METOP-A DE-ORBITING USING VERY LARGE IN-PLANE MANEUVERS

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Abstract: *Metop-A, the first satellite of the EUMETSAT Polar System (EPS), was successfully launched in October 2006. Thanks to a very accurate injection into the operational orbit and to a close to optimal orbit maintenance, together with the fact that no major anomaly at platform level has occurred, a large amount of fuel has been saved in comparison with the design case during the first nine years of operations. The decision has been made to allocate most of this fuel to trying to place the satellite in a faster-decaying orbit which will result in an atmospheric re-entry around 25 years after the end of operations, taking into account the constraints imposed by a spacecraft that was not designed to comply with the international regulations on space debris mitigation. A de-orbiting strategy has been defined, compatible with this design and the objectives of freeing the Metop operational orbit, lowering the orbit enough to achieve the target re-entry time and emptying the spacecraft fuel tanks. Initially, the strategy considered the execution of medium-size double in-plane maneuvers, but further analysis showed that these led to operational issues. This paper presents a revisited strategy based on large single in-plane maneuvers that simplify operations while at the same time achieving the same de-orbiting objectives.*

Keywords: *End of Life, De-Orbit, Mission Extension, Maneuvering Strategy, Debris Mitigation.*

1. Introduction

Metop (see Fig. 1) is a series of three polar orbiting satellites that constitute the space segment component of the EUMETSAT Polar System (EPS), Europe's first low Earth orbiting operational meteorological satellite system and the European contribution to the joint Europe-US polar satellite system called the Initial Joint Polar System (IJPS). Although originally meant to operate successively, the excellent health and behavior of the first satellite (Metop-A, launched on October 19, 2006) has allowed operating it in parallel with the second of the series, Metop-B, since the latter's launch on September 17, 2012. As well as providing redundancy to the instruments in orbit, these dual operations have proven to be extremely beneficial in terms of mission return to the end users.

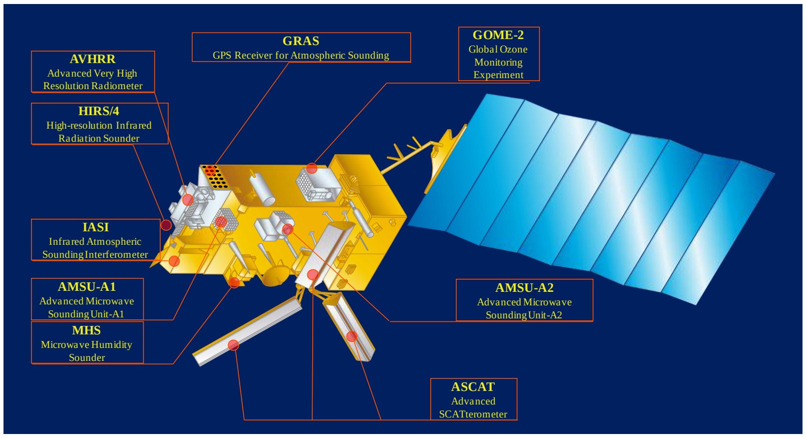

Figure 1. The Metop spacecraft

The satellites are required to fly on a sun-synchronous circular orbit, with a repeat cycle of 412 orbits in 29 days, staying within 5km around the nominal ground track and within 2 minutes from the nominal local time of the descending node, which is 9:30 UTC. In order to stay on the operational orbit, maneuvers need to be carried out regularly to compensate for the natural altitude loss and decrease in inclination. The out-of-plane maneuvers, besides being the ones causing most of the fuel consumption by nature, require a slew of the platform that is controlled by thrusters (see [1]). This has an impact on the selection of the dates and size of this kind of maneuvers with the objective to maximize the inclination change per fuel kilogram (see [2]).

Besides maneuvers, fuel is also used to control the satellite's attitude after separation from the launcher and during platform contingencies. All these contributions had to be taken into account in the mission's fuel budget prepared during the design phases, which resulted in a lifetime of 5 years. Fortunately, the assumptions made back then for estimating the fuel required for acquisition of the operational attitude and orbit following launch and for spacecraft contingencies have proven to be quite pessimistic in the case of Metop-A. Thanks to the selection of a separation state vector that avoided the need for inclination maneuvers during the first 18 months of operations, to a very accurate ingestion into orbit and to the lack of contingencies triggering a thruster-controlled attitude mode up to the present, together with an almost optimal orbit maintenance strategy according to [2], the fuel left on board 9 years after launch is well above expectations, as shown in Tab. 1.

