

## The Swarm Constellation: two critical milestones. The exploitation of the counter-rotating orbits and the orbit raise campaign to fight Solar Cycle 25

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### Abstract

Swarm is ESA's first constellation mission for Earth Observation, consisting of three identical satellites named Swarm Alpha, Bravo and Charlie, launched on November 22, 2013. Dedicated at creating a highly detailed survey of the Earth's geomagnetic and electrical fields, and their temporal evolution, it was initially placed with the two "lower pair" satellites, Alpha and Charlie, flying side-by-side at 462 km of altitude, with an along-track separation between 4 and 10 seconds, and Bravo flying above them, at a 511 km mean altitude.

Due to the natural evolution of the orbits and their planes, a unique – every ~7.5 years – opportunity to have Bravo *counter-rotating* on the same orbital plane of the lower pair satellites presented in 2021. This alignment, welcomed by the Swarm and magnetosphere scientific community, was anticipated by a manoeuvre campaign in 2019 to revert a fixed relative offset in the Right Ascension of the Ascending Node between the lower pair, and implemented with three different *configurations*, playing with the along-track separation of the lower pair, to offer different science cases: from variable separation to a fixed 4 seconds, down to only two-seconds, implying additional precaution measures to ensure monitoring and action in case of any issues.

The second milestone achieved by the mission teams in 2022 has been even more fundamental to ensure a science mission extension, recommended by ESA in order to have the mission to cover one full Solar Cycle: counteracting the effects of the ramping-up Solar Cycle 25. Due to the impossibility to predict the full cycle, various models were studied and a stepwise approach to be implemented during the years, depending on the real Solar Cycle effects on the orbits, was developed. The first phase consisted of a series of *orbit raise manoeuvres* – with unprecedented firing duration for Swarm – to raise the lower pair altitude of ~45 km, consuming ~40% of the consumables left. A total of 25 long-duration manoeuvres were planned and executed, preceded by a series of test manoeuvres with Bravo to characterise the behaviour of the Cold Gas Propulsion System for long-duration burns. The operation had to be carefully planned to ensure the safety of the constellation and the robustness with respect to space debris predictions, ground station acquisition, minimum impact on science and eccentricity of the orbits. This 10-week journey, carried out in May-June 2022 is presented with all details, discussing all criteria, challenges and including all lessons learned.

**Keywords:** Swarm, Solar Cycle, Orbit Raise, Counter-rotating, Constellation, ESA

## 1. Introduction: The Swarm constellation and the orbital evolution

### 1.1. The Swarm satellites: a first look

Swarm is ESA's first constellation mission for Earth Observation (EO) and part of the Earth Observation Programme (EOP). The mission consists of three identical satellites named Swarm-A, Swarm-B and Swarm-C

(nicknamed Alpha, Bravo and Charlie) launched on 22 November 2013 into a near-polar orbit. Swarm is dedicated at creating a highly detailed survey of the Earth's geomagnetic field and its temporal evolution as well as the electric field in the atmosphere, by using the satellite constellation payloads: an Absolute Magnetometer (Absolute Scalar Magnetometer, ASM), a Vector Magnetometer (Vector Field Magnetometer, VFM), an Electrical Field Instrument (EFI, composed by a Thermal Ion Imager and two Langmuir Probes) and an Accelerometer (ACC), a precise Star Tracker (STR) with three optical heads and a GPS Receiver [1]. The mission objectives range from capturing and understanding the Earth's core dynamics and mapping the near-Earth environment response to the Solar Cycle, to mapping ocean tides and electrical conductivity in the mantle and study the lithospheric Magnetic Field.

The satellite platform is composed by a redundant On-board Computer hosting the Mass Memory Unit and the Telemetry and Telecommanding Modules, a redundant S-band transponder, a Thermal Control Subsystem based on heaters and thermistors, an Electric Power Subsystem based on body-mounted Solar Arrays and an internally redundant Power Control and Distribution Unit. The Attitude and Orbit Control Subsystem ensures a Local Nadir Earth-pointing in Fine Pointing Mode, in addition to the lower modes and the Orbit Control Mode. The sensors are two redundant Star Trackers, with three optical heads, in addition to Coarse Earth and Sun Sensors, three platform magnetometers and a GPS Receiver. The actuators are three magnetorquer coils and a fully redundant Cold Gas Propulsion System, providing attitude torques in all axes and orbit control thrust in-plane and out-of-plane [1].

Because of the excellent status of the platform and the instruments of the three satellites, apart from the ASM on Swarm-C, that failed during launch and spacecraft commissioning, and a limited number of full science orbits for the Thermal Ion Imager component of the EFI, the mission was extended many times and looking forward to cover the full Solar Cycle 25, considering the amount of the consumables of the Cold Gas Propulsion System aboard.

### *1.2. The Swarm Cold Gas Propulsion System*

The main purpose of the CGPS of Swarm is to perform attitude and orbit manoeuvres: attitude control, by generating all the reaction moments when the required torque exceeds the capability of the magnetorquers, attitude manoeuvres such as slew yaw manoeuvres, and orbit transfer and maintenance manoeuvres. The fuel used is monopropellant Freon 14 (CF<sub>4</sub>) cold gas, which has a higher volumetric efficiency compared to nitrogen when considering the 64-litre capacity of the two on-board tanks.

The architecture of the CGPS is conventional and simple, with two pressure vessels or tanks for storage of the pressurised gas, a redundant Feed System Module to control the supply of the gas to the thrusters, a piping system, a redundant Thruster Module with small cold gas thrusters in the milli-Newton range. High Pressure and Low Pressure sections are separated by the Pressure Regulators and the inactive branch sealed with a closed High Pressure Latch Valve. Pressure Transducers, two in the High Pressure section (HPTs) and one per each active and inactive Low Pressure section (LPTs) are ensuring the monitoring of the pressures of the system.

The two thruster types, Attitude Control and Orbit Control are essentially identical, with the only difference being the throat diameter, and hence the thrust produced: the CGPS has two branches, one active branch – branch A in all satellites – and an inactive branch – branch B. The Attitude Control Thrusters (ACTs) are eight 20 mN thrusters per branch, working in pairs to produce a net torque along a specific axis, while the Orbit Control Thrusters (OCTs) are four per branch, generating the thrust during orbit manoeuvres: two 50 mN OCTs are accommodated at the front side of Swarm such, that in the nominal case of being operated simultaneously they produce a force into anti-flight direction and no net torque around any of the three principle axis. These thrusters are used for common altitude and inclination change manoeuvres. Two 50 mN OCTs are accommodated on each +Y/-Y side of the satellite such, that their thrust level acts nearly through the centre of mass and being oriented also in the XY-plane, they produce a force into the across-track direction and no torque around the three S/C axis. These thrusters are used for inclination change manoeuvres. The nominal branch OCTs are accommodated on the +Y side while the redundant branch OCTs on the -Y side [1].

Due to the required torques for attitude control and orbit control of Swarm, the sizing of the milli-Newton range thrusters, ACTs but most importantly OCTs are deemed adequate for all phases of the mission. However, it shall be noted that this low thrust gives modest  $\Delta V$  values, in the order of 2 cm/s with a firing duration of 95 seconds; a meter per second  $\Delta V$  requires therefore dozens of manoeuvres or a single long duration manoeuvre.

### *1.3. The Swarm orbits: a one-of-a-kind constellation*

The initial constellation of the mission was achieved after an orbit acquisition campaign at the beginning of 2014: Swarm-A and Swarm-C, called the “Swarm lower pair” were flying side-by-side at an altitude of 462 km, with only

1.4 deg separation in Right Ascension of the Ascending Node and an along-track difference kept between 4 and 10 seconds, while Swarm-B was placed in a higher orbit at 511 km mean altitude. The operational orbit acquisition campaign was a complex operation carried out entailing batches of dozens of firings at the orbital nodes, in order to have the maximum effect on orbital plane inclination. In routine, the along-track separation of the lower pair is the only variable controlled, kept smaller than 10 seconds for scientific purposes, but greater than 4 seconds for safety aspects, should an anomaly occur. The difference in eccentricity between Swarm-A and Swarm-C trajectories is also monitored and kept small.

Due to the different altitudes and different inclination (that is causing the Right Ascension of the Ascending Node of the Swarm-B orbital plane to drift at a different rate with respect to the one of the lower pair), the satellites pair and the higher satellite experience different orbital perturbations, mainly due to atmospheric drag: the decay rate for Alpha and Charlie is clearly stronger than the one for Bravo, and the satellites orbital planes are also evolving differently: the drift of Swarm-B's plane inclination has been in fact around 24 deg/year with respect to the very similar plane of Swarm-A and Swarm-C.

#### *1.4. Opportunities and real needs: the two milestones between 2021 and 2022*

This paper presents the two milestones achieved during the last two years by the Swarm mission, the first one being triggered by the desire to actively take advantage of the natural evolution of the orbital planes of Swarm-A/C with respect to Swarm-B to create new science cases, and the second one triggered by the need to establish the preconditions to have a long duration mission:

- The *counter-rotating orbits phase*: to actively utilise the natural evolution of the orbital planes, i.e. their Local Time of the Ascending Node (LTAN), to reach in addition, when the satellites LTANs were closer – at 20.4h - a specific and in some weeks closer *along-track* configuration for the lower pair. This required an analysis of the lower pair distance and the implementation of tiny manoeuvres to keep them close as it was designed.
- The *orbit raise campaign*: to avoid re-entry in 2025 at the peak of Solar Cycle 25 it was fundamental to plan and execute an orbit raise for Swarm-A and Swarm-C, at least as precondition for other phases, to be implemented when the prediction of the solar activity would be more stable.

These two milestones are thoroughly described in detail in the next chapters of this manuscript, presenting rationale, requirements, and constraints of both campaigns, discussing the challenging points and the solutions, presenting the operations as performed and concluding with the lessons learned.

## **2. The counter-rotating orbits phase**

Every ~7.5 years the Swarm-B orbital plane and the two planes of Swarm-A and Swarm-C become almost coplanar, with the higher satellites either co-rotating or counter-rotating; this offers a repeating, but also rare scientific opportunity to observe phenomena closer at specific latitudes and times: addressing especially areas of the magnetosphere-ionosphere-thermosphere and their coupling at different spatial and temporal scales.

This opportunity was about to realise again in late 2021, with the closest LTAN at the beginning of October 2021, and Swarm-B counter-rotating with respect to Swarm-A/C. This was named *counter-rotating orbits phase* for Swarm.

#### *2.1. A small manoeuvre campaign in 2019: out-of-plane manoeuvres to reduce the relative LTAN*

With the goal in mind of having one of the satellites counter-rotating with respect to the lower pair in 2021, already in 2018 the Swarm community and the management started to discuss the reduction of the relative Right Ascension of the Ascending Node (RAAN) – in other terms, relative LTAN – of the lower pair, that had been kept frozen to 1.4 deg since satellite commissioning: the idea was that, with a reduced campaign of out-of-plane manoeuvres, the lower pair satellites would reduce their relative RAAN down from 1.4 deg to zero by the time of the closer angular separation with Swarm-B, thus maximising the science return. From October 2019 onwards the  $\Delta$ LTAN between Swarm-A and Swarm-C orbits has been reducing from 1.4 deg towards zero in October 2021. Afterwards the  $\Delta$ LTAN started to increase at the same rate but to the opposite side. The campaign was performed in 2019 and included 19 manoeuvres [2], the majority with Swarm-A and mostly out-of-plane to introduce a difference in inclination that would bring the two orbital planes to drift together., but it is not discussed in this manuscript; on the other side its effects allowed to achieve a closer orbital plane configuration for the lower pair, fundamental to the success of the science exploitation of the counter-rotating orbits.

