SpaceOps-2023, ID # 341

Lessons learnt from conducting a successful decommissioning of Metop-A

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Abstract

Mitigation of space debris has become increasingly important due to the Iridium-Cosmos collision and the Fengyun-1C anti-satellite test that have increased the debris population at Metop's altitude. EUMETSAT is sensitive to the topics of space sustainability and committed to decommission its satellites in a clean way even though the first generation of Metop satellites have an old design. For Metop-A, the deorbiting operation started on the 15th November 2021 and was successfully concluded on the 30th November 2021, leaving the satellite in a state of propulsive and electrical passivation, and on a path to re-enter in the atmosphere within 25 years. This paper describes the details of the deorbiting operation and explains all the challenges, anomalies and lessons learnt identified during and after the activities, limited not only to satellite operations, but also extending to team management, ground segment operations and implications for the lifetime extension of the other Metop satellites in the fleet.

Keywords: end-of-life, deorbiting, operations, passivation, lessons learnt

Acronyms/Abbreviations

AOCS	=	Attitude and Orbit Control System
AOS	=	Acquisition of Signal
CFS	=	Central Flight Software
EOL	=	End-of-Life
EPS	=	EUMETSAT Polar System
EPS-SG	=	EUMETSAT Polar System Second Generation
GNSS	=	Global Navigation Satellite System
LOS	=	Loss of Signal
LTAN	=	Local Time of Ascending Node
OCM	=	Orbit Control Mode
OCMT	=	Orbit Control Mode Thrust phase
OPM	=	Operational Mode (= Fine Earth pointing attitude)
PFT	=	Possible Final Thrust
PSO	=	Position in Orbit
RF	=	Radio Frequency
RRM	=	Rate Reduction Mode
RW	=	Reaction Wheel
SOI	=	Special Operations Instruction
SSR	=	Solid State Recorder
UTC	=	Coordinated Universal Time

1. Introduction

After 15 years spent in orbit, it was time for Metop-A to retire. In the last five years, several analyses had been conducted by the operational teams (with contribution from the satellite manufacturer) to understand if the satellite lifetime could be further extended. After August 2016, the satellite did not have enough propellant to use for an out-of-plane manoeuvre to keep the initial Metop orbit requirements. Therefore, since the instruments were still very healthy, a decision was taken to allow the LTAN to drift, and therefore extend further the mission. Assuming that no serious anomalies consuming propellant would occur, the satellite would be able to carry on with its activities for many years, limited only by the power and thermal energy margins.

Such analyses were described extensively in [1], concluding that an extension until the very beginning of 2023 would have been possible for the power margins, but it would have been trickier to find a threshold for the thermal margins. With the LTAN drift, eclipses would shorten and therefore the power margins would increase, but the geometry of the satellite would see a different thermal environment changing very quickly between around January and March, becoming unpredictable in the case of a serious anomaly where the satellite payload would switch-off.

In such scenario, the risk of propellant freezing in the propulsion lines could not be excluded, as temperature could drop quickly (non-linear effect) and some of the heater lines would have saturated impacting the overall thermal balance until an extent that was not fully clear. Thermal analyses were conducted, but the finite element thermal model of Metop was very old, some components were not modelled accurately and it had several uncertainties.

Other solutions were studied, like the possibility to modify the yaw steering law in order to shift it by 90 degrees in orbital phase to restore the nominal thermal environment. However, simulations revealed that special patching to the magneto-torquers attitude law would have been necessary, requiring extensive analyses and testing before on-board implementation, which was considered too complicated to be a realistic solution.

In the end, given that it was very difficult to prove that the satellite thermal environment would have been stable enough in 2022 (especially in February, the worst month), it was decided to deorbit the satellite starting in November 2021 with the plan of concluding the operation before the problematic season.

2. Overall deorbiting strategy for Metop-A

The main constraints and drivers for the overall deorbiting strategy were:

1. Clear the EPS operational orbit as soon as possible.
2. Minimise re-entry time by lowering the orbit, particularly the perigee, as far as possible to achieve a 25-year re-entry in accordance with ISO guidelines [2].
3. Target a South Pole perigee to maximise the Svalbard pass durations during passivation.
4. Minimise the risk of running out of propellant before starting passivation by allowing plenty of margin.

In order to understand how the deorbiting strategy is derived, it is first useful to understand the final target orbit and why this has been selected. An elliptical final orbit is chosen as this minimises re-entry time for a given propellant expenditure – the reduction in semi-major axis is approximately linear with respect to the amount of propellant used, whereas atmospheric drag increases exponentially as altitude is reduced. It is therefore more efficient to reduce the semi-major axis asymmetrically. Moreover, by targeting a perigee around the South Pole (bearing in mind the argument of perigee may drift by ca. 3 degrees per day), the pass duration for Svalbard and other Northern stations will actually be longer than normal. This is beneficial for the final passivation operations. In addition to lowering the perigee, the apogee is also lowered slightly to clear the EPS and EPS-SG Orbit. This strategy clearly meets the first 3 drivers listed above and is illustrated in Fig. 1.

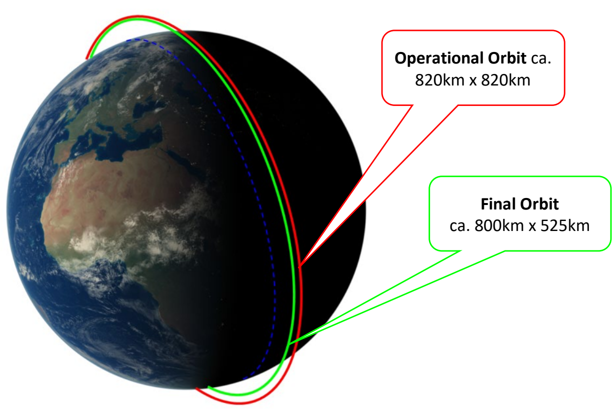

Figure 1. Metop deorbiting strategy

The overall deorbiting strategy is divided in 4 phases.

During phase 1, the spacecraft is prepared for the deorbiting activities, and this mainly includes a yaw bias manoeuvre of 8°, patching the CFS, switching off the instruments not needed for the deorbiting and the deletion of on-board commands and on-ground scheduled activities.

The need of performing such yaw bias manoeuvre comes as the answer to an anomaly happened in July 2019, when the satellite suffered a Single Event Upset on one of the electronic boards of the Central Communication Unit. The generation of a 1Hz signal, used to compute the RW rates and command the pressure transducer measurements, suddenly stopped. The missing RW measurements led to a misbehaviour of the magneto-torquers, inducing a disturbing torque on the spacecraft. To compensate the disturbance, the RW rates started to increase uncontrollably, until an on-board monitoring on the RW currents triggered an entry into RRM, a non-nominal mode where the satellite fires thrusters and uses propellant to control the attitude.

During the recovery, that lasted a few days, some of the propellant reserve needed to perform the deorbiting sequence was spent in attitude acquisition and maintenance. Therefore, the team had to look for a creative solution to somehow make up from the "lost" propellant and a yaw bias manoeuvre designed to align the thruster-firing axis with the velocity direction during the orbit lowering manoeuvres was considered to be an efficient solution. The advantages of such a manoeuvre were clear, but this operation had never been performed with such large bias angles, and moreover the bias was never applied for such a long time. Extensive analyses and testing were performed, and after final feasibility assessment performed during the third Technology Test Campaign [3], the manoeuvre was added to phase 1 of the deorbiting sequence.

During phase 2, the perigee target is limited to 525km and as far South as possible ready for the passivation operations in phase 3, bearing in mind that the argument of perigee will be drifting at approximately 3 degrees per day by the end of phase 2. This places the apogee as far North as possible and increases the duration of the ground station passes used for passivation in phases 3 & 4. By performing long thrusts to lower the perigee, the apogee is also gradually lowered to around 790 km. Every thrust will be ~1060s. Since the criteria to build the manoeuvre sequence is based on a limit of 22kg of estimated propellant (to comply with the 4th driver for the deorbiting strategy mentioned above), in practice, the altitude which will be reached in the end of the manoeuvre sequences is ~580km rather than 525km.