Table 1. Design vs. actual fuel budget for Metop-A (September 2015)

Fuel (kg)	Design	Actual
At launch	315.0	314.6
Acquisition	60	11.6
Routine operations	180 (20kg/year)	114.7
Contingencies	270 (30kg/year)	0
Total left	< 0	188.3
Margins	5	10
Available	< 0	178.3

Metop satellites were designed and built before current international regulations on space debris mitigation, which are therefore not applicable to them. The figures in Tab. 1 actually show that it was foreseen that at the end of the predicted lifetime of 5 years no fuel would be left on board, making the de-orbiting of the spacecraft impossible. However, it is EUMETSAT's desire and policy to perform an uncontrolled re-entry of the satellites within 25 years from their end of operations, as long as this is compatible with this platform.

In order to achieve this, lifetime extension reviews take place yearly in order to assess the status of the spacecraft and its operability, together with the probability of achieving the objective of a re-entry in 25 years. In parallel, and as shown in [3], different options are considered for extending Metop-A's mission without compromising that objective and, at the same time, obtaining significant benefits for meteorology and climate monitoring. Current plans are to continue Metop-A operations until the end of the commissioning of Metop-C, foreseen for the first half of 2019, with a further extension up to 2021 being considered. However, the strategy and operational procedures for the de-orbiting are already being defined and fine-tuned, so that end-of-life operations can be carried out at any point in time in case there is a risk of Metop-A becoming not operable, or if a significant change to its conditions jeopardizes the objective of complying with current recommendations.

2. Metop de-orbiting

Current operations implementation plan foresees four phases for Metop-A end-of-life operations:

1. Preparation of the ground segment for the de-orbiting operations, and reconfiguration of the spacecraft for the environment conditions it will have to face during the de-orbiting.

2. De-orbiting of the satellite performing negative in-plane maneuvers.

3. Passivation of the propulsion subsystem.

4. Complete passivation and switch-off of the satellite.

The following will focus on the phases of major interest from the Flight Dynamics point of view, namely the execution of the in-plane maneuvers for the de-orbiting and the passivation of the propulsion subsystem, which is also performed by commanding in-plane maneuvers.

After summarizing the objectives of the de-orbiting and presenting some constraints that affect the operations, the two most realistic de-orbiting scenarios in terms of initial conditions will be presented. These two scenarios will be the ones analyzed in detail later on, considering the different strategies taken into account for the Metop-A end-of-life operations.

2.1. Objectives

As mentioned above, the final objective of the de-orbiting is to bring the spacecraft into an orbit for which the natural decay will lead to an uncontrolled re-entry into the atmosphere in less than 25 years from the end of the operations.

In attempting this, other intermediate objectives have to be considered, mostly to avoid disturbances to the rest of the Metop spacecraft still operational, to future EUMETSAT polar orbiting missions or to other operated satellites. Such objectives can be synthesized as follows:

- Metop-A needs to be brought far away from the Metop operational and separation orbits during the early stages of the de-orbiting, in order to avoid the risk of collisions with other flying Metop spacecraft or with future satellites after separation.

- Collision risks with other operated spacecraft need to be avoided as far as possible.

- Interferences with the operations of other flying Metop satellites need to be minimized, since timely and reliable data delivery to the end users of the Metop operational missions still needs to be guaranteed.

2.2. Constraints

While the strategy finally chosen for the implementation of the Metop-A end-of-life operations shall have to target the achievement of all objectives mentioned above, it will also have to take into account different constraints affecting these operations, for which neither the spacecraft nor the EPS ground segment were designed. The main sources of such constraints are the satellite platform, the ground segment, and the need to perform operations in a reliable and safe way.

Following are the constraints imposed by the spacecraft:

- Although it is an obvious constraint, it is worth mentioning that the fuel on board is limited. The amount of fuel available when starting the de-orbiting operations will determine how much the orbit can be lowered and, consequently, how long the re-entry time will be. In order to be able to comply with the international recommendations, at some point in time inclination control will have to be abandoned in order to maintain on board enough fuel for a successful de-orbiting.

