A CHALLENGING TRIO IN SPACE

"ROUTINE" OPERATIONS OF THE SWARM SATELLITE CONSTELLATION

Frank-Jürgen Diekmann(1), Ignacio Clerigo(2), Giuseppe Albini(3), Laurent Maleville(4),
Alessandro Neto(5), David Patterson(6), Ana Piris Niño(7), Detlef Sieg(8)

(1)ESA/ESOC, 64293, Darmstadt, Germany, e-mail: Frank.Diekmann@esa.int
(2)ESA/ESOC, 64293, Darmstadt, Germany, e-mail :Ignacio.Clerigo@esa.int
(3)RHEA Systems SA, 1300, Wavre, Belgium, e-mail: Giuseppe.Albini@esa.int
(4)LSE Space GmbH, 82234, Wessling, Germany, e-mail: Laurent.Maleville@esa.int
(5)LSE Space GmbH, 82234, Wessling, Germany, e-mail: Alessandro.Neto@esa.int
(6)Telespazio VEGA Deutschland GmbH, 64293, Darmstadt, Germany, e-mail: David.Patterson @esa.int
(7)Telespazio VEGA Deutschland GmbH, 64293, Darmstadt, Germany, e-mail: Ana.Piris.Nino@esa.int
8)ESA/ESOC, 64293, Darmstadt, Germany, e-mail: Detlef.Sieg@esa.int

ABSTRACT

Swarm is the first ESA Earth Observation Mission with three satellites flying in a semi-controlled constellation. The trio is operated from ESA's satellite control centre ESOC in Darmstadt, Germany. The Swarm Flight Operations Segment consists of the typical elements of a satellite control system at ESOC, but had to be carefully tailored for this innovative mission. The main challenge was the multi-satellite system of Swarm, which necessitated the development of a Mission Control System with a multi-domain functionality, both in hardware and software and covering real-time and backup domains. This was driven by the need for extreme flexibility for constellation operations and parallel activities.

The three months of commissioning in 2014 were characterized by a very tight and dynamically changing schedule of activities. All operational issues could be solved during that time, including the challenging orbit acquisition phase to achieve the final constellation.

Although the formal spacecraft commissioning phase was concluded in spring 2014, the investigations for some payload instruments continue until now. The Electrical Field Instruments are for instance still being tested in order to characterize and improve science data quality. Various test phases became also necessary for the Accelerometers on the Swarm satellites. In order to improve the performance of the GPS Receivers for better scientific exploitation and to minimize the failures due to loss of synchronization, a number of parameter changes were commanded via on-board patches.

Finally, to minimize the impact on operations, a new strategy had to be implemented to handle single/multi bit errors in the on-board mass Memories, defining when to ignore and when to restore the memory via a re-initialisation.

The poster presentation summarizes the Swarm specific ground segment elements of the FOS and explains some of the extended payload commissioning operations, turning Swarm into a most demanding and challenging mission for the Flight Control Team at ESOC.

1 INTRODUCTION

The in-orbit history of Swarm, ESA's magnetic field mission ([1], [2]), began in the afternoon of the 22nd Nov 2013, when the three identical satellites perfectly separated from the upper stage of the Rockot launcher at an altitude of about 499 km. Control of the trio was immediately taken over by the Flight Control Team (**FCT**) at ESA's Space Operations Centre (**ESOC**) in Darmstadt, Germany. Following a series of extensive check-out tests during the initial Launch and Early Orbit Phase (**LEOP**), a 3-months commissioning phase targeted the switching on and testing of all on-board subsystems, including the payload instruments. After many thorough calibration activities, the three satellites were then manoeuvred to new orbit positions in early 2014 to form a constellation with two satellites (Swarm-A and Swarm-C) at circa 468 km and Swarm-B at a higher altitude of 516 km. The two lower spacecraft were separated by a RAAN difference of 1.4 degrees. In addition, Swarm-A follows Swarm-C within 4 to 10 seconds and is controlled to remain at an altitude difference of ±10 m. A slightly different inclination of the Swarm-B orbit resulted in the intended slow drift of its orbital plane with respect to the two lower satellites.