2.2. *The counter-rotating orbits: study of the lower pair along-track evolution in 2021*

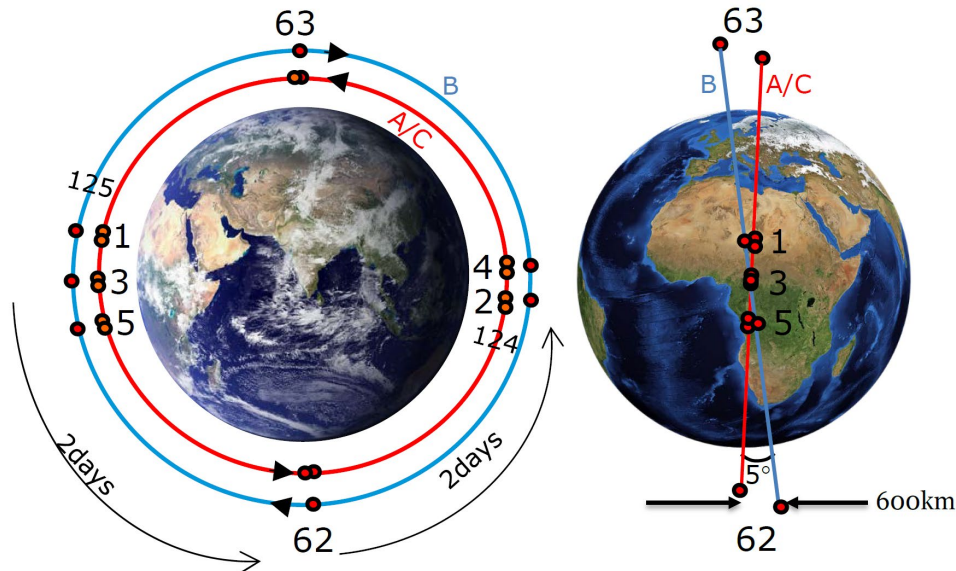
In order to take advantage of the reduced angular separation of the satellite’s orbital planes, specifically between mid-July 2021 and mid-December 2021, i.e. for five months, the *along-track separation* of Swarm-A and Swarm-C was carefully analysed [3]. This has covered more than 12 hours in LTAN. In particular, the main idea of the scientific community, endorsed by ESA, was that during the closest angular separation, for a few weeks in October 2021, with the closest alignment happening on October 3, the satellites would be as close as possible, for around two weeks period. This period would be preceded by keeping a separation close to 4 seconds and then, starting from mid-October, let them drift apart in a variable separation, before re-establishing the routine constellation. At the 10th Swarm Data Quality Workshop (DQW), the different separation strategies for the lower pair during the counter rotating orbits configuration were proposed to the user community, in order to explore different phenomena and time scales during this phase. The following three cases were discussed and have been combined into a scenario for the campaign, that will be extensively discussed in the next sections:

- *separation of 2s* for limited period of time of two weeks when the angular separation was at its minimum.
- *separation of 4s*, i.e., fully within the current separation strategy (+4, +10s) and to be implemented at the beginning of the campaign.
- *variable separation >4s up to ~40s* to observe co-rotating phenomena, at the end of the campaign.

Table 1 shows the LTAN / LTDN evolution of the three satellites at the beginning, at the end and at the time of the maximum angular alignment of the orbital planes.

**Table 1. Local Time of the Ascending Node at the beginning, max proximity and end of the campaign**

Date	Satellite	LTAN/LTDN, [h]	Phase
15.07.2021	Swarm-A	3.60 / 15.60	beginning of the counter-rotating orbits
	Swarm-B	3.25 / 15.25	
	Swarm-C	3.61 / 15.61	
03.10.2021	Swarm-A	20.40 / 8.40	same LTAN closest angular separation
	Swarm-B	20.40 / 8.40	
	Swarm-C	20.40 / 8.40	
15.12.2021	Swarm-A	13.82 / 1.82	end of the counter-rotating orbits
	Swarm-B	14.14 / 2.14	
	Swarm-C	13.81 / 1.81	



**Fig. 1 – Visual sketch of the orbital planes of Swarm-A/B/C during the counter-rotating orbits weeks. Even at the maximum alignment, the subsatellite points at the Poles are more than 600 km apart.**

It has to be kept in mind however, that in the middle of the campaign on 03/10/2021 the satellite configuration was such that Swarm-B Ascending Node position corresponds to the lower pair satellites Descending Node (overfly point

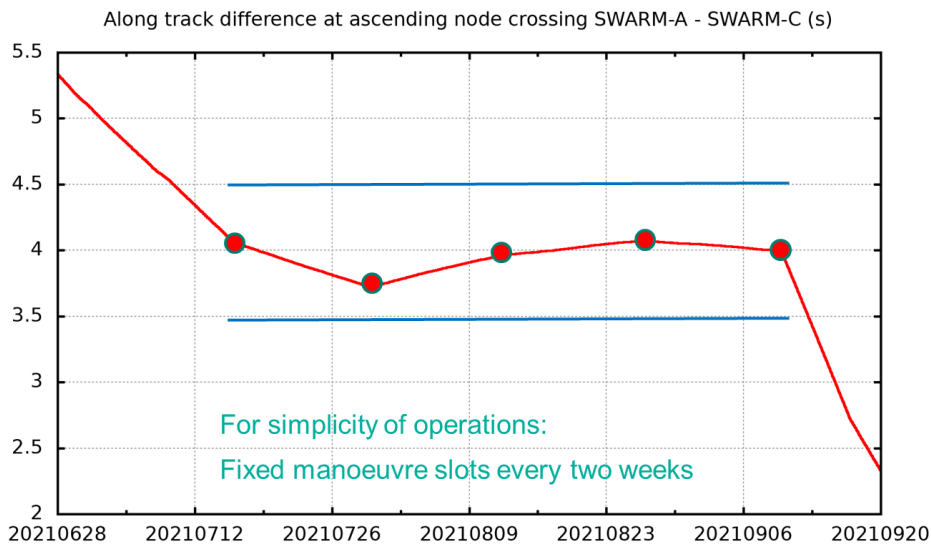
3 in Fig. Fig. 1), but the trajectory has a significant out-of-plane separation of 600 km at highest and lowest latitudes (overfly points 62 and 63 in Fig. 1); this is due to the fact that the orbits are counter-rotating and to the difference in orbital inclination. Moreover, the positions on the orbit where Swarm-B overflies the lower pair satellites are changing with each revolution, due to the difference in orbital period – Swarm-B has a 90 seconds longer orbital period.

### 2.3. The four seconds separation phase

The first phase of the counter-rotating orbits has implied the reduction of the along-track separation between Swarm-C and Swarm-A down to 4 seconds, i.e. at the edge of the routine control dead-band. The implementation started with a first two-burn constellation maintenance manoeuvre with Swarm-A on the 01/06/2021 that started drifting towards Swarm-C [3]. The acquisition of the phase completed on 15.06.2021. This phase, despite not requiring additional operational attention because fully in line with the routine mission concept, demanded a tighter control of the along-track separation in a much more reduced dead-band, agreed to be between 3.5s and 4.5s: this resulted in a constellation maintenance manoeuvre every two weeks: three manoeuvres in total were necessary to keep the separation within the agreed margins, as reported in Table 2. The phase lasted therefore from 15.06.2021 until the 09.09.2021, when the manoeuvre to start the drift down to only two seconds separation was commanded. Fig. 2 shows the manoeuvres performed, the achieved separation and the target along-track distance, between 3.5s and 4.5s.

**Table 2. Orbital manoeuvres to reach and maintain the 4s separation phase**

	Satellite	Phase	Burn duration
01.06.2021	Swarm-A	Routine – Start drift	Two burns of 7s
01.07.2021	Swarm-C	Routine	One burn of 2s
15.07.2021	Swarm-C	Stop drift to reach 4s	One burn of 7s
29.07.2021	Swarm-C	Keep 4s	Two burns of 3s
12.08.2021	Swarm-C	Keep 4s	One burn of 2s
26.08.2021	Swarm-A	Keep 4s	One burn of 2s



**Fig. 2 -Along-track difference (seconds) between Swarm-A and Swarm-C during the four seconds separation phase of the counter-rotating orbits. The manoeuvres are indicated with the red dots.**

### 2.4. The two-seconds separation phase

During the two weeks when the LTAN difference between Swarm-A/C and Swarm-B was at its minimum it was agreed to plan for the minimum along-track distance between two Swarms since commissioning, resulting in only 2

seconds of separation. Due to the importance of this phase for the scientific community, it was chosen to keep this distance with a tighter margin than the 0.5 seconds of the previous phase. This is evident from section 2.4.1, where the maximum error in along track has been 0.07 seconds [3].

The core assumption for the Flight Operations Segment in terms of safety of the space segment is in fact that each Swarm can survive a safe mode for a period up to 72 hours, if no additional anomaly occurs, and no reaction is granted from ground before this time, even if normally it is the case. It is from this requirement that the minimum separation of 4-seconds between Swarm-A and Swarm-C was derived. Changing the minimum separation to 2-seconds meant that the initial assumption has to be revisited and fully analysed, in terms of safety of the space segment at all times. Hence, a feasibility study was carried out with all mission teams and industry, in order to ensure that all safety considerations were taken into account, analysed and mitigated with proper measures: these are outlined in section 2.4.1 and constitute the essential challenge of the entire operation.

#### *2.4.1. Challenges and implications: an eye on the satellites safety and the measure taken*

When a close separation is chosen for two or more satellites, the paramount objective is to maintain the safety at all costs, i.e. to ensure no risks of collision exist between the satellites in orbit. When the satellites have the same cross-section and therefore experience very similar orbital decay, the safety measures consist mainly to maintain them separated by a safety distance, or Ascending/descending node crossing time, to ensure the separation. A safe distance is determined such that, in case of anomaly in one of the two spacecraft, the Flight Control Team (FCT) could focus on the anomaly resolution without risk of collision. The proposal to change the lower pair separation from the current values (4s, 10s) to something smaller, like 2 seconds, introduces several challenges and the need to analyse carefully once again the safety profile during a potential anomaly, because outside the envelope of the original analysis. This analysis, performed before the implementation of the three phases, was performed by the Flight Dynamics (FD) and Flight Control Team (FCT) of Swarm at ESOC.

In order to assess the vertical separation building up in case of anomaly and ensuring overall safety, the FD analysis takes into account the solar activity evolution, increasing in the dawn of the Solar Cycle 25 in early 2021. In a scenario of predicted solar activity causing a natural decay between 10 km per year (50th percentile) and 30 km per year (95th percentile) for the lower pair orbits, the additional decay caused by safe mode would correspond to a figure between 5.5 and 16 meters/day.

