The Swarm constellation – Almost nine years of successful spacecraft operations: an exciting journey

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The status of the Swarm space segment

The status of the platform and payload of the Swarm constellation is condensed in the following tables

Subsystem	SW-A	SW-B	SW-C
DMS CTU, RU	OK **PS1 only**	OK	OK
AOCS MTQ, CGPS, CESS, FGM	OK	OK	OK
TT&C	OK	OK	OK
Thermal	OK	OK	OK
Power PCDU, Battery, SA	OK All SAR OK	OK All SAR OK	OK All SAR OK
ASM	OK	OK	FAILED (A&B)
VFM	OK	OK	OK
EFI (TII and LP)	TII 4 SC/Orb/day	TII 8 SC/Orb/day	TII 1 SC/Orb/day
ACC	OK	OK	OK

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Spacecraft operations concept… and evolution

Swarm ground segment and Flight Operations Segment: many upgrades through the years!
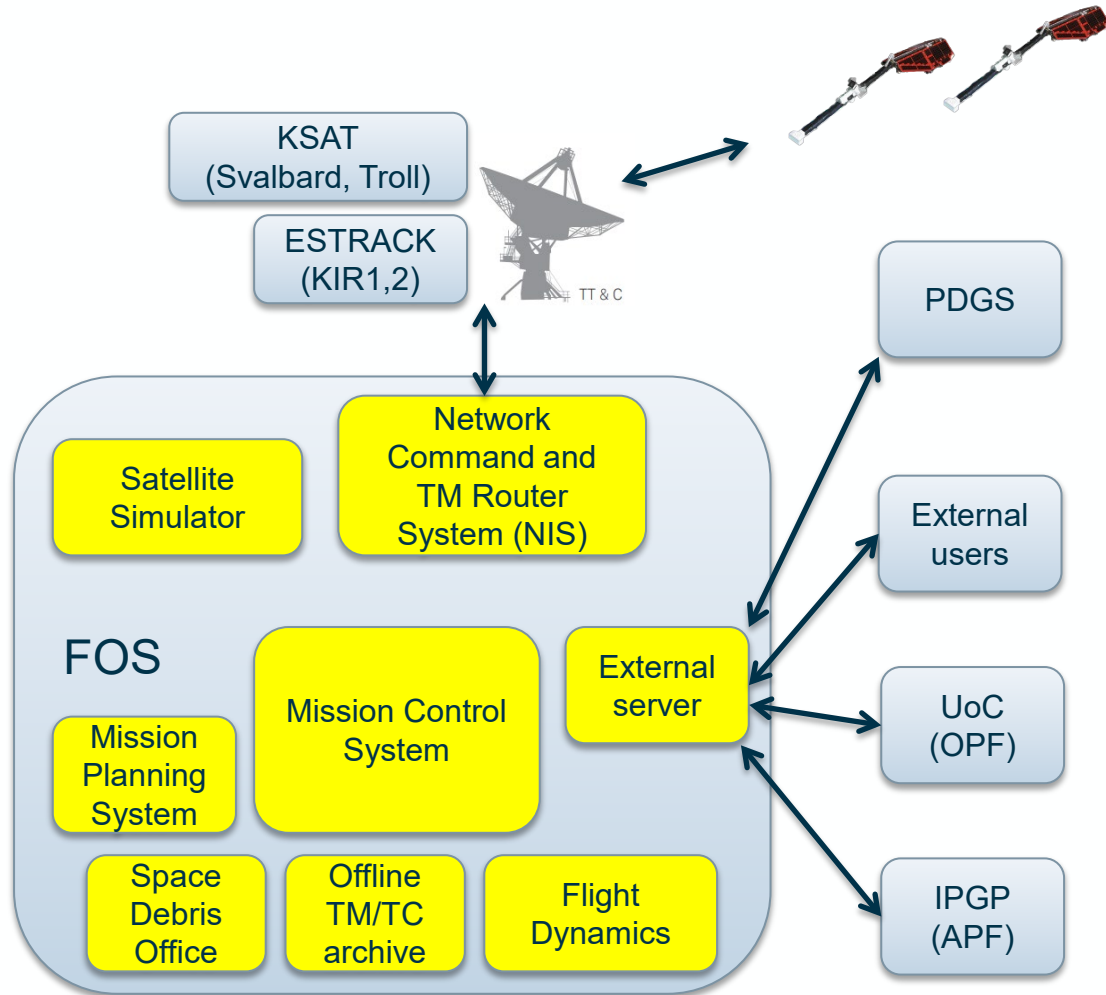
Two **new interfaces** introduced in 2015/2018 and 2021:

- With University of Calgary (EFI instrument) to introduce new IF (with exchange of Operations Planning File) including configuration / science orbits and scrubbing

- With IPGP (ASM instrument) to schedule ASB mode sessions and Burst Mode sessions via APF Planning File

- Both cases: instruments are operated using these input files and FOS Mission Planning System

Many **FOS systems upgrades**:

- Mission Control System porting, new External servers, new Mission Planning system, logging tools, etc…

- New stations validated (Troll-9), pass strategy updated

In-orbit activities to keep us busy

Almost every week the Swarm Flight Control Team has performed some **special operations** (**SOR**s) dealing with software maintenance,Star Tracker CCD images, orbit control manoeuvres…

❑ Software maintenance on many subsystems

- Upgrade of OBC On-Board Control Procedures (OBCPs)

- Update of STR Star Catalogue and Database (see dedicated slide)

- Update EFI software and EFI TII configuration in RAM and EEPROM, including CCD Gain Maps

- Update of GPSR software, disable of events, fine tuning of configuration

❑ Star Tracker CCD image to evaluate hardware aging

❑ Orbit Control Manoeuvres

- Collision Avoidance (see dedicated slides)

- Routine manoeuvres to keep lower pair satellites between 4-10s along track separation