The phase 2 perigee altitude limit of 525km is based on predictions of: atmospheric density, the torque that this would apply to the solar array, and on the subsequent increase of the wheel kinetic momentum. If the wheel momentum exceeds 38Nms, an AOCS mode transition will be triggered, switching off the reaction wheels to avoid damages. The wheels are carefully monitored and lowering of the perigee has to be halted if the momentum exceeds 30Nms. Even if the wheel kinetic momentum is well within limits, a solar flare could cause rapid atmospheric expansion and therefore increase the wheel momentum quickly, so the 525km limit should be respected in phase 2. If either the wheel or perigee limits are reached, the manoeuvre strategy is changed to lower the apogee.

Manoeuvres in phase 2 follow a 48-hour cycle, with 3 burns 12 hours apart at around 8 UTC and 20 UTC on day n, followed by a burn at around 8 UTC on day n+1. There is then a 24-hour gap to allow more thorough wheel speed analysis and orbit determination. Five such sequences of manoeuvres are performed.

Phase 2 ends when the estimation of remaining on-board fuel reaches 22kg (likely the height of this orbit would be ~580 km), from which point we enter phase 3 and each burn is considered as a Possible Final Thrust – or PFT.

During phase 2, the lower orbit creates unique conditions for the instruments, which see new configurations achievable for the first time. After removal of the pre-applied yaw bias, some special Technology Tests would occur during this deorbiting phase, where all but the RF instruments are still switched on and taking measurements in nominal scanning mode. The concept of such tests was described in [3] and [4], the main tests including a Backflip manoeuvre (explained below), special Simultaneous Nadir Overpasses with the other Metop satellites (exploiting the lower orbit of Metop-A) and gathering data directly on an elliptical low orbit.

In phase 3, fluidic passivation is achieved by so-called Possible Final Thrusts. These are in-plane manoeuvres executed when it is calculated that less than 22kg of propellant remains on board. These PFTs can contribute to the overall deorbiting if the reaction wheels are not close to saturation and the perigee altitude is above 500km, limited by the Earth sensor field of view with a 6-degree roll/pitch off-pointing tolerance. This 22kg propellant prediction covers the ca. 8kg of unusable propellant on-board, plus significant margins for taking into account errors in the estimation of the remaining propellant mass (10kg) and of the amount of unusable propellant (4kg).

The PFTs are constrained to occur during visibility from the Svalbard ground station, which will be close to the apogee, and so the PFTs can only control the perigee. If either the reaction wheel or perigee limits are reached before propellant depletion, the manoeuvre strategy will be changed to bounce the perigee up and down from the limit, until propellant is depleted.

As its name suggests, each PFT may be considered to be the last thrust that the satellite can perform, after which propellant is depleted and passivation of the S-band and electrical subsystems must be executed.
According to modelling, at least 6 PFTs have to be performed to meet the 25 years re-entry ISO guidelines [2].

PFTs are executed during double visibilities, which allows sufficient time to observe the PFT and perform electrical and RF passivation. EUMETSAT will use their own ground station located in Svalbard, but will have to book overlapping passes with another ground station in the North Pole region owned by an external agency, such as Fairbanks. Due to the duration of the PFTs and the interaction with ground to identify when propellant is depleted to command electrical passivation, a single Svalbard pass duration is too short.

From experience on similar spacecraft, propellant depletion indicators such as helium bubbles are difficult to identify in real time. However, there is no particular risk in completely exhausting propellant – even if it is not possible to complete the electrical and RF passivation during the same pass, the worst case scenario is that an AOCS mode transition is triggered and then the satellite enters an un-converged safe mode (as the satellite rates cannot be controlled). In a subsequent pass, the strategy would be to simply re-enable bus couplers before electrical and RF passivation.

PFTs are therefore executed until the platform is no longer able to sufficiently control the attitude with thrusters – no longer converging from OCM to OPM (the nominal pointing mode) at the end of a burn, or there is a spontaneous AOCS mode transition during the burn.

The PFTs are commanded as a number of pulses, which would typically equate to 360s. However, as attitude control in OCM is performed by off-modulation of thrusters, the thrust duration is not fully deterministic. In principle, the duration could be 720s if the centre of mass was perfectly aligned with one thruster, but initial analysis from the supplier showed that the maximum credible increase in duration is 20%, and so a 30% margin was taken. However, it is important to re-assess the thruster off-modulation during the manoeuvres, in order to define the appropriate value for the timeout for triggering of phase 4. With a 30% margin, the thrust duration may therefore last ~486s.

Fluidic passivation is considered to have occurred once the OCM does not converge to OPM within 828s (calculated considering the maximum duration for each sub-mode plus the margin given by the off-modulation) after the initial transition from OPM to OCMT (Orbit Control Mode Thrust phase) or if there is a spontaneous AOCS mode transition during the manoeuvre. In the first case, an AOCS mode transition is manually triggered before the electrical and RF passivation commands are sent. The reason for this is that an AOCS mode transition is very likely to occur shortly after failure to converge to OPM, and by manually triggering the AOCS mode transition we can control when this occurs and therefore ensure that it does not disturb the final passivation operations and that the electric passivation sequence is not interrupted.

Phase 4 is performed by disconnecting 4 of the 5 batteries, followed by the S-band transponder transmitter switch off and then followed by the final battery disconnection. The active S-band transmitter must be disabled before the final battery is disconnected to prevent the regulated bus voltage varying with array shunt section switching. In order to avoid problems caused by a possible lack of ground station visibility to provide enough commanding time or commanding interrupted by a possible satellite reconfiguration, the passivation commands have to be sent encapsulated in a platform command and set with on-board execution at few seconds in the future. At the end of phase 4 Metop-A will have been decommissioned with all stored energy within the spacecraft depleted and all RF transmitters switched off.

3. Planning of the activities

Held two weeks before the deorbiting, the Operational Readiness Review was the formal meeting that gave the go ahead to the beginning of the end-of-life activities. All procedures and operational timelines were defined at this point, but it was clear that the timeline could easily change and was subject to evolution according to how the operations were actually performing.

As the Metop-A deorbiting was the first deorbiting of a Low Earth Orbit satellite ever performed by EUMETSAT, unexpected behaviours during the activities or under/over-performances of manoeuvres were likely. If operations were run through mission planning as during routine operations, where the next 36h of commands are already on-board, it would have been very complicated to delete the content in the on-board commanding buffers and then continue/re-schedule operations in case of discrepancy of the commanded timetags (due to manoeuvre performance).

A more flexible approach was needed, retaining the mission planning (so that all nominal activities could be generated automatically through the well-established and validated set of rules) but only with 4h worth of commands in the future. This would guarantee an autonomy of two orbits, and it would simplify the rescheduling due to unexpected events or time-shifting of commands already on-board.

The drawback of such approach is that most of the operations are to be done manually, and great care is to be paid by the operational teams to regularly manually activate set of commands.

Activities to be manually commanded were tracked in SOIs, documents to be used by spacecraft controllers and engineers to understand what will be commanded (and for which operation) to the satellite in the next orbits.

The global timeline containing the full sequence of all SOIs to be run and which were running in parallel was developed with a different tool, the Pass-by-Pass plan. The Pass-by-Pass Planning tool is an Access database, which allows the user to create a detailed plan (see Fig. 2 for an example of the output) in terms of operational activities for every commanding pass, including constraints like pass duration or accounting for available extra stations.

The tool pulls the orbital information of AOS and LOS of the passes from a flight dynamics database through a MySQL query, and such pull is done regularly so that updates to the timings can be made with the evolving orbital knowledge of flight dynamics, that changes the times according to the modification of the eccentricity of the orbit as long as the satellite goes along with the orbit lowering manoeuvres.

The tool can therefore be used to quickly re-plan activities. The Operations Coordinator was in charge of running the tool, being aware of all constraints between the different operations and procedures. In case of an anomaly impacting the activities of pass X, all the activities for the following passes would need to be shifted, new suitable orbits to run specific activities would need to be identified and a reshuffling of procedures might be necessary in order to meet the general timeline. The tool would take all this into account and produce a *pdf* with the global timeline, that can be used to follow operations in parallel with the SOIs. This would ease the workload on the Spacecraft Operations Engineers on shift, who would not have to waste time into rewriting the SOIs just to change timings, and the spacecraft controller could rely on the *pdfs* to know what would need to be commanded in the next orbits.