Now, in spring 2016, the three Swarm satellites have been operated from the Flight Operations Segment (**FOS**) at ESOC in their routine phase for more than two years and continue to provide essential data for characterizing the Earth's magnetic field as well as the electric field in the upper atmosphere. During these first years the Swarm FCT has faced a number of challenges related to a novel Mission Control System (**MCS**) supporting a multi-domain software and hardware environment including a complex Mission Planning System (**MPS**). But, in particular, the on-going fine-tuning of the on-board payload instruments like the Electrical Field Instrument (**EFI**), the accelerometer and the GPS receiver (**GPRS**) have required continuous attention of the entire team to optimize the science data quality to the highest possible level. The satellite constellation is maintained within tight limits, only interrupted by a few collision avoidance manoeuvres so far. Discussions have been started on possible orbit changes, which are constrained by the fuel left on-board the three satellites.

This paper is organized as follows. Section 2 provides an overview of Swarm's ground segment with a focus on the multi-spacecraft features. Section 3 presents an overview of the Swarm constellation and the manoeuvres required to maintain it. Section 4 describes the major operational challenges faced in the last two years. Section 5 concludes this paper.

2 A GROUND SEGMENT FOR MULTISATELLITE OPERATIONS

2.1 Ground segment overview

The concept for control of the SWARM mission during the routine phase is presented in Fig. 1. It is based on the use of a single control centre at ESOC, in conjunction with a prime ground station at Kiruna, augmented by external stations (Svalbard and ESRANGE) when required, and interconnected by a general purpose, highly available ground network. This is collectively called the Flight Operations Segment (**FOS**).

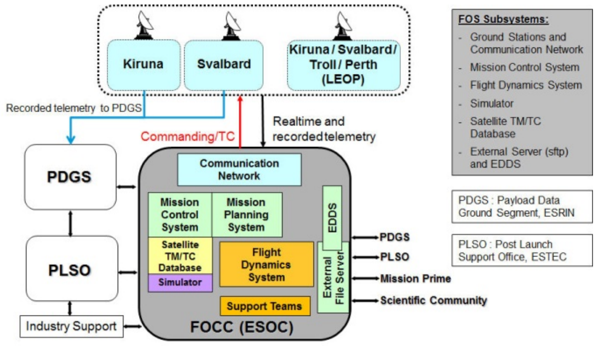

Figure 1: elements of SWARM Flight Operations Segment

The control centre, otherwise referred to as the Flight Operations Control Centre (**FOCC**) in ESA parlance, is comprised of the following systems:

- The SWARM Mission Control System to support, with both hardware and software, the data archiving and processing tasks essential for controlling the mission. Together with the MCS, the EGOS Data Dissemination System (EDDS) takes care of providing the Swarm data to all external interfaces.
- The SWARM Mission Planning System, supporting command request handling and the scheduling of spacecraft/payload operations.
- The Flight Dynamics (FD) System, supporting all activities related to attitude and orbit determination and prediction, preparation of slew and orbit manoeuvres, spacecraft dynamics evaluation and navigation in general.
- The Spacecraft Simulator, to support procedure validation, operator training and the simulation campaign before each major phase of the mission.

Data acquired by the FOS is retrieved directly from the ground stations by the Payload Data Ground Segment (**PDGS**) located at ESRIN, which is in charge of processing the raw data to generate scientific products and making them available to the scientific community. Additionally, satellite housekeeping data is provided through the EDDS system to the Post-Launch Support Office (**PLSO**) located at ESTEC.

2.2 Mission control system and mission planning

The main challenge of the FOS was the multi-satellite system of Swarm, which necessitated the development of a multi-domain MCS distributed across several physical machines, and organised in a nominal and a backup chain. This was driven by the need for flexibility for constellation operations and parallel activities.

The Swarm MCS is based on ESOC's generic SCOS-2000 infrastructure software and implements three separate domains in hardware and software, one per spacecraft, while a fourth domain handles all processes common to the three main domains. The system allows the control of the three spacecraft at the same time when required, as demonstrated during the LEOP phase, when two satellites were commanded in parallel and data was received, processed and archived for the three of them: real-time telemetry (VC0 and VC1 data streams) and recorded TM from the on-board mass memories (VC2 and VC4 data streams). In routine, only one satellite is commanded at a time, but processing of the recorded telemetry dumped during the passes may occur in parallel for the three satellites depending on the separation between spacecraft passes.

Commanding is supported by the MPS, which generates two command schedules, the Schedule Increment Ground Schedule (**SIGR**) and the (Schedule Increment On-Board Schedule (**SIOS**).