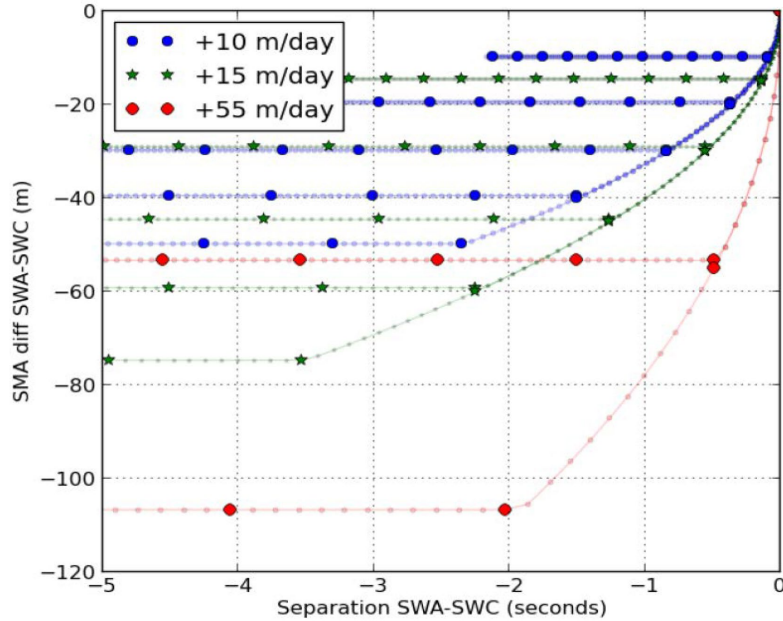
In Fig. 3, the various scenarios of the vertical separation between Swarm-A and Swarm-C are presented, the top right point representing an equal altitude (zero semi-major axis difference) and zero deviation of along-track separation from nominal.

From the top-right, to the bottom-left, the curve shall be followed based on the desired decay rate. Each small dot represents 2h, each big marker (dot, star, etc) represents one day. The curve line has to be followed until the safe mode is recovered and Fine Pointing Mode established, then the horizontal line is applicable.

It can be noted that, for example following +15 m/day decay rate, it takes 4 days for the relative altitude drop to reach 6m and the along track separation changes by 2.2 seconds: this, in case of having Swarm-A and Swarm-C separated initially by 2 seconds, meaning a crossover. This also means that if the safe mode is recovered quickly, e.g. after one day, the altitude drop is only 15 meters, but another 6 days before the change in along track separation reaches 2 seconds. Another prerequisite is that there is no significant initial relative drift rate between the satellites. Such an initial drift would then have to be considered on top.

Important to mention that Fig. 3 is valid regardless of the initial separation at the ascending node crossing, since it presents the future vertical separation in time during the recovery and at the end of the recovery, regardless the initial conditions in terms of ascending node crossing difference, shall this be 2s, 3s or 4s.

The worst-case scenario given by the FD analysis is obviously the one with largest decay (55 m/day separation) and red circles. In case the satellites would be separated by two seconds, as reported in the proposal in section 2.4: in two days they would crossover, if safe mode is not solved before with a transition to FPM, but resulting in a considerable vertical separation of more than 100 meters. It is clear that, even if vertical separation is this particular case is ensured, the approach that would be taken is avoiding crossover at all times.



**Fig. 3 – Semi-major axis difference between Swarm-A and Swarm-C as a function of the along-track separation (x axis). The graph shall be read from the top-right corner, following the assumed solar activity line.**

From the analysis above, a few key points and considerations can be summarised as per Swarm FD and FCT conclusions:

- The altitude difference shall be maintained as small as possible, at plus/minus 20 meters level, such that a certain altitude difference remains for cases where the satellites could crossover in two days (that is the worst-case scenario). This altitude difference is maintained small controlling the difference in eccentricity between the two trajectories.
- It is paramount to avoid a lower pair crossover, due to the non-negligible effort in re-establish the constellation afterwards and the non-negligible collision risk: this could be avoided by moving the satellite not impacted by the anomaly. This conclusion is totally endorsed by all parties and no crossover shall occur between the lower pair due to the impossibility to ensure vertical separation at all times, especially during the current Solar cycle evolution.
- The worst case analysed by FD is a potential satellites crossover, i.e. collision risk, after two days – 48 hours - Swarm-A anomaly implying the loss of Fine Pointing Mode;
- An anomaly on Swarm-C implying the loss of Fine Pointing Mode is of no concern for the safety of the constellation, because it implies the increase of satellites separation.

**Table 3. Orbital manoeuvres to reach and maintain the 4s separation phase**

Relative decay with respect to unaffected satellite	Solar Activity	Time between FPM anomaly on Swarm-A and satellites crossover
+10 m/day	Minor	~110 h
+15 m/day	Average	~90 h
+55 m/day	Maximum	~48 h

Following the above analysis, new safety requirements were established at the Swarm Flight Operations Segment, to provide a robust form of mitigation towards the risks presented. In case of anomaly on Swarm-A – the trailing satellite of the lower pair – implying a safe mode or a loss of Fine Pointing Mode (AOCS fallback) the coarse attitude would cause an increased orbital decay due to larger cross section exposed to the orbital velocity vector: this would mean a decrease of the separation with respect to Swarm-C and clearly an issue for the safety of the constellation.

In particular, the satellite crossover or even worse collision risk would be avoided if a manoeuvre drifting one satellite apart is performed not later than 48 after the anomaly, under the worst Solar activity conditions and maximum drag. In order to ensure such a reaction, two approaches could be followed [4]:

- Implement and execute, as soon as feasible, an OCM with the unaffected satellite, i.e. Swarm-C;
- Focus on Swarm-A recovery, in particular the recovery of platform, STRE and GPSR, to be able to enter Fine Pointing Mode and then OCM to perform a manoeuvre in the shortest time possible.

Considering the large safety implications of such a scenario, the most rational approach would imply to implement and execute an OCM with Swarm-C to ensure spacecraft separation – implemented as non-optimised manoeuvre by the FD team – and at the same time focus on Swarm-A recovery, with less time pressure, at least on the constellation safety aspects. In order to get additional visibility of such a potential anomaly, considering the current ground station passes allocation for Swarm (two passes per day per satellite, one constrained during working hours) the following was decided:

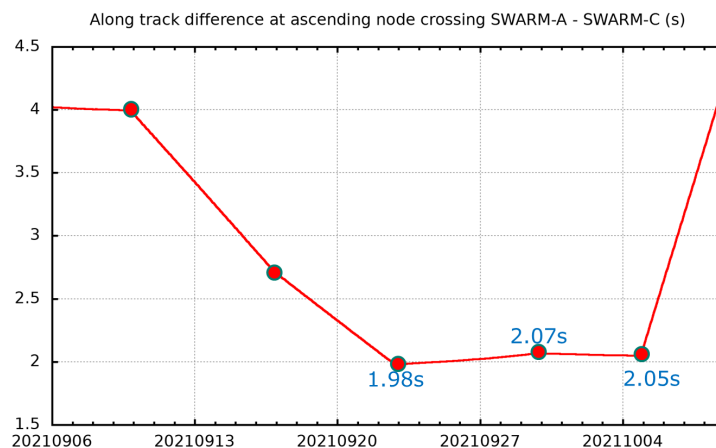
- for Swarm-A, one additional pass per day will be booked. A total of three passes per day will be booked;
- for Swarm-A, the spacing between the passes should not exceed 12 hours: this scenario was robust even with one pass lost due to ground station anomaly;
- immediate ground anomaly notification from the stations operators to the Flight Control Team, including generic anomalies on the ground segment or specific antennae, to reduce operational outages;
- increased support coverage from Ground Operations Engineers, Spacecraft Operations Engineers and Flight Dynamics teams.

#### 2.4.2. The operational implementation

The two seconds separation phase run nominally, and all risk mitigation measures as described in the previous section were implemented. The acquisition of the phase started on 09.09.2021 and lasted until the 22.09.2021, where the target along-track separation was achieved. This was kept from the 23.09.2021 until the 05.10.2021, when the first manoeuvre to begin the variable separation phase was commanded [3]. The manoeuvres are logged in Table 4 and the along-track separation in Fig. 4.

**Table 4. Orbital manoeuvres to reach and maintain the 4s separation phase**

	Satellite	Phase	Burn duration
09.09.2021	Swarm-A	Start drift to 2s	Two burns of 13s
16.09.2021	Swarm-C	Reduce drift to 2s	One burn of 4s, one burn of 5s
22.09.2021	Swarm-C	Stop drift to 2s	Two burns of 9s
29.09.2021	Swarm-A	Keep 2s	One burn of 3s



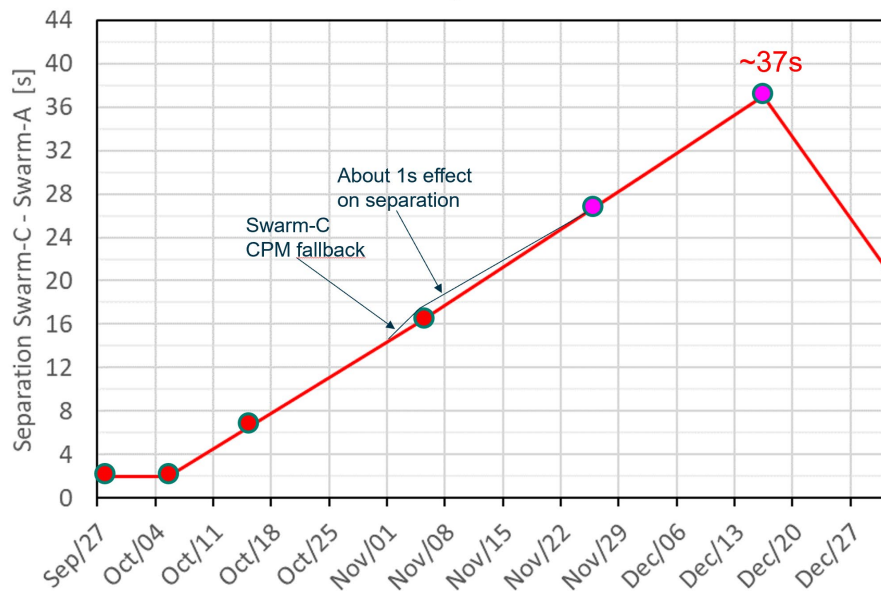
**Fig. 4 - Along-track difference (seconds) between Swarm-A and Swarm-C during the two seconds separation phase (including acquisition) of the counter-rotating orbits. The manoeuvres are indicated with the red dots.**

### 2.5. The variable separation phase

The variable separation phase acquisition started on the 04/10/2021, with the usual orbital drift, in this case of Swarm-C. A few maintenance manoeuvres were necessary to stay within the plan; the return to the routine configuration started on 16/12/2021 and completed on the 13/01/2022. The manoeuvres are logged in Table 5 and the along-track separation is shown in Fig. 5. It can be seen that the maximum along-track distance achieved was 37 seconds in mid-December 2021, before the start of the drift back to the routine constellation configuration [3].

**Table 5. Orbital manoeuvres to reach and maintain the variable separation phase**

	Satellite	Phase	Burn duration
04.10.2021	Swarm-C	Start variable separation	Two burns of 37s
04.11.2021	Swarm-A	Keep variable separation	Two burns of 35s
25.11.2021	Swarm-C	Keep variable separation	One burn of 4s
16.12.2021	Swarm-C	Start drift to routine	Two burns of 120s
13.01.2021	Swarm-A	Stop drift to routine	Two burns of 76s



**Fig. 5 - Along-track difference (seconds) between Swarm-A and Swarm-C during the variable separation phase (including acquisition) of the counter-rotating orbits. The manoeuvres are indicated with the red dots.**

### 2.6. Challenges and Lessons Learned

The first challenge of this exceptional phase was the time and effort required to analyse all safety implications of such a close distance between Swarm-A and Swarm-C, to ensure a safe separation and a timely reaction in case of collision avoidance, anomalies on-board and robustness in case of ground segment issues. This challenge was accepted by all teams, and it is thanks to the team effort of the Flight Control Flight Dynamics, Ground Operations, Management, Industry teams that the final plan was accomplished and all mitigation measures were effective, even if not necessary to be used.

