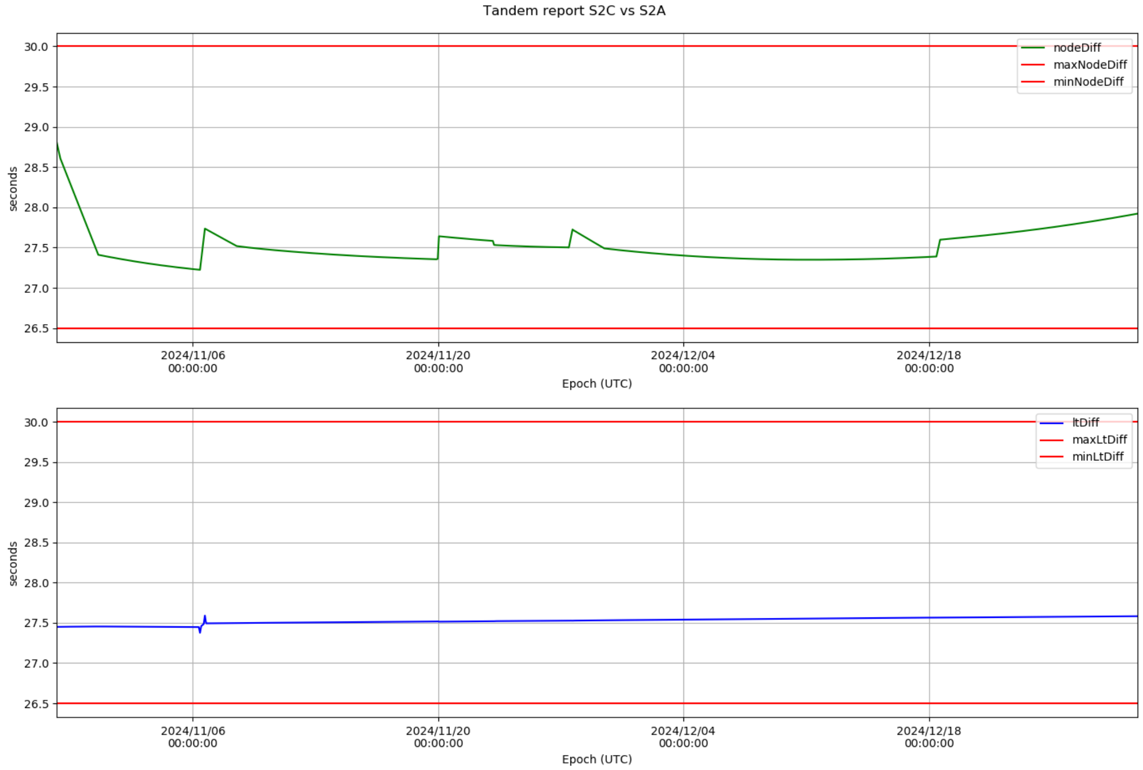

Fig. 16. Evolution of the along-track separation and MSLT between Sentinel-2C and Sentinel-2A during the tandem phase adopting the "Same Ground Track" strategy.

3.2. Relaxing the satellite constellation after the tandem phase

The tandem phase between Sentinel-2C and Sentinel-2A ended with the IOCR on 19 December 2024, even though the across-track separation stayed below the 700 m level well past the end of the year. On 18 December 2024, both S/C were manoeuvred for orbit maintenance, executing a slightly bigger manoeuvre on S2C than S2A, which introduced a slow drift apart (see Fig. 15). Sentinel-2A has broken the formation at the end of January, while Sentinel-2C stays in the same orbit position, already compliant with the nominal orbit requirements in terms of MSLT and ground-track. An OOP manoeuvre plan has been established to slowly drift the MSLT towards the operational 22:30 MSLT time by the end of 2025.

4. Conclusions and recommendations

Prior to the launch of Sentinel-2C on September 5, 2024, a tandem phase with Sentinel-2A during its commissioning was deemed necessary. Requirements for orbit control during this phase were established, leading to the identification of two worthwhile strategies:

1. **Drifting Strategy:** This involves flying the satellites at slightly different altitudes with weekly manoeuvres (executed one day apart on each spacecraft) to maintain separation.
2. **Same Ground Track Strategy:** This involves flying the satellites at the same altitude most of the time, performing orbit maintenance manoeuvres as needed, including touch-up manoeuvres two days later to correct any residual drift.

Both strategies were evaluated through extensive simulations over a 60-day period, considering average solar activity conditions around the launch of Sentinel-2C. The simulations included manoeuvre performance errors, orbit maintenance manoeuvres, and collision avoidance manoeuvres. Results indicated that both strategies were viable.

After analysing the advantages and disadvantages, the "Same Ground Track" strategy was selected for the tandem phase operations. This strategy was chosen because it offers tighter control of across-track differences, reduces the workload on operators (less manoeuvres to implement), and does not require adjustments to the orbit maintenance of the leading satellite in routine operations.

On October 31, 2024, Sentinel-2C reached its tandem position, exactly 27.5 seconds behind Sentinel-2A, following the same ground track. Despite differences in manoeuvre performances between the two satellites, two collision avoidance manoeuvres, and an inclination orbit maintenance manoeuvre required on Sentinel-2A, the cross-track separation remained well below the 100-meter level at all latitudes for the entire tandem phase that lasted 50 days. The along-track separation stayed almost constant at 27.5 seconds, adhering to the selected strategy.

The results demonstrate the effectiveness of the chosen orbit control strategy and the overall success of the tandem phase in maintaining high data quality and operational reliability, paving the way for future tandem operations with the Copernicus missions.

Disclaimer

The views expressed herein can in no way be taken to reflect the official opinion of the European Space Agency or the European Union.

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