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Sentinel-1B End-Of-Life Operations

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Abstract

The end-of-mission of the Sentinel-1B spacecraft was declared in 2022 and since then, teams from Industry and the operator, ESA, have conducted post-mission disposal activities. This paper provides an in-depth look into the complexities of these end-of-life operations, particularly focussing on this example of a large institutional spacecraft that was designed at a time when space debris mitigation was not as much of a design driver as it is today. This paper will highlight the objectives, strategy definition, and challenges faced during the deorbiting and passivation process, including the significant difference between the pre-launch assumptions, the adopted end-of-life plan and the operational reality.

Sentinel-1 is the first mission under the EU Copernicus program and consists of an operational pair of Synthetic Aperture Radar satellites in a 693 km dawn-dusk polar orbit. The second of these spacecraft, Sentinel-1B, launched in April 2016 with a projected service duration of seven years unfortunately encountered a critical payload power supply failure in December 2021. This malfunction led to the termination of its mission in August 2022, prompting the commencement of decommissioning activities to adhere to space debris mitigation policies. Originally, the spacecraft was designed to be deorbited to meet the guideline of not exceeding a remaining orbital lifetime of 25 years. Although the deorbit process was scheduled to be completed within 2023, it continued into 2024 due to unexpected complications.

Formulating the deorbit strategy necessitated evaluating the spacecraft's potential to function in an altitude below its intended orbit and new ways of using the propulsion system to achieve the necessary disposal delta-v. Determining a reliable estimate of the residual orbital lifetime because of these activities was a further key challenge, requiring that assumptions were reduced to the greatest extent feasible.

The document will outline the development of this strategy and delve into the substantial modifications it underwent as the deorbit proceeded. We faced various issues and unforeseen spacecraft behaviour, specifically with AOCS, Thermal, and notably with our propulsion system. The document will discuss these challenges and the solutions implemented to address them.

Alongside deorbiting, the craft's final passivation at its end of life was evaluated. However, fully eliminating all energy sources wasn't possible because of design constraints and the issues encountered during the deorbit. Although the partial passivation lessened fragmentation risks, it didn't align completely with the original campaign goals or the updated ESA space debris guidelines. Nonetheless, the deorbit adhered to the 25-year guideline, keeping the lasting effects on space debris minimal.

As well as describing these activities, the paper will look at lessons learned for the remaining Sentinel-1 spacecraft and for end-of-life operations in general. This includes the limitations identified in pre-launch preparations compared to what was necessary in flight. Additionally, it involves highlighting common anomalies that could arise and crucial considerations during the conception and planning of end-of-life activities.

In conclusion, the disposal of Sentinel-1B was an intricate balance between comprehensive planning and operational agility. It offers critical insights for future disposal of missions in an increasingly congested orbital environment, reinforcing the need for adaptive strategies to ensure the sustainability of space operations.

Keywords: Sentinel-1, Disposal, Deorbit, Operations Experience, End-Of-Life, Space Debris

1 Introduction

The Sentinel-1B satellite, part of the European Union's Copernicus program, has played a crucial role in Earth observation since its launch in 2016 [1][2][3]. However, following a power system anomaly in December 2021, Sentinel-1B was ultimately declared unrecoverable, leading to a need for deorbiting and disposal planning in compliance with space debris mitigation guidelines. This paper presents the strategy developed for Sentinel-1B's end-of-life operations, detailing the technical challenges, operational constraints, and regulatory considerations involved in safely deorbiting the satellite.

The disposal of Sentinel-1B serves as a critical case study for future missions, particularly within the Sentinel-1 program, which continues with the upcoming launches of Sentinel-1C and 1D. By examining the lessons learned from this disposal process, this paper aims to contribute to the evolving best practices for responsible satellite end-of-life management in low Earth orbit.

2 Sentinel-1B Anomaly and End of Mission

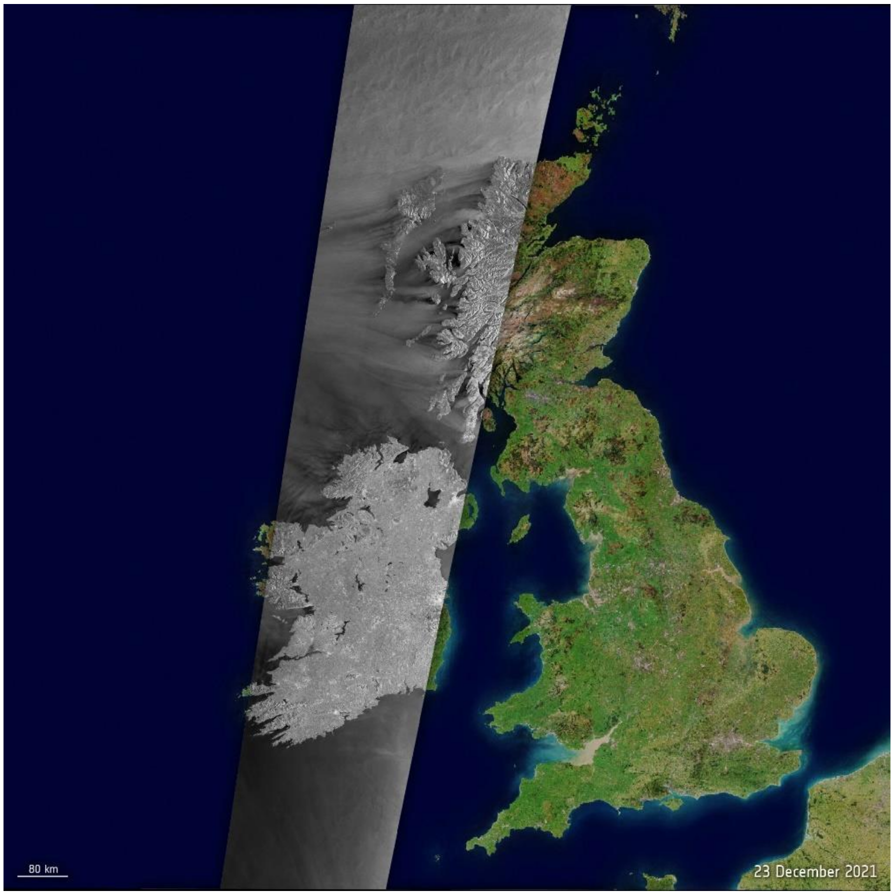


Fig. 1 Final Image Captured by Sentinel-1B on 23 December 2021

On the evening of December 22, 2021, the main instrument of Sentinel-1B – a C-Band Synthetic Aperture Radar (CSAR) – started generating event messages indicating issues with the power supplied to it. The following morning December 23, 2021, a major anomaly occurred when the instrument stopped responding on the main avionics 1553 data bus. This initial failure also caused blockages on the 1553 bus that prevented some commands of the spacecraft's autonomous thermal control, resulting in overheating of propulsion system elements. The initial anomaly response involved switching off the CSAR payload to unblock the bus and restore full thermal control. This was effective and further analysis determined that the overtemperature on the propulsions system did not cause any damage. However, initial attempts to power on the CSAR were ineffective. Investigations quickly focused on the spacecraft's CSAR Antenna Power Supply (CAPS) unit, as telemetry data indicated a failure in the 28V regulated power bus, which supplies power to the SAR electronics. This unit features redundant regulators, but it appeared that neither regulator was responding to commands.

The subsequent root cause investigation [4] identified a probable failure mode linked to a ceramic capacitor used in the power regulators. This component had been reworked during manufacturing using a now-obsolete soldering process, which may have introduced latent defects. Specifically, the capacitor was replaced due to a non-compliance issue detected during production, and the subsequent repair used a soldering method that, while meeting product assurance standards at the time, was later deemed unreliable and prohibited under revised ECSS standards in 2017. The failure of both the main and redundant 28V power regulators suggested a common-cause failure, likely due to degradation or failure of this component over time. Despite extensive recovery attempts, including various command sequences to reactivate the regulators, changes in power cycling, temperature variations, and burst-mode command executions, no sustained recovery of the CAPS power system was achieved. The only momentary response observed was a brief 4.4-second activation of the main power regulator during a rapid command burst, after which it autonomously reverted to the OFF state.

While this response provided valuable diagnostic insight into possible failure modes, it did not restore operational functionality. Additional analyses considered the possibility of independent failures of both regulators, but the evidence strongly supported the hypothesis of a common failure mechanism, most likely linked to the compromised capacitors. Investigations further revealed that this defective soldering process had been applied to both Sentinel-1A and Sentinel-1B, raising concerns over Sentinel-1A's long-term reliability. However, Sentinel-1A's CAPS unit continued to function nominally, and additional monitoring measures were implemented to track its performance closely. To prevent similar issues in future missions, Sentinel-1C and Sentinel-1D underwent design modifications, including an improved electrical layout for the CAPS unit and a shift to cold redundancy operation, enhancing overall reliability and mitigating the risk of a similar power system failure. Additionally, as part of the response strategy, ESA increased the use of Copernicus Contributing Mission (CCM) data, particularly from Radarsat-2 and other C-band missions, to compensate for the loss of Sentinel-1B’s observational capacity.

On August 3, 2022, with no further recovery actions possible and Sentinel-1B unable to fulfil its mission, ESA officially declared the end of the Sentinel-1B mission [5], confirming that the spacecraft would no longer be able to support operations due to the failure of its payload. Following this decision, and with the spacecraft platform in an otherwise healthy state, the focus shifted to ensuring a safe and controlled deorbiting process while minimizing any risk to other space assets. This process was kicked off shortly after the end of mission was declared, with the plan being to conduct a nine-month preparation phase pausing before actual execution of the deorbiting campaign until after the launch and commissioning of Sentinel-1C, which at the time was planned for March 2023.

3 Disposal Goals

After the end of the mission, the preparation phase was the first step in planning the disposal of Sentinel-1B – this phase was planned to last nine months and encompass not only the scheduling of deorbiting but an assessment of the goals of the campaign, the technical feasibility, any necessary preparatory studies or procedure implementation and the management of the campaign.

The first step in this phase was to set out the goals of the disposal campaign. ESA has a space debris mitigation policy that applies to all missions operated by the Agency and by the end of the disposal campaign the (at time of writing) regulation that was universally applicable was the *ESA Space Debris Mitigation Policy (ESA/ADMIN/IPOL(2023)1)* [6]. However, a phased approach to introducing the new regulation was adopted and as such the policy applicable at the time of the Sentinel-1 FAR/QAR was considered applicable. This was the *ESA Space Debris Mitigation for Agency Projects (ESA/ADMIN/IPOL(2008)2)* [7] with the two key applicable requirements being the following:

1. **OR-01:** Space systems operating in the LEO protected region shall be disposed of by reentry into the Earth’s atmosphere within 25 years after the end of the operational phase.
2. **OR-02:** Passivation of a space system shall be completed within two months after the end of the operational phase. This includes launcher stages which remain in orbit.

3.1 Orbit Lowering Goal

Satisfying **OR-01** required lowering the orbit of the spacecraft from the operational orbit of 693km to an altitude where the remaining duration in orbit after passivation would be less than 25 years. The task of assessing the actual orbit that would achieve this result was conducted by the ESA Space Debris Office. Defining a reliable number proved to be one of the greatest challenges of the disposal process, as several assumptions had to be made that significantly influence the final outcome. Some of these, such as the semi-major axis, or the spacecraft mass were deterministic based on the planned deorbit activities, but others needed to be estimated. It was found that Argument of Perigee and

Coefficient of Reflection had negligible impact on the re-entry duration but the solar activity, Drag Coefficient (C_d) and assumed cross section area could have a significant impact.

The first of these assumptions was the solar activity that would be experienced over the remaining lifetime in orbit. 25 years covers more than 2 solar cycles. To perform this, three methods were considered:

1. The default in the ESA DRAMA tool, based on ISO 27852, where the average of the last 13 cycles is taken and corrected by a factor derived from the current sunspot number.
2. A best and worst case, where for each predicted month the best (<75% of cases) and worst (> 25% of cases) samples are taken from past data.
3. Monte Carlo sampling, again based on ISO 27852, where random samples are taken form the last observed cycles.