- Manoeuvres to support dedicated phases (see next slide)

❑ Instrument calibrations, configuration update, including ASM Burst Mode sessions

❑ Additional passes for station validation

540 SORs

More than 80 Manoeuvres
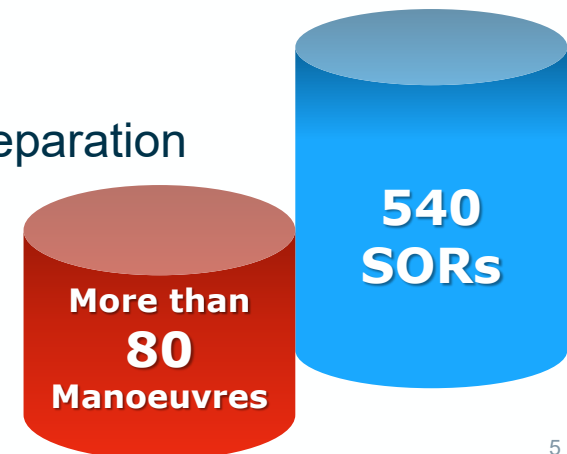
Instrument performance: routine is never routine

Since commissioning, many anomalies on the instruments were tackled and mostly solved in many way to reach a rather stable configuration and good performance, just to mention EFI change of operations concept…

ASM

- Manoeuvres to calibrate VFM-ASM
- Update of motor parameters
- New interface with IPGP <> FOS to schedule Burst and Vector Mode sessions

VFM

- Recurrent SEUs affecting science data, HK data: few power cycle ops necessary to date
- Other anomalies detected by VFM FDIR triggering instrument off solved

ACC

- EDAC-Code Area anomaly leading to OBC SysLog fill-up : new OBCP developed and uplinked
- Calibration man in early mission years with Cold Gas firing

EFI

- Image anomaly led to: change of operating concept "few science orbits per day" + scrub
- Many manual ops
- New interface (OPF) also updated to include tests and scrub
- Application software updated (Image B)
- Configuration tuned
- Peripheral anomaly-led high-voltages shutdown
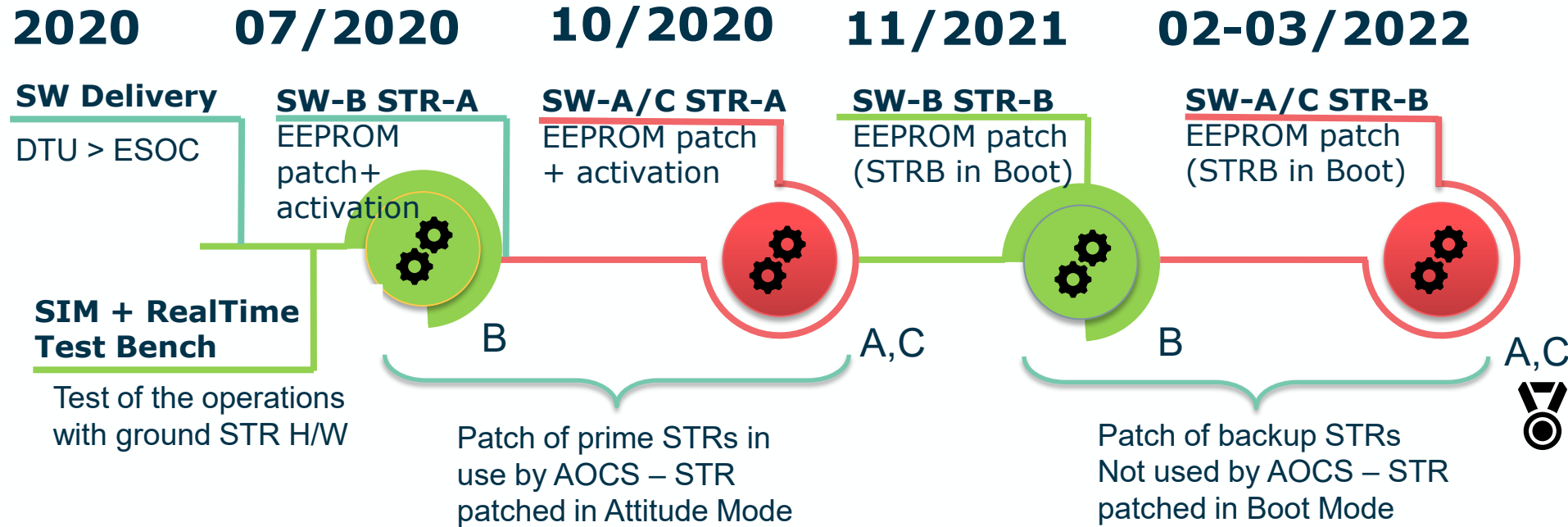- Temperatures trend check