The Operations Coordinator would share with the rest of the team a new timeline as soon as available, and the latest timeline was discussed altogether on the daily EOL briefing meeting.

Daily Planning: M02

ORB	STAT	DATE	AOS	DUR	LOS	SUBSYS	ACTIVITY	SOI_REF	SHIFT	COMMENT
78217	CDA	15-Nov-21	05:52:17	11:39	06:03:56	N/A	Basic Pass			Basic Pass activities, no EOL specific operation performed
78218	CDA	15-Nov-21	07:33:06	12:37	07:45:43	SVM	Disable Authentication - MO_SGE_AUDIS	SOI_SEL_A_01	A	PHASE 1
						SVM	Go to AD mode	SOI_SEL_A_01	A	
78219	CDA	15-Nov-21	09:13:39	12:57	09:26:36	PLM	Deactivate HRPT - MO_HRP_DEAC	SOI_SEL_A_01	A	HRPT is switched off.
						PLM	PLOFF procedure: selected instrument switch off - MO_SEL_PLOFF	SOI_SEL_A_01	A	ASCAT, ADCS, SARR and SARP are switched off. TT: 09:25
						PLM	Dump PLM TTQ: MO_PMC_TTQ_DUMP	SOI_SEL_A_01	A	
78220	CDA	15-Nov-21	10:53:56	12:52	11:06:48	SVM	Go to SVM GEO mode - MO_SAO_PSOMOP	SOI_SEL_A_01	A	Guidance mode is now FPM GEO. TT: 11:49:00.703
						SVM	Update the theoretical canonical position crossing window to ±30deg - MO_SAO_PSOMEG	SOI_SEL_A_01	A	
						SVM	Request all PLM reports	SOI_SEL_A_01	A	to investigate ADCS incomplete switch-off. EUM/EPS/AR/19747 raised.
						SVM	Go to DEF_ROUT - MO_SGE_IMRTF	SOI_SEL_A_01	A	
						SVM	Disable SVM surveillances - MO_SEL_SURV	SOI_SEL_A_01	A	
						SVM	Change SVM FDIR thresholds - MO_SEL_FDIR	SOI_SEL_A_01	A	
						SVM	Patch STD Earth Diameter parameter - MO_SEL_PAMR	SOI_SEL_A_01	A	
						SVM	Update STD hw masking - MO_SEL_STDHM	SOI_SEL_A_01	A	TT: 11:20
78221	CDA	15-Nov-21	12:33:58	12:46	12:46:44	SVM	Patch pressure transducer reading frequency - MO_SEL_PTFQ	SOI_SEL_A_01	A	
						SVM	Dump STD Earth diameter parameter - MO_SEL_DUMR	SOI_SEL_A_01	A	
						SVM	Modify DB: DBASE_MODIFY_EOL_PHASE_1	SOI_SEL_A_01	A	
						SVM	Uplink SHINHSTD for bias application	SOI_SEL_A_01Y	A	
						SVM	Uplink SLEWMAN procedure for bias application	SOI_SEL_A_01Y	A	TT: 14:39.000

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Figure 2. Daily planning of the activities

4. Deorbiting timeline

The overall strategy explained in the previous paragraph was condensed in 16 days of operations, starting on the 15th of November 2021.

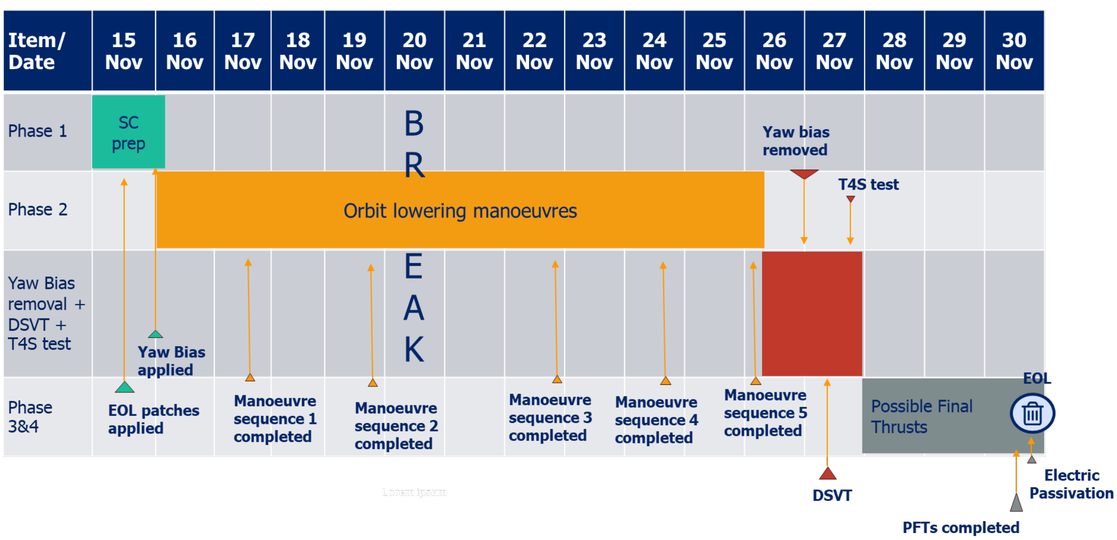


Figure 3. Deorbiting timeline

4.1 Phase 1: Satellite preparation phase and yaw bias application

On 15th November, end of mission was declared and dissemination to all users (except to some special users to receive the technology test data) was stopped from 09:24 UTC sensing time onwards.

Afterwards, the activities performed were the initial satellite configuration for the deorbiting, the switch-off of the instruments not needed for the technology tests, and the application of a positive yaw bias in two steps, a total of 8°. Spacecraft performances were nominal and, even though a total of 8° yaw bias was never applied to any Metop satellite before, the telemetry showed that the satellite behaved as expected, in line with the simulations performed.

The yaw bias application or removal execution is accompanied by a mode transition. This causes the CFS estimated gyro drift to go to 0 and later it gradually settles to the values estimated by CFS. It is observed that the biased attitude during phase 2 has an effect on the drift estimation and return to nominal values is observed when bias is removed before the Backflip manoeuvre.

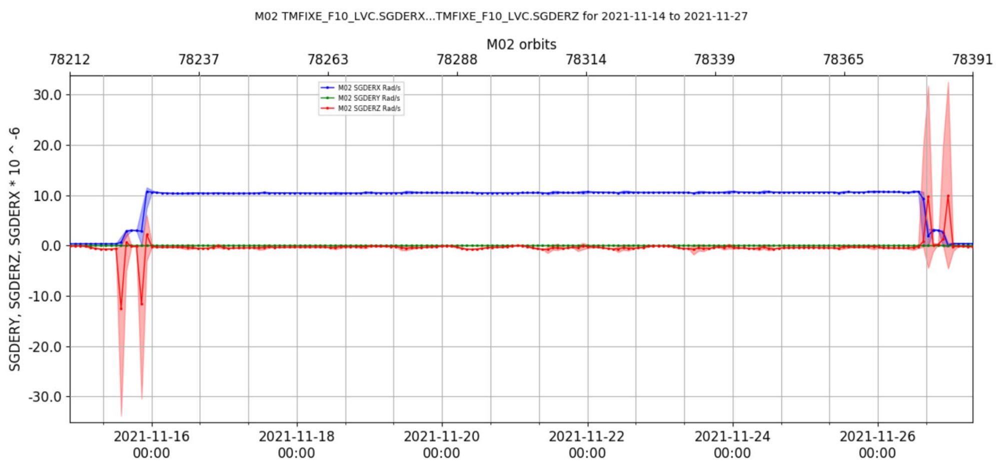


Figure 4. Estimated drift from yaw bias application to removal

Effect of biased attitude on the wheel momentum is clearly observed in Figure 5 which shows the how the wheel momentum excursion changed at the time of bias application and later returned to nominal values when the bias was removed before the Backflip manoeuvre. The observed values are similar to the ones predicted and these changes could be explained by slight variation in external disturbance torques and a modified gyroscopic torque resulting from the yaw bias.