An additional challenge encountered during the counter-rotating orbits phase has been the increase of collision warnings received during the period. In particular, a collision warning between Swarm-C and a cubesat from the Planet constellation, with Time of Closest Approach on 19/09/2021, was particularly difficult to handle due to very close separation between Swarm-A and Swarm-C – almost two seconds on that date – the instability of the predictions and an upcoming Solar storm. A Collision Avoidance Manoeuvre was prepared and loaded, but it was aborted briefly before the close approach due to a last minute change of the predictions showing that not performing the manoeuvre was safer. Another two warnings were received during the period, one resulting in a Collision Avoidance Manoeuvre for Swarm-B and another one for Swarm-A which did not require a change in the orbit. However, the close approach notifications from Space Debris office did not affect in any way the campaign and the target separation.

A major challenge has been the AOCS fallback to Coarse Pointing Mode (CPM) of Swarm-C, that happened during the 4s separation phase. The anomaly, caused by a Single Event Upset on the Star Trackers Electronics on 01.11.2021, caused the loss of Fine Pointing and required ground intervention to recover the satellite from CPM to FPM. In this case, the Flight Control and Flight Dynamics teams acted very fast to recover the attitude, so no additional manoeuvre was required to maintain the designed lower pair separation during the ramp-up to ~40s seconds, i.e. not affecting the separating planned drift.

In summary, the target along-track separation during the counter-rotating orbits phase was fully accomplished, no major anomaly affecting the generation of the science data occurred. This opened the way to study several phenomena, such as small-scale ones up to the co-rotating phenomena for years to come. The Swarms orbital planes will be perpendicular in early 2025 and then coplanar (but co-rotating) in mid-2029. But this will be a new chapter of the Swarm history books.

### 3. The lower pair orbit raise campaign

The great success of Swarm, its data and its relevant impact on the magnetosphere and plasma physics, was the key for the mission to be extended twice since the end of the routine phase; the last extension being proposed by the Earth Observation Program Board of ESA in 2022 and eventually formalised after the processing of the overall budget of the Ministerial Council in early 2023. Each of the mission extension processes culminated acknowledging not only the fulfilment of the mission objectives, but also new fields, applications, processes and products coming out of the processing of Swarm's science data. But in order to achieve these objectives, from 2023 and at least for the next three years, the most basic requirement would have to be fulfilled: to have a mission *flying*.

#### 3.1. Overall strategy and $\Delta V$ budget

Due to the relatively low altitude of the two Swarm lower pair satellites, Swarm-A and Swarm-C, about 430 km of mean altitude\*, it was therefore of paramount importance to *counteract the effects of the Solar Cycle 25* with a substantial *altitude raise of the orbits*, whose effects on the routine decay of 2.5 km/year started to parabolically increase to an average of 20 km/year just before the orbit raise. It was clear that the first step of an orbit raise, always discussed since a few years, had to be implemented to ultimately avoid re-entry between end of 2024 and mid-2025.

The orbit raise was discussed since the beginning not in basic "survival" terms, but with the specific goal to get through the entire Solar cycle 25 and achieve an altitude, at the next solar minimum in 2030-2031, between 300 km and 400 km, to ensure the lithospheric studies mission objective to be met. Hence, a study was conducted by the ESOC Flight Dynamics group in early 2022, considering the evolution of the Swarm orbits, the fuel budget, the predictions of the Solar Cycle 25 with relevant confidence errors, and the goal to achieve an average altitude of 350 km at the beginning of 2030. This is discussed in the next sections and constitutes an input to the entire implemented campaign, also discussed in the second part of this chapter.

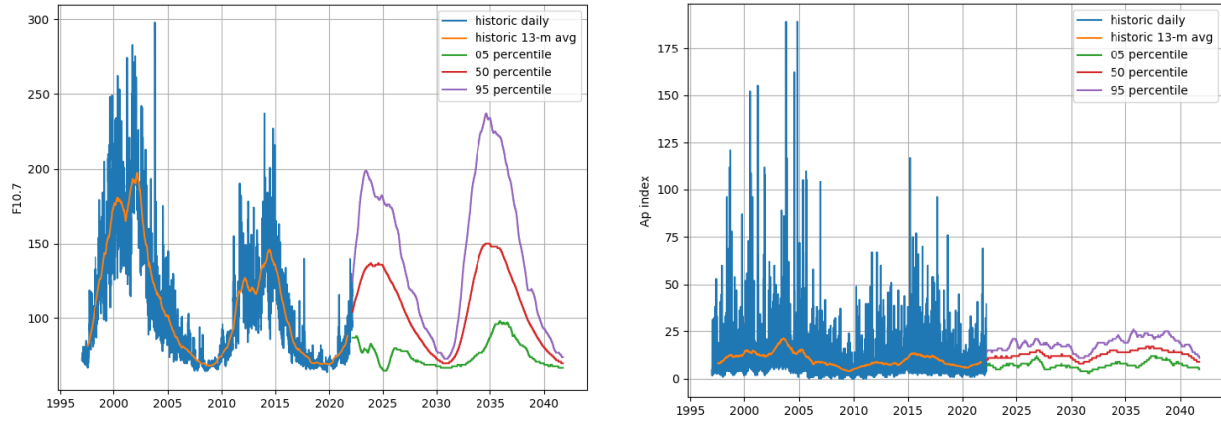
##### 3.1.1. The study of the $\Delta V$ as function of the Solar Activity level

To achieve an operational orbital altitude of 350 km at the beginning of 2030 for Swarm-A and Swarm-C it was necessary to determine how much altitude increase would be necessary and consequently the impact on the  $\Delta V$  budget. To do this, the Flight Dynamics group propagated the Swarm orbits with different levels of the solar activity, using as input the forecast provided by the NASA Marshall Space Flight Center and comparing this with ESA Space Weather Office data.

The forecasts provided estimates for the solar radio 10.7 cm flux (F10.7), and the geomagnetic planetary index, Ap. These indices are the inputs for the atmospheric density model NRLMSISE-00 used to perform orbital propagations. As such, the indices have an important effect on the long-term evolution of the orbit, impacting the decay rate and affecting the semi-major axis evolution [5]. The forecasted solar indices represent the 13-month smoothed values consisting of a best estimate value stated as a 50-percentile value along with the 95 and 5 percentile statistical values. Fig. 6 shows the current forecast values, together with historical daily values and 13-month moving average of the daily values.

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\* Mean value before the orbit raise campaign in Summer 2022.



**Fig. 6 – Left: F10.7 index from NASA MSFC from 1995. Predictions following 5, 50 and 95 percentiles for any future data. Right: Ap index from NASA MSFC from 1995. Predictions following 5, 50 and 95 percentiles for any future data.**

As it can be inferred in Fig. 6, the current solar cycle (Solar Cycle 25) started in December 2019 and will peak around 2025, and it is expected to reach the minimum around 2031. The best estimate at the time the study [5] was conducted, was that the cycle would be similar as the previous one.

To have the widest range of predictions as possible however, the 13-month averages of the 5 and 95 percentiles were considered to provide two extreme references of the best and worst cases in terms of altitude evolution of Swarm.

### 3.1.2. The Swarm consumables and the overall $\Delta V$ available budget

The analysis of the Swarm consumables and fuel budget evolution was a fundamental step before the planning of the campaign, and was considered at the same time of the analysis of the  $\Delta V$  budget to achieve the final objective to extend the mission until 2030+. Therefore the focal points of this analysis are reported in this section.

Before the implementation of the orbit raise, the fuel available on Swarm’s CGPS were 58 kg for Swarm-A and 57 kg for Swarm-C. The amount of fuel needed for 1 m/s  $\Delta V$  is about 0.9 kg, while the fuel budget for attitude control and Collision Avoidance is estimated in  $\sim 1$  kg/year, and assumed that a lower altitude will not increase the fuel needed for attitude control. Considering this assumption, the fuel available for the orbit raise was 48 kg for Swarm-A, with an available budget of 53 m/s, and 47 kg for Swarm-C, with an available budget of 52 m/s. It must be noted that the available budget has to include the yaw slews to re-orient the satellite by 180 degrees and fire the OCTs along the velocity vector: each of these pairs costs 60 grams of fuel: this has been taken into account into the  $\sim 10$  kg estimated fuel needs for AOCS, CAMs and slews in the period 2022-2030. Also, it is important to note down that the above analysis would leave Swarm with no guaranteed reserves after 2030, as a consequence, this was taken into account in the planning. The figures are summarised in Table 6.

**Table 6 – Swarm-A/C fuel reserves before the campaign and fuel budget available for the orbit raise**

	Fuel available, April, 2022	Fuel for AOCS CAM and slews 2022-2030	Fuel available for orbit raise	$\Delta V$ available for orbit raise (no reserves as of 2030)
Swarm-A	58 kg	$\sim 10$ kg	48 kg	53 m/s
Swarm-C	57 kg	$\sim 10$ kg	47 kg	52 m/s

### 3.1.3. Finalisation of the orbit raise objectives: the stepwise approach and baseline $\Delta V$

In order to look into the  $\Delta V$  budget to fulfil the objective, we can start with one consideration: the most fuel-efficient strategy to arrive at 350 km altitude in 2030 is to perform a single manoeuvre: in fact, splitting the strategy into several altitude-raise manoeuvres results in more  $\Delta V$  needed – for a given solar activity rate – because the satellite spends more time at a lower altitude, where the decay is higher. However, it is not realistic to perform one single manoeuvre, for many reasons: first from an operational and monitoring perspective, second because it would

not be possible to adapt the  $\Delta V$  needed with the Solar Cycle predictions. The single manoeuvre scenario gives an overview of the total minimum  $\Delta V$  needed, which can be useful as a baseline when comparing other manoeuvre strategies. Therefore, to produce a robust scenario and considering the uncertainties of the solar cycle on the altitude over the years, it was decided to implement the orbit raise with a *stepwise approach*. This means performing the campaign in batches, with a  $\Delta V$  achieved during several manoeuvres in a period of one or more weeks, followed by several months / year with no altitude raise, and then by the next batch(es). In particular the following was studied and identified as the baseline:

- a *first step* of altitude raise in April/May 2022 (three cases were studied, with 18 m/s, 25 m/s and 30 m/s  $\Delta V$ );
- a *second step* in June, 2023;
- a *third step* in June, 2025 (after the Solar Cycle peak).