The SIGR contains commands to be sent in real time and is typically related to automated pass operations by setting up the link configurations to the respective ground stations and management of the on-board mass memory (start and suspend transmission of stored data and deletion of old data).

The SIOS provides time-tagged telecommands to be loaded into the satellite mission timeline (**MTL**) on-board and mainly controls the critical data downlink strategy (transponder switch on/off, on-board statistics housekeeping, instrument mode transitions, etc.)

The default planning interval is based on seven days corresponding to a calendar week from Monday 00:00:00 UTC until Sunday 23:59:59 UTC. It is nominally prepared on Thursday of week N-1 with an execution time starting on Monday of week N and is uplinked on Friday.

2.3 All for less: A data downlink strategy

The data downlink strategy is based on just two ground station passes per satellite per day during working hours; with each pass allowing 4 to 9 minutes of commanding.

During the first pass a long data dump after the overnight out-of-coverage is performed while the second pass is a few hours after the first contact and allows to dump any remaining data that could not be retrieved during the first pass. The second pass makes the schedule more robust against outages and guarantees that the backlog is quickly recovered in case a pass is lost. It also allows recalling any data from previous passes and offers a second commanding window, which is crucial for complex payload and platform special operations that cannot be performed in a single pass.

After each pass, old data is partially deleted. This strategy ensures that always up to three days of science data (fill status of packet store up to 70%) and up to two days of housekeeping data (fill status of packet store up to 50%) are available on-board. Any data gap larger than 5 minutes detected on ground is systematically recovered by re-dumping the data. An example of the evolution of the mass memory fill level for one satellite and one week is presented in Fig. 2.

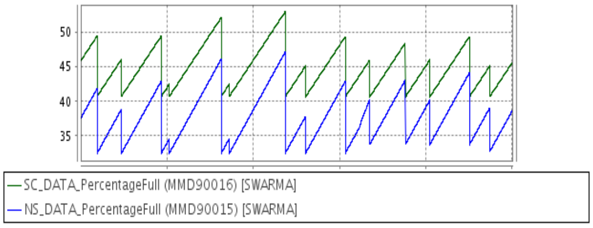

Figure 2: Swarm-A mass memory fill level (science: green; housekeeping TM: blue) on week 15, 2016

3 ASPECTS ON MANOEUVERING THE SWARM SATELLITE CONSTELLATION

3.1 Orbit acquisition

The three months of commissioning in 2014 were characterised by a very tight and dynamically changing schedule of activities. All operational issues could be solved during that time, including the challenging orbit acquisition phase to achieve the final constellation. About 36% of the originally available fuel was consumed for these manoeuvres.

The near polar orbit for good global coverage and regular 24 hours local time coverage about every 9 months was achieved straight away due to the nominal injection into the common separation orbit. It remained to establish the relative differences between the lower pair formed by Swarm-A/Swarm-C and the upper satellite Swarm-B. The targets in altitude and inclination difference were selected to be 50km and 0.4 degrees. Mainly the latter determines the relative drift rate of the local time of ascending node (**LTAN**) of the orbital planes between the lower pair and Swarm-B. This drift is still on-going and the LTAN difference will reach 4 hours in October 2016 and should then ideally remain within 6h +/- 2h during the continuous natural decay down to 300km until 2022 or later. To achieve this, another manoeuvre campaign is needed to slow down the relative drift. In addition, the lower pair had to be separated by 5-6 minutes in LTAN and fly side by side with less than 10 seconds along track difference.

The LTAN separation of the lower pair was achieved indirectly by performing the inclination changes of Swarm-A and Swarm-C at different times leaving, on average, six weeks in between with different nodal precession. The firing direction of the manoeuvres was selected such that the semi-major axis was lowered at the same time. To achieve the required delta-v of 32m/s with the low thrust cold gas system capable of 2x0.05N each satellite had to perform more than 130 manoeuvres. The finalization of all manoeuvres was completed during only 12 weeks, whereby each week was dedicated to a batch of manoeuvres with a single satellite only. For each satellite a small test batch was performed to obtain a first thruster calibration. The subsequent batches consisted of 22-34 consecutive orbits with a 20 minutes manoeuvre around each ascending and descending node and slews in between. Here the main challenge was to come up with a robust strategy, which could be adjusted easily in case of manoeuvre failures and excluded any collision risk when Swarm-A approached the side-by-side configuration after completion of four additional revolutions during the six weeks drift phase. The original pre-launch manoeuvre plan is shown in Fig. 3.