- There is also a limitation in the accuracy with which the real amount of useable fuel left on board is known. Thus, margins will have to be accounted for, both in order to take into account the most pessimistic values for the computation of the final orbit that can be reached, and in the definition of the strategy for the complete passivation of the propulsion subsystem regardless of the actual values within reasonable margins.

- The duration (and hence the size) of maneuvers is limited. During routine operations, the maneuver duration is limited to 1000 seconds, according to the information provided by the manufacturer, in order to avoid long-term damage to the thrusters.

- Outside maneuvers and contingencies, the satellite’s attitude is controlled by means of magneto-torquers and reaction wheels. Saturation of the reaction wheels has to be avoided (this will also avoid waste of fuel during contingency modes where the attitude is controlled by thrusters), which means that the spacecraft cannot be operated in a controlled way if the atmospheric drag is too high, i.e. too low into the atmosphere. The minimum altitude guaranteed so far by the spacecraft manufacturer in order to be able to operate without risk of saturating the wheels is 525km, computed with respect to the equatorial radius.

- Because of the above, wheel rates need to be monitored regularly, and more often in case the values are close to the limits recommended by the manufacturer. This can constrain the amount of maneuvers that can be performed in successive orbits during the passivation of the propulsion subsystem.

- In case the wheel rates get close to the maximum allowed values, a wheel off-loading command shall be sent. This modifies the total kinetic momentum around which to control the spacecraft with the help of the magneto-torquers, thus reducing the wheel rates. Before the execution of the following maneuver, ground control needs to make sure that the rates are low enough, meaning that further monitoring of these rates is required. Consequently, the timing of the following maneuvers can be affected.

- The on-board estimation of roll and pitch attitude relies on gyroscopes and on measurements from the Earth sensor. In order to be able to keep the spacecraft's attitude deviation within acceptable limits, the Earth-space transitions need to be detected by the sensor, which also imposes a lowest boundary to the minimum altitude of an orbit in which Metop-A can be operated safely. The minimum altitude guaranteed so far by the spacecraft manufacturer in order to be able to operate without risk of losing Earth sensor measurements is 500km, computed with respect to the equatorial radius.

- The frequencies used by the on-board transponders are the same for all Metop satellites, which means that if two of them are too close to each other, as seen from a ground station, their signals will interfere. Tracking, dumping of real-time telemetry, commanding and dumping of science data (maintained in Metop-A as far as possible because they include GPS navigation data extremely helpful for orbit determination) will have to be stopped on one of them in order to be able to operate the other one nominally. Since Metop data are really useful for operational meteorology and contribute largely to the long-term archives for climate monitoring, frequent or extended interference periods cannot be accepted.

- The deviation of the local time of the ascending node with respect to the nominal one is also limited, due to visibility of the Sun from the Sun sensor, illumination conditions of the solar panel, thermal constraints or duration of the eclipse. This means that, once inclination control is abandoned in order to save fuel, and keeping in mind that the satellite's altitude will have to be maintained in order to avoid repeated interference periods with other Metop satellites for an extended period of time, the local time of the ascending node will start to shift, and Metop-A end-of-life operations will have to be completed before the maximum deviation is reached. Currently, the maximum deviation allowed by the manufacturer is 40 minutes, though further analyses are being carried out in order to determine whether a larger deviation could be tolerated safely by the satellite and, consequently, extend the operational lifetime and mission return of Metop-A without additional fuel usage.

- Pre-heating of the thrusters is required before each maneuver and it is commanded together with the maneuver itself. During routine operations, this pre-heating is required to last 90 minutes, which means that the maneuver commands need to be uplinked well in advance. Since other constraints impose the compression of the de-orbiting to the maximum within the limitations of the platform and the robustness and safety operations, a reduction of the pre-heating duration has been analyzed together with the spacecraft manufacturer, who has allowed setting it to a minimum of 65 minutes.

- A maneuver command can include a maximum of two burns, with configurable number of pulses and separation between burns.

- Following a maneuver and the transition to nominal attitude mode, a time is required for the convergence of all on-board attitude estimation parameters before the next maneuver can be executed confidently. For the maneuver sizes considered for end of life, this time is of around 7 orbits.