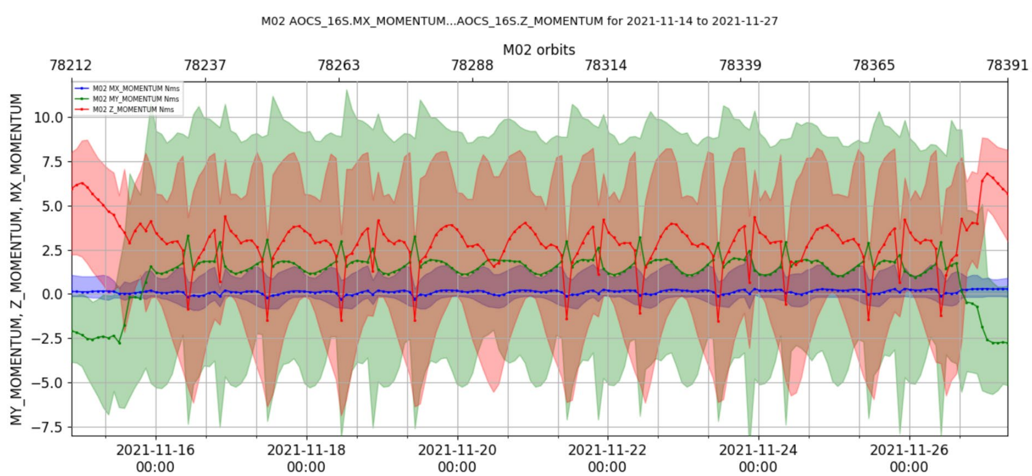


Figure 5. Reaction wheel momentum from yaw bias application to removal

4.2 Phase 2: Orbit lowering manoeuvres

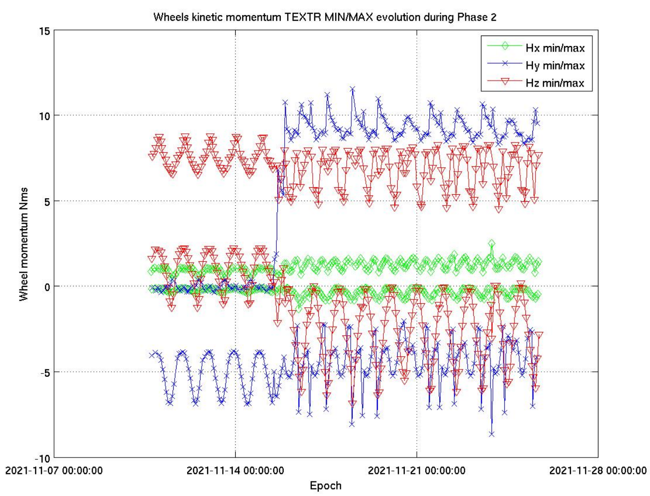
From the 16th November until the 26th November, the 5 sequences of 3 manoeuvres were performed, all with a duration of ~1060s, except the first burn (~400s) and the last burn (~800s). The full manoeuvre sequence is reported in Table 1. At the end of the manoeuvre sequence, the satellite was left with 22kg of estimated propellant on-board. The manoeuvres were executed every day with the exception of the 20th November, a break day for the team.

Satellite performances in phase 2 were as expected, except for two aspects: reaction wheel kinetic momentum and off-modulation.

The reaction wheel kinetic momentum was initially a concern, as the expectation was that such values would increase with the decrease of the orbit. However, there was no substantial change during the whole phase 2: as it can be seen from Fig. 4, the momentum was oscillating around stable minimum and maximum and it was never close to dangerous thresholds. Of course in case of a solar flare the situation could have evolved very quickly, but most likely the outcome would have been better than what was anticipated.

Industry had previously assessed that based on the expected movement of centre of mass due to propellant depletion, the maximum credible off modulation rate would have been 20%. However, already in the end of the last phase 2 manoeuvre, the satellite had reached 25.95% of off-modulation. It was clear that such value would increase further in phase 3, but it was decided not to change the strategy for ground station commanding, as off-modulation could still be taken into account with a careful planning of the pass usage.

Besides the two points mentioned above, phase 2 concluded well and it ended with the removal the 8° yaw bias previously applied, to ease operations for the technology test activities on the following day.



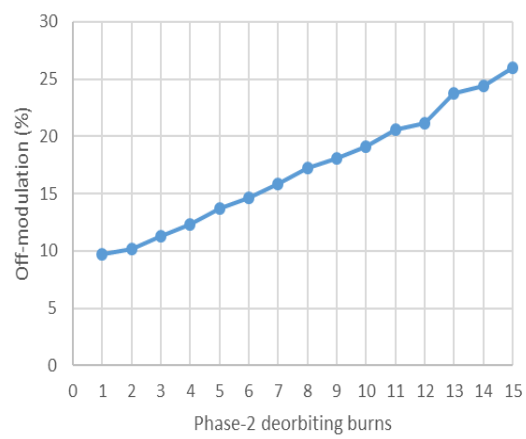


Figure 6. (Left) Reaction wheel kinetic momentum extrema in phase 2. The change of trend on the 16th November is due to the application of the 8° of yaw bias. (Right) Off-modulation of the thrusters in phase 2.

Table 1. Manoeuvre sequence for phases 2 and 3

num	target	manoeuvre_start	manoeuvre_end	duration	thrust	Isp	dv	fmass_sta	fmass_end	p_start	p_end	apo_start	apo_end	per_start	per_end
		[UTC]	[UTC]	[s]	[N]	[s]	[m/s]	[kg]	[kg]	[bar]	[bar]	[km]	[km]	[km]	[km]
1	target_aop	2021-11-16T10:45:50.909	2021-11-16T10:52:30.909	400	21.31	218.29	2.18	151.58	147.60	8.62	8.51	831.19	824.16	814.98	813.62
2	target_aop	2021-11-16T20:47:57.951	2021-11-16T21:05:37.951	1060	20.91	218.25	5.67	147.60	137.24	8.51	8.26	824.07	816.90	813.74	799.03
3	target_aop	2021-11-17T11:57:19.400	2021-11-17T12:14:59.400	1060	20.37	218.17	5.53	137.24	127.16	8.26	8.02	816.79	815.87	799.26	779.12
	no_mano														
4	lower_perigee	2021-11-18T11:30:34.001	2021-11-18T11:48:14.001	1060	19.87	218.07	5.41	126.52	116.68	8.02	7.80	815.42	815.03	779.26	759.12
5	lower_perigee	2021-11-18T21:33:31.427	2021-11-18T21:51:11.427	1060	19.41	218.01	5.30	116.68	107.06	7.80	7.60	814.78	814.20	759.28	739.65
6	lower_perigee	2021-11-19T10:55:53.576	2021-11-19T11:13:33.576	1060	18.98	217.95	5.20	107.06	97.65	7.60	7.41	814.09	813.70	739.82	720.61