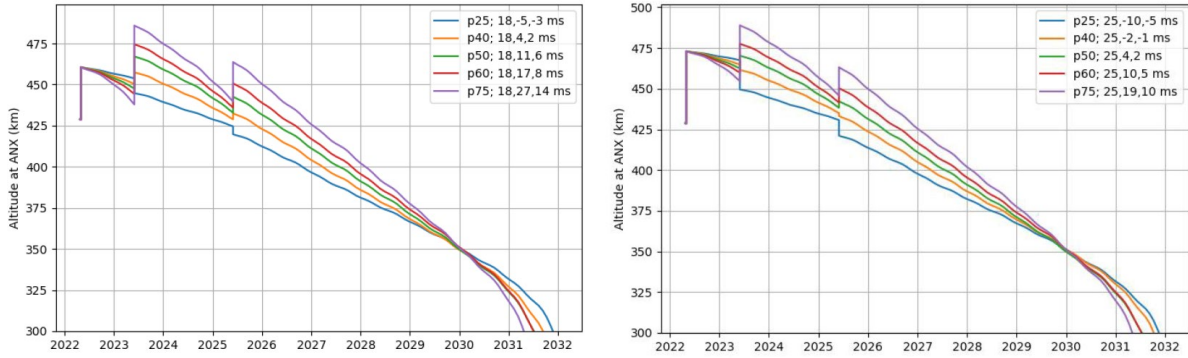
The analysis of the FD group therefore considered the above time-frames as inputs, the final altitude in 2030 as desired target and three different  $\Delta V$  figures as first step input, in order to offer a first level comparison of the step-wise approach with respect to the single burn reference scenario, and then to derive the chosen scenario. Additionally, the scenarios were analysed at different percentiles of the solar activity indexes. The strategies studied are summarised in Table 7.

**Table 7- Comparison of the different strategies studied before the campaign**

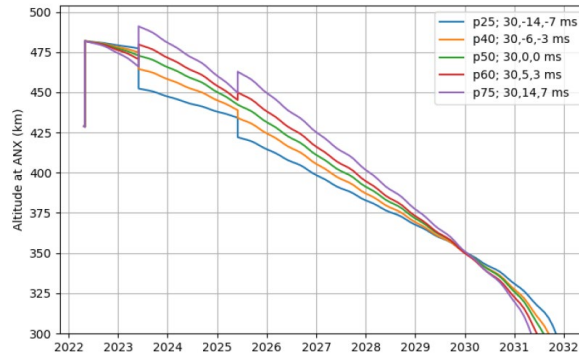
Scenario Family	Target	Scenario	Notes	Analysis
Single burn	350 km altitude in 2030	One single manoeuvre or single batch in 2022	Reference case (most fuel-efficient), but	Assumes Solar Cycle fully known in 2022
Step-wise approach	350 km altitude in 2030	Three batches (2022,2023,2025)	Adaptation of dV with evolving solar cycle	First batch 18 m/s Second batch Third batch ( Fig. 7 )
Step-wise approach	350 km altitude in 2030	Three batches (2022,2023,2025)	Adaptation of dV with evolving solar cycle	First batch 25 m/s Second batch Third batch ( Fig. 8 )
Step-wise approach	350 km altitude in 2030	Three batches (2022,2023,2025)	Adaptation of dV with evolving solar cycle	First batch 30 m/s Second batch Third batch ( Fig. 9 )

The study produced graphs of the altitude predictions of Swarm-A and Swarm-C from the current time to 2032, considering the target of reaching 2030 with an average altitude of 350 km, with the three steps of altitude raise and different  $\Delta V$  sizes based on the solar activity expressed in percentiles as pXY, i.e. p50: 50 percentile. These graphs, considering the first step of 18 m/s (Fig. 7) or 25 m/s (Fig. 8) or 30 m/s (Fig. 9) are presented. At this stage of the analysis, no assumption was made on the type or how many manoeuvres to execute, but only the  $\Delta V$  to be provided in the first step, and next steps, to achieve the target.

The analysis culminating in the figures below, opened the way for a trade-off to understand which initial  $\Delta V$  had to be implemented starting April/May to begin with the first orbit raise phase. The actual  $\Delta V$  figures of the entire campaign, not only the first batch, are reported in Table 8, in order to show which approach is preferred for low, medium and high solar activity levels.



**Fig. 7 (left) Fig. 8 (right) – Altitude prediction of Swarm-A or Swarm-C at the Ascending Node, assuming a first phase with 18 m/s  $\Delta V$  (left) or 25 m/s  $\Delta V$  (right). Solar activity used to parametrize the curves.**



**Fig. 9 - Altitude prediction of Swarm-A or Swarm-C at the Ascending Node, assuming a first phase with 30 m/s  $\Delta V$ . Effect of different solar cycle predictions are reflected in the various curves at different percentiles.**

**Table 8 – Total  $\Delta V$  to reach final target varying initial step and the Solar Activity level**

Solar Activity level	Strategy Total $\Delta V$ (18 m/s initial)	Strategy Total $\Delta V$ (25 m/s initial)	Strategy Total $\Delta V$ (30 m/s initial)	Reference (30 m/s at 50 percentile)
25	26	40	51	11
40	24	28	39	22
50	35	31	30	30
60	45	40	38	36
75	59	54	51	45
Note	If Solar Activity is low, $\Delta V$ is low.  If Solar Activity is high (> 75 perc.) it is not possible to reach 2030+.	If Solar Activity is low, $\Delta V$ starts to increase.  If Solar Activity is high (>75 perc.) it is also not possible to reach 2030+. Until 70 percentile, it is.	For both low and high solar activity levels, the figures grow to the max available budget.	

In conclusion, the  $\Delta V$  used to arrive at 350 km of altitude in 2030 clearly depends on the selected strategy, in terms of initial manoeuvre size, frequency of the batches and the evolution of the solar cycle. The trade off this analysis demanded, resulted in the following considerations:

- earlier big correction manoeuvres are beneficial for the overall  $\Delta V$ , because of less time spent at lower altitude, but the uncertainty on the future evolution of the solar activity will be bigger;
- an altitude raise in batches is beneficial in terms of robustness with respect to the predictions;
- executing an intermediate 25 m/s first  $\Delta V$  manoeuvre batch (about 85% the size of the required  $\Delta V$  for the theoretical 50 percentile case) results in a better balance between high and low solar activity.
- in the above case, the target altitude can be reached for solar activity levels between 25 and 70 percentile. The remaining  $\Delta V$  at the end of the campaign will serve as maintenance at 350-300 km altitude.

For this reason, a first manoeuvre campaign with  $\sim 25$  m/s  $\Delta V$  was considered the baseline to be further studied in detail, planned and implemented on Swarm-A and Swarm-C starting April/May, 2022 and subject of the remaining part of this manuscript.

### *3.2. Assumptions: large firing duration*

One aspect that arose at the beginning of the planning of the altitude raise was linked to the considerably larger  $\Delta V$  required, both as absolute value and as first batch (as it can be inferred from the previous section), with respect to the routine maintenance manoeuvres or CAMs of Swarm: a two-digits  $\Delta V$  required versus a few cm/s of a routine manoeuvre (ref. section 1.2). Therefore, considering that:

- in the past, during constellation acquisition in 2014, the highest duration of the OCT firing had been 24 minutes;
- the maximum firing duration implemented in the past was necessary to maximise the effect on the inclination, as those manoeuvres aimed at modifying the semi major axis and the inclination and executed at the nodes;
- no constraints in addition to the maximum OCT firing command duration in the on-board software (86400 seconds) exist to implement larger manoeuvres

it was assumed, in agreement with Industry, to analyse the possibility to implement larger firing – the maximum duration will be discussed after the sections 3.3 and 3.4.

### *3.3. Requirements*

This section summarizes the requirements of the altitude raise campaign step executed in 2022: the orbit raise overall sizing requirements, resulting from the trade-off after the study of the potential alternatives and the final target (ref. section 3.1), and the requirements of the campaign planning and execution, derived from the current operational phase of the mission, the CGPS system architecture, the operational requirements derived from the need to perform a tandem but robust operation, minimising the overall campaign duration and science data outage. Each of the following sub-sections clarifies the main requirements that will lead to the plan later discussed.

#### *3.3.1. Manoeuvre campaign: overall $\Delta V$ sizing of the first batch*

The first requirement that became evident after the study of the  $\Delta V$  to reach the 350 km average altitude in 2030 was the determination of the  $\Delta V$  itself. A trade-off analysis was carried out at ESOC and the figure of 25 m/s aggregated  $\Delta V$  – per spacecraft – in the first batch of the campaign in 2022 was considered the best compromise to cover a low Solar Cycle and a rather high one, i.e. covering, with the current fuel reserves, from 5 to around 70 percentile as presented in [5] and summarised in 3.1.

#### *3.3.2. Manoeuvre campaign duration and minimisation of science data outage*

An important requirement was the need to minimise the overall campaign duration, without any compromise on spacecraft safety while limiting the science outages, since during the manoeuvre slots one of the Swarm instruments, the Electrical Field Instrument (EFI) is put to a lower state. For the mission, it was considered acceptable to have a few weeks of operations, ideally below 10-12 weeks; this also in consideration that, outside the manoeuvre slots, science data production would be nominal.

### 3.3.3. *Crossovers and multiple revolutions: asynchronous manoeuvring*

A second requirement derived from Swarm being a constellation of satellites: from a purely theoretical constellation maintenance point of view, the best option to raise a pair of satellites flying 4 to 10 seconds separated in along-track would be executing simultaneous manoeuvres, to minimise the along-track relative drift. However, this creates two families of potential issues:

- any relevant *over* or *under*performance or anomaly would cause a substantial drift that could lead to increase the satellites separation, but also decrease it, with the risk to crossover (change position between the leading Swarm-C and trailing Swarm-A) and even satellite collision;
- raising the altitude of Swarm-A and C asynchronously (i.e. with some hours / days in between manoeuvres) and in the proper order introduces some along track distance between the satellite that would minimize the risk of cross over;
- the workload on operational teams to prepare, screen, monitor and verify the execution of manoeuvres in parallel.

For this reasons, it was decided to manoeuvre only one satellite per day, having a minimum interval time between manoeuvres of one day. In addition, the accumulation of the drift caused by the above approach shall not lead to one of the satellite to experience one or more additional revolutions with respect the other one. This additional requirement was assumed and checked, although it was clear that it would be unlikely not to be compliant with it.

### 3.3.4. *Operational requirements: Manoeuvre slots and science planning*

The minimum interval between consecutive manoeuvres (for a given satellite) was identified in one day, to allow for proper calibration of the  $\Delta V$ , generation of commands and uplink of the manoeuvre. They manoeuvres would be performed during working hours (06:00 – 16:00 UTC), to ensure quick reaction times in case of failures or contingencies. The time slots allocated for the manoeuvres will be placed early in the morning, so at the beginning of the working hours. In this way, the first calibration of the manoeuvre could happen already during the early afternoon and Space Debris Office could screen the trajectory containing the calibrated manoeuvre on the same day of the manoeuvre execution, ensuring a quick reaction in case of unforeseen conjunctions.

Another requirement is that the manoeuvre should execute outside of ground station visibility: this is to avoid that the antenna could potentially process the wrong Two Line Elements (TLE). Since pass times are booked two weeks in advance before the optimization from FD is performed, a fixed time slot for the whole duration of the manoeuvre campaign has been used.

In addition, the agreement of manoeuvre slots was beneficial to coordinate the science schedule of the EFI instrument, without the need to coordinate it weekly with the instrument teams.

### 3.3.5. *Operational requirements: weekly number of manoeuvres*

The manoeuvres are planned only on working days and, in view of the requirement to avoid synchronous manoeuvres, determines the requirement to have maximum *four manoeuvres per week*, two per spacecraft. Having the same number of weekly manoeuvres for both satellites was also considered an important requirement to avoid the accumulation of additional drift that had to be reverted at the end of the campaign.

## 3.4. *Analysis of the constraints*

In this chapter the constraints assumed before the planning and execution of the altitude raise campaign are discussed.