The use of these methods showed a wide variation in outcomes and a strong sensitivity on the remaining time in orbit to the chosen solar activity prediction. For example, in one of the test cases, method 1 gave a figure of 22.81 years, while method 2 gave an interval from 12.34 to 36.51 years and method 3 gave 11.92 years. In order to have a basis for comparison it was decided to take the worst case (i.e. maximum lifetime) of Method 1 and Method 2.

The next assumption was the assumed C_d, where an average value of 2.2 was selected. Nonetheless analysis was performed on the sensitivity to this number, assuming a possible range of 1.8 to 2.8. The lower end of the range, 1.8, resulted in a 23.16% longer residence time in orbit than with 2.2. The higher end of the range, 2.8, resulted in a 31.7% shorter residence time in orbit than with 2.2. Therefore for residence duration of 25 years, assuming a C_d of 2.2, the actual residence duration could range from 17.1 (C_d 2.8) to 30.8 years (C_d 1.8).

The final variable was the assumed cross-sectional area of the spacecraft after the passivation. This was a major challenge because once the spacecraft is switched off there would be no active attitude control.

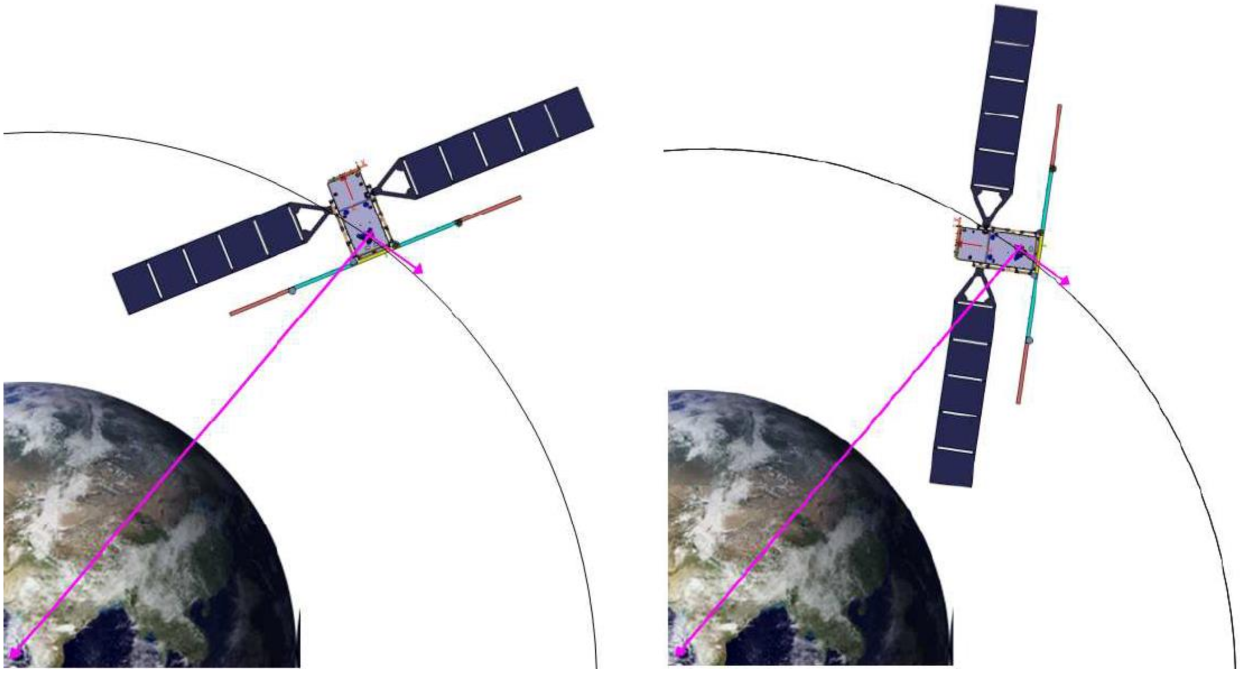


Fig. 2 Statically Stable Attitudes for Sentinel-1

The following possible attitude cases were considered for analysis:

1. Random tumbling – this is the default for analysis as it requires no attitude knowledge of the spacecraft. In this case the cross section was assumed to be 23.3 m^2
2. Stable attitude – analysis suggested that without attitude control, the spacecraft was mostly likely to settle into one of two statically stable attitudes (See Fig. 2) based on drag and gravity gradient stabilisation. This

resulted in an attitude pitched 60 or 120 degrees from nominal. In this attitude two cross sectional areas were considered:

  a. Arrays face-on – in this case the arrays would be rotated to create maximum drag, resulting in a cross-section of 27.62 m^2
  b. Arrays edge-on – in this case the arrays would be rotated to create minimum drag, resulting in a cross-section of 12.25 m^2

This also showed a strong sensitivity in the remaining orbital lifetime, for example, for all other assumptions fixed, this resulted in a lifetime of 24.62 years for Case 1, 22.81 years for Case 2a and 47.97 years for Case 2b. Ultimately a trade-off was made that it was more important to point the solar arrays in such a way as to minimise the chance of the battery recharging following passivation, which also resulted in the minimum cross section, so Case 2b was used.

Taking all of these assumptions into account, a final reference target was determined to achieve 25 years remaining in orbit, and the resulting orbit had a perigee of 582 km and an apogee of 628 km. It should be noted that this was the minimum goal for the deorbiting, as discussed in Section 4.4, it was considered possible to improve on this and go even lower, further reducing the time remaining in orbit.

3.2 Passivation Goal

The goal of spacecraft passivation was the removal and isolation of all stored energy sources on the spacecraft. This was identified as having three components:

- *Removal of fuel* – the fuel in the tank of the spacecraft represents a source of chemical energy and the associated pressure also acts as stored energy. Sentinel-1 is not designed with a valve to vent fuel or depressurise the tank in orbit so the only mitigation possibility was to burn the fuel using the thrusters until the tank was empty.
- *Removal of kinetic energy* – the only stored kinetic energy on the spacecraft is in the four reaction wheels. The mitigation here is simple and it was clearly part of the passivation goals that the reaction wheels were brought to zero speed before switch-off. Any attitude rates could also be considered a form of kinetic energy and therefore it was considered desirable to leave the spacecraft in a stable attitude that was likely to be passively stable.
- *Removal of electrical energy* – the other major goal of the passivation was the removal of electrical energy. The simpler part of this was a goal to switch off all units and isolate them as far as possible by opening the latching current limiters. The more challenging part of the goal was depletion of the charge in the spacecraft batteries and the prevention of their future charging. Depletion of the battery charge is something that could be naturally assured if the recharge could be prevented, however Sentinel-1 does not have the ability to disconnect the battery charge circuit. Therefore the only mechanism available is to assume a stable attitude and point the solar arrays in such a direction as to prevent charging.

It was therefore concluded that although complete passivation was not possible for Sentinel-1B, we would at least adopt the goals to deplete all remaining fuel, remove all kinetic energy and prevent, as far as possible, the charging of the batteries.

4 Technical Preparation

Following the initial definition of the goals of the campaign, the next step was the technical implementation. This consisted of a number of studies to determine how to operate the spacecraft during the deorbit phase and how to plan the deorbiting campaign.

4.1 *Manoeuvre Options*

The Sentinel-1 spacecraft is designed with seven 1N thrusters – three used for orbit control in the prograde, retrograde and out-of-plane direction, as well as four on the spacecraft’s Z-axis which are designed to provide attitude control after initial separation and in certain failure modes of the spacecraft. These are shown in Fig. 3 below:

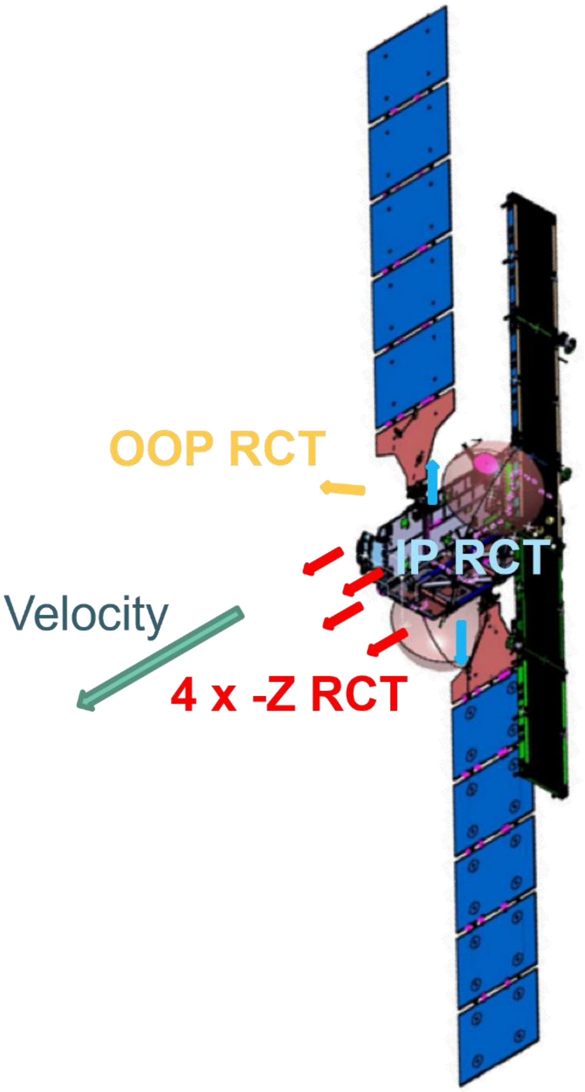


Fig. 3 Sentinel-1B Thruster Directions in Pitch Slew Attitude

As designed, the in-plane retrograde thrusters (prime and redundant) would be responsible for performing the orbit lowering activities. However, there is a design issue on the Sentinel-1 spacecraft that causes the Solar Array and CSAR antenna to impinge the thruster plumes. This causes torque build-up on the spacecraft which ultimately cannot be countered by the reaction wheels. To mitigate this, the Sentinel-1 spacecraft has strict limitations on the burn duration and therefore delta-v that can be performed in a single burn using the prograde/retrograde thrusters that are impacted by plume impingement. In the case of Sentinel-1B, the retrograde thruster at the start of the deorbiting campaign was limited to a maximum delta-v of 1.6 cm/s per burn in order to keep torque build-up under control. After each of these small burns there would need to be a wait period of at least half an orbit before the next burn could be performed. The advantage of these burns was that they were the same type of manoeuvre executed throughout the mission for routine orbit maintenance and therefore were well validated and considered completely safe. However, the major disadvantage was that with such a small amount of delta-v available per-burn it would take 10000 manoeuvres to complete the necessary delta-v to perform the orbit disposal.

To perform a higher delta-v there were two other manoeuvre options considered – called yaw slew and pitch slew. The yaw slew manoeuvre was used during the initial orbit acquisition of Sentinel-1B and involved yawing the spacecraft by 90 degrees and using the out-of-plane thruster to perform the manoeuvre. This had the advantage that it had been previously tested, and as the out-of-plane thruster had no plume impingement issues could execute burns of up to 600 seconds or 24 cm/s. However, the process of yawing the spacecraft was very operationally intensive and thermal and power issues in the yawed attitude meant that the spacecraft would have to be slewed to that attitude and back again for every single burn. Effectively this would mean a maximum of one yaw slew OCM per day, with approximately 250 yaw slews being needed. This would allow completion within a year of the deorbiting campaign but at significant cost to the team resources.

Ultimately, it was decided that the bulk of the orbit lowering would be performed using a new manoeuvre mode – the pitch slew (as shown in Fig. 3). In this case the satellite was pitched 90 degrees, pointing the Z face of the spacecraft in the flight direction and using the four attitude control thrusters together to perform the deorbit burns. This gave a good delta-v per manoeuvre of 700 seconds burn duration and 0.7m/s delta-v. In addition, the pitched attitude, while not nominal, was stable from a power and thermal attitude so the spacecraft could be slewed to that attitude and then remain there between deorbit burns. The disadvantage of this manoeuvre type was that it was never part of the original spacecraft design and so all of the necessary work to implement and validate it had to be performed as part of the preparation phase, taking a significant amount of effort by both the satellite manufacturer and the operations team. This included checking the feasibility of such an operation, including modelling the power and thermal effects as well as the visibility of the antennas on board, such as the GPS antenna and the S-Band TT&C antennas. It also included modelling of the burn performance with the four attitude thrusters and the development and testing of procedures to perform the burns. Finally, as this mode had never been used in flight, there was concern of a catastrophic failure causing the spacecraft to be lost in the operational constellation orbit. The likelihood was considered extremely low but as the impact would have been severe, it was decided that the operational orbit would initially be cleared using the known retrograde thrusters before testing and then ultimately performing the bulk of the orbit lowering using these pitch slew manoeuvres.