- Due to the eccentricity of the target end-of-life orbit, the masking strategy for the Earth sensor needs to be modified with respect to routine operations: the large variation, during one orbit, in the Earth size as seen from the sensor makes impossible the pitch and roll estimation with only one trace and one value for the Earth diameter, so it becomes necessary to mask the two traces of the sensor simultaneously. This implies that, whenever there is a need to avoid blinding from both the Sun and the Moon and these are in opposite directions as seen from the satellite (i.e. close to full moon), the sensor has to stay masked for most of the orbit, complicating the on-board attitude estimation and consequently the convergence after maneuvers. Although still under analysis, the manufacturer’s preliminary recommendation is to avoid maneuvering in such a situation, which impacts the selection of the dates for performing the de-orbiting operations, in case this selection is possible.

The most relevant constraints imposed by the EPS ground segment are as follows:

- The antenna pointing information needed by the ground stations needs to be accurate enough to allow acquisition of signal at the start of passes. Later during the pass auto-track can be enabled, meaning that in most situations this accurate pointing is required only at low elevations, where both the apparent speed of the satellite with respect to the antenna and the mapping of orbital errors on the antenna pointing angles are lower.

- When maneuvers are entered into the system, the antenna pointing information generated by current configuration is valid only after the end of the maneuver. Pre-maneuver pointing relies on information sent prior to the insertion of the maneuver. This applies also to double in-plane maneuvers, meaning that in this case any pass taking place between both burns will have to rely on pointing information that does not take into account the effect on the orbit of the first burn.

- The EUMETSAT ground station, as well as most of the external ground stations that can be used to support acquisition of telemetry and commanding of the spacecraft, is located at a high Northern latitude (in the Svalbard archipelago, Norway). This, together with the need to closely monitor the passivation of the propulsion subsystem, leads to the selection of a de-orbiting orbit with the perigee close to the South Pole, in order to achieve longer passes. Coincidentally, this perigee location is the one providing the shortest re-entry times, as shown in [3].

- The human resources for the operation of the ground segment are limited. Being the operations for the de-orbiting of the spacecraft highly demanding, it is advisable to perform these in the shortest possible time. Among other things, this minimizes the probability of contingencies or operational situations requiring intensive human intervention happening on other Metop satellite.

- Following a maneuver, at least two consecutive tracking passes are required to collect enough data for the calibration of the maneuver and the update of the orbit estimation.

- The time required for computation of the maneuver parameters and the generation of the corresponding command has to be taken into account in the planning of the de-orbiting maneuver sequence. It also has to be taken in consideration that the visibility of the satellite, and therefore the opportunities for the uplink, is limited to some portions of the orbit.

Finally, safe and reliable operations impose following constraints:

- For the robustness of routine operations, all time-tagged commands are uplinked more than one orbit before their execution time, in order to provide a back-up uplink opportunity in the pass following the nominal one (since, as mentioned above, nominally all commanding is performed solely from the EUMETSAT ground station in Svalbard). This applies also to maneuver commands, and the same principle shall be applied, except for well justified exceptions (see below), to the de-orbiting maneuvers. This extra time required for the uplink of the commands needs to be considered in the maneuver planning.

- In order to avoid unforeseen problems after the passivation of the propulsion subsystem, and to guarantee that the satellite is completely switched off and the batteries disconnected in a controlled manner, the need has been identified to perform these final operations immediately after confirmation has been received that no more maneuvers are possible. In order to do this, from a certain point onwards all maneuvers need to take place during visibility of a ground station. Moreover, there must be enough commanding time after the end of these maneuvers to complete phase 4 of the end-of-life operations. As a consequence, these final maneuvers have to be programmed to take place at the start of double-visibility passes (i.e. when acquisition of signal from a ground station can take place before loss of signal from the previous one), making use of the EUMETSAT ground station and one of the external TT&C ground stations used routinely in EPS operations and which visibilities overlap with the nominal antenna: NOAA’s Fairbanks or ESA’s Villafranca.