### 3.4.1. *Manoeuvre Space Debris screening robustness*

The large  $\Delta V$  required by the campaign compared with the usual  $\Delta V$  of a routine constellation maintenance or Collision Avoidance manoeuvres for Swarm – 25 m/s versus some cm/s determines the possibility to execute larger burns, instead of implementing hundreds of manoeuvres to generate the required accumulated  $\Delta V$ , as discussed in section 3.2. One aspect before determining the max duration burn, since not constrained to a “realistic” value at software level, is the robustness of the orbital predictions for Collision Avoidance screening purposes.

In particular, it is desired to stay within the screening volume for a minimum timespan of 2 days, meaning that any manoeuvre orbit screening outcome would be robust to predict close approaches within 2 days. Every manoeuvre introduces an uncertainty that is related to the difference between the predicted and the actual  $\Delta V$  performed ( $\Delta V$  error). The maximum  $\Delta V$  error acceptable under these conditions is of the order of 4 cm/s: it was hence studied the impact of a commanded  $\Delta V$  misperformance on the screening.

**Table 9 – Impact of 1.5% and 1% misperformance depending on the  $\Delta V$**

<b>Case if single firing</b>	<b><math>\Delta V</math></b>	<b>1.5% misperformance</b>	<b>1% misperformance</b>
1 revolution burn	1.2 m/s	1.8 cm/s	1.2 cm/s
2 revolutions burn	2.4 m/s	3.6 cm/s	2.4 cm/s
3 revolutions burn	3.6 m/s	5.4 cm/s	3.6 cm/s

Considering the figures in Table 9, the conservative approach of max 2.5 m/s (regardless the implementation strategy) with 2 days of predictions validity was considered the best solution. It must be noted that, at this stage, the constraints of 4 cm/s accepted error is not linked to a specific manoeuvre strategy, i.e. one or multiple firing.

### 3.4.2. Eccentricity control

During the routine phase, the eccentricity difference between the trajectories of Swarm-A and C is kept small (less than E-5) to avoid problems of collision in case the trailing satellite goes into Safe Mode or loses FPM and starts to drift towards the leading one (ref. section 2.4.1 and Fig. 3).

This requirement is of primary importance if the along-track separation is small (less than 10 seconds). As it will be shown in the next chapters, with the selected manoeuvre strategy during the manoeuvre campaign, the along-track separation between the two spacecraft is drastically increased, meaning that this requirement in the eccentricity could be relaxed. However, when coming back to the nominal along-track separation, the eccentricity difference should be brought back to small values. It is therefore desired to plan the manoeuvre durations such that the effect on the eccentricity is minimised, e.g., performing burns which last an integer number of revolutions. In this way, the net effect of the manoeuvre on the eccentricity is theoretically absent.

### 3.4.3. Operational constraints on satellite acquisition and Ground Stations predictions

Long manoeuvres pose a risk of satellite acquisition in case of manoeuvre abortion, as the position of the satellite will start to drift away from the predictions which the Ground Stations are using to follow the spacecraft. In particular, any specific accumulated  $\Delta V$  – for simplicity at this stage considered achieved in one single step – leads to a Time Offset Value, in other terms a delay in Acquisition of Signal (AOS) in Ground Station acquisition if the manoeuvre is not executed, ref. Table 10.

**Table 10 – Impact of manoeuvre abortion: Time Offset Value study**

<b>Case if single firing</b>	<b><math>\Delta V</math></b>	<b>ToV at the end of planned firing (mano aborted)</b>	<b>Additional ToV for every revolution</b>
1 revolution burn	1.2 m/s	1.5 s	3 s
2 revolutions burn	2.4 m/s	6 s	6 s
3 revolutions burn	3.6 m/s	13.5 s	9 s

Due to this risk, never experienced before due to the small duration of the thruster firings to date, additional measures were discussed to fulfil the operational constraint to allow safe *satellite acquisition* in case of manoeuvre abortion:

- presence on-site of the Ground Operations Engineer for real-time troubleshooting and spacecraft search, in case of no Acquisition of Signal;
- weekly planning included in advance the set of manoeuvres supposed to be executed, such that, in the nominal scenario, only the potential small misperformance errors could lead to prediction errors staying within 1 minute, accepted for the G/S acquisition (but needing a spacecraft search).

In order to understand if there was a maximum manoeuvre duration causing an issue with the *planning*, assuming a slightly higher misperformance than 1.5%, i.e. 2%, the impact of the original predictions on the spacecraft acquisition has been studied. The analysis has considered the worst-case scenario and reported in Table 11, namely:

- 2 manoeuvres per week for a given spacecraft, each one with 2.4 m/s  $\Delta V$  (since already identified to be a robust approach for collision avoidance screening purposes): drift 1.7 s/day caused by a misperformance of 2%;
- misperformance of 2% always assumed in one direction (under or over, to ensure worst case);
- manoeuvres executed on Tuesday and Thursday (worst case because drift accumulated over more days);
- station and commands plan executed on day 0 (Monday, plan is executed) and valid the following week (from Monday to Sunday of day 14, end of validity of the plan).

**Table 11 – Impact of manoeuvre 2% misperformance on the station predictions**

Manoeuvre on day	Drift contribution on day 14	Total drift for all manoeuvres on day 14	Drag prediction error at day 14
1	22.1 s (1.7*13 days)	22.1 s	30 s worst case
3	18.7 s (1.7*11 days)	40.8 s	30 s worst case
8	10.2 s (1.7*6 days)	51.0 s	30 s worst case
10	6.8 s (1.7*4 days)	57.8 s	30 s worst case

It has however to be noted that the above analysis does not constitute a constraint, since larger performance errors and even anomalies or manoeuvre abortion would be promptly looked after with an additional *ad hoc* replanning session, including the station acquisition times. However, the chosen approach, i.e. a maximum accumulated  $\Delta V$  of 2.5 m/s, corresponding to an equivalent firing for 2 consecutive revolutions, is also robust for what concerns the station predictions.

#### 3.4.4. Platform constraints and FDIR modifications

The following temporary modifications of the platform FDIR were envisaged to be applied during the campaign:

- CGPS Tank PUS FDIR Monitorings (Service 12) limits to be lowered from 30 degC to 10 degC, in order to be more robust to longer duration firing;
- High Pressure Transducer (HPT) of the high pressure section of the CGPS to be adapted due to propellant depletion, before every long duration manoeuvre;
- EFI instrument PUS FDIR Monitorings (Service 12) limits on temperatures to be increased from 50 degC to 60 degC due to the additional risk to heat-up the unit, in the ram face of the satellite, after the 180 degrees slews about the yaw axis, due to shorter duration of the thermal “orbital” cycle and avoid unnecessary FDIR triggering.

#### 3.5. Validation of long-duration manoeuvres with Swarm-B

As discussed in the previous section, no constraint on the spacecraft platform, AOCS subsystem or on ground prevented to plan manoeuvres with a consistently larger firing duration compared to the past. However, during the campaign early discussion, it was agreed to plan for some test and characterisation manoeuvres, of increasing duration, with Swarm-B CGPS. These tests had the benefit to confirm the full feasibility to perform, on-board and on-ground, long duration manoeuvres with Swarm, without affecting in any way the lower pair constellation.

In particular, three manoeuvre slots were reserved, over different weeks starting mid-March 2022: after each operation, an extensive analysis of the AOCS and platform was carried out by the Flight Control and Flight Dynamics teams, in addition to the satellite Prime Contractor. The final goal was to go up to the limit identified by the constraints in sections 3.4.1 and 3.4.3, i.e. up to two consecutive revolutions  $\Delta V$ , 2.4 m/s.

**Table 12 – Dates and size of the Swarm-B characterization manoeuvres to validate long-duration burns with the Swarm CGPS before the implementation of the orbit raise campaign.**

	Satellite	Manoeuvre	Burn duration
16.03.2022	Swarm-B	Characterisation manoeuvres	40 minutes
30.03.2022	Swarm-B	Characterisation manoeuvres	1 revolution
06.04.2022	Swarm-B	Characterisation manoeuvres	2 revolutions

The test manoeuvres with Swarm-B, summarised in Table 12, have been a fundamental step to allow to plan the campaign with the feasibility confidence that routine long-duration manoeuvres could be performed on Swarm, taking into account all measures to be additionally implemented, such as the presence of the Ground Operations team at the AOS of any long duration manoeuvre to react in case of no signal. All manoeuvres on Swarm-B were executed with no issues, the performance of the AOCS, CGPS and the platform was nominal, opening the way to the determination of the maximum manoeuvre duration and the final planning of the 25 m/s  $\Delta V$  campaign for the lower pair.

### 3.6. The maximum manoeuvre duration

The nominal execution of the characterisation manoeuvres allowed to confirm the manoeuvre maximum duration to 2 consecutive revolutions, i.e. 2.4 m/s  $\Delta V$ . This information has been the fundamental input to the final planning of the campaign, identifying the manoeuvring days and the number of the campaign weeks.

### 3.7. Final schedule and implementation aspects

This chapter describes the final manoeuvre campaign schedule as it was discussed and approved before the implementation. The schedule was compliant with the requirements discussed in section 3.3 and sub-sections, the constraints in section 3.4 and sub-sections, and the maximum accepted manoeuvre duration of 2 consecutive revolutions, as compatible with the constraints and confirmed fully feasible after the validation and characterisation manoeuvres undertaken in March / April, 2022 with Swarm-B. Table 13 reports the full plan, with the week (Monday to Friday), the burn duration, the scheme (A: Swarm-A manoeuvre, C: Swarm-C manoeuvre), the accumulated  $\Delta V$  and the accumulated along-track separation between the lower pair. Fig. 10 shows the weekly plan in a calendar form: the weeks with four manoeuvres can be easily spotted.

In the first two weeks of the campaign only one revolution and two revolutions manoeuvres, two in total per week, were planned. This was considered an additional validation, for any spacecraft of the Swarm constellation to perform long-duration burns, in addition to the tests and characterisation manoeuvres of Swarm-B.

The along-track separation increases during the manoeuvre weeks, up to ~10 minutes from the routine 4-10 seconds bandwidth, as a side effect of the increasing drift imposed by executing manoeuvres in different days and not simultaneously. This was not only acknowledged by the Swarm management, but seen as a robust approach in case of anomalies (allowing focusing on one satellite only). Moreover, the planned scheme, changing around the middle of the campaign from A-C to C-A, allowed to revert the drift and then naturally come back to a lower separation. It has also to be noted that the last Swarm-A manoeuvres were planned with consistently smaller size because “touch-up manoeuvres” to restore the along-track separation in a safe way.

One important implementation aspect has been the daily and weekly allocation of ground station passes, in order to streamline the manoeuvres uplink, the Orbit Determination processes – to be used to generate the products for station predictions and screened against space debris, and the manoeuvres verification. In particular, the following was agreed:

- the working day before the manoeuvre, one pass was constrained before 11:00 UTC for OD purposes;
- the day before the manoeuvre, one morning pass as in routine was kept for monitoring purposes, while two passes were booked after 12:00 UTC to uplink the manoeuvre (prime and redundant);
- on the manoeuvre day, one pass was scheduled between 6:00 and 07:00 UTC, just after the manoeuvre execution, one pass after one orbit (to increase monitoring robustness) and one three orbits after, to be used for complete OD
- no passes were foreseen during the firing, to ensure that the used TLEs were based on before/after the manoeuvre and avoiding the station to use non-updated TLEs causing potential tracking issues;
- on the 4-manoevrue weeks, one additional pass before 6:00 UTC the day after the first manoeuvre of the same satellite, to allow to perform an OD to be used for additional debris screening in between the two big manoeuvres.