4.2 Ground Station Planning

There were a number of issues with the scheduling of ground stations that had to be considered during the preparation of the campaign, as described in the following sections.

4.2.1 Overlapping visibility

The two Sentinel-1 spacecraft during routine operations are maintained 180 degrees apart in orbit and therefore there is maximum separation between the spacecraft during ground station visibility. This is important to avoid the need for the spacecraft controller to have to take simultaneous passes for both spacecraft. In addition, the spacecraft have the same transmitter and receiver so if both enter the same antenna beam then there will be interference between the spacecraft.

During the deorbit operations, the position of the two spacecraft relative to one another would start drifting as soon as Sentinel-1B left its operational orbit. This would be initially a gradual drift during the early slower parts of the orbit lowering but then rapidly speed up for the bulk lowering of the orbit. Fig. 4 shows the angular separation of the two spacecraft during the first year of deorbit operations:

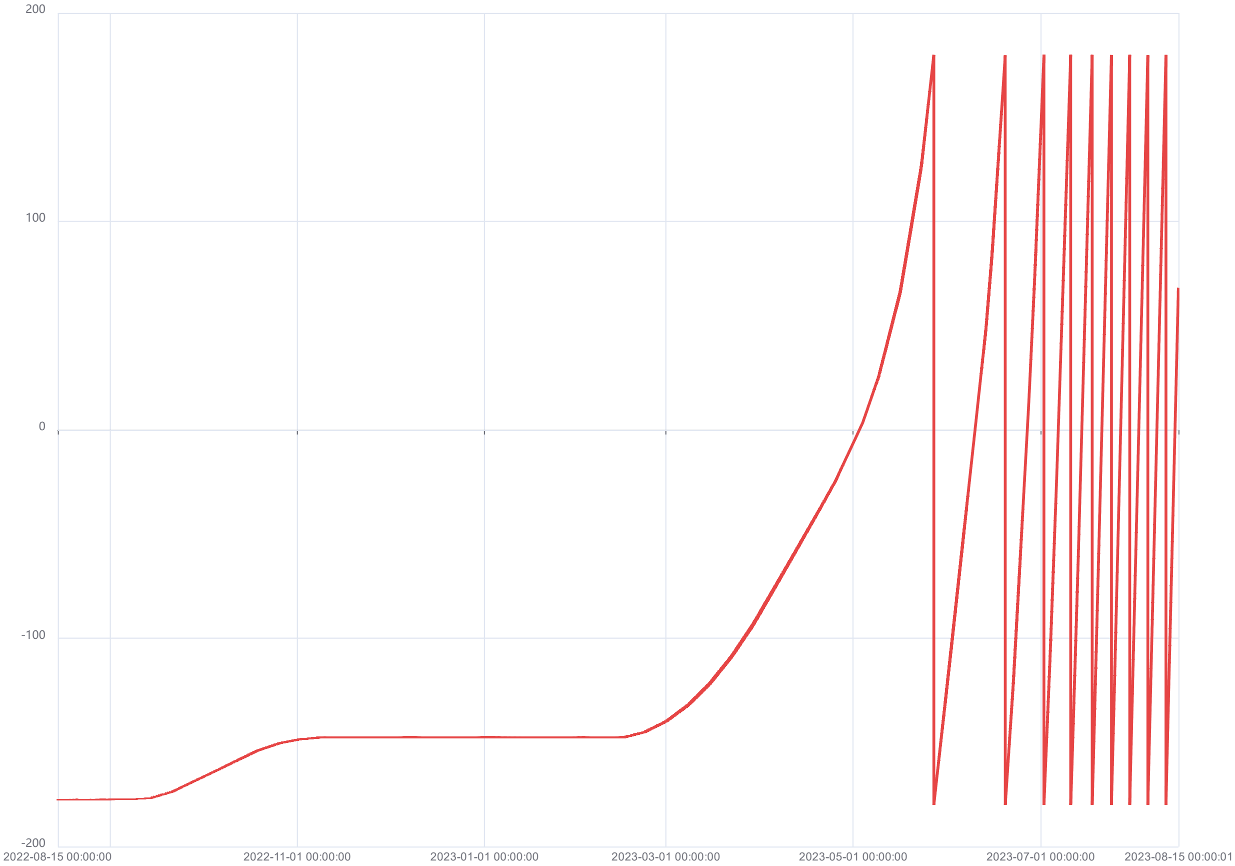


Fig. 4 Angular Separation between Sentinel-1B and Sentinel-1A during first year of deorbit operations

To mitigate the impact of the ovelap period, daily predictions were produced by the Flight Dynamics team based on the position of the two spacecraft, indicating whether they would occupy the same position in the sky. This was not just a question of the angular position in the orbit, as shown above, because as the altitude of Sentinel-1B decreased there was also a significant change in geometry.

To mitigate any impact of the co-location of the two spacecraft, scheduling rules were adopted to ensure that overlapping or adjacent passes were not booked. This allowed sufficient separation between passes for the spacecraft controller but also ensured that there were no interference issues, although ultimately direct geometric overlap was rare so the potential for interference was minimal.

4.2.2 Antenna Polarisation

The Sentinel-1 spacecraft has two omni-directional S-Band antennas on opposite sides of the spacecraft. In nominal attitude one is pointed in the Nadir direction and the other in the Zenith direction (see Fig. 5).

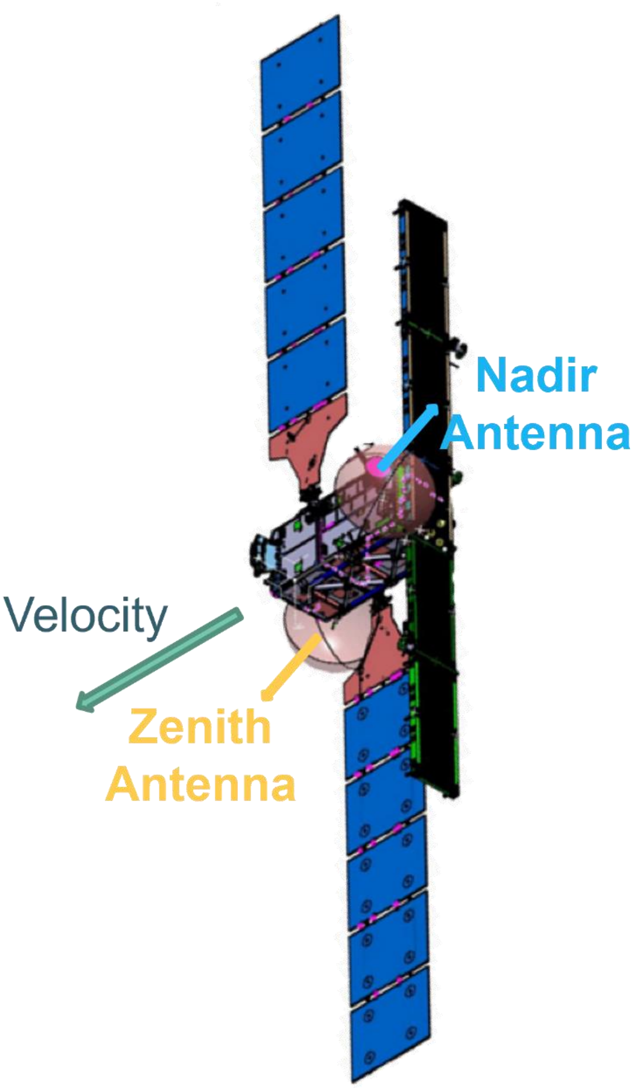


Fig. 5 Sentinel-1B antenna configuration in pitched attitude

However, as the plan was to adopt the pitched attitude for the duration of the deorbiting campaign, it was possible that either of the antennas would be visible to the ground station depending on the direction of the spacecraft track over the ground station.

To allow for differentiation between the two antennas on the spacecraft, each has a different polarisation. In the pitched attitude it was determined that while passing over a ground station, the pass could start on one antenna and conclude on the other. While the downlink signal is combined at the ground station, this could result in the loss of the uplink so during the preparation phase a new Flight Dynamics product was defined that would predict for the operators when to use which polarisation. It was then coordinated with the whole ground station network in use to be prepared for an uplink polarisation swap during the pass. This then became a routine operational task during pass conduction while in the pitched attitude – the on-console operator used the polarisation product to instruct the ground station to perform a polarisation swap at the correct point.

4.2.3 Drift in case of missed OCM

Given the size of the deorbit OCMs being performed, there was a risk that if an OCM was missed there would be a significant shift in the actual compared to predicted along-track position of the spacecraft. Based on the S-Band ground station network in use by Sentinel-1, it was assessed that the station could acquire the spacecraft up to 5 seconds early or later compared to its nominal position. Calculations were performed to assess the amount of change in delta-v from expected to executed that would breach this threshold. It was found that a difference in executed delta-v of 2 m/s compared to what was planned would result in a drift of 4 seconds per orbit.

Taking margin this value of 2 m/s was therefore taken as the maximum amount of delta-v that could be planned without ground station coverage, and it was defined that there should be a ground station pass within one orbit of the last delta-v. This ensured that even if no delta-v was performed, for example due to an on-board anomaly, the ground station would still be able to acquire. Although there would be subsequent drift after this, the offset obtained from that first pass after the burns could be propagated forward to ensure good acquisition in the following passes. However, it should also be noted that in case of missed burns there needed to be an immediate loop with the ground station scheduling team because after 2-3 days the pass timing could drift so far as to invalidate the planned times of ground station contact.

4.3 Space Debris screening for large OCMs

A further area of study was the screening strategy for collision risks with space debris. As with the ground station planning mentioned in Section 4.2.3 above, there was a concern that an under or overperformance of the thrusters could result in the spacecraft drifting outside the volume screened for space debris. This volume is an ellipsoid of approximately 25 km (along-track), 25 km (across track) and 2 km (radial). The analysis performed showed the maximum deviation from expected to executed delta-v should remain below 4 cm/s to remain within this volume for approximately 60 hours. This represented a 2% total over or under performance of the planned maximum batch size of 2 m/s, which was considered in line with the expected performance variation of the thrusters.

The issue with this analysis was that it did not account for a complete failure of the burns to take place (e.g. due to on-board autonomy suspending the burns). Given that this would be a highly unusual scenario, and would not happen in densely populated orbits, it was considered during the planning phase that no specific action was necessary to cover this scenario, although this was revisited during execution (see Section 6.4) and was ultimately what led to the suspension of the deorbit campaign.

4.4 Minimum Operational Altitude for the Spacecraft

The next major area of study was attempting to determine how low the spacecraft could be safely operated. Given the importance of passivating the spacecraft at the end of the disposal process it was mandatory that the spacecraft remained under control for the whole process. The key concern was the ability of the AOCS sensors and actuators to operate at lower altitude than their design altitude of 693 km. This involved several considerations:

4.4.1 Attitude Control at Lower Altitude

The first task that was performed was to assess whether the spacecraft attitude control could be overwhelmed by the increased attitude perturbations at lower altitudes. Specifically, the drag effect, the solar radiation pressure and the gravity gradient effect on the spacecraft while in either nominal attitude or pitched attitude were modelled by the TAS-I ADELE simulation software. These studies were conducted down to a minimum altitude of 350 km.

In all cases no build-up of angular momentum was observed on the reaction wheels even at lower altitudes and although the simulation showed higher attitude errors at lower altitudes, it was always below $2x10^{-3}$ radians and therefore well within the FDIR limits of the spacecraft attitude.