- During routine operations, all mission planning is automated via a schedule that is prepared and checked in advance, once a week. This automation provides a high level of robustness to the operations, and is to be maintained for end-of-life operations. However, combination of the end-of-life operations with the routine operations of the rest of operational Metop spacecraft is not straightforward, which makes it advisable to try not to modify the end-of-life schedule in real time. There is a requirement to try to stick as much as possible to the original maneuver plan, once this has been selected and provided to mission planning, and to closely monitor differences in the actual orbit with respect to the originally predicted one, so that only if these reach a given threshold the generation of a new schedule can be triggered.

- Collision with uncontrolled space debris is to be avoided at all times. However, the large size of the maneuvers (and, hence, the large uncertainty in their performance) as well as the short interval between them make the computation of the probability of collision difficult and unreliable. It is therefore consider that the best way to avoid collisions during the de-orbiting is to complete this in as short a period of time as possible.

- Also collisions with operated spacecraft need to be avoided at all times. This means that the initial planning of and any updates to the de-orbiting maneuvers have to followed by a check of the resulting orbit against those of known, operated satellites in the same orbital region. Given the large uncertainties in the knowledge of the Metop-A orbit, also the margins considered for these checks have to be very large.

2.3. Possible scenarios

One of the outcomes of the yearly satellite lifetime extension reviews mentioned above is the authorization for continuing inclination control. The last review concluded that a double-burn out-of-plane maneuver could be performed in Fall 2015. Although one further single maneuver could be performed one year later leaving enough fuel on board for a successful de-orbiting complying with the above objectives, it has not yet been decided whether this maneuver will be carried out. As mentioned in [3], different options are considered for the extension of Metop-A's lifetime. One of them, sketched in Fig. 2, is to allow a drift in local time while hopping to different legs of the reference ground track in order to avoid the phase separation between two operational Metop satellites becoming too small, which would have a negative impact in the assimilation of their data into the numerical weather prediction models.