In order to increase the robustness of the operations, the following was also decided:

- the manoeuvres of week N are included in week N-1 orbit file (EVF) to ESOC’s Scheduling Office the Monday afternoon of week N-1: ideally in case of low misperformance errors and good drag prediction, no replanning will be required, because station booking will be consistent with reality (Event files will be however checked by FCT);
- FCT would compare the predictions (EVF) used to allocate the passes and the ones provided after the manoeuvres throughout the week: if the difference between predicted and real station timings (e.g. AOS/LOS) had exceeded the minute, a replanning session would be implemented;

Finally, additional measure were taken:

- The Swarm OnCall Engineer was on-console, together with the Ground Operations Engineer, for each AOS of any pass after the execution of a long duration manoeuvre, to ensure monitoring and, if required, trigger spacecraft search. The search would, if triggered, look for ToVs of 1.5 seconds at the end of burn, in case of abortion, for a one revolution manoeuvre, or 6 seconds for a 2 revolutions manoeuvre. Early ToV, in case of manoeuvre abortion, was expected.
- If, for any reason, a manoeuvre had to be cancelled (e.g. due to CAM), if it was the first one of a pair, also the second one would be not executed. In case the affected manoeuvre was the second of the pair, the plan had to be adapted.
- In case of manoeuvre cancellation, a station replanning had to be performed, including deletion of the on-board timeline and uplink of the updated commands;
- In terms of commanding, the tuning of the High Pressure Transducer (HPT) FDIR had to be calculated and commanded before the firing, to ensure the FDIR value was updated before the manoeuvre;

**Table 13 – Final schedule**

<b>Week</b>	<b>Burn duration (revolutions or m/s)</b>	<b>Scheme</b>	<b>Total accumulated <math>\Delta V</math></b>	<b>Total accumulated along-track separation</b>
2-6 May	1-1	A1-C1	1.2 m/s	42 s
9-13 May	2-2	A2-C2	3.6 m/s	126 s
16-20 May	2-2-2-2	A3-C3-A4-C4	8.4 m/s	294 s
23-25 May	2-2	A5-C5	10.8 m/s	378 s
30 May – 3 Jun	2-2-2-2	A6-C6-A7-C7	15.6 m/s	546 s
7-10 Jun	2-2	C8-A8	18.0 m/s	462 s
13-15 Jun	2-2	C9-A9	20.4 m/s	378 s
20-24 Jun	2-2-2-1	C10-A10-C11-A11	25.2 m/s (C) 24.0 m/s (A)	210 s
27 Jun – 1 Jul	0.9 m/s + 0.18 m/s	A12-A13	25.08 m/s (A)	21 s
4-8 Jul	0.12 m/s	A14	25.2 m/s (A)	0 s (routine 4-10s)



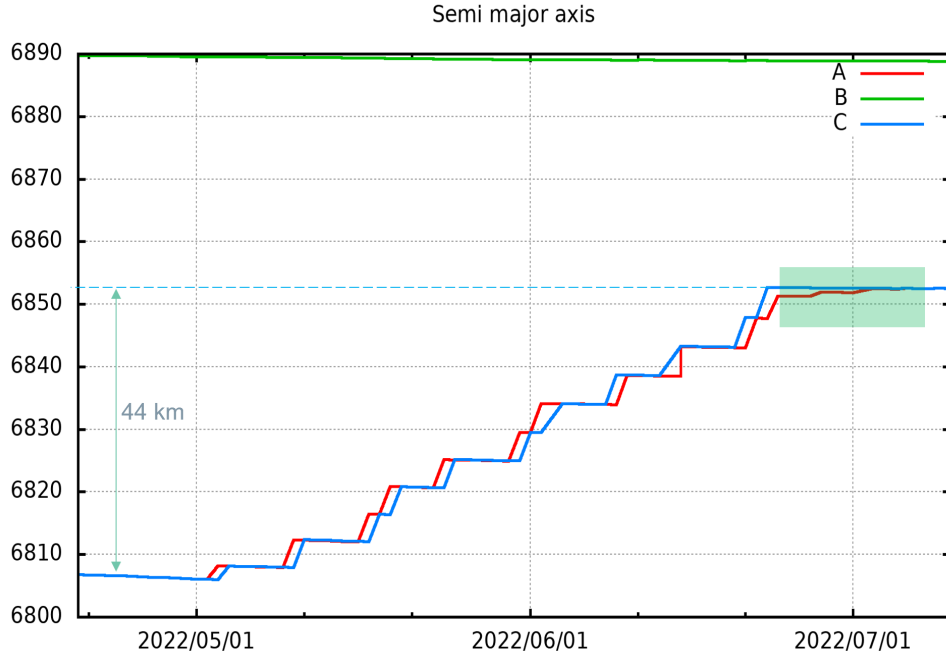
Fig. 10 – Final plan: manoeuvre slots for Swarm-A (red) and Swarm-C (blue).

### 3.8. Operational execution and Fuel budget

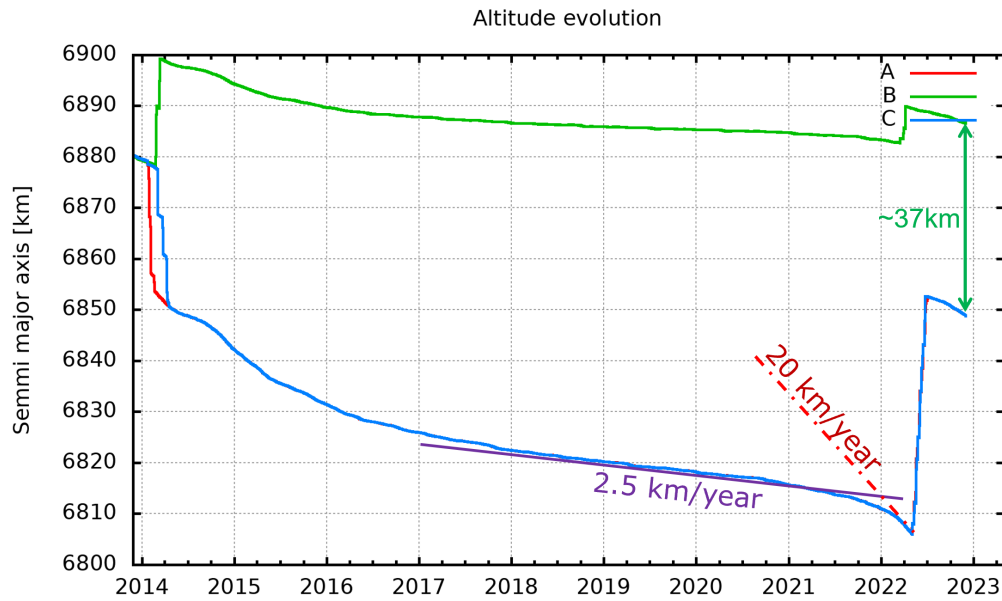
The current section contains the details of the campaign executed, including the exact days of the manoeuvres, the burn duration and the altitude increase, in Table 14. In Fig. 11, the semi-major axis of all three Swarm is shown, in Fig. 12 the same information is plotted since the beginning of the mission, showing the average decay during the previous Solar Cycle minimum and the raising trend, while Fig. 13 shows the fuel used for the manoeuvres.

**Table 14 -Dates and size of the Swarm-A and Swarm-C altitude raise manoeuvres.  
 A refers to Swarm-A manoeuvre, C refers to Swarm-C.**

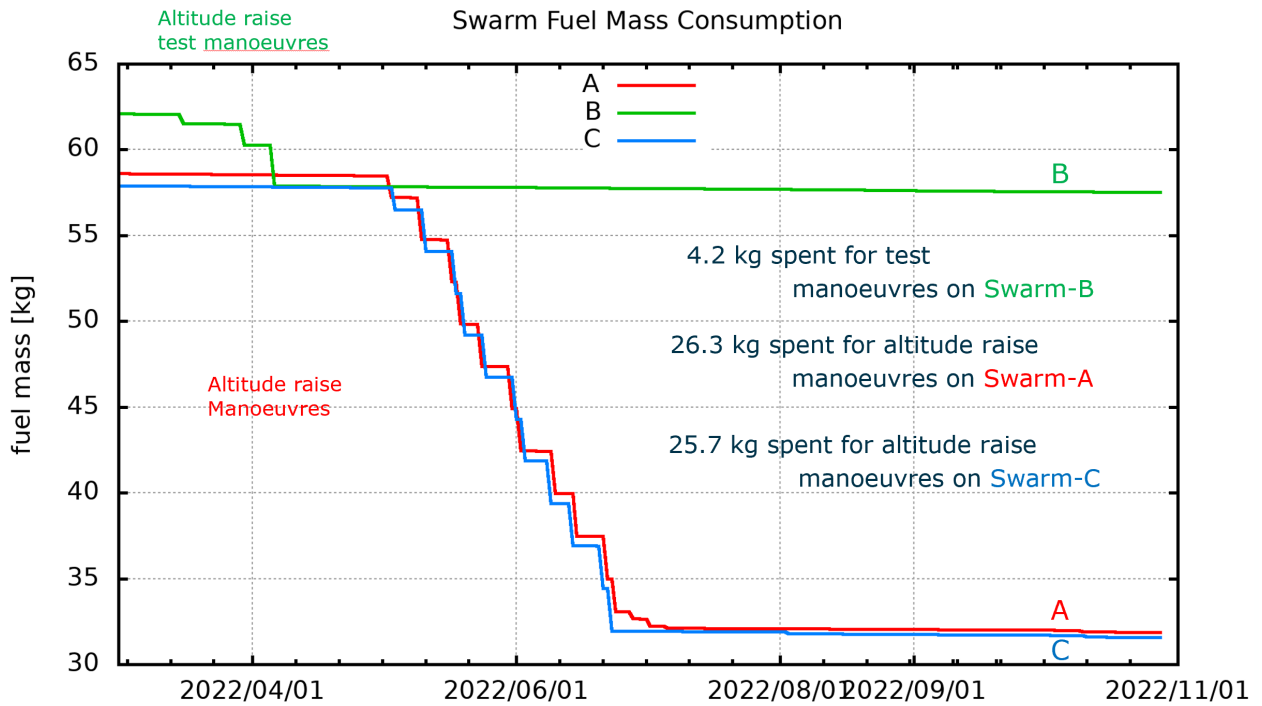
Day	Satellite	Manoeuvres ID	Burn duration	Outcome
03.05.2022	Swarm-A	A1	1 revolution	Nominal
04.05.2022	Swarm-C	C1	1 revolution	Nominal
10.05.2022	Swarm-A	A2	2 revolutions	Nominal
11.05.2022	Swarm-C	C2	2 revolutions	Nominal
17.05.2022	Swarm-A	A3	2 revolutions	Nominal
18.05.2022	Swarm-C	C3	2 revolutions	Nominal
19.05.2022	Swarm-A	A4	2 revolutions	Nominal
20.05.2022	Swarm-C	C4	2 revolutions	Nominal
24.05.2022	Swarm-A	A5	2 revolutions	Nominal
25.05.2022	Swarm-C	C5	2 revolutions	Nominal
31.05.2022	Swarm-A	A6	2 revolutions	Nominal
01.06.2022	Swarm-C	C6	2 revolutions	Nominal
02.06.2022	Swarm-A	A7	2 revolutions	Nominal
03.06.2022	Swarm-C	C7	2 revolutions	Nominal
09.06.2022	Swarm-C	C8	2 revolutions	Nominal
10.06.2022	Swarm-A	A8	2 revolutions	Nominal
14.06.2022	Swarm-C	C9	2 revolutions	Nominal
15.06.2022	Swarm-A	A9	2 revolutions	Nominal
21.06.2022	Swarm-C	C10	2 revolutions	Nominal
22.06.2022	Swarm-A	A10	2 revolutions	Nominal
23.06.2022	Swarm-C	C11	2 revolutions	Nominal
24.06.2022	Swarm-A	A11	First burn: 7055s, second burn: 1472s	Nominal
28.06.2022	Swarm-A	A12	First burn: 826s, second burn: 722s	Nominal
30.06.2022	Swarm-A	CAM	Single burn: 189s	CAM, nominal
01.07.2022 => 02.07.2022	Swarm-A	A13	First burn: 813s, second burn: 813s	Aborted due to CAM, moved to 02.07.2022
06.07.2022	Swarm-A	A14	First burn: 36s, second burn: 163s	Nominal