num	target	manoeuvre_start	manoeuvre_end	duration	thrust	Isp	dv	fmass_sta	fmass_end	p_start	p_end	apo_start	apo_end	per_start	per_end
		[UTC]	[UTC]	[s]	[N]	[s]	[m/s]	[kg]	[kg]	[bar]	[bar]	[km]	[km]	[km]	[km]
	no_mano														
7	lower_perigee	2021-11-21T11:18:56.894	2021-11-21T11:36:36.894	1060	18.22	217.84	5.00	96.71	87.67	7.33	7.16	813.02	812.63	720.86	702.44
8	lower_perigee	2021-11-21T21:18:19.212	2021-11-21T21:35:59.212	1060	17.87	217.80	4.91	87.67	78.81	7.16	7.00	812.45	811.85	702.57	684.57
9	lower_perigee	2021-11-22T10:35:56.837	2021-11-22T10:53:36.837	1060	17.53	217.75	4.83	78.81	70.11	7.00	6.86	811.81	811.43	684.70	666.99
	no_mano														
10	lower_perigee	2021-11-23T11:28:46.942	2021-11-23T11:46:31.942	1065	17.13	217.69	4.76	69.58	61.04	6.78	6.64	811.12	810.76	667.01	649.66
11	lower_perigee	2021-11-23T21:24:45.184	2021-11-23T21:42:30.184	1065	16.84	217.65	4.68	61.04	52.64	6.64	6.52	810.60	810.04	649.77	632.76
12	lower_perigee	2021-11-24T08:58:45.125	2021-11-24T09:16:30.125	1065	16.56	217.62	4.62	52.64	44.39	6.52	6.39	810.03	809.59	632.87	616.03
	no_mano														
13	lower_perigee	2021-11-25T11:22:26.875	2021-11-25T11:40:11.875	1065	16.22	217.57	4.53	43.97	35.87	6.36	6.25	809.36	809.01	616.43	600.05
14	lower_perigee	2021-11-25T21:15:12.442	2021-11-25T21:32:57.442	1065	15.97	217.54	4.47	35.87	27.91	6.25	6.14	808.89	808.32	600.12	584.05
15	lower_perigee	2021-11-26T10:24:09.546	2021-11-26T10:37:31.219	801.673	15.76	217.51	3.33	27.91	21.99	6.14	6.06	808.36	808.06	584.10	572.11
	no_mano														
16	stat_CDA__FBK_	2021-11-28T16:31:29.614	2021-11-28T16:37:29.614	360	15.44	222.55	1.47	21.56	19.01	5.97	5.94	807.78	807.23	572.17	567.28
17	stat_CDA__FBK_	2021-11-28T19:48:06.416	2021-11-28T19:54:06.416	360	15.33	222.54	1.46	19.02	16.49	5.92	5.89	807.35	806.58	567.35	562.66
18	stat_CDA__MAD_	2021-11-29T07:23:11.372	2021-11-29T07:29:11.372	360	15.26	222.53	1.45	16.49	13.98	5.89	5.86	806.83	806.64	562.62	557.41
19	stat_CDA__MAD_	2021-11-29T09:00:56.166	2021-11-29T09:06:56.166	360	15.19	222.53	1.45	13.98	11.47	5.86	5.83	806.73	806.52	557.51	552.36
20	stat_CDA__ISS_	2021-11-29T17:08:00.564	2021-11-29T17:14:00.564	360	14.94	222.51	1.42	10.87	8.40	5.75	5.72	806.67	806.19	552.35	547.55
21	stat_CDA__FBK_	2021-11-29T18:45:33.636	2021-11-29T18:51:33.636	360	14.87	222.50	1.42	8.40	5.95	5.72	5.69	806.40	805.76	547.53	542.87
22	stat_CDA__MAD_	2021-11-30T07:57:15.949	2021-11-30T08:03:15.949	360	14.81	222.50	1.41	5.95	3.51	5.69	5.66	806.02	805.82	542.81	537.76
23	stat_CDA__MAD_	2021-11-30T09:35:01.868	2021-11-30T09:41:01.868	360	14.74	222.49	1.41	3.51	1.08	5.66	5.63	805.96	805.79	537.83	532.84

4.3 Technology Tests: Backflip manoeuvre and other platform testing

On the 27th November, the day started with the Backflip manoeuvre. Such manoeuvre was extensively described in [3] and [4] and consisted in inverting the pitch rotation of the satellite for half orbit such that during the middle portion of the manoeuvre, the instruments that normally look at the Earth would look at the deep space. Such manoeuvre was particularly interesting for radiometers to assess asymmetric scan biases and other types of disturbances affecting the measurements. More use cases and details on the manoeuvre are described in [4].

The spacecraft rotation rate about pitch axis was inverted from +0.06°/s to -0.06°/s at PSO 240°. A quarter of an orbit later the instruments achieved the desired pointing, and nominal rotation rate was commanded at PSO 60°. To ensure that the science data recorded during the manoeuvre was not overwritten in the memory, the SSR stopped recording data after Backflip end. The data was nominally dumped during the Svalbard pass immediately after Backflip end and later SSR recording was resumed.

Table 2. Backflip manoeuvre timeline

n°	Orbit	Station	Time	Event
1	78390	CDA		Uplink of post-Backflip SSR dump and stop record commands. Offline: go/no-go check
2	78391	CDA		Uplink of the Backflip commands (nominal opportunity) Offline: go/no-go check
3	78392	CDA		Uplink of the Backflip commands (backup pass) Possibility to abort the manoeuvre
4	78392	PAR	2021/11/27-10:09:24	Start of the Backflip manoeuvre (PSO: 240)
5	78392	-	2021/11/27-10:31:00 2021/11/27-10:36:00	Instruments which normally see the Earth will see the deep space

n°	Orbit	Station	Time	Event
6	78393		2021/11/27-10:58:41	End of the Backflip manoeuvre (PSO:60)
7	78393	CDA	after AOS5 and step6	Svalbard X-band dump
		PAR		SSR restart recording. Continue normal operations
8	78394	CDA		Svalbard X-band dump (backup)
		PAR		SSR restart recording. Continue normal operations

AOCS performance during the Backflip manoeuvre was nominal. The actual performance also matched very well with the ground simulations.

Before the uplink of the Backflip manoeuvre commands to the spacecraft, Go/No-Go checks were done to ensure that the reaction wheel momentum was within the thresholds and the spacecraft would be able to handle the momentum change due to the manoeuvre. The first Go/No-Go check on wheel momentum (the most critical parameter during the manoeuvre) was performed after CDA pass 78390. As the values were within thresholds (see Fig. 7), the backflip manoeuvre commands were uplinked during CDA pass 78391. After this pass, the checks were repeated and the Go criteria was still met, confirming the feasibility of the manoeuvre.

During the Backflip manoeuvre the Earth sensor updates were not used in loop and its surveillances were kept inhibited.

Since the magneto-torquer actuations are only valid for geocentric (or similar) pointing and are not suited for such attitude configuration, their gains were set to zero so that no actuations during Backflip manoeuvre are possible.

The solar array rotation rate remained the same during the manoeuvre, without any issues.

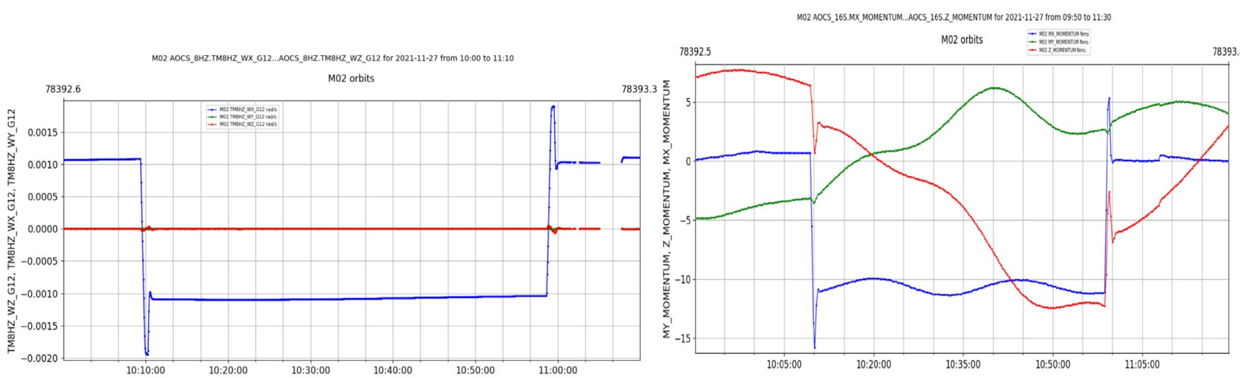


Figure 7. (Left) Modified spacecraft rate about pitch axis during Backflip manoeuvre. (Right) Reaction wheel momentum during Backflip manoeuvre.

Given the observed telemetry and the excellent spacecraft performance during the Backflip, the risk for any future execution of such manoeuvre is to be decreased. The recommendation is to perform it also for the next Metop satellites, to collect more data in different configurations.

On the same day, an additional technological test was successfully performed on the platform: the capability of switching two bus couplers in parallel was demonstrated. Such need arose from an anomaly on the Metop-C satellite, that has lost the capability to send telecommands through the nominal data-handling bus coupler. The tested workaround would ensure the restoration of the commanding capability, avoiding multiple satellite reconfigurations on components not normally used in orbit.

4.4 Phase 3: Possible Final Thrusts and fluidic passivation

At the beginning of this phase, the payload module and remaining instruments were intentionally switched off before beginning with fluidic passivation through several PFTs. The SSR and the X-band subsystem were switched off along with rest of the payload module, therefore only S-band data was available.