Therefore it was concluded that even at very low altitudes there was no concern with the ability of the spacecraft to maintain attitude control/

4.4.2 Precise Orbit Determination Performance

The Sentinel-1 spacecraft has a Precise Orbit Determination function that fits sensor data from the GPS receiver to determine its position in orbit. For the higher-level attitude and orbit control functions to work properly this function needs to be active, therefore it was investigated what the effect would be of operating at a lower altitude.

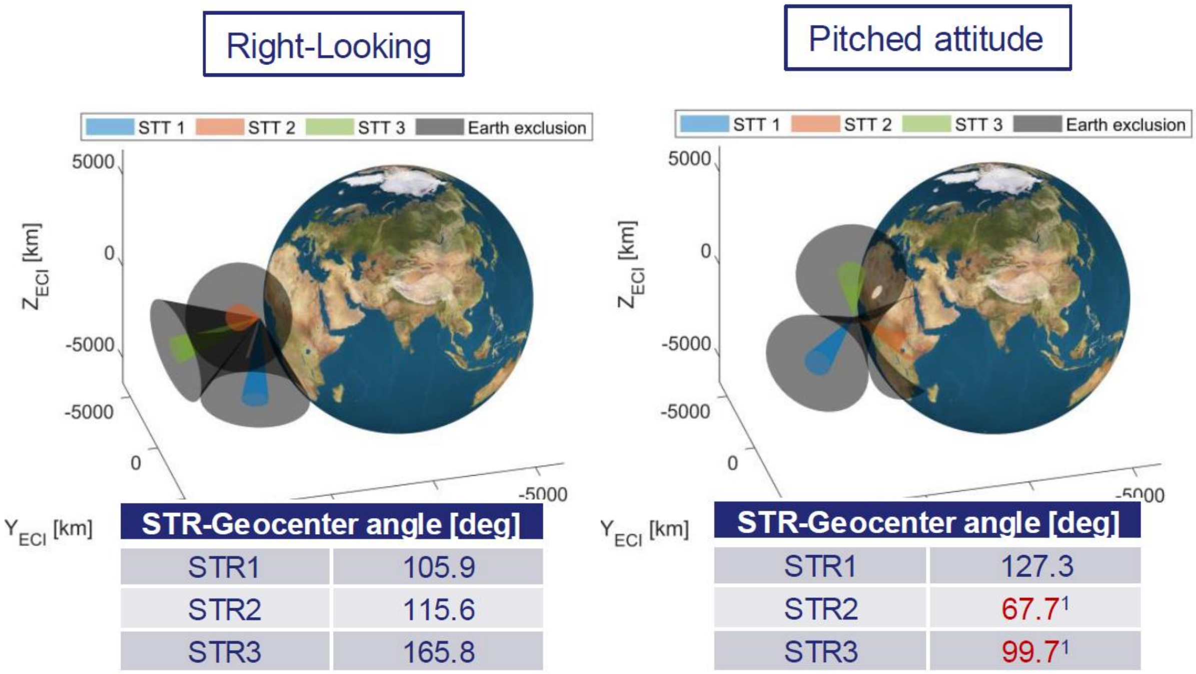
It was found that the function would operate properly, even at significantly lower altitudes but as it incorporates a complex model of the spacecraft orbital dynamics, a number of updates were necessary to allow it to properly model the spacecraft orbit as it descended:

- The function contains a reference altitude table that contained Min/Max atmospheric density parameters but did not go low enough for the full range of the disposal. This table was extended with new predicted values for these density values.

- The spacecraft mass assumed when calculating acceleration due to drag required updates throughout the deorbiting process as the fuel depletion caused a significant shift in the overall assumed mass of the spacecraft
- Operating at lower altitude, with non-nominal GPS antenna pointing and a higher drag environment could have caused the precise orbit determination function to fail to converge. Therefore adjustments were also made to widen the thresholds of uncertainty that it would accept, which was considered safe considering that the mission was not operational.

4.4.3 Star Tracker Blinding

Another key issue was the ability of the Star Trackers to properly determine the spacecraft attitude. The three star trackers on Sentinel-1 are designed to provide an unobstructed view of the sky (aside from temporary blindings by the Moon) in the nominal attitude and the nominal altitude. When lowering the altitude the key issue that was found was that the increasing angular size of the Earth would cause it to enter the field of view of the star trackers at a given altitude (see Fig. 6).



STR-Geocenter angle [deg]	
STR1	105.9
STR2	115.6
STR3	165.8

STR-Geocenter angle [deg]	
STR1	127.3
STR2	67.7[1]
STR3	99.7[1]

Fig. 6 Sentinel-1B Star Tracker view directions in nominal Right-Looking pointing and deorbit Pitched Attitude

While one star tracker would always remain unblinded, it was considered for robustness of operations that we could only operate with a minimum of two available star trackers. The critical star tracker in the attitude we would be in for disposal operations was STT-3. In this attitude the angle between the boresight of this star tracker and the Earth Geocentre would be 99.7 degrees, assuming a circular orbit. Considering that a 30-degree exclusion cone from the boresight to the Earth must be maintained, it was therefore determined that as soon as the earth reached an angular size in the star tracker field of view of 69.7 degrees we would have to consider the star tracker as occulted. By calculating the apparent size of the Earth for different altitudes, it was found that in a circular orbit the star tracker would be usable down to almost 420 km altitude (see Fig. 7). This therefore became the lower bound for operability of the spacecraft.

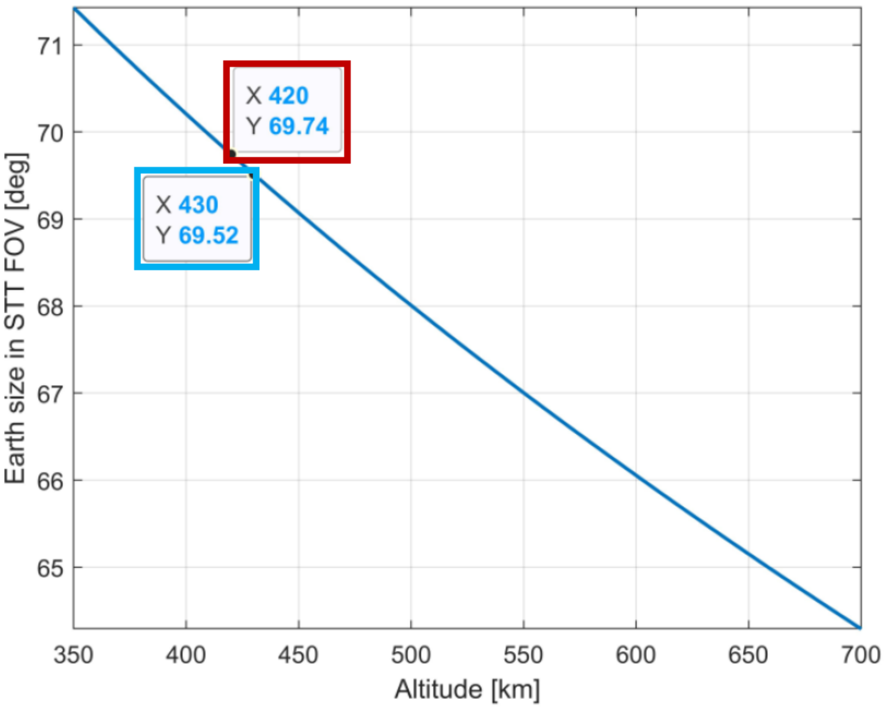


Fig. 7 Size of Earth in Star Tracker field-of-view as a function of altitude

5 Disposal Plan

Based on all the above considerations, a multi-phase disposal plan was developed to ensure the goals in Section 3 were met. As well as meeting the goals, there were several key constraints and trade-offs that fed into the plan development:

1. **Spacecraft Safety:** Given the responsibility as operators of an active spacecraft to mitigate any potential collision risk, spacecraft safety was considered of paramount importance. It was a key principle of the disposal plan that until the spacecraft was safely passivated, we would not accept any higher operational risk than during routine operations. This meant that we did not want to push the envelope of satellite capabilities any further than necessary or conduct unnecessary operations as this could increase the risk of a premature loss of spacecraft control.
2. **Resource Profile:** Executing the disposal as rapidly as possible would have meant a large, temporary increase in resources – potentially involving working around the clock with increased ground station coverage. The alternative was a much longer period of disposal operations but ultimately this is what was chosen as it allowed us to conduct all disposal operations within the routine resource envelope for Sentinel-1 operations.
3. **Target Disposal Orbit:** This was the final trade-off – what orbit would we target as an end result. The key options were either a circular lowering, reducing as far as possible both the perigee and apogee, or moving to an elliptical orbit, reducing primarily the perigee alone. The elliptical approach would be most efficient in terms of remaining lifetime in orbit, as it would allow a much lower perigee, placing the spacecraft in a higher drag regime for the highest velocity part of the orbit. However, the circular approach was chosen, first because just lowering the perigee would have caused the spacecraft to operate for parts of the orbit below the minimum identified safe altitude (see Section 4.4). Second, the collision impact of crossing multiple orbital altitudes rather than a homogenous decay of altitude would have increased the cumulative collision probability for the elliptical case.

With these considerations made, the following plan (Fig. 8) was made for the disposal operations:

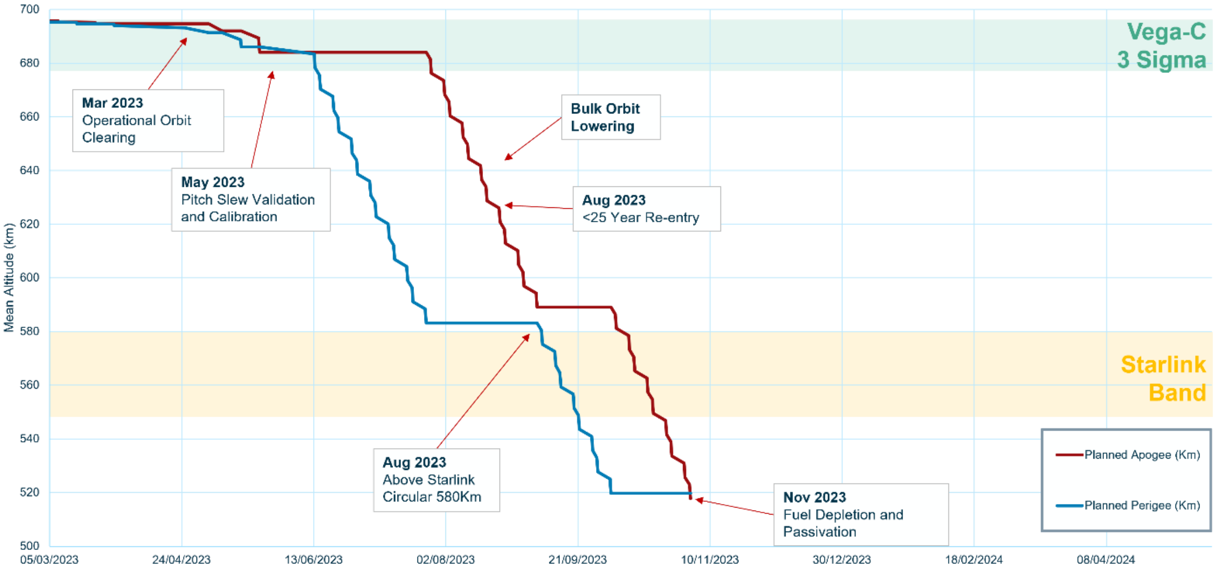


Fig. 8 Overview of planned Sentinel-1B orbit lowering

The different phases in this approach are described in more detail in the following sections.

5.1 Operational Orbit Clearing

This first phase of the deorbit operations was the most safety critical, as it was imperative to remove Sentinel-1B safely from its operational orbit position, as that position would be needed by the replacement Sentinel-1C spacecraft and any loss of control of Sentinel-1B close to its operational position could have also posed a collision risk to its sister spacecraft, Sentinel-1A.

The goal decided on for this phase was to lower the Sentinel-1B orbit by approximately 2 kilometres, which would give a sufficient safety margin with respect to its operational position. The other key element of this phase was to take minimal risk, to maximise the chances of successful orbit clearance. Therefore it was decided to use the routine in-plane thrusters that were used reliably throughout the spacecraft lifetime.