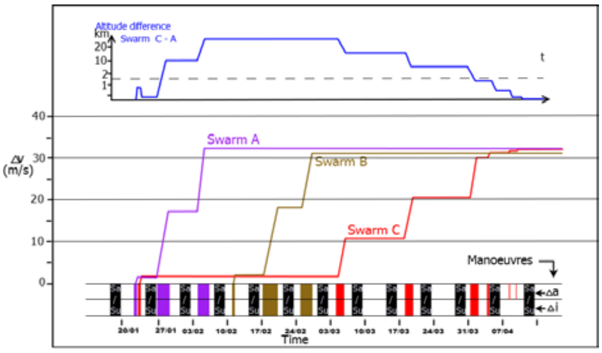

Figure 3: planned initial orbit acquisition after commissioning phase

This paid off when the first Swarm-A manoeuvre sequence did, indeed, abort after 69% of the planned delta-v due to an on-board software problem with a shared memory address. Details of the strategy and the recovery can be found in [3].

About 36% of the loaded fuel was consumed for the orbit acquisition. This leaves enough fuel for a later manoeuvre campaign to slow down the relative node precession in the near future in order to stay within a LTAN difference of 6h +/- 2h. The decision about when and how far to slow down needs to be taken by the end of 2016 at the latest and requires also the best possible prediction and planning of the further decay from 440km down to about 300 km altitude [4].

3.2 Routine and non-routine manoeuvres

The initial orbit for the lower pair, Swarm-A and Swarm-C, was targeted at an altitude of 468 km and an inclination of 87.35 degrees. It is now maintained in a side-by-side constellation separated along track such that their ascending node crossing time differences are between 4 and about 10 seconds. The lower limit guarantees that both spacecraft will not accidentally collide.

In addition, their eccentricity vectors are to be kept close enough to ensure an altitude difference of always less than 5 km. Also for mitigating collision risks, the eccentricities are kept as close as possible. Since the end of commissioning, 9 manoeuvres on Swarm-A have been performed using a total of approximately 80g and none on Swarm-C until now.

The other spacecraft, Swarm-B, was placed in a higher orbit (altitude circa 516 km), with an inclination higher than the lower pair by 0.4 degrees at 87.75 degrees. Its orbit is not controlled after the orbit acquisition phase except for necessary collision avoidance manoeuvres.

Two collision avoidance manoeuvres had to be executed so far, one on Swarm-B and one on Swarm-A each using around 30g of fuel to avoid debris that endangered the safety of the satellite.

Several attitude slews were also performed to calibrate various instruments on board. Slew manoeuvres were for instance performed in May 2014 to characterise the observed residuals of the two magnetometers VFM and ASM. They required careful preparation in order to ensure that they would not affect the power or thermal budget of the satellite and are compatible with the flight domain of the AOCS.

Furthermore, during the routine phase the on-board fuel is spent for normal attitude maintenance (12g per week on average).

Tab. 1 summarizes the amount of fuel consumed per satellite. In total more than 60kg of Freon are still available per satellite.

	SWA	**SWB**	**SWC**
Initial fuel	105.3	105.0	102.7
Orbit acquisition	38.6	37.7	38.2
Constellation maintenance	0.080	0	0
Collision avoidance	0.030	0.030	0
Normal attitude maintenance since routine phase	1.63	1.23	1.54
Remaining fuel	**64.96**	**66.04**	**62.96**

Table 1: fuel consumption from launch until April 2016. All values in kg.

4 CHALLENGES OF SWARM OPERATIONS

4.1 Payload operations

Although the actual spacecraft commissioning phase was concluded in spring 2014, the investigations for some payload instruments are still on-going ([5], [6]).

One of the payloads of the Swarm constellation is the Electrical Field Instrument in cooperation with the University of Calgary (**UoC**) in Canada and devoted to the measurement of spacecraft potential, electron temperature, ion properties and ultimately the electric field. Two Langmuir probes (**LP**) are used to measure the electron properties and spacecraft potential, while a Thermal Ion Imager (**TII**) is used to capture the plasma particles and produce 2D maps with two CCD sensors.