Each commanded PFT was ~360s long and was performed over extended visibility using an additional station together with Svalbard (Metop's nominal ground station). Station swap time was selected to ensure that nominal manoeuvre end as well as manoeuvre timeout could both be observed and sufficient time to send electrical passivation sequence was available.

A total of 7 PFTs were successfully completed in this phase and return to OPM was observed. At the end of PFT8, return back to OPM was not observed within computed manoeuvre cut-off duration and electrical passivation was executed afterwards.

Thruster and Flow Control Valve temperatures as well as tank pressure were carefully monitored during each PFT. Off-modulation was computed based on pulses fired during OCMT.

As seen in Fig. 6, a gradual increase in off-modulation was observed for PFTs 1 to 5 and return to OPM was as expected. The attitude and rate performance were similar to a nominal burn. During PFT6, a significant increase in off-modulation and divergence of attitude and rate deviation was observed, signalling towards propellant depletion. For PFT6 and PFT7 return to OPM was however observed before the manoeuvre timeout.

During PFT8 (the last burn), the drop in off-modulation probably indicates that neither of the thrusters were getting enough propellant and generating sufficient thrust. Return to OPM was not observed at the manoeuvre timeout and therefore manual triggering of RRM was commanded before sending the electrical passivation commands.

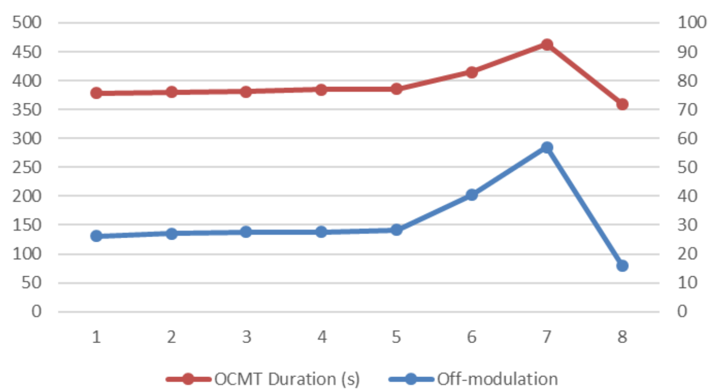


Figure 8. Observed OCMT duration and off modulation during Phase-3 PFTs

Table 3. PFTs performance

PFT No.	Cmd Pulses	Obs Z+/Y+ Pulses	Obs Z+/Y+ Pulses	Obs Off Mod %	OCMT Dur (s)
1	5266	2237	3029	26.147	378.625
2	5253	2214	3038	27.123	379.750
3	5255	2208	3048	27.559	381.000
4	5300	2227	3073	27.530	384.125
5	5298	2211	3087	28.377	385.875
6	5299	1979	3320	40.392	415.000
7	5295	1595	3701	56.904	462.625
8	5295	2418	2876	15.925	359.500

Figure 9 shows the thruster temperature during all PFTs performed, for each thruster. The decrease of thruster temperatures and increase of Flow Control Valve temperatures especially towards the final PFTs shows clear signs of hydrazine depletion. Due to some remaining hydrazine bubbles, the thruster and Flow Control Valve temperatures may have transient increases.

Thrusters 13 and 15 are the ones normally used in in-plane manoeuvres. After burn #6, the average temperature decreases, as the propellant is being exhausted in the pipes leading to those thrusters. The other thrusters start to compensate, but in PFT8 almost all of them are decreasing, meaning that fluidic passivation was achieved in almost all thrusters. Thrusters 1,7, 11 are still not showing a temperature decrease, which is however reached later when the spacecraft is in RRM and the following acquisition modes.

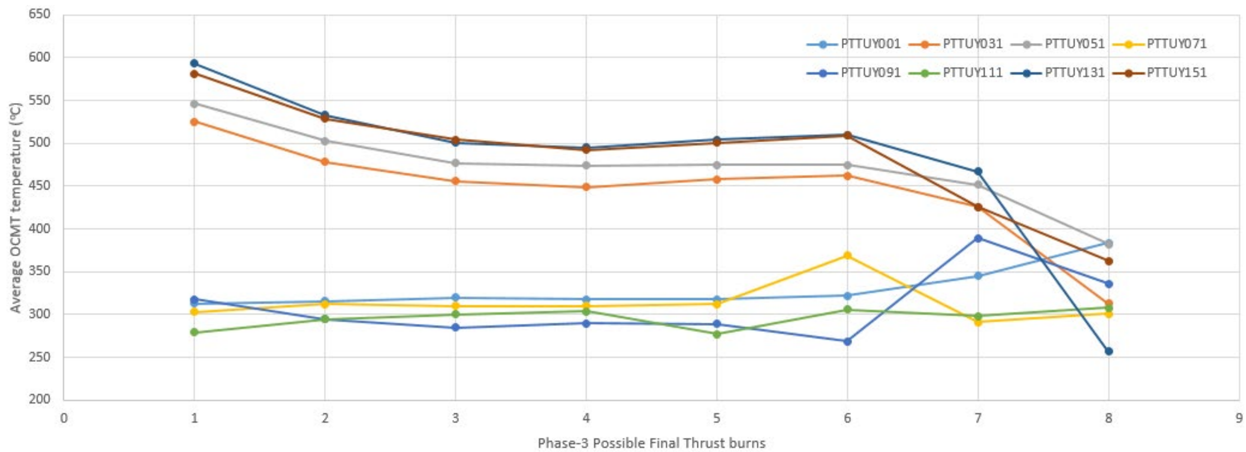


Figure 9. OCMT temperatures during the phase 3 burns

4.5 Phase 4: Electric passivation

During this phase, after confirming fluidic passivation i.e. depletion of hydrazine, RRM was manually triggered as return to OPM was not observed within manoeuvre timeout. At this point, the electric passivation sequence was triggered and the spacecraft was observed reaching until Fine Pointing Acquisition Mode, a stable AOCS mode depleting the last drops of propellant in the pipes. It is to be noted that the thresholds for autonomous transition from course to fine acquisition modes is quite wide and Metop-A could meet those thresholds with the remaining hydrazine bubbles or cold gas firings. Thruster temperature increase was also observed on most of the branch A thrusters during the forced re-acquisition.

The electric passivation sequence sent the commands to disconnect the batteries one by one using both bus couplers (one at the time), and then switched off the S-band transponder before disconnecting the last battery. The batteries were fully charged before final disconnection.

5. Team management

Arranging the activities for such a complex and long operation with a small team was not an easy task. Given that most activities would occur during working hours (or slightly outside working hours), it was decided to arrange two daily shifts with a variable start/end time depending on the activities of the day. The first shift (A) would start around 7AM and finish around 2PM, while the evening shift (B) would start around 2PM and finish around 9PM with a bit of overlapping between the two shifts to attend the daily operations briefing that was held around 2PM. Outside the shifts, operations and the non-critical night activities were covered by the spacecraft controllers.

The Metop Flight Control Team had only three members that were highly trained and skilled on AOCS, power/thermal and data-handling subsystems, which meant that only three people were able to cover the two daily shifts.

Since the operations were running for longer than two weeks, it was really important to give a break day to the team. Therefore, the operations were paused and the satellite was "babysitted" by the spacecraft controllers for a full day. It would have been preferable to have more break days or to stop completely the operations over the weekend, but it was considered too dangerous with the knowledge at the time. The more the orbit was getting lower, the more impact was expected on the loads generated on the reaction wheels, due to the increased atmospheric disturbance. In the (unlikely, but still possible) event of a large solar flare, the situation could have become very critical very quickly, and it was therefore decided not to take the risk, keeping the deorbiting duration as short as possible, also to create little impact on the Mission Planning, avoiding too many re-planning and rescheduling activities.

In addition, Metop-A EOL operations have been heavily affected by the current Covid-19 pandemic situation. When normally operations would be conducted from the nominal control room and only one additional support room, in this case three support rooms were needed. The core team on shift A would use only one room, while the core team on shift B would use only the second room, and the people of shift A and B would never mix, to minimize the chances of Covid-19 cross-contamination impacting the whole deorbiting team. The third room was used by coordinators, other members of the team and by the Project Support Team to follow the daily activities from screens that would duplicate the displays in the control room, allowing everyone to monitor telemetry, telecommmands and all that was being sent/received by the satellite. Besides, when activities allowed some team members were able to work remotely, either from their offices or from home.