As the routine in-plane thrusters were severely limited in available delta-v (as described in Section 4.1), this initial phase was much slower. To fit within the resource constraints of the teams involved, it was decided to perform one batch of manoeuvres per week, on a Wednesday. This allowed time in the working week before the burns to properly plan the batch and time afterwards to calibrate the performance. Each batch consisted of 10 maximum duration OCMs at minimum spacing – half an orbit apart. This allowed for a cumulative delta-v per batch of approximately 16 cm/s resulting in a weekly reduction in semi-major axis of approximately 300m. This implied a total duration of this phase of approximately seven weeks.

This phase also resulted in the first of the impacts of disposal operations becoming apparent as the reduction in altitude resulted in a relative angular drift starting between Sentinel-1A and Sentinel-1B, resulting in the need to start monitoring for conflicting ground station passes, as described in Section 4.2.1.

5.2 Pitch Slew Validation and Calibration

Once the spacecraft had safely been removed from its operational orbit, it was considered safe to begin testing of the new pitch slew manoeuvre mode describe in Section 4.1. This was a one-month phase that also included the wrapping up of all the operational planning necessary to begin the subsequent bulk lowering of the spacecraft orbit using these pitch slew manoeuvres.

Prior to performing a pitch slew manoeuvre there were several activities that were first performed to ensure safety:

- The in-use star trackers were swapped to using star trackers 1 and 3. In nominal conditions all star trackers can be used but it was known that star tracker 2 could experience earth blinding in the pitched attitude.
- FDIR modifications were made to ensure that there would be no triggering due to the unexpected (from the default configuration) use of the safe mode attitude thrusters for orbit control
- The roll steering and yaw steering laws that were used to optimise payload performance were disabled to avoid unnecessary impact on the attitude

- The actual pitch slew manoeuvre was executed, which involved two steps – first rolling the spacecraft from its nominal 30-degree attitude to be parallel to the nadir direction and then pitching the spacecraft 90 degrees to point the attitude thrusters in the retrograde direction

With these actions performed the spacecraft was ready to perform the burns in the new attitude. The plan was then to start performing these burns with a phased approach to build up to the intended performance of 3 burns in a batch of 0.7 m/s per burn. The first burns were done with only one burn a day, starting with much lower delta-v and gradually increasing the delta-v until 0.7 m/s was reached. Then the number of burns was increased, first with two and then three burns in a day.

By performing this we would achieve a safe ramp-up to the required performance while at the same time being able to characterise the burn performance in flight and the entire performance of the spacecraft system in this new mode. In addition, this test phase allowed validation of the various new products and interfaces, such as the polarisation product referred to in Section 4.2.2. At the end of this phase a 2-3 week gap was envisioned to allow all of the results to be consolidated and any necessary updates made before the full orbit lowering.

5.3 Bulk Orbit Lowering

The bulk orbit lowering phase was planned as the main part of the orbit lowering for Sentinel-1B. During this phase the pitch slew burns validated in the previous phase would be executed systematically until the fuel on-board was almost completely depleted. The plan for this phase was to execute a total of 140 manoeuvres, split into batches of 3 0.7m/s manoeuvres in a day, with 2 batches being executed per week. This resulted in a total expected duration of this phase of 24 weeks. Each of the batches was configured to use the 3 burns to either lower the perigee or the apogee, by choosing the relevant apside.

It was recognised that during the orbit lowering a significant amount of fuel would be burnt off, resulting in a corresponding drop in tank pressure throughout the phase. Reduced pressure resulted in reduced performance of the thrusters, which had two implications. The first was that the on-board settings had to be adjusted every 3 bar of pressure drop so that if the avionics needed to perform emergency attitude control using the thrusters it could properly model the expected performance. The second effect was that the actual burn duration had to be constantly increased to ensure that each burn of each batch achieved the target of 0.7 m/s delta-v.

The actual strategy on whether to lower apogee first, perigee first, or alternate both was split into a series of plateaus, where first the perigee would be lowered and then the apogee lowered to circularise the orbit at the next plateau. The first of these was a lowering of the mean altitude to a circular orbit ~20km below the operational orbit. This was an important milestone as it meant that Sentinel-1B was outside of the worst-case dispersion envelope (plus margin) of the Vega-C launcher that would launch the replacement Sentinel-1C satellite. Therefore after reaching this altitude, it could be considered that there was no constraint on launch day or trajectory of the Sentinel-1C launch due to Sentinel-1B.

The next plateaus were much lower and were introduced to take account of the Starlink constellation. It was identified that there was a significant increase in orbital population due to Starlink in the range from 530 km to 580 km. Therefore it was decided that the next plateau targeted would be a circular orbit at the upper limit of this band (580 km). A checkpoint would then be held to assess the performance of the spacecraft and the safety of powered descent through Starlink, with the assumption being that a ballistic passage through Starlink would be preferable to a passage where the performance was unpredictable. Assuming the performance was good, then a double “hop” through Starlink was planned, with a plateau in the middle of the band at 560 km and then a second lowering to circularise the Sentinel-1B orbit at the final plateau of 530km, below Starlink. From this point onwards, only perigee lowering would be performed until the remaining fuel was largely depleted, which was assumed to be minimal.

A further key milestone during this phase was passing the point at which remaining orbital lifetime would reach 25 years, and therefore meet the goal identified in Section 3.1. This was expected to be reach once the perigee lowering to 580 km was achieved. It was also agreed to check the progress at this point and review the planning following this to understand what could realistically be achieved.

5.4 Fuel Depletion

The ESOC Flight Dynamics team predict the fill level of the fuel tank on the spacecraft using both pressure and temperature estimation and bookkeeping of executed manoeuvres. However, during the disposal planning it was agreed that the bookkeeping method would not be sufficient to determine tank depletion, especially as it did not take account of the reduction in mass flow as the tank pressure changes, leading to an overestimation of the fuel remaining. It was therefore agreed to set the threshold to stop the bulk orbit lowering by determining that the tank was largely empty based on the evolution of the temperature and pressure measurements. We would then enter a final fuel depletion phase where we would continue performing 2 manoeuvre batches per week but with only one 0.7 m/s burn in each batch.

The reason was because the chance was high that the fuel would deplete and therefore at some point one of the burns would be ineffective and limiting the delta-v without ground interaction meant that we could avoid introducing a large drift from the expected position – with a single burn that would be limited to 21 seconds of along track drift per day.

After every burn in this phase it was planned to carefully assess the spacecraft's attitude behaviour and perform orbit determination to detect the point at which the thrusters stopped producing delta-v due to fuel depletion. Once this was detected then it was planned to rapidly initiate the final passivation.

5.5 Passivation

The final passivation plan matches the intended goals outlined in Section 3.2. It was envisaged to be an activity spread across one day with four passes being taken to complete. It was also planned to have overlapping ground station coverage for the final pass with Sentinel-1B to provide extra redundancy and to allow for a slightly longer TM/TC duration, assuming the use of different polar stations.

Although the final implementation of the passivation activities was agreed to be decided while performing the orbit lowering, the high-level activities were agreed as follows:

- Pass 1: Close the latch valves to isolate the tank from the RCS, turn off the on-board authentication unit for commanding and place the S-Band transponder in its low bitrate mode with ranging enabled.
- Pass 2: Disable FDIR monitoring to ensure no autonomous actions interrupted the upcoming passivation activities. Switch off all of the payload LCLs and transition to coarse orbit determination.
- Pass 3: Rotate the +Y solar array wing to the anti-sun position (rotation of 210 degrees)
- Pass 4: Rotate the -Y solar array wing to the anti-sun position and perform the final switch-off of all remaining units and the transmitter.

At this point the spacecraft would effectively be passivated although a complete switch off could not be performed as it is not possible to isolate the battery. It was in any case though expected that the spacecraft would remain passively stable with the arrays pointed away from the sun and therefore in the days following passivation the battery would completely deplete, and the spacecraft would completely switch off.

6 Disposal Execution

The actual execution of the campaign began in February 2023, with the target (from the plan outlined in the previous section) being to complete the disposal operations around the end of October 2023. Unfortunately multiple anomalies occurred during the disposal process which forced the campaign to be replanned multiple times. Fig. 9 below shows the planned execution of the campaign along with the actual execution. The milestones will be further described in the following sub-sections.

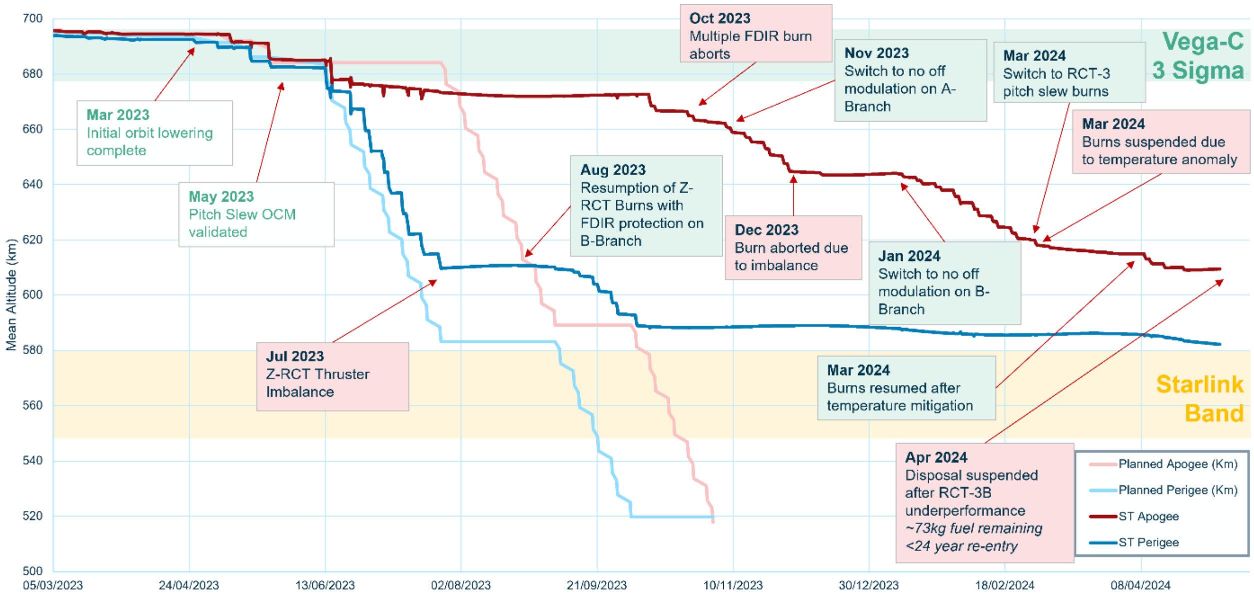


Fig. 9 Planned vs. Actual execution overview of Sentinel-1B orbit lowering

6.1 Thruster Imbalance Issues

Initially the campaign proceeded exactly as defined in Section 5 above, with the initial 2km orbit lowering out of the operational orbit being successfully completed in March 2023 and then the validation of the new Pitch Slew manoeuvre mode also being completed by the end of May 2023. In June 2023 the bulk orbit lowering began and, on the 15th June 2023, the first milestone was reached by lowering the spacecraft to first circular plateau at 680 km - outside the 20km dispersion envelope of the Vega-C launcher that was going to launch the replacement Sentinel-1C spacecraft.