Instrument activities: the case of the EFI

Condensed and clearly "unreadable" view of the principal activities on the EFI instrument to date
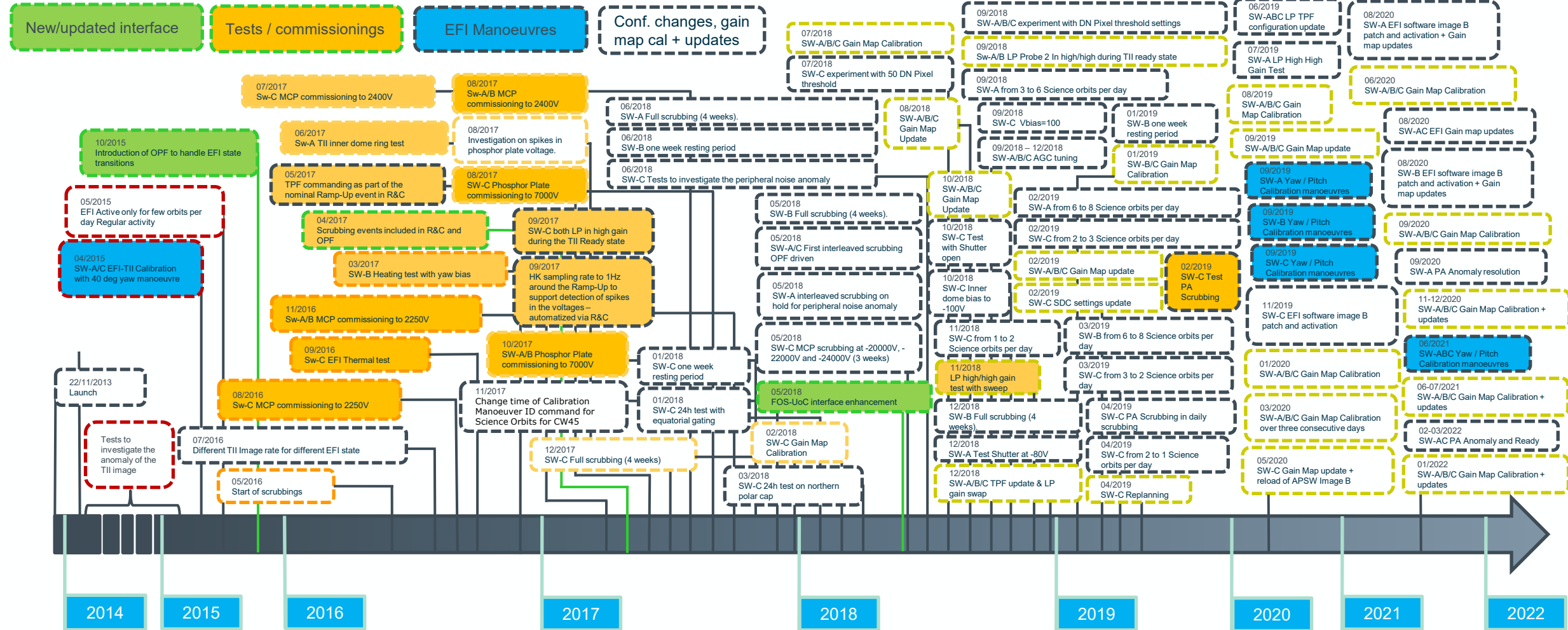
Software evolution: the new GAIA Star Catalogue

- The Swarm uASC STR (DTU Denmark) was loaded with Hypparcos Star Catalogue and Star Database.

- In view of the mission lifetime, decided to upload a new Star Catalog and Database based on ESA's GAIA star measurements => better Star reference, more correct EPOCH, expected improved attitude determination

2020

SW Delivery
DTU > ESOC

SIM + RealTime Test Bench
Test of the operations with ground STR H/W

07/2020

SW-B STR-A
EEPROM patch+ activation

B

10/2020

SW-A/C STR-A
EEPROM patch + activation

A,C

Patch of prime STRs in use by AOCS – STR patched in Attitude Mode

11/2021

SW-B STR-B
EEPROM patch (STRB in Boot)

B

02-03/2022

SW-A/C STR-B
EEPROM patch (STRB in Boot)

A,C

Patch of backup STRs Not used by AOCS – STR patched in Boot Mode

Massive activity:
- 8000 commands per STR/satellite
- 20 G/S passes to uplink commands to the on-board schedule per STR
- Switch from A>B STR operation is not trivial
- Backup STRs: 5 test orbits to test attitude

Results: Residual (or confidence level), the misfit between observed and catalogued stars, expressed in arc-seconds decreased with new Star Catalogue update. This shows a Star matching accuracy increase between 10% and 25% across all Swarms
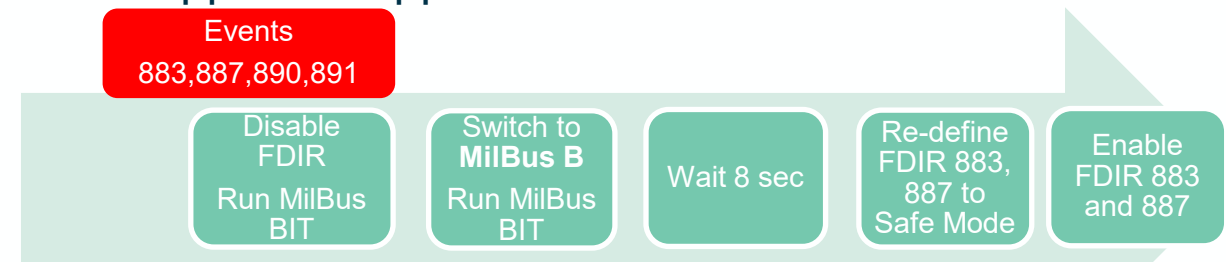
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On-board anomalies: Swarm-C MILBUS anomaly

A major anomaly on the On-Board Computer of Swarm-C affecting MILBUS communication happened in April, 2019:

❑ The MILBUS is in charge of supporting the communication from/to OBC to other instruments / equipment (TM/TC)

❑ An issue with the MILBUS on OBC-A led to safe mode (single reboot) and then to OBC switchover to B side (with all equipment on backup side!)

- Safe mode recovery performed + equipment on nominal side

- Tested MILBUS-A on OBC-B: MILBUS-A is still usable!

- In July, evaluation of a complex test in-orbit with switch-back to OBC-A side using MILBUS-B and partial evaluation of MILBUS-A: successful !