The Project Support Team from the satellite manufacturer was expected on-site to support the most critical activities, but already a week before it was clear that the team could not have travelled to Germany, because of close contacts with Covid-19 infected relatives.

However, with the current screens and tool set-up for the deorbiting, it was very easy to monitor and follow closely all the activities from remote. A conference channel was created with telemetry displays and another conference channel would show the telecommands, together with the audio connection with the voice loop in the main control room. The conference link and password would be distributed to the team members who needed to support the deorbiting operations, and with these means, the Project Support Team leader was able to closely follow the activities and to support in real time the operations, giving verbal feedback directly to the team in the main control room.

6. Coping with problems and other planned contingency measures

During the Metop-A deorbiting operations, a few anomalies were encountered. Luckily, such number was quite low, but many contingency measures were in place in order to cope with unexpected issues.

6.1 Anomalies encountered during the deorbiting

Proficiency Metop-A Fairbanks passes were conducted from mid-November up to 28 November without issues with the exception of an incorrect Two Line Elements load which was rectified. However, issues were encountered with the Metop-A EOL Fairbanks passes where the satellite could not be commanded during the final critical PFTs, causing a rescheduling of the activities and the use of different ground station that had to be requested. NOAA and Fairbanks team were very accommodating in accepting, giving priority to and quickly preparing for additional emergency Metop-A test passes, launching investigation and attempting to troubleshoot issues in real-time. In the end, the issues were identified in the weather conditions in Fairbanks, that built up snow and ice in the dish of the used antennas, impacting the commanding capabilities.

The procedures in place for these scenarios were executed, re-planning the manoeuvre sequence, rescheduling the timeline and the activities for the following passes and requesting passes over different ground stations. On the spacecraft side, the major impact was the impossibility to command after the end of a PFT, implying that if that manoeuvre would have been the last one, the nominal electric passivation sequence would have been very difficult to send in a reliable manner. However, even in such scenario the team had back-up plans, having different type of sequences to cope even with the satellite in safe mode in the following orbit and still be able to passivate.

As a final anomaly, the time-tagged electric passivation (the baseline chosen by EUMETSAT) failed. The commands required for the electrical passivation were uplinked on-board, but could not be stored in the correct buffer due to an asynchronous task of the CFS, running at an unexpected time, and did not execute. At this point, the back-up strategy consisting in the manual passivation was immediately executed. This implied using different procedures that send the commands one by one, via both the on-board decoders and at a fixed rate, successfully performing the passivation.

6.2 Contingency measures "in the back pocket"

As mentioned before, the RW kinetic momentum was a concern during the deorbiting, as the loads on the wheels could have been higher with the lower orbit and higher torques generated by the atmospheric drag. The values were carefully monitored and a contingency plan was prepared in case of quick changes in the RW kinetic momentum: with an ad-hoc developed software, the team would have calculated an optimised set of coefficients for the magneto-torquer actuation, in particular the gains used by the desaturation control law, to be uplinked and obtain a decrease of the RW kinetic momentum absolute values. The telemetry to be used by the optimization software has been requested with higher frequency for one orbit after every manoeuvre, to have a fresh set of parameters ready to be uplinked via command if needed.

Before the start of the Backflip manoeuvre a time tagged command was sent to stop the recording of science data. This was to ensure that no collected data would be overwritten in case the first dump after the Backflip would not be successful. In this case a contingency procedure was put in place to manually reset the SSR playback pointer to the pre-Backflip position, which was recorded at the end of the last Svalbard pass, and then perform a re-dump of the science data. In theory this operation could have been repeated indefinitely, if also the following dumps were to be unsuccessful.

Several contingency measures were in place to cope with "loss of personnel". In case of Covid-19 contamination or sickness, back-up personnel were identified and trained to take over operations in case of need. A remote monitoring system that had been put in place, allowing watching the same telemetry displays and command queues as if you were in the main control room, was a very powerful tool, allowing (in the worst case scenario) the engineers to guide from remote the satellite controllers in the execution of the procedures, giving feedback in real time on what to do or not to do.

In case of anomalies due to the applied yaw bias (reminding the reader that the Metop satellite was never designed to operate with such a high yaw bias and for a long time – two weeks in this case), an emergency procedure was prepared to remove very quickly the bias. Such procedure would have been needed also in case of a satellite reconfiguration to RRM due to a platform anomaly: in this case the bias has to be removed, otherwise the attitude law would be affected, as not compatible with an attitude bias.

The emergency removal procedure would remove the applied bias in only one orbit, causing a non-negligible sudden jump in the attitude parameters. However, simulations and comparisons with the real telemetry showed that the satellite would be able to easily absorb such jumps and that there was no risk in applying such quick emergency bias removal procedure.

7. Impact on the ground segment

On the ground segment, for an organisation like EUMETSAT that not only has the control of the satellite, but also of the whole data production, processing and dissemination chain, the decommissioning of a satellite has a non-negligible impact.

The first aspect to note was that EUMETSAT needed to develop a series of actions to inform the user community of the satellite decommissioning. This included listing all the entities treating data from Metop-A, and all the existing interfaces and data exchanges. Dedicated personnel was identified for coordinating the communication. The deorbiting dates were communicated in several instances to partners and users, first with a tentative date and then with the final plan once the deorbiting dates were confirmed. Information was also published in the EUMETSAT website [5], [6], [7] and the EUMETSAT Delegate Bodies were also regularly informed of the plans twice per year during the delegate meetings.

Prior to the beginning of the deorbiting operations, before the attitude and orbit of the satellite were changed and the instruments were switched off, dissemination of the products had to be stopped for the user community, to avoid feeding them with products not compliant with the normal standards of quality.

This process was slightly more complicated for Metop because some "special users" were supposed to receive the Metop-A data until the very end, to ingest and process directly the data needed for the Technological tests on the instruments. The Dissemination Engineers had to stop selectively single data-flows to different users, but the process worked well and was handled flawlessly by the ground segment.

The data processing facilities were of course never designed to process data from a non-nominal orbit. Investigation were carried over before the deorbiting, to ensure that the facilities would cope well, but it was not possible to know with absolute certainty if all the data processing would work as expected. With the experience of Metop-A, we can tell that the L0 processing of the data showed no problems, and also the higher levels were not impacted. Processing for some instrument was even able to run with attitude of the Backflip manoeuvre.

No special activities had to be done to "remove Metop-A from the ground segment". Since there are still other two Metop satellites flying, only simple configuration files (or satellite procedures and parameter argument files) would need to be removed from the operational files in the ground segment, without any impact on the other operational mission. The full list of the items to be removed was produced and the full process of removing all the needed items took approximately one year to complete.

8. Main lessons learnt

In this chapter are summarized all the main lessons learnt from the deorbiting that will be useful to plan the EOL operations for the next Metop satellites.

8.1 Break days

Given the Metop-A experience where the reaction wheel kinetic momentum (due to the lower orbit) was still very low, more than 1 break day shall be considered in planning the sequence of operations.

With 16 days of operations, even with shift A and B the team was quite tired towards the end. Therefore, at least 2 break days shall be accounted for. Even in the case of a large solar flare (whose likelihood is low), the situation is likely to be under control and one extra day would not make a big difference, if planned not too late in the operations sequence.

8.2 Keeping the yaw bias in phase 3 and shifting the Backflip manoeuvre

It would be useful to leave the yaw bias applied also for phase 3, in order to optimize the PFT efficiency, further lower the perigee and save the time required to remove the bias.

However, the yaw bias should be removed before the execution of the Backflip, as recommended by the satellite manufacturer. After the excellent performance of the Backflip manoeuvre and the proven stability of the platform, performing such operation is considered now low risk. Therefore, a solution would be to anticipate the Backflip before the beginning of EOL Phase 2, so that the bias is not yet applied.

8.3 Off-modulation evolution

The propellant consumption after each manoeuvre will shift the centre of mass away from the initial position, causing the thrusters Z-Y+ to fire more than thrusters Z+Y+, causing the off-modulation to increase. The value predicted from the analysis done by the satellite manufacturer was 17.86%, while at the end of phase 2 a value of 25.95% has been recorded. Before the first signs of tank depletion (PFT #5) it reached 28.38%. It has to be noted that non-nominal evolution of centre of mass can result in higher off-modulation rate. The observed off-modulation shall be accounted for planning future burns and for re-computing the cut-off time for return to OPM.