The intended concept of the TII was full-time operations of the imager, but, in practice, some indications of image degradation arose after a period of continuous operation depending on the satellite. Therefore, in order to maximise the scientific return, it was decided to operate the TII for just a limited and fixed number of orbits per day, in order to ensure good quality data in regions where the physical phenomena, especially at high latitudes, are of higher interest. The

LPs are not affected and are always producing good quality data.

This modified concept required the need of a formal coordination between the FOS and the scientific community in order to define the times of activation: in particular a new data interface called Operations Planning File (**OPF**) has been defined to automatically process the inputs created by UoC and integrate them in the mission planning process at ESOC.

In parallel with the scientific measurements, several tests were carried out, mainly for Swarm-C, in order to raise the TII voltages and the temperatures of the inner instrument and to scrub possible contaminants from inside the chamber, suspected as the possible source for the image degradation. After these tests, several parameter setting updates were applied and, during the last year, the number of orbits used for science operations has successively increased, a sign of the improvement in the continuous and step-by-step fine tuning of the instrument operations. Moreover, a periodic calibration of the CCD gain maps was performed for the two sensors of each TII separately, in order to provide the conditions for good data exploitation.

Tab. 2 summarizes the different kind of tests performed in order to characterize the TII image anomaly. All these unforeseen activities, far beyond the original assumptions, resulted in a significant extra workload for the FCT. Large efforts were necessary to prepare, schedule and execute all the tests in a setup closer to a "extended commissioning phase" than routine operations.

Special activities performed	SWA	SWB	SWC
CCD gain map updates	5	5	4
Fixed - micro channel plate voltage tests	1	-	6
Correction of AGC settings	> 20		
Inner dome scrubbing tests	> 5		
Phosphor screen voltage updates	> 20		
Shutter duty cycle tests	> 5		

Table 2: summary of EFI tests performed since commissioning phase

The health status of the Vector Field Magnetometers (**VFM**) and the Absolute Scalar Magnetometers (**ASM**) is excellent, with the exception of the failure of both ASMs on Swarm-C (ASM-B just after launch and ASM-A in 2014). The ASMs on Swarm-A and Swarm-B are routinely operated in Vector Mode and the three active VFMs are producing data at 50Hz on the three spacecraft. Careful monitoring of temperatures, voltages, currents and other payload parameters is performed by the FCT on a regular basis to detect any anomalous behaviour.

A residual bias was identified between the measurement of the VFM and the ASM, which was presumably related to a thermal effect of the instruments. In order to characterize this behaviour, Swarm-B was slewed four times by 90 degrees. The spacecraft remained in this special attitude for 5 orbits. This operation was performed as well with coordinated slews of Swarm-A and Swarm-C, four times by 90 degrees in reverse direction and offset by 3 orbits. The two satellites remained in each attitude position for 6 orbits.

Additional tests became also necessary for the Accelerometer instruments (**ACC**) on-board the Swarm satellites. The dependency of the ACC performance with respect to temperature variations appeared to be more complex than anticipated during the design phase. Tests were created in order to reduce thermal variations by using different On/Off heater strategies, in some cases with the nominal and the redundant heaters used in parallel. Those tests required careful preparation to schedule and execute more than 6000 commands synchronized with Sun eclipses.

Fig. 4. shows an example of heater profile activation for one of the tests performed. The heater profiles are designed to analyse the impact of various delay activations versus start and end of eclipses in order to achieve stabilisation of the ACC temperature. The *tmax* and *tmin* times closely match the entry and exit of Sun eclipses and are used as reference for the heater activation.

Test campaigns with attitude thruster activations were conducted to deduce ACC scale factors needed to adjust accelerometer deviations for all satellites. All three axes were calibrated using dedicated thruster activations designed to minimized the impact on the attitude and the orbit.