From this point the orbit lowering proceeded with 2 manoeuvre batches per week, as planned, initially lowering the perigee to reach the plateau agreed above the Starlink constellation. This was planned to be completed in August 2023 but in one of the burns on 18th July 2023 an imbalance in the thrust of the four thrusters being used was detected. The imbalance in the thrust imparted an unexpected torque on the spacecraft and the reaction wheels had to speed up to compensate. This repeated during a subsequent batch on the 25th July 2023 but this time the imbalance was significant enough to trigger a reaction wheel overspeed protection 624 seconds into the third burn, as seen in Fig. 10 below:

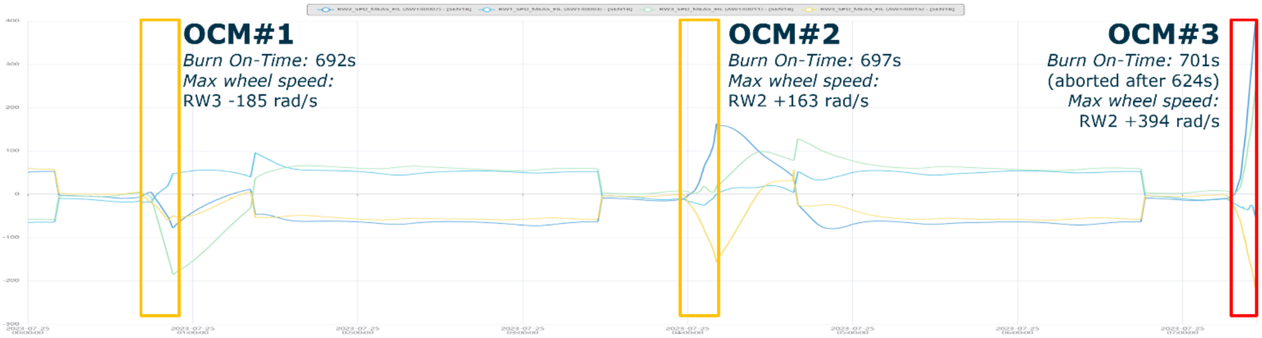


Fig. 10 Reaction wheel speeds for Sentinel-1B Z-Thruster deorbit burn on 25th July 2023

The spacecraft response to the Reaction Wheel overspeed protection was to enter safe mode, interrupting the burn and the disposal operations. With uncertainty about the ability to continue the pitch slew manoeuvres, the spacecraft was returned to its normal attitude to preserve the ability to perform collision avoidance activities with its nominal in-plane thrusters.

The spacecraft remained in this state, not manoeuvring, until 29th August 2023. During this time the issue was assessed but no root cause could be determined, and no predictive method was feasible to adapt to the variable performance of one of the four thrusters being fired. It was therefore decided to implement a new fault detection, below the warning threshold mentioned above, that would gracefully terminate a burn without entering safe mode, in case either the reaction wheel speed, attitude error or rate error reached a given threshold. It was also considered that this new protection should also take account of the pressure reading and terminate a burn in case pressure dropped below a threshold, to avoid a large attitude transient in case the tank emptied of fuel before entering the final depletion burns described in Section 5.4. This new protection is discussed further in Sintes Arroyo et al. [8].

With the protection in place to minimise the largest impact of a thruster imbalance, deorbiting operations were restarted. It was decided at this point to also swap to the B-Branch of the thrusters in the assumption their performance would be more stable. However, due to the issues experienced it was decided to start with significantly reduced delta-v per burn, gradually increasing during each batch of manoeuvres if the torque from the thruster imbalance remained under control. By the 21st September 2023 this gradual increase was halted at 0.35 m/s per burn due to observation of increasing torque. This was half the originally planned delta-v per burn and with this reduced delta-v the progress was slower but by the 6th October 2023 the perigee target above the Starlink constellation was reached and apogee lowering was started.

While executing a batch of manoeuvres on the 12th October 2023, the new monitoring triggered for the first time, aborting the burn. To mitigate any further interruptions the delta-v per burn was reduced back to 0.13 m/s per burn but in subsequent batches on both the 26th and 31st October 2023 further aborts were triggered by the FDIR protection. Although the burn aborts with the new protection had less impact than with the protection that triggered Safe Mode, it was still a significant issue. The key problems were that by halting the execution of the burn, an unexpected drift was introduced between the predicted and real position of the spacecraft. This caused issues with ground station acquisition and with space debris screening, as described in Section 4.2.3 and 4.3 above. It was therefore decided at this point that the pitch slew burns could no longer continue as-is.

6.2 Off Modulation Suspension

The next major step came with the observation in telemetry of the failed burns that showed significant temperature fluctuations in the thruster catalyst beds. By oversampling the temperature telemetry it could be seen that this appeared to correspond with the thruster valve opening as the thruster executed its nominal off modulation pattern during firing. This can be seen in Fig. 11, where the red line shows the underperforming thruster temperature and its relationship to the off-modulation cycles in yellow on the background:

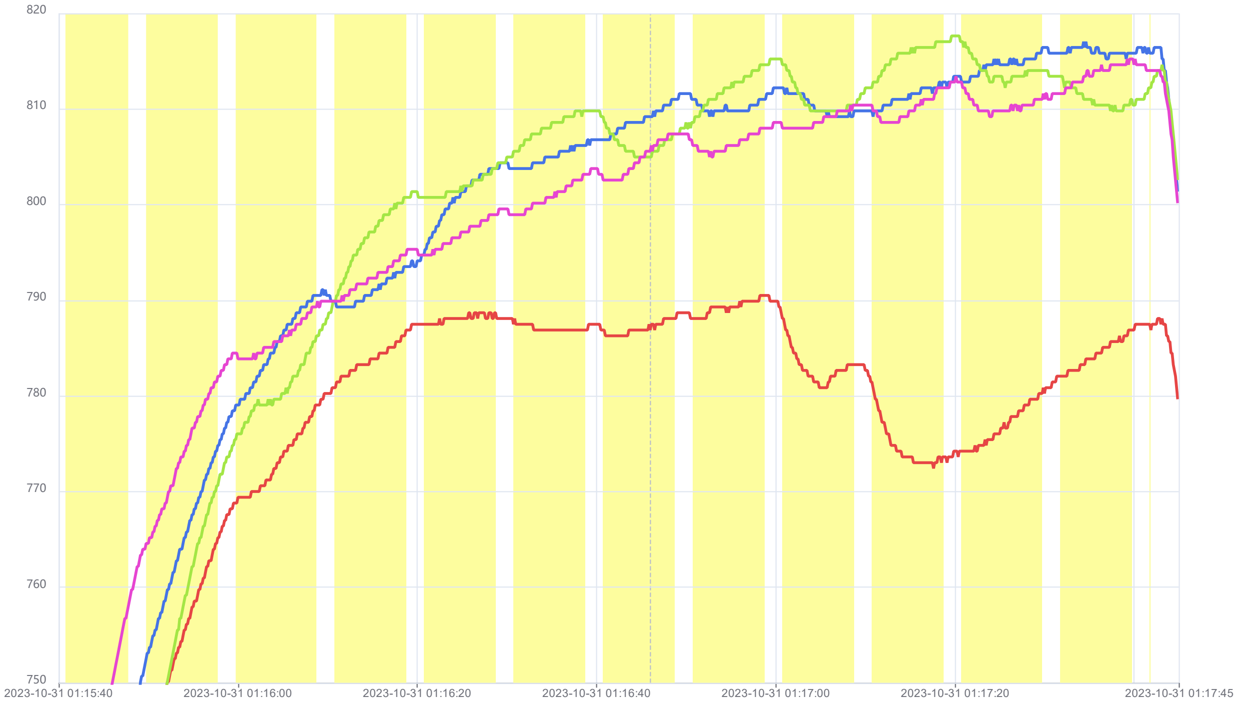


Fig. 11 Thruster temperatures and off-modulation during Sentinel-1B burn October 2023

Although no physical explanation for this could be determined, it was decided to attempt continuation of thruster activities but with the off modulation disabled, and a steady state firing of the thruster for the whole duration. This allowed a restart of orbit lowering operations on 7th November 2023, also returning to the use of the A-Branch thrusters. The same cautious approach of starting with smaller burns and ramping up was adopted, eventually reaching batches of four 0.19 cm/s burns. These allowed further orbit lowering to continue for another month, until 12th December 2023, when, even with off modulation disabled, there was a further burn interruption due to the torque protection. At this point it was decided to end thruster operations with the 4 A-Branch thrusters that had been in use up to this point.

After a break to give the team rest around the Christmas period, deorbit operations were resumed with the B-Branch thrusters, using the same disabled off modulation technique. To further try and mitigate the impact of thruster imbalance, the number of burns in a batch was increased but the delta-v per burn reduced, e.g five burns of 0.069 m/s each or even nine burns of 0.057 m/s each. No further interruptions were observed, but the torque levels were observed to be increasing, therefore it was considered only a matter of time until these thrusters would also become unusable. On the 29th February 2024 the major milestone of 25 years remaining lifetime in orbit was reached and it was decided too suspend burns with the four Z-RCT thrusters to avoid the risk of further interrupted burns.

6.3 Out-Of-Plane Thruster Use

Before the final suspension of pitch slew burns using the four Z thrusters, the team had already started working on an alternative approach. The attitude would still stay the same, pitched 90 degrees, but the thruster originally designed for out-of-plane manoeuvres in nominal attitude would be used. This was not directly aligned with the retrograde direction (see Fig. 3) and therefore resulted in a loss of efficiency but as there was a considerable amount of fuel remaining this was not considered critical. The key advantage to this approach was that as this was just a single thruster, any variation in performance would cause a change in the delivered delta-v but no impart an unexpected torque on the spacecraft and therefore not abort the burn. Unfortunately, the position of the thruster limited the maximum delta-v per burn to 0.098 m/s but by executing multiple burns per batch this could be mitigated.

However, during some of the first manoeuvres using this thruster, on the 5th March 2024 a temperature anomaly triggered on board following a temperature measurement on the pipeline leading to this thruster of >50 degrees. This can be seen in Fig. 12.

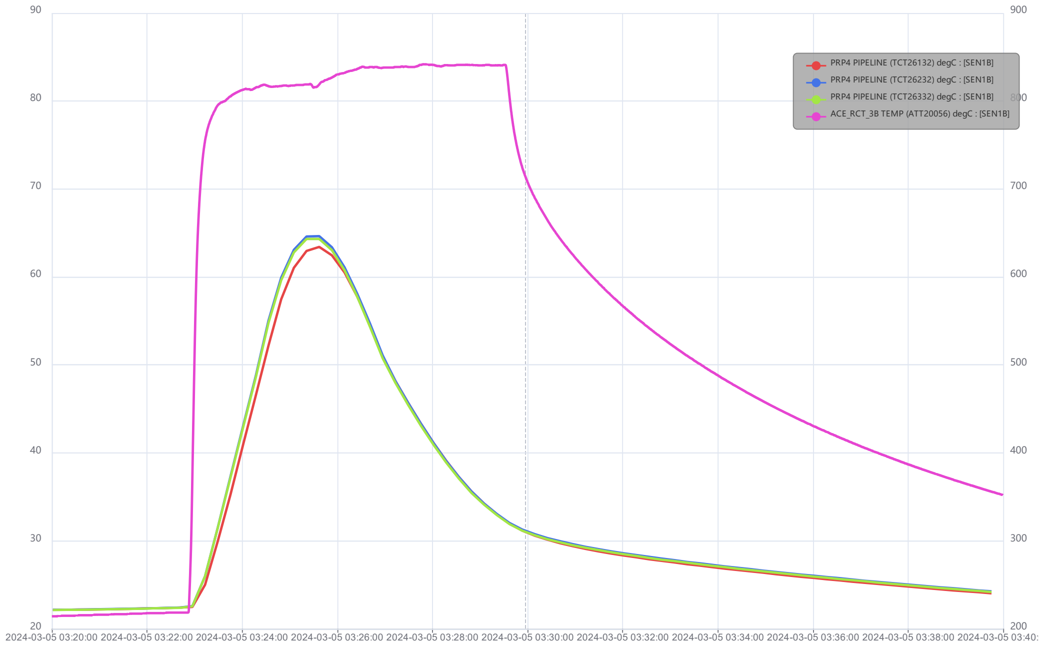


Fig. 12 PRP4 Pipeline temperature (degC, left axis) and RCT3 thruster temperature (degC, right axis) during Sentinel-1B deorbit burn 5th March 2024

What can be seen is that the burn begins (thruster temperature in pink) and then shortly afterwards there is a peak in the pipeline temperature (in red, blue and green). The physical explanation assumed is that further down the pipeline there was an area being overheated by the thermal control creating a hotspot. When the thruster is fired it pulls this overheated fuel up the pipeline and across the thermistor, resulting in the spike in temperature. As the thruster continues firing then the temperature again drops off again as cooler fuel is pulled through from the fuel tank.