- Mitigation strategy adopted by upgrading OBCP to toggle MILBUS, to attempt a MILBUS switch rather than full OBC switchover in case re-occurrence

- Restoration of OBC-A MILBUS-A with this robustness approach applied

❑ New approach applied in RAM on-board:

- Attempt switch to MILBUS-B keeping OBC-A

- Re-def original action in case not cured

Events
883,887,890,891

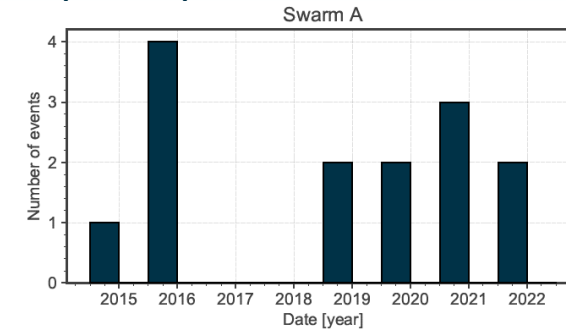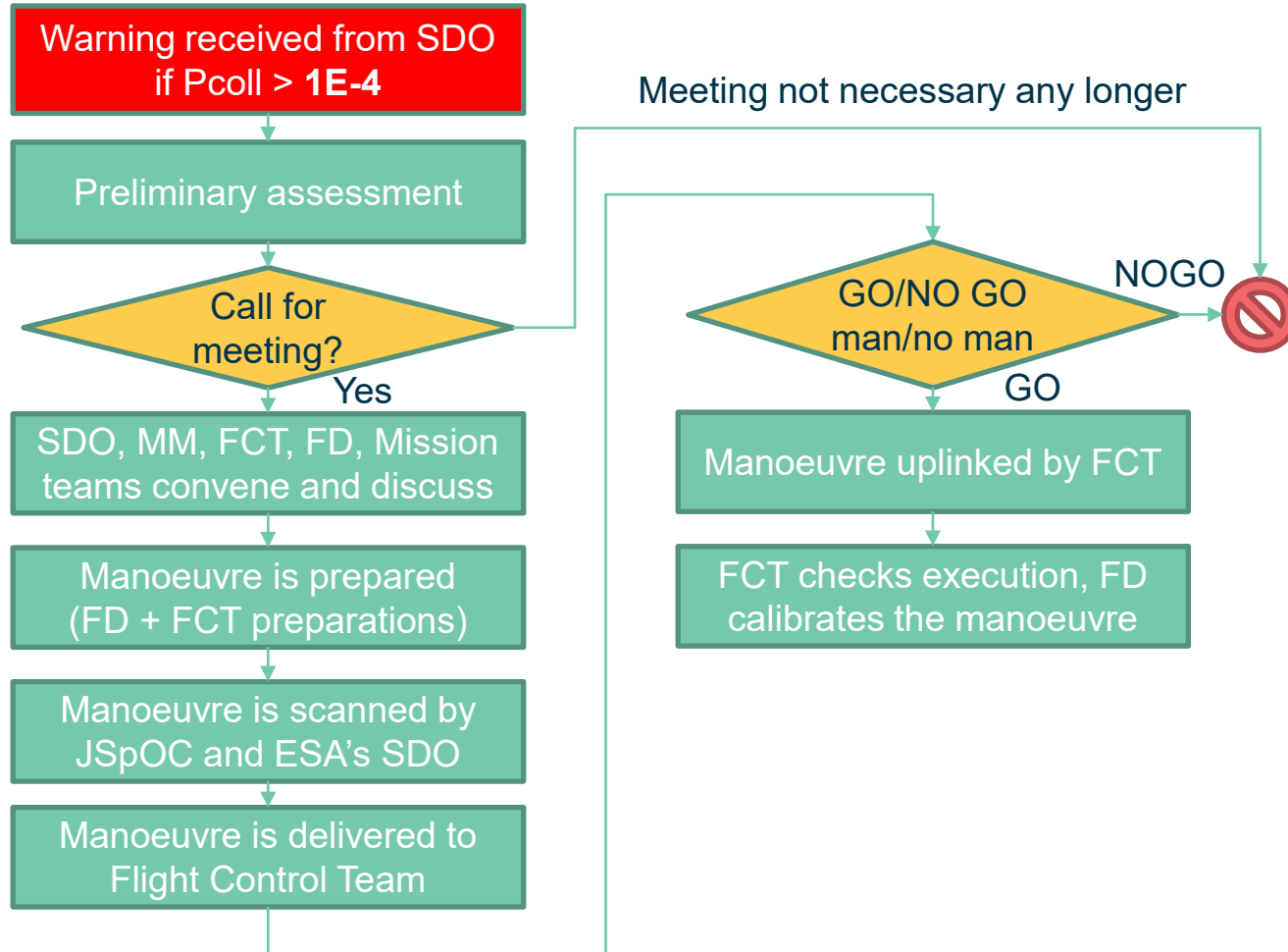| Disable FDIR Run MilBus BIT | Switch to **MilBus B** Run MilBus BIT | Wait 8 sec | Re-define FDIR 883, 887 to Safe Mode | Enable FDIR 883 and 887 |

On-board anomalies: Swarm-A downlink anomaly

A major anomaly on the On-Board Computer of Swarm-A affecting the downlink of science TM happened in 2020: after a certain number of good TM frames from the Mass Memory Unit "Science" storage, the frames were corrupted

❑ Attempts to re-dump the data ruled out G/S issue and MMU storage issue

❑ Issue in downlinking (but only science data): H/W TME<>MMU

❑ Many tests performed, including reboot of TM Module and encoder that led to safe mode => issue not solved by reboot, but also not permanent

❑ Necessity to resume science downlink:

- Approach "think outside the box" applied
- Routing all TM into single MMU storage, MMU re-partitioned
- Big effort on ground to re-adapt V-Channellisation concept
- Specific ground and on-board configuration on Swarm-A adopted since
- Great team effort, good approach to avoid going to full OBC-B side and loose the redundancy on the OBC hardware (very important!)
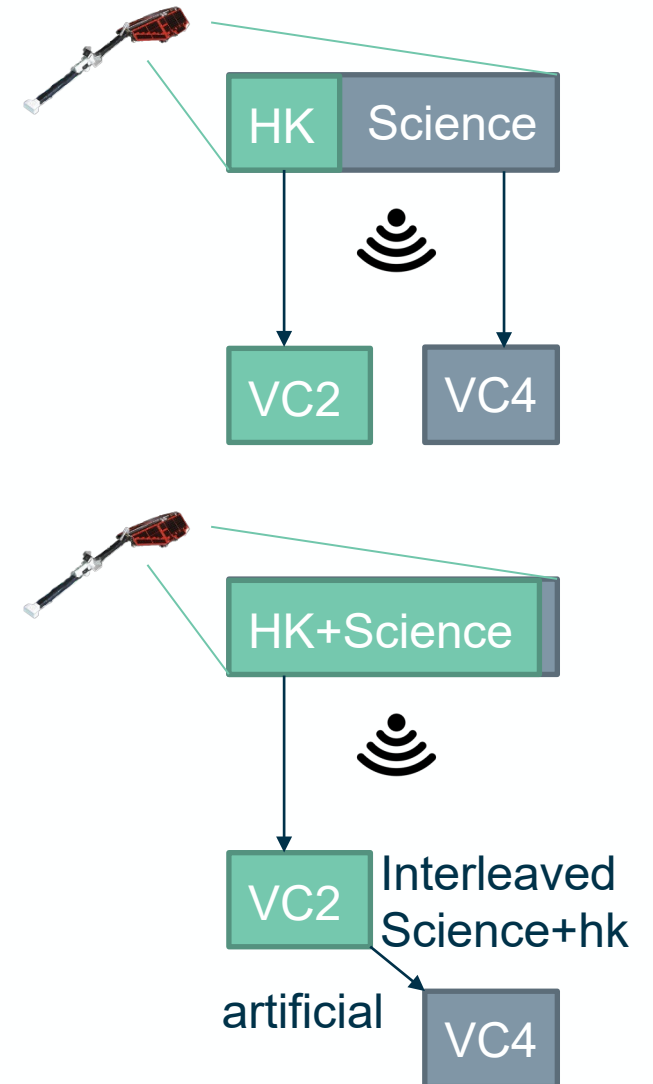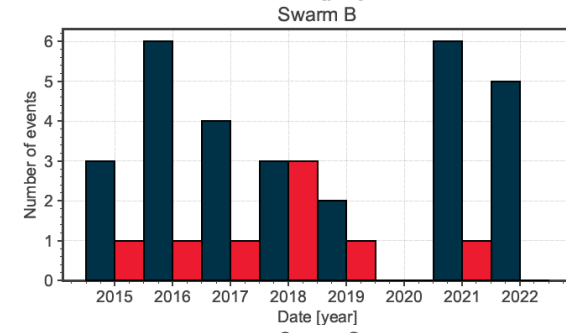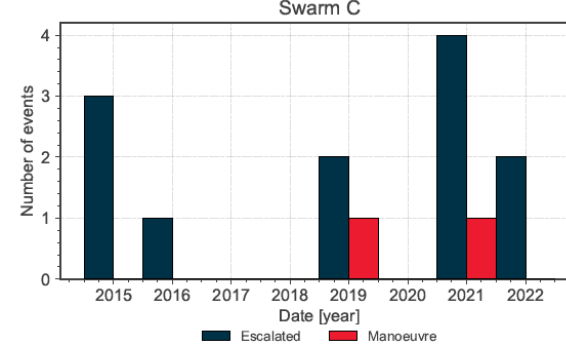
Collision Avoidance strategy and statistics

Since launch, a series of Collision Avoidance Manoeuvres has been undertaken to ensure a proper risk mitigation after the notification of a close approach from ESA's Space Debris Office (SDO).

Flowchart:
- **Warning received from SDO if Pcoll > 1E-4**
- Preliminary assessment
- Call for meeting? — Yes → Meeting not necessary any longer
- SDO, MM, FCT, FD, Mission teams convene and discuss
- Manoeuvre is prepared (FD + FCT preparations)
- Manoeuvre is scanned by JSpOC and ESA's SDO
- Manoeuvre is delivered to Flight Control Team
- GO/NO GO man/no man — NOGO 🚫 / GO
- Manoeuvre uplinked by FCT
- FCT checks execution, FD calibrates the manoeuvre

Swarm A — Escalated: 14, CAM: 0
Swarm B — Escalated: 29, CAM: 8
Swarm C — Escalated: 12, CAM: 2

# Collision Avoidance strategy and statistics

- The launch of satellite constellations and mega-constellations in Low Earth Orbits is already visible in the fraction of Close Notifications caused by constellations:

  ❑ COSMOS-1408 Anti Satellite Test event in November, 2021

  ❑ Analysis: Space Debris Office for all events with Pcoll > 1E-6

  ❑ Data: ESA's Space Debris Office
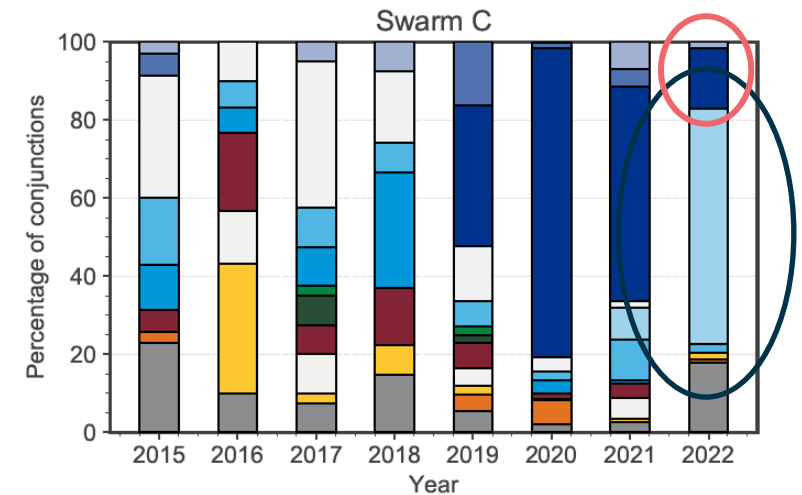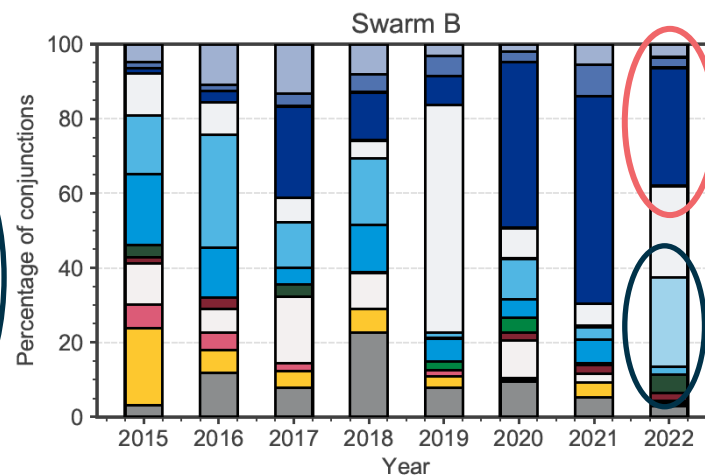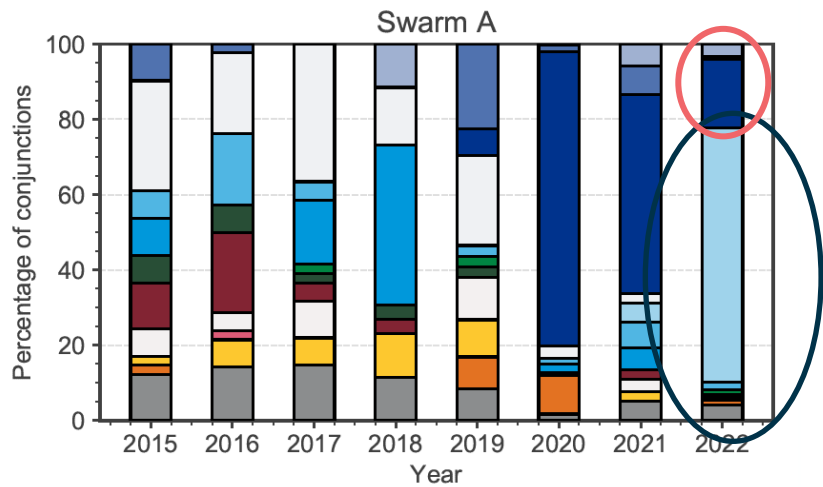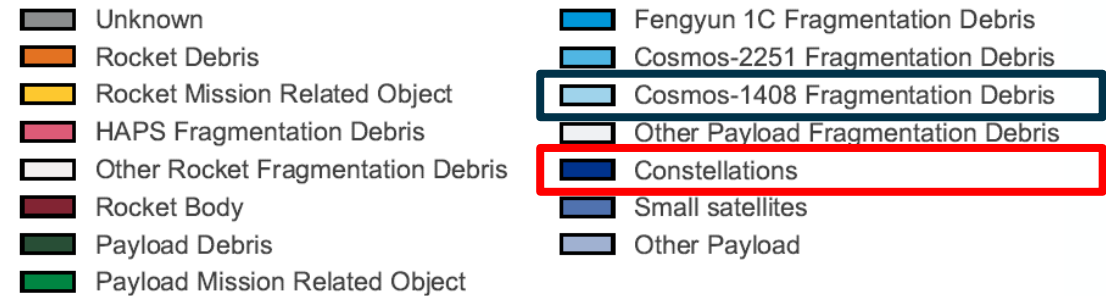
Orbital evolution: counter-rotating orbits in 2021

Due to the different altitudes, the Swarm spacecraft orbital planes (inclination 87.3deg) are rotating at different speed (consequence of non-Synchronism): therefore every ~7.5 years the planes of Swarm-A/C and Swarm-B end-up quasi co-planar (co-rotating satellites or counter-rotating satellites) opening exciting science opportunities:

- Counter-rotating scenario in 2021

- Closest alignment on 3 October, 2021

Take benefit of this natural orbital configuration:

- In 2019, a small manoeuvre campaign was undertaken to let the Swarm-A/C relative RAAN evolve to zero by October, 2021