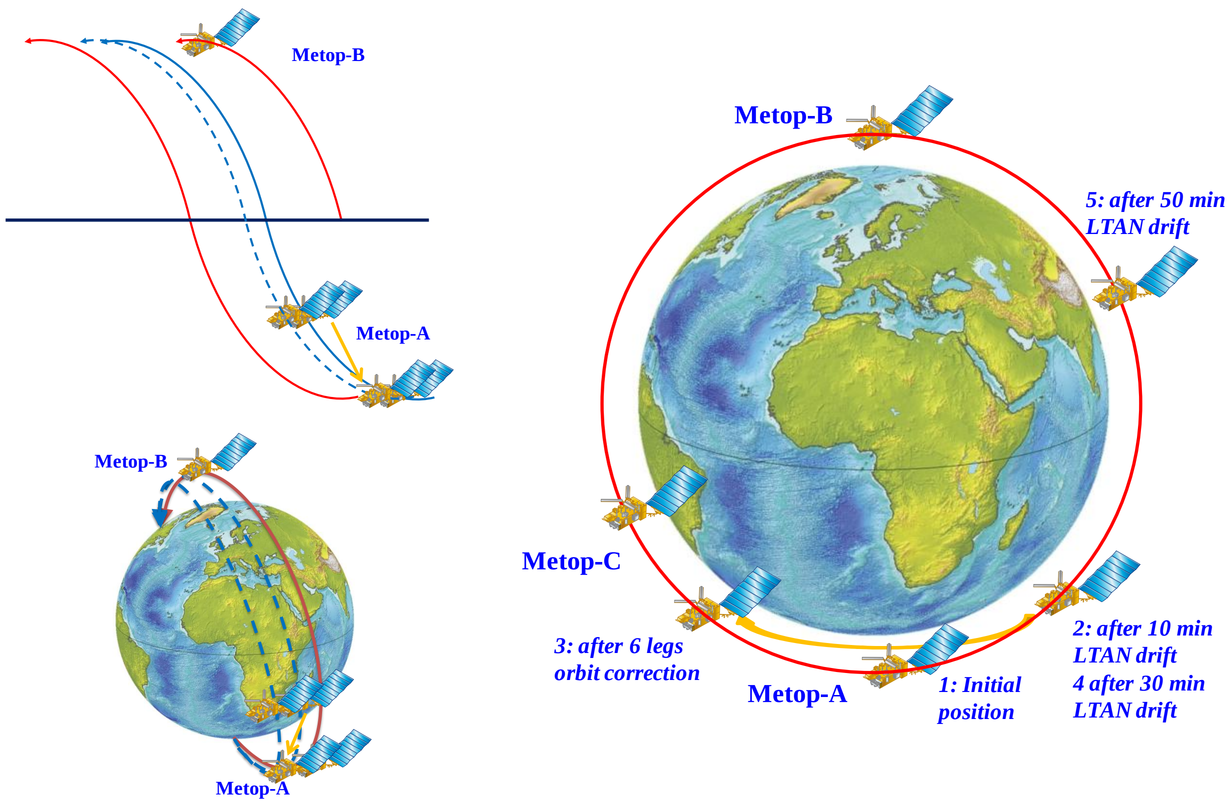

Figure 2. Example of hopping strategy for Metop-A lifetime extension

As detailed in [1], the rotation of the platform for the execution of out-of-plane maneuvers has to take place within the Earth's eclipse. However, analysis of the last maneuvers and discussions with the platform manufacturer have proven that it is possible to extend the maneuver duration by using a more realistic computation of the times required for those rotations (instead of a worst-case scenario, as considered at the start of the mission) and by allowing part of the rotations, while the deviation from the nominal satellite attitude is small, to take place immediately before or after the Earth's umbra. This possibility of extending the duration (and consequently the size) of the maneuvers will be exploited in the 2015 maneuvers in an attempt to avoid, as far as possible, conditioning the decision of whether to perform a further inclination maneuver in Fall 2016: simulations have shown that with this strategy the impact of the local time deviation on the satellite's instruments will not be significant until 2018 independently of that decision.

A consequence of the above is that the initial conditions for the spacecraft de-orbiting, in terms of fuel mass, are unknown. Therefore, the analysis presented in this paper will consider both possible scenarios:

a) Scenario A: the initial fuel mass is the one left after the out-of-plane maneuvers in 2015.

b) Scenario B: the initial fuel mass is the one left after a further out-of-plane maneuver in 2016.

3. Maneuver strategy

The maneuvers for the de-orbiting of Metop-A will have to be planned with the mind set on the objectives mentioned in 2.1 above, but taking into consideration the limitations and constraints imposed by the system and listed in 2.2.

The first objective of the de-orbiting, to be achieved by the first maneuvers, is to clear the operational orbit by lowering both apogee and perigee. Thus, even if due to some catastrophic failure no more maneuvering is possible, launch and operations of current and future Metop spacecraft will still be feasible and safe. Also, being the operational orbit a circular one, at some point during the early stages of the de-orbiting the maneuvers will have to be planned in such a way that the perigee is placed in the desired argument of latitude, close to the South Pole.

Once the operational orbit has been cleared, next objective is the lowering of the perigee in order to increase the effect of the atmospheric drag on the satellite and accelerate the decay rate. Wheel rates and the actual perigee altitude will have to be monitored in order to avoid violating the limits imposed by the platform, as communicated by its manufacturer, plus some margins to allow the execution of the following maneuvering phase.

In order to achieve the best possible results, up to this point the location of all maneuvers within the orbit will be driven exclusively by their effect on the orbit. This means that they will not necessarily happen during station visibilities. Consequently, it has to be ensured that the spacecraft is still operable at the end of each of those maneuvers. This is achieved by finalizing this phase once the estimated on-board fuel reaches a very conservative value that takes into account the assumed errors plus some margins. The selected value is 22kg.

For this phase, it is expected to reach a minimum altitude of the perigee equivalent to the minimum allowed by the manufacturer plus a margin to take into account the expected decrease achieved during the following phase.

Although there is an interest in completing the de-orbiting in the shortest possible time, part of the constraints mentioned above impose a limit to the minimum interval between consecutive maneuvers. As a trade-off, a maximum of two maneuvers are planned per day during this phase. Besides, in order to reduce the pressure on the operations and to avoid the need of continuous support from flight dynamics engineers, the decision is made to group maneuvers in sequences of three, separated by around 12 hours, the first two executed in the same day and the third one in the morning of the following day (see Fig. 3, which highlights the orbit numbers where a maneuver or the first burn of a double in-plane maneuver take place). The first two maneuvers in a sequence are not calibrated, and no orbit estimation is performed between them. In this manner, preparation of the commands for a maneuver can take place even before the previous one has been executed on board. However, since there is a need to monitor the deviation from the nominal end-of-life orbit and, most importantly, to keep the antenna pointing accurate enough to continue tracking and commanding the spacecraft, the time offset value is estimated following each pass, and flight dynamics products updated accordingly. Only after the third and last maneuver in each sequence will an orbit determination be performed (followed, of course, by updated products for antenna pointing and mission planning, as required) and the maneuvers in that sequence be calibrated. The output of this process will be taken into account for tuning the planning of the remaining maneuvers and as a-priori calibration for next maneuver sequence.