This created a safety concern and therefore these new out-of-plane thruster burns were suspended to investigate. The investigation indicated that the root cause was either a failure of the prime heater or an issue with it cycling to much and overheating the pipeline. In the latter case this had never been observed in flight and the reason why was assumed to be that the area around the pipe was much colder, because unnecessary units had been switched off at the start of the disposal causing the pipe heater in turn to increase its duty cycle to compensate. To mitigate the issue, it was decided to take action that would address either of the root causes - first the redundant thermal control was used, to eliminate the possibility of a failure in the main heater. Then, the unused mass memory unit was reactivated and the thresholds of surrounding heaters increased, to take the thermal burden off the pipe heater. This resulted in a successful reduction in duty cycle of the pipe heater, as seen in Fig. 13 and no further indications of temperature spikes during thruster operations.

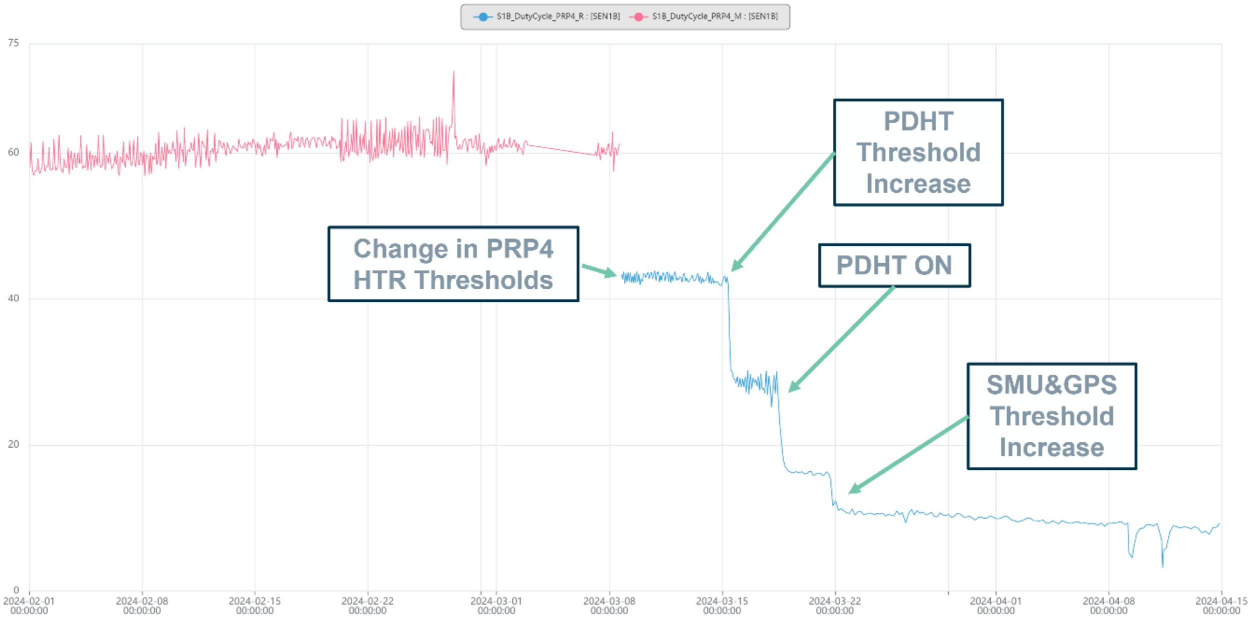


Fig. 13 Reduction in Duty Cycle (%) on redundant pipeline heater (in Blue) of Sentinel-1B PRP4 pipeline

The go-ahead to resume thruster operations was given on the 26th March 2024 and deorbiting burns continued using the out of plane thruster until April 2024.

On the 16th April 2024 an underperformance of up to 15.2% was noted in one of the burns of the manoeuvre batch. In the subsequent batch on the 23rd April 2024 the final burn in the batch had an even more significant reduction in performance of 50.4%, as shown in Fig. 14.

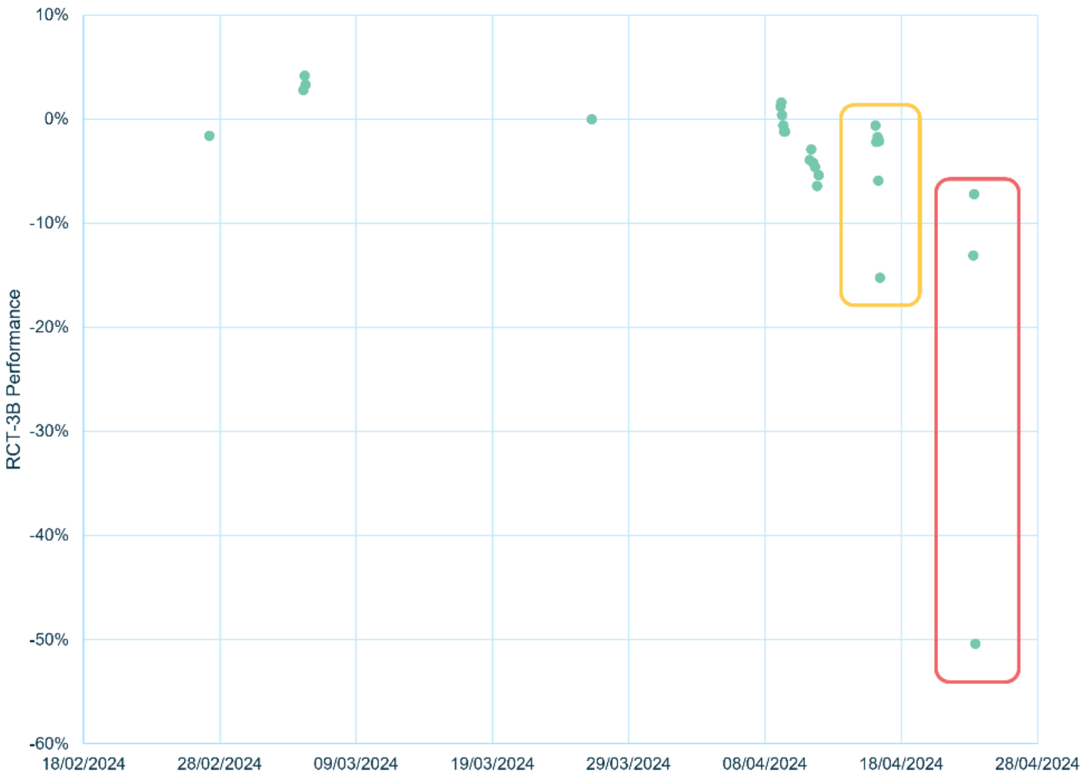


Fig. 14 Performance of Sentinel-1B Out-Of-Plane thruster RCT-3B from Feb-May 2024

This level of underperformance, especially with such large delta-v, was considered unsustainable because it risked invalidating the collision avoidance screening process and, in case of a collision warning, made our ability to respond uncertain. Therefore all deorbiting operations ceased as of the 23rd April 2024.

6.4 Final Deorbiting Status

While the spacecraft was still stable, and the thrusters could still be fired and impart delta-v, by the end of April 2024 it was considered that the confidence in the ability of any particular burn to deliver the delta-v planned was too low. It was agreed by all parties that at this point a ballistic (i.e. passivated) spacecraft was safer than a spacecraft that was manoeuvring unpredictably.

This was especially true as the next step would be to pass through the dense Starlink band, where unpredictable reported positions of Sentinel-1B could hamper the ability of Starlink to perform autonomous collision avoidance. Analysis was performed based upon an assumption that SpaceX would need 12 hours before a conjunction, with 4 hours added to the start for the downlink of Sentinel-1B telemetry and preparation of an NDM, plus another 4 hours of screening for SpaceX to ingest and process the data. This gave a drift duration of 20 hours and the displacement considered acceptable was 12.5 km, i.e. half of the 25 km screening volume (to allocate half to Starlink and half to Sentinel-1B). Using these numbers, it was calculated that the maximum acceptable deviation of a single burn would be 5.8 cm/s. A batch of burns could all be cancelled autonomously before telemetry would be available and therefore the de facto maximum batch size would also be 5.8 cm/s. This was far too small to perform continuation of bulk deorbiting and therefore decided that the only safe option was to stop deorbit operations and prepare for spacecraft passivation.

The final point reached at the end of the deorbiting operations was a perigee around 580 km, just above the Starlink band, and an apogee of around 610 km. This resulted in a predicted time remaining in orbit of 24 years, which satisfied the target of reducing below 25 years, as described in Section 3.1. Unfortunately the goal of depleting all of the fuel on board could not be reached, with an estimated remaining fuel load of approx 70 kg of hydrazine.

7 Passivation Execution

With the end of propulsive deorbit operations the preparations started for the final passivation of the spacecraft. This would not be a complete passivation, as per the aim described in Section 3.2, due to the remaining fuel on-board.

However, to best try and satisfy the goals described, the "electrical passivation" of the spacecraft still went ahead, i.e. performing all steps of the planned passivation except expending the stored fuel. This approach was reviewed and agreed by the ESA Clean Space team as being the maximum possible that could still be achieved with Sentinel-1B to reduce its risk of accidental break-up following passivation.

7.1 Assessment of risk for remaining stored fuel

The increase in risk associated with the remaining fuel in the tank was discussed but it was determined that there were too many variables to make a firm conclusion on what additional risk to the space debris population the fuel presented was. It was assumed that the fuel would freeze following passivation, but to what extent and how fast were difficult to predict with uncontrolled attitude. This freezing was not considered relevant to the space debris risk because hydrazine does not expand like water and so it was not expected to cause any physical damage to the spacecraft. Whether or not the fuel froze, the risk of accidental ignition was also considered negligible without a catalyst. The key remaining driver of increased risk was considered to be the remaining pressure in the tank, and the fact that this might add to the energy released in case of an impact fragmentation event. No firm conclusion could be drawn here because it is highly dependent on the energy and direction of any impactor. However, it was noted that the tank is well-shielded in the centre of the spacecraft and any impactor large enough to puncture the tank would likely in any case cause a complete fragmentation of the spacecraft. Given the amount of energy released in such an event, the extra energy from the tank pressure would likely be negligible. Consideration was also given to ways in which the fuel could be vented as part of passivation, but the only option would be to flow the fuel through the thrusters. The highly unpredictable delta-v that would occur from such an activity was determined to present a higher risk of a space debris incident than leaving the fuel in the tank.

7.2 Electrical Passivation

Following the conclusion of the propulsive deorbiting, the focus of the work turned to preparing for the electrical passivation of the spacecraft. During this final phase the exact sequencing and procedures were developed and validated and in parallel an independent review by the ESA Clean Space team was conducted to ensure that there were no other options left open except to perform the passivation. With all of these concluded, the date for passivation was set to be the 11th and 12th September 2024.

The first steps of the passivation on the 11th September were preparation of the spacecraft for the final switch-off activities. This began with turning off the unused payload mass memory unit that we had powered on to provide extra heating for the manoeuvring activities, as described in Section 6.3. Following this we opened all of the Latching Current Limiters that provided power to the payload. Even though the payload was no longer switched on, this step severed the electrical path to prevent any future powering of the payload. The next step was to inhibit the ultimate safe mode of the spacecraft to prevent any unwanted reconfiguration or autonomous recovery either during or after the passivation activities. Next was isolation of the no longer needed propulsion system with the closure of the latch valves between the fuel tank and the rest of the propulsion system. This was also designed to contain any leaks in the propulsion system in the years following passivation. The final activity on the day before final passivation was related to preparing the communications with the spacecraft to be as robust as possible for the terminal activities. This included disabling the unit that authenticates commanding during routine operations, reducing the bitrate and turning on ranging. This is our default configuration for giving the highest reliability of communications both up and down to the spacecraft.

On the day of passivation we booked seven passes to complete the final passivation of the spacecraft, including margin. The first of these was taken to monitor the health of the spacecraft and verify that all parameters were as expected to perform the passivation. The second pass was used to complete a number of activities to prepare the software for the spacecraft switch-off and switch-off any units not required for the final passivation execution. The software preparation at this stage largely involved the global disabling of the on-board fault monitoring to avoid any reconfiguration or autonomous recovery action. With this in place we could proceed with switching off the final parts of the payload power supply, disabling the precise orbit determination on-board to allow switch off of the GPS receiver and the redundant star tracker units.