- The along-track separation of the lower pair has been studied to provide different separation phases: 4 seconds, 2 seconds and variable separation phase: campaign start 15/07/2021 and end on 15/12/2021
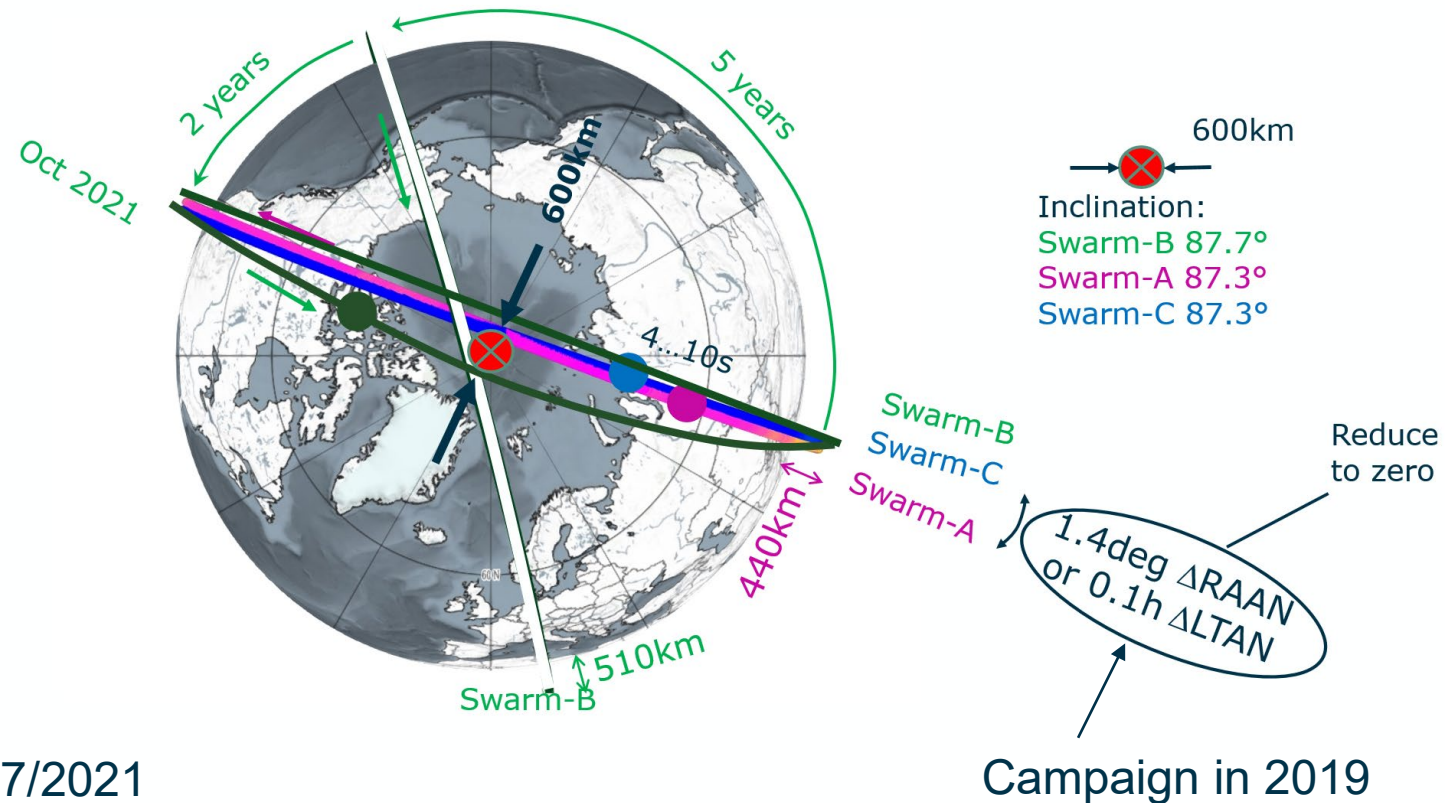
Orbital evolution: counter-rotating orbits in 2021

Along-track separation achieved with series of Orbit Control Manoeuvres
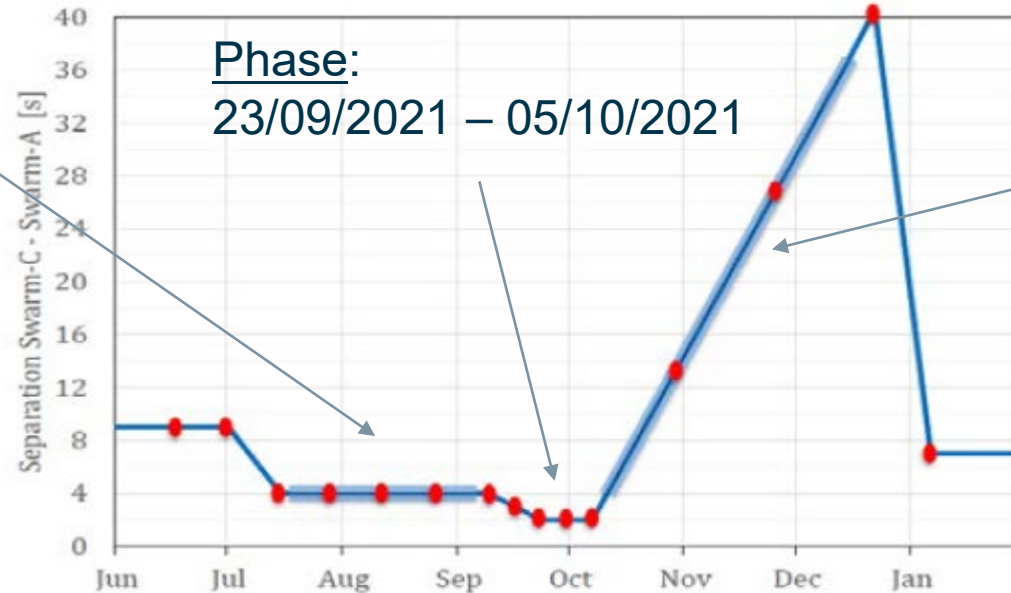
4s separation
(kept 3.5s to 4.5s)

Acquisition:
01/06/2021 – 15/06/2021

Phase:
15/06/2021 – 09/09/2021

2s separation
(kept as close as possible)

Acquisition:
09/09/2021 – 23/09/2021

Phase:
23/09/2021 – 05/10/2021

Variable separation
(maintenance +/- 1s)

Start drift 05/10/2021
Maint: 14/10/2021
Maint: 04/11/2021
Maint: 25/11/2021

Return to operational configuration
16/12/2021 – 13/01/2022

See relevant poster at LPS22
Albini, Sieg, Petrucciani

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Counteracting the Solar cycle: orbit raise in 2022