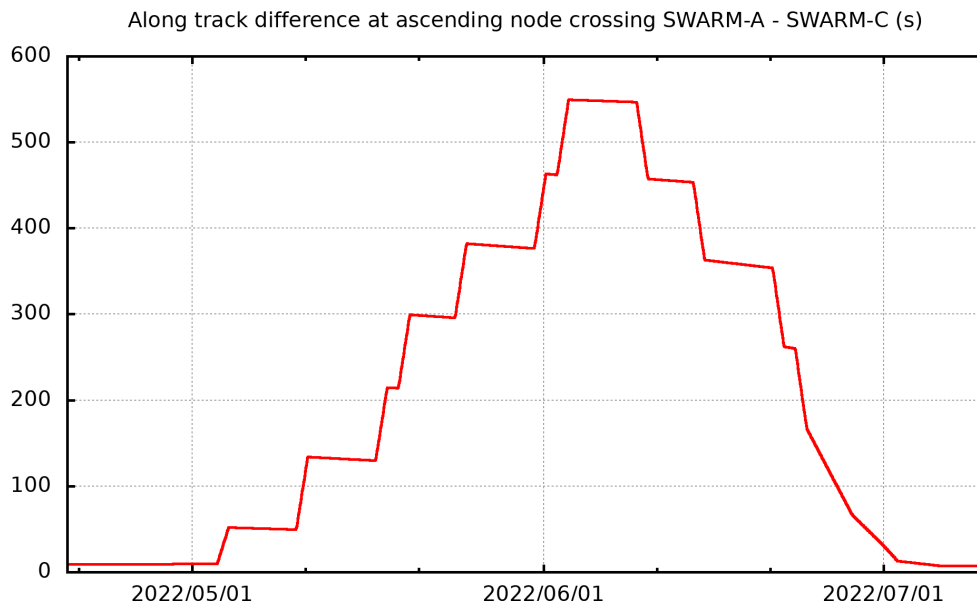
**Fig. 11 - Semi-major axis of the Swarm satellites from the end of April, 2021 until the end of the orbit raise campaign. The rationale of the operations in alternating days is clearly visible. The green area shows the touch-up manoeuvres to re-establish, with a drift reduction in a controlled day, the routine constellation separation.**



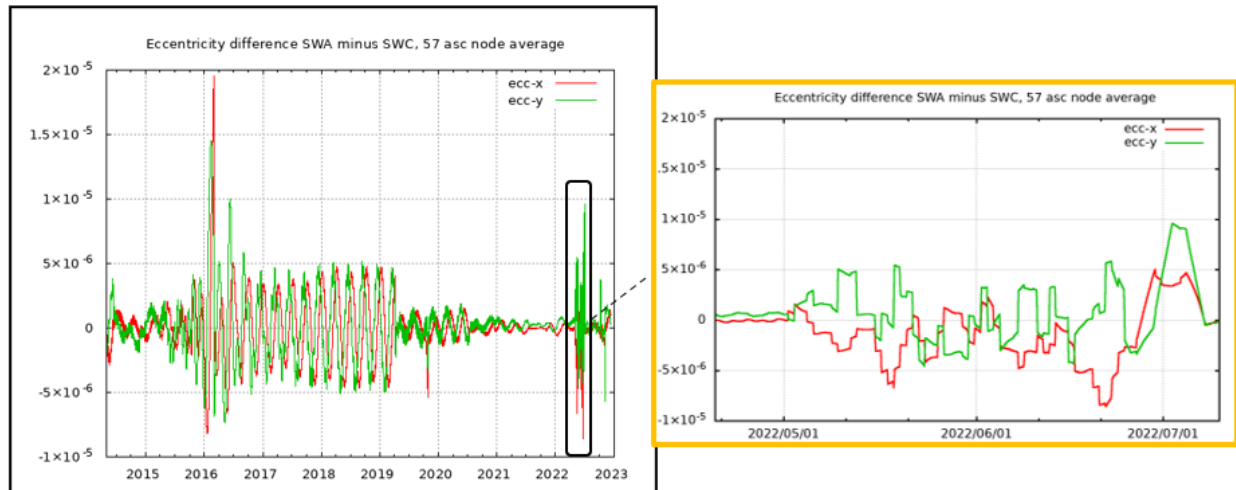
**Fig. 12 - The absolute semi-major axis evolution of the Swarm satellites since launch. The decay rate change, at the beginning of the current Solar Cycle 25 is clearly visible, as the orbit raise of Swarm-B (characterisation manoeuvres) and Swarm-A/C. The lower pair absolute altitude separation wrt Swarm-B has decreased to ~37 km.**



**Fig. 13 - The fuel mass of the Cold Gas Propulsion System of the Swarm satellites since March, 2021, including the depletion due to the test & characterisation manoeuvres of Swarm-B and orbit raise campaign. The major fuel depletion is visible for Swarm-A (26.3 kg of fuel spent) and Swarm-C (25.7 kg of fuel spent).**



**Fig. 14 - Along-Track distance between Swarm-A and C expressed as difference in Ascending Node Crossing times during the manoeuvre campaign. It is visible the effect of the first phase in increasing the distance up to 549 seconds; during the second and the third phase the distance decreases again.**



**Fig. 15 - Eccentricity difference between Swarm-A and Swarm-C trajectories, expressed in terms of x and y components of the difference between the eccentricity vectors.**

### 3.9. Challenges and Lessons Learned

A challenge that the teams faced at the end of the campaign was a close approach warning issued by the Space Debris Office on 30/06/2022 at 13:49, warning the teams about the possibility of collision between Swarm-A and an unknown object (1982-092BXT) with an initial Probability of Collision of  $1.12E-4$ . The Time of Closest Approach was at 30/06/2022 22:29, so less than 8 hours after the notification, and most importantly the manoeuvre A13 was already loaded on-board to further reduce the drift towards Swarm-C, to contribute to re-establish the constellation along-track separation. The decision taken was to delete the manoeuvre from the on-board timeline and plan for a CAM with 4.5 cm/s against the flight direction (i.e. with semi-major axis decrease) and then re-plan the manoeuvre A13. This was even more challenging due to the following:

- during the CAM a secondary event did pop-up, but luckily with collision probability slightly below our thresholds.
- the CAM was uplinked on Thursday 30/06/2022 evening – only 4 hours after the notification - and executed nominally.
- the original manoeuvre had to be re-designed in one day, to ensure that the drift of Swarm-A towards Swarm-C was slowed down, so in practise avoiding that the two satellites would crossover. This was prepared on Friday 01/07/2022 and executed on Sunday 02/07/2022 early morning.

All in all, these events have shown an incredibly fast reaction time of all teams, considering that it is very rare that a conjunction is escalated less than 24h before the event. Not only the effort was fundamental to decrease the collision risk of Swarm-A with another object, but the quick replanning of the A13 manoeuvre was fundamental to avoid Swarm-A crossover with Swarm-C.

As general lesson learned it is important to mention the level of coordination among the parties involved in a major operation campaign as the one described in this chapter. The work outlined in this sections followed many meetings, internal analysis and simulations and agreements between various actors involved in the Swarm mission operations: the Flight Operations Segment (FOS) at ESOC, the Flight Control Team, the Flight Dynamics Team, the Space Debris Office, the Ground Operations Engineering Team and all teams involved in the day to day activities; the contribution of Industry, the satellite Prime Contractor (Airbus Defence and Space) was essential to confirm the initial assumption to perform long duration manoeuvres, together with the analysis of the validation and characterisation manoeuvres with Swarm-B. The Mission Management and the entire Payload Data Ground Segment (PDGS) and Data Quality teams, mostly at ESRIN, the Post Launch Support Office (PLSO) in ESTEC gave a fundamental contribution to the activity. It is also worth to mention the involvement of the instruments Principal Investigators, in particular the University of Calgary of the EFI instrument.

One of the important lessons learned was indeed the allocation of the manoeuvres in dedicated daily slots, in days where the manoeuvre was supposed to occur. This way, the EFI instrument planning was greatly streamlined, avoiding to ping-pong timelines to be then updated on both sides.

#### 4. Conclusions

This paper has presented two fundamental milestones achieved in 2021 and 2022 by ESA's Swarm mission: the exploitation of the counter-rotating orbits configuration in 2021 and the altitude raise campaign in 2022. In these pages, the rationale, objectives and requirements, space segment and ground segment constraints, operational constraints and approaches, possible implementing solutions and the final timeline, schedule and execution are discussed for both campaigns.

The exploitation of the counter-rotating orbits configuration showed that the natural evolution of the orbital planes could offer exciting cases for science by tuning the along-track separation of the Swarm lower pair satellites. This implied to also achieve the minimum separation since launch, during the two-seconds separation phase, where additional safety measures were implemented to avoid that anomalies could cause satellites crossover or collision. The journey of this exciting months is presented, along with the description of the operations as executed.

The altitude raise campaign for Swarm-A and Swarm-C was the second and greatest achievement of 2022 for the Swarm mission, otherwise condemned to sink from its orbit some time in 2025 due to the strength of the Solar Cycle 25. The rationale of the orbit raise, with the objective to reach 2030 with an average altitude of 350 km has been discussed, outlining the potential alternatives of executing the manoeuvres in batches over different years, anticipating the first batch in May/June 2022. The discussion of the trade-off towards long-duration manoeuvres, to implement the accumulated 25 m/s  $\Delta V$  to achieve the 44 km altitude raise, has been presented, together with the requirements and the constraints taken into account. Finally, the final schedule, implementation aspects and the description of the operations, and the 24 long-duration manoeuvres executed, is offered. The campaign, requiring around 40% of the fuel reserves of Swarm-A and Swarm-C, has been a fundamental success for the mission, for the scientific community and for ESA, showing once again one example of teamwork.

## Acknowledgements

The milestones described in this manuscript have been achieved thanks to the passion, commitment and hard work of the following teams: at the European Space Operations Centre (ESOC in Darmstadt, Germany) the Swarm Flight Control Team, the Swarm Flight Dynamics Team, the Ground Operations Team, the Mission Control Systems hardware and software teams, the Product Assurance Team; at the European Centre for Earth Observation (ESRIN in Frascati, Italy): the Swarm Mission Management, the Swarm Payload Ground Segment, the Swarm Data Quality teams; at the European Space & Technology Centre (ESTEC in Noordwijk, the Netherlands): the Post Launch Support Office; the Swarm Prime team at Airbus Defence and Space (Friedrichshafen, Germany); the entire Swarm scientific community.

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