The third pass on the day of passivation was used to begin the key activity to trigger the passivation of the spacecraft – the rotation of the solar array. The two solar array wings can be rotated independently and in the final configuration only one is required for the spacecraft to be power positive. Therefore in this penultimate passivation pass it was decided to rotate first one solar array wing. As mentioned in Section 3.2, it is not possible to disconnect the batteries and power bus on Sentinel-1 from the solar arrays. It was though assessed that the attitude after passivation would likely be passively stable in approximately the same attitude at passivation, allowing a final solar array position to be selected to minimise the debris risk. The selected position of the arrays was opposite to the sun vector, minimising the risk of post-passivation power generation. This position was edge-on to the flight direction and a trade-off with the optimum position to maximise drag, which would have been face-on to the flight direction. It was ultimately decided that maximising the drag was not as critical as minimising any electrical activity on the spacecraft, especially given the inability to disconnect the batteries. The movement of the solar arrays was tested in the days before passivation, as they are not nominally rotated. This was successful and then the final rotation on the day of passivation was also successful. The same activity was performed in the final passivation pass and the power generated by the arrays was successfully observed to drop to near zero (see Fig. 15).

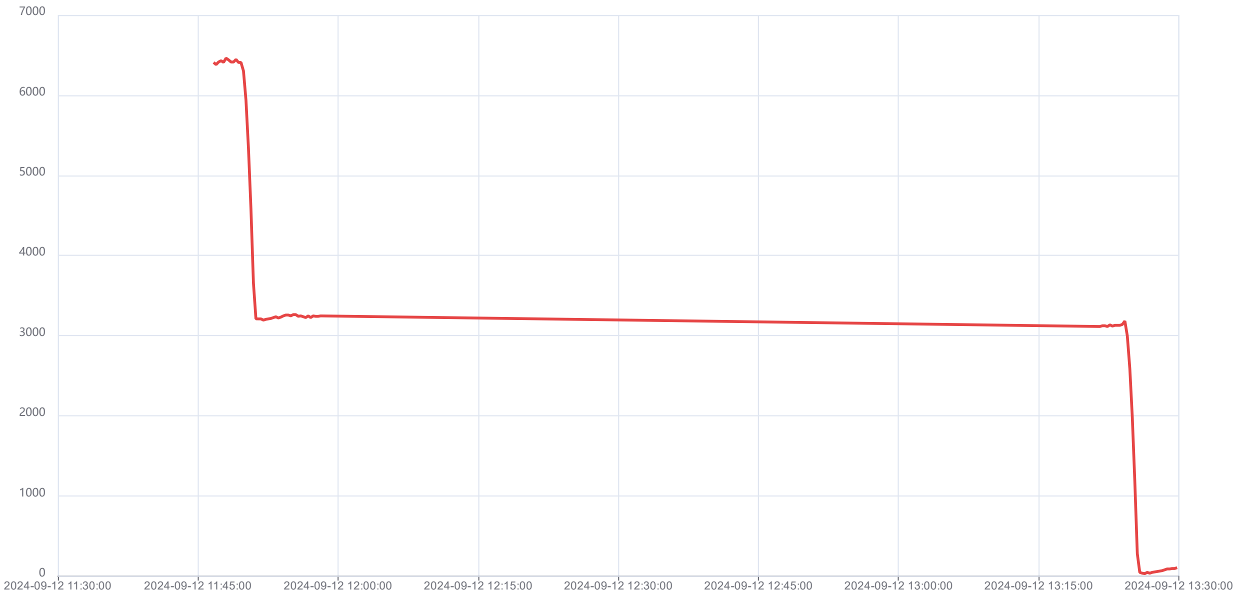


Fig. 15 Drop in Solar Array Power (W) during turning of Sentinel-1B final passivation

The final activities in the last passivation pass were the complete disabling of the spacecraft. This first involved the switch-off of all remaining attitude control units, including the gyroscopes, reaction wheels, remaining star tracker and GPS receiver. At this point the attitude control of the spacecraft was effectively disabled and therefore the attitude was uncontrolled, although stable. The next step was to disable all remaining autonomous recoveries in the on-board non-volatile memory. This step was intended to prevent any autonomous power-up or recovery of the spacecraft after passivation in the case where the solar arrays became illuminated. Finally all other units on board were powered off, including the onboard processor modules. At this stage the passivation of the spacecraft was effectively complete, the only remaining electrical units still powered were the transmitter and receiver and the hardware telemetry and telecommand capabilities. The last stage of the passivation was to power off the transmitter, which signalled the completion of the passivation. The remaining pass after this was taken to confirm the transmission from the spacecraft had stopped and indeed there was no further signal from Sentinel-1B.

The final passivation of Sentinel-1B was therefore completed with the final loss of signal observed at 13:32:11Z on 12th September 2024 [9]. At the point of loss of signal there was still charge in the batteries although as far as possible all electrical units were isolated and transmission and recovery was inhibited. Over the days following passivation it was expected that the battery would slowly deplete, and the spacecraft attitude would passively stabilise. The final steps to be taken were to inform the relevant authorities to update the status of Sentinel-1B in the international catalogues/registries from an operational spacecraft to an inactive object.

8 Lessons Learned

The experience gained from the disposal of Sentinel-1B, along with lessons from earlier missions such as the disposal of ERS-2 [10], provides valuable insights for other missions and programmes in planning and executing spacecraft end-of-life operations. These lessons will be directly applied to the upcoming deorbiting of Sentinel-1A, as well as to the eventual disposal of the replenishment spacecraft Sentinel-1C and Sentinel-1D. While the key lesson learned in the campaign was to expect the unexpected when operating a spacecraft in novel ways, below we highlight some key takeaways that the authors believe are worth considering in both current and future missions.

From the perspective of space debris mitigation, the experience demonstrates that there are still significant knowledge gaps or room for interpretation that can complicate the assessment of a disposal campaign. The first encountered, as described in Section 3.1, were the variable options for assessing assumed solar cycle, along with other key variables such as C_d value when assessing the remaining lifetime in orbit. This is particularly relevant for long periods that spread across multiple solar cycles. In these cases small changes in the assumptions can have a large effect on the outcome. Although no assumption can be 100% correct, a more standardised approach across the industry would help in allowing comparison of approaches. Following on from this was the assumed attitude of the spacecraft once uncontrolled after passivation, which was initially assumed to be a random tumble. In many spacecraft, it is highly unlikely that this will the final attitude as statically stable attitudes from drag and gravity gradient will take over. This should be carefully modelled and considered when determining cross-sectional area during remaining lifetime in orbit studies. The next lesson came from the fact that at the point of passivation, a significant amount of fuel remained in the tank. While the safest option would be to remove all the fuel, more study is necessary on the real impact of leaving a pressurised tank. In the case of Sentinel-1B the tank is deep within the structure, covered by units and two walls. The assumption is that the fuel will freeze and this “shielding” will protect the tank from any small impacts, whereas a large impact that could puncture the tank would be so catastrophic as to make the energy from the pressurised tank negligible compared to the overall energy released in the collision. Future research into the post-passivation behaviour of systems like this could allow for more options when considering passivation methods. Finally, the process to highlight the challenges experienced due to design and anomalies should be communicated transparently and in a timely manner to the relevant bodies, in our case the ESA Clean Space Office. This is already taking place for Sentinel-1A and even if a full disposal was not possible for Sentinel-1B it is critical to involve all stakeholders as early as possible.

From a spacecraft technical perspective, this experience shows that the capabilities of the propulsion and attitude control subsystems are crucial to successfully carry out the disposal phase. These subsystems need to be robust, high-performing and to include functions dedicated to this phase. Important aspects to consider in the spacecraft design phases include the capability to use up the whole fuel complement, the ability to perform large impulses and the resistance to reduced performances and to unit failures. From this experience, it appeared that the capability of the spacecraft to generate large impulses is essential to achieve fuel depletion and a final disposal orbit within a reasonable time. Furthermore, the capability of the spacecraft to perform such large impulses predictably and reliably is essential to ensure collision avoidance screening and thus to ensure the safety of the spacecraft and its environment. Requirements on future spacecraft to ensure a maximum given delta-v error at end-of-life could be placed, considering the impact unreliable delta-v has on both ground station acquisition and space debris screening.

From an overall system technical perspective, the challenges posed by the disposal of Sentinel-1B disposal showed that this phase requires a holistic approach. The functions, resources and constraints of the ground segment were crucial factors for the detailed planning of this phase; those ground segment issues had to be balanced with those related to the spacecraft as well as those related to the integration of the two segments. For instance, the duration of individual de-orbiting burns, the time separation between burns, the number of burns per batch and the time separation between batches are key variables of a disposal plan and each of these variables is derived from both spacecraft as well as ground segment considerations. Therefore, the disposal assessment conducted in the spacecraft design process and carried out, notably, by the prime is necessary but not sufficient. It is imperative that this assessment already considers the practicality of any given disposal plan given the concept of operations available at that point. This should be verified against corresponding assessments performed at the ground segment level and coordination must be performed at the overall system level to ensure that the disposal plan is robust, consistent and comprehensive.

From a programmatic perspective, this experience demonstrates that the disposal preparation needs to be considered in all the phases of the project. Successfully addressing the challenge of disposal requires a comprehensive assessment in phase A/B1 and in phase B2/C/D/E1. An assessment is necessary at the space segment level, to ensure that the design provides the spacecraft - in particular the propulsion and attitude control subsystem - with all the required capabilities and at the overall system level, to ensure that a disposal strategy was devised considering both the constraints originating from the spacecraft and from the ground segment. It is critical that operational experience is fed into the process at all phases of the design to apply real-world experience to theoretical planning of disposal operations. Furthermore, for the phase E2/F, a significant level of expertise and resources must be anticipated for both the Spacecraft Maintenance teams (Post Launch Support at ESTEC) and Spacecraft Operations Teams (Flight Operations Segment at ESOC). In this phase, it may be necessary to substantially restructure the disposal plan elaborated in earlier phases because of degraded performances of the spacecraft resulting from in-orbit anomalies, evolution of ground segment constraints and capability or programmatic constraints, such as allocation of resources for other operational events such as launch preparation or commissioning. The key message is that a simple task on paper can evolve into a multi-month (or even multi-year) campaign of analysis and execution if the goal is to maximise the potential of the spacecraft to meet its disposal goals.

9 Conclusion

Overall, the considerable efforts made by the Sentinel-1 teams at ESA and industry in preparing and executing the disposal phase of Sentinel-1B have yielded benefits that extend far beyond the significant reduction in the risk the spacecraft poses to the space environment post-operations. From the outset, the teams undertook extensive planning and analysis to cover every aspect of the disposal process.

However, the execution phase deviated significantly from the original plan due to a series of anomalies and unforeseen events. These challenges demanded constant innovation and engineering agility to progress as far as possible toward the mission’s disposal objectives. Ultimately, the spacecraft was safely passivated with a remaining orbital lifetime of less than 25 years, thereby minimizing its long-term impact on the space debris environment.

As a result of this experience, the mission team is now significantly better prepared for the disposal of the remaining Sentinel-1 spacecraft. More broadly, the campaign has provided valuable lessons applicable across other programmes, contributing meaningfully to the development of ESA’s expertise in implementing its Clean Space policy.

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Acronyms/Abbreviations

AOCS	Attitude and Orbital Control System
CAPS	C-Band Antenna Power Supply
CSAR	C-Band Synthetic Aperture Radar
ESA	European Space Agency

ESOC	European Space Operations Centre
ESTEC	European Space Research and Technology Centre
EU	European Union
FDIR	Fault Detection, Isolation and Recovery
FOV	Field Of View
GPS	Global Positioning System
HTR	Heater
LCL	Latching Current Limiter
LEO	Low Earth Orbit
NDM	Navigation Data Message
OCM	Orbit Control Manoeuvre
PDHT	Payload Data Handling and Transmission System
PRP	Propulsion Pipeline
RCS	Reaction Control System
RCT	Reaction Control Thruster
RW	Reaction Wheel
SAR	Synthetic Aperture Radar
SMU	Spacecraft Management Unit
STT/STR	Star Tracker
TAS-I	Thales Alenia Space Italy
TC	Telecommand
TM	Telemetry