The latest journey taken with the Swarm trio is the series of manoeuvres to raise the orbits to survive re-entry that would happen in 2025 due to the effect of the increased drag in Solar cycle #25 (images ESOC FD group)
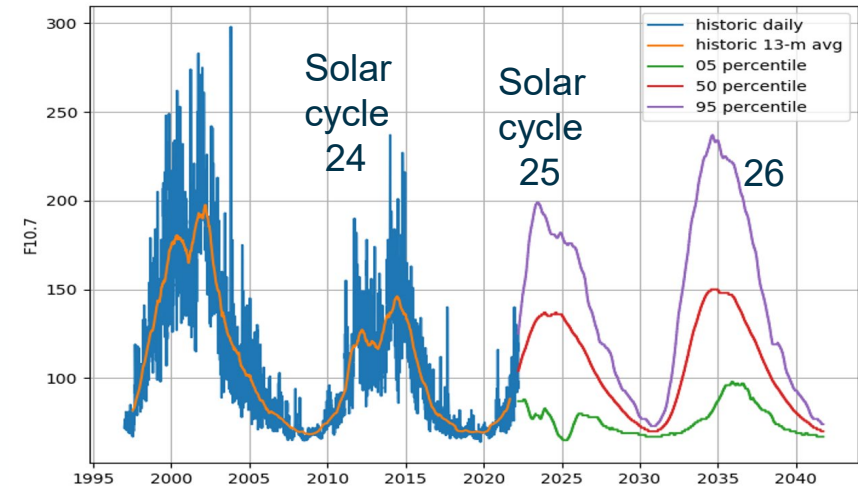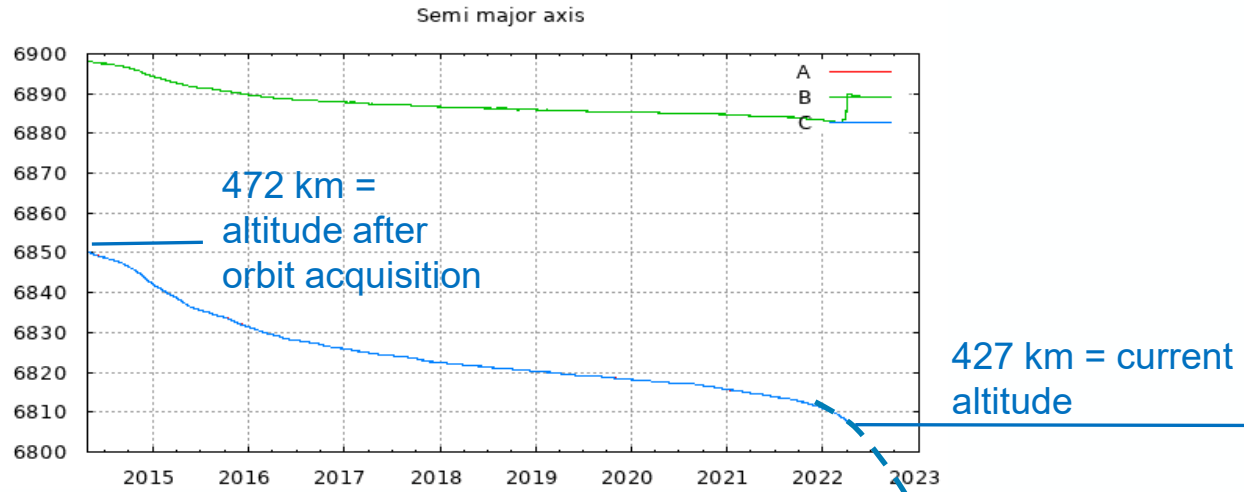
Target: keeping the Swarm lower pair flying up to next Solar minimum (2030+)

To achieve a long mission without re-entry in 2025 the orbit will have to be raised depending on the strength of the solar cycle => analysis performed by ESOC Flight Dynamics

- Step-wise approach

- Rather big first phase: 45km raise (25.5 m/s) : usual orbit manoeuvres with Swarm are cm/s !

- Next phases will be planned for the next years depending on the Solar cycle evolution

Counteracting the Solar cycle: orbit raise in 2022

Plan:

- Start early May to get benefit from ramp-up Solar cycle
- Duration 10 weeks nominal
- OCM Thrust phase multiple of 1 revolution to minimise eccentricity effects
- Each manoeuvre is in-flight direction: satellite will have to slew by 180deg in Yaw before firing thrusters

Operational aspects

- Up to four manoeuvres per week
- Along track separation increase (safety aspects)
- Crossover risk will be avoided in case of anomalies
- Several additional passes for manoeuvre uplink, acquisition, orbit determination, etc.
- EFI instrument will be in Ready State during OCMs

Week	Burn	Week Scheme	Dv (tot)	D Along-Track (tot)
2-6 May	1 rev	[A1 – C1]	1.2 m/s	42 s
9-13 May	2 rev	[A2 – C2]	3.6 m/s	126 s
16-20 May	2 rev	[A3 – C3 – A4 – C4]	8.4 m/s	294 s
23-25 May	2 rev	[A5 – C5]	10.8 m/s	378 s
30 May–3 Jun	2 rev	[A6 – C6 – A7 – C7]	15.6 m/s	546 s
7-10 Jun	2 rev	[C8 – A8]	18.0 m/s	462 s
13-15 Jun	2 rev	[C9 – A9]	20.4 m/s	378 s
20-24 Jun	2-2-2-1 rev	[C10 – A10 – C11 – A11]	25.2 m/s (C) 24.0 m/s (A)	210 s (drift: 42s/day)
27 Jun–1 Jul	0.9 m/s + 0.18 m/s	[——A12—— A13]	25.08 m/s (A)	42s (after first [A]) -> 21s (after second [A])
4–8 Jul	0.12 m/s	[———A41]	25.2 m/s	Routine separation 4-10s

Conclusions & Outlook

- ❑ 9 years of successful operations driven by close collaboration between all mission teams

- ❑ Many ground and spacecraft anomalies solved and mitigated

- ❑ Swarm spacecraft are aging nicely and ready to continue their mission (as per Swarm In-Orbit Performance Review meeting #16 in 2022)

- ❑ Exciting scenarios have been used for science   See relevant poster at LPS22 Albini, Sieg, Petrucciani

- ❑ Swarm-A/C (lower pair) orbit raise campaign ongoing

- ❑ Evolution of Flight Operations Segment will continue to cope with hardware and software evolution