8.4 RW kinetic momentum behaviour

It has been observed that the real space weather conditions and the elliptical orbit had a very small impact on the reaction wheel loads. Therefore, for future EOL activities, the frequency of manual requests of special reaction wheel telemetry can be highly decreased, reducing the manual commanding and the daily activities. Also the effort from the Flight Dynamics team would decrease, as they would need to analyse the telemetry only once every manoeuvre sequence, to check for propulsion parameter updates. A more frequent monitoring would be required in case a perigee below 530 km would be reached, as recommended by the manufacturer.

8.5 Leaving the payload on in phase 3

The current strategy foresees switching off the payload (and therefore the Solid State Recorders) at the end of phase 2, implying that telemetry is available only from the S-band transponder during the visibility windows from the beginning of phase 3 onwards. However, the experience shows that the payload module can technically be left on during phase 3 and it would be useful to have X-band telemetry, GNSS measurements (for more robust orbit determination and manoeuvre calibration during the PFTs), for additional instrument technology tests, and to increase the satellite inner temperatures.

Therefore, the next deorbiting operation should consider switching off the payload module in phase 3 right after the occurrence of the first bubble in the thrusters during a PFT, implying that only the last PFTs (and orbits in between) will be performed with only S-band telemetry available during the pass window.

8.6 Temperature environment

With LTAN ~19:50 and the payload off, the observed temperatures were much higher than forecast by the models. This is due to a number of limitations from the used models, like heater set point changes made after thermal analysis runs, incomplete internal temperature modelling, much higher thermal coupling between payload module and service module cylinders, and likely much darker radiators than the one modelled for a 5-year end of life. This lowers the risk assessment for hydrazine freezing in the pipes in case of a payload switch-off, implying that lifetime can be further extended until the hard limits of power consumption are reached.

8.7 Power consumption

The main driver to select the time of deorbiting was the constraint on power and thermal subsystem. However, due to much lower than modelled heater power consumption and a better than expected power subsystem performance, the overall spacecraft power consumption was significantly lower than anticipated. In the original modelling, it was assumed that power consumption would remain fairly constant during LTAN drift: extra heater power demand would be balanced by reduced battery recharge times due to shortening eclipses. But from what has been observed, due to smaller than forecasted heater power increases, power consumption dropped significantly due to the shortening of eclipses and therefore lower battery power consumption. This unexpected margin allows planning for an additional year of lifetime, i.e. to reach an earlier LTAN, for the remaining Metop satellites, increasing the science return.

8.8 Propellant estimation

In preparation for the deorbiting operation, the satellite manufacturer developed a new more precise propellant gauging method to be used during the end-of-life activities. The analyses of the propellant estimation performed following the end of the deorbiting showed no reason for changing the propellant bookkeeping during routine operations, and that the values resulting from applying the methods proposed by the satellite manufacturer where too pessimistic. They also show that if the bookkeeping method applied during routine would have been applied as well during the deorbiting manoeuvres, the result would have been satisfactory. It is therefore proposed not to modify, for Metop-B and C, the operational propellant mass at the beginning of the deorbiting operations, and to use the same procedure as in routine for the operational computation of the propellant consumption during the deorbiting manoeuvres.

8.9 Tank temperature settings

The nominal set points for the propellant tanks are 15/18°C. A more stable tank temperature would help the estimation of the burn performances and the calculations of the remaining propellant mass. It can also be observed that higher tank temperature causes high thruster catalyst temperatures and therefore improved manoeuvre performance.

Therefore, the lower set point could be increased to 17°C and keep only 1°C temperature variation.

8.10Perigee minimum altitude

The constraint on the minimum perigee altitude allowed for deorbiting operations considered by the satellite manufacturer was 525km. However, the actual hard constraint for the perigee is 400km, given by the hardware masking of the Earth sensor.

It is considered acceptable now, when planning the manoeuvre sequence, to use such value as the target minimum perigee altitude to obtain shorter re-entry times. Only a change to the expected value of Earth diameter, measured by the Earth sensors, has to be applied and will be provided by the manufacturer for the future deorbiting operations. The wheel behaviour will be monitored, and the procedures already foresee what needs to be done in case certain limits are reached because of too high loads in the lower orbits. There is consequently no need to consider a separate hard constraint because of the wheels.

9. Implications on the lifetime extension for Metop-B and C

As explained before, the driver to trigger the beginning of Metop-A end-of-life operations was the risk of getting too cold in February 2022, especially in the case of a payload switch off.

However, after the Metop-A experience, it can be concluded that the thermal margins are much higher than expected. The temperatures of the satellite core and of the platform propulsion sub-system were very stable, also when the payload module was switched off in the days before the final electric passivation. The high margins compared as well to the thermal models and the thermal forecast, showed that there are big deltas and the risk associated to thermal environments in February 2022 would have been negligible.

Therefore, one extra year of drift looks possible for Metop-B and C, assuming that they follow the same LTAN drift and ground-track maintenance strategy. A short period of lifetime with no eclipses is also acceptable for the battery management, without further modification of the on-board software.

After this extra year of drift, the power/thermal situation would worsen dramatically and it would be too risky to further extend the lifetime to the following winter, meaning that for Metop-B the deorbiting should start latest in November 2028, giving it one full extra year of mission compared to Metop-A.

10. Conclusion

After the conclusion of deorbiting operation, the Metop-A final status was the following:

- Propellant depletion: achieved
- Electric passivation: all batteries and transponder disconnected
- Final orbit: apogee ~800km, perigee ~536km
- Estimated re-entry time: 21.5 years
- All Technology tests performed successfully (including the Backflip manoeuvre)

All the guidelines in the Debris Mitigation Standard [2] were met, excluding keeping the casualty risk below 10^{-4} with the 90% confidence level. This cannot be fulfilled with the propulsion module design or available propellant, even at launch. It would have required a controlled re-entry (which was never part of the Metop design) or a debris collection service. The modelled casualty risk is $7.5x10^{-4}$.

The re-entry time shorter than 25 years was achieved to 21.5 years despite concerns on available propellant (July 2019 platform anomaly that caused attitude loss/thruster activation) and taking advantage of the yaw bias thrust approach.

All the activities went as planned, with only minor issues and anomalies. This was merit of a team of great professionals and a careful planning.

The deorbiting gave incredibly valuable information, directly applicable to the other Metop satellites, either from the Technological tests or for improvements to the actual deorbiting strategy itself. Moreover, high confidence is given to further extend the lifetime of the other satellites by one extra year, compared to what was done for Metop-A.

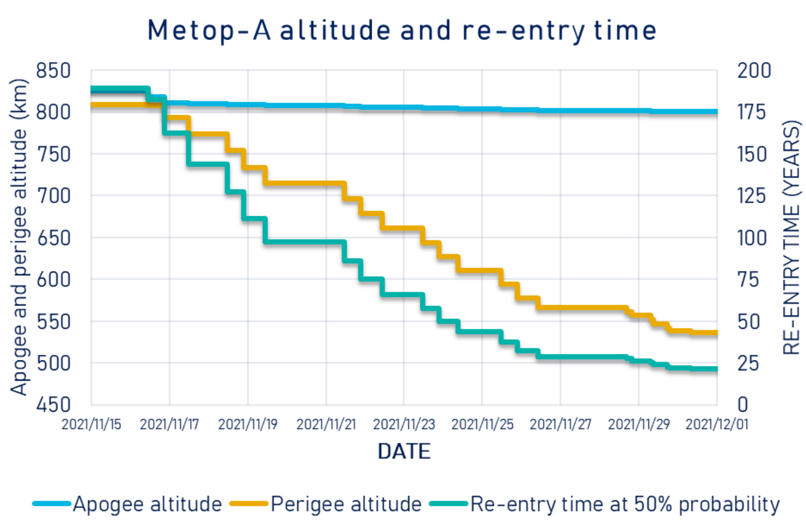


Figure 10. Metop-A altitude and re-entry time

Acknowledgements

The authors thank all team members from NOAA, CNES, Airbus DS and EUMETSAT, together with all contracting companies who have contributed to this project.

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