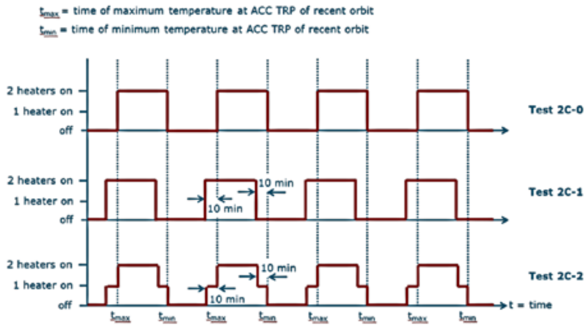

Figure 4: example of heater profile activation during ACC thermal tests

Fig. 5 shows an example of the along track scale factor calibration scenario used for all Swarm satellites. It shows the impact of the thruster activations selected on the orbit and rotation of the satellite. It consisted in four separated firing designed to test along-track acceleration in both positive and negative direction and to bring back the satellite to its original position and rotation at the end of the operation. Those tests required a de-activation of the AOCS and had to be geolocalised for best performance. They, therefore, required a very careful preparation and analysis from the FCT before their execution. Currently, a six months calibration campaign is on-going to verify the stability of the scale factor over time.

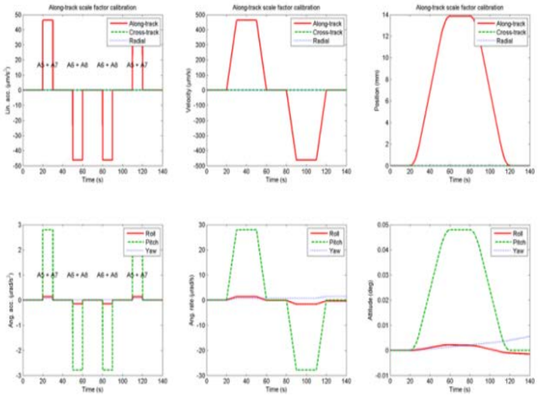

Figure 5: ACC scale factor calibration manoeuvres

4.2 Platform operations

The Swarm platform has proven to be very robust and are behaving remarkably well. All units, nominal and redundant, are working fine on all three spacecraft, and there have been very few anomalies since launch.

The main platform related activity has been the redefinition of the strategy to handle the different errors in the on-board mass memory (**MMU**). The new approach takes into account the error type and the error area to better decide when to ignore and when to re-initialize the memory. It is particularly important to differentiate between single event functional interruptions (**SEFI**) and single stuck bits (**SSB**); as both disturbances are regularly observed in Swarm MMUs. Tab. 3 summarises the non-correctable errors reported by the three spacecraft.

	SWA	SWB	SWC
SEFI	6	6	15
SSB	1	41*	1

Table 3: summary of SEFI/SSB since commissioning phase. For Swarm-B 40 of the non-correctable errors (stuck bits) belong to the same address

With the old strategy, all non-correctable errors (single/multi) detected by the memory scrubber were recovered from ground by performing an MMU re-initialisation, which resulted in about 30 minutes of data loss each time. From launch until early 2015, about 5 hours (in total for the three satellites) of data were lost due to unnecessary MMU resets.

The new strategy avoids these MMU re-initializations - unless strictly necessary - and discriminates between SSB and SEFI. In particular, in case of single stuck bits, no recovery procedure is executed since the error is corrected by the error detection and correction logic of the memory each time the cell is readout (e.g. during downlink of data).

In case of a SEFI, the decision is based on the impacted area; the MMU re-initialization is not performed if the affected area is storing housekeeping and science data and not MMU meta-data, since the anomaly condition disappears after the affected memory is rewritten.

Finally, in order to improve the performance of the GPS receivers – as another platform subsystem - for better scientific exploitation and to minimize the failures due to loss of synchronization, a number of GPRS setting changes were commanded by patching the GPRS on-board software. The updates include a stepwise increase of the GPS field-of-view to now 88 degrees in order improve performance of the GPS with a reduced number of satellites in tracking.

5 CONCLUSIONS

In this paper the current status of the Swarm ground segment and a summary of the major operational challenges since launch have been presented.

After a challenging commissioning and orbit acquisition phase to achieve the target constellation, the three satellites are now working remarkably well and the complete flight operations segment is running smoothly and without major interruptions despite the additional complexity of a multi-spacecraft mission.

On the other side, payload operations have been more complex than initially anticipated. Testing and fine-tuning activities, especially for EFI, have continued after the planned commissioning phase and are imposing a continuous challenge for the FCT. Nevertheless, all the additional work is paying off, and thanks to the joint effort of all involved parties, uncertainties in Swarm’s data are diminishing. The entire mission teams are ready for the challenges expected in the upcoming years, in particular related to further mission extensions beyond the nominal mission lifetime.

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