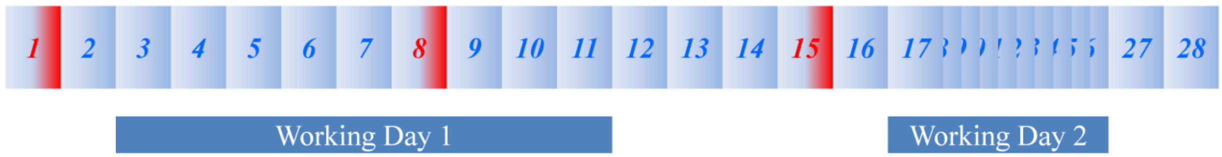

Figure 3. Allocation of phase 2 maneuvers within a two-day sequence

Once the selected fuel level threshold is reached, phase 2 of the end-of-life operations will be considered finished. From then on, it is assumed that any maneuver may be the final one. Maneuvers in this phase are hence called Possible Final Thrusts (PFTs). For the reasons explained above, these PFTs will have to take place during double-visibility ground station passes, and must leave enough time, after maneuver end, to monitor the spacecraft behavior and, if it is considered that the passivation of the propulsion subsystem has been completed, to command during the second part of the double-visibility pass the switch-off of all subsystems and the disconnection of the batteries. Location of these maneuvers will therefore be driven by the start of such combined passes, and their duration will be limited to 6 minutes in order to allow time for assessing whether the passivation of the propulsion subsystem can be considered completed and, if so, to issue the final commands. Figure 4 shows the sequence of events during one of these possible final thrusts.

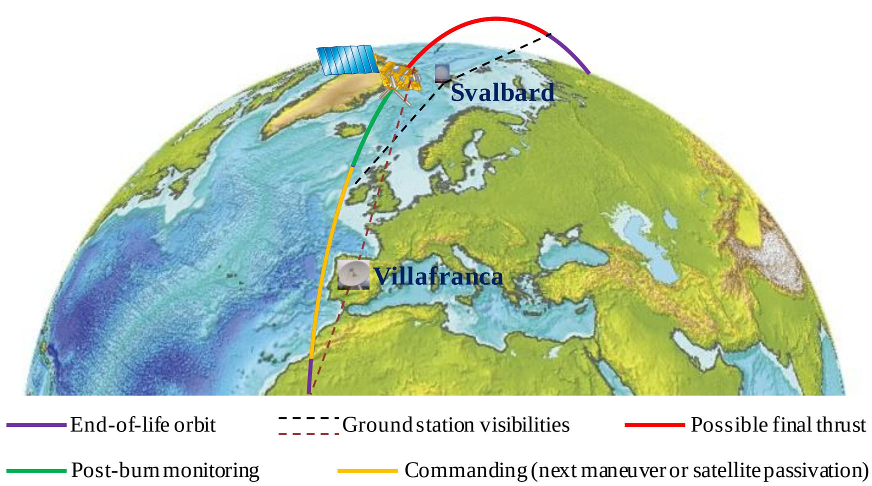

Figure 4. Metop-A possible final thrusts

During this last maneuvering phase the constraints in the monitoring of the wheel rates impose that no more than four maneuvers are executed in consecutive orbits. Depending on the values observed for those rates at the end of the previous phase, the decision could be made not to execute maneuvers in consecutive orbits at all. In any case, the system has to be ready to execute maneuvers in consecutive orbits, in case signs of fuel depletion are not yet observed and further burns have to be executed. This can be achieved either by commanding double maneuvers or by uplinking a maneuver command immediately after the execution of the previous one. As for most of the maneuvers during previous phase, no maneuver calibration or orbit determination will be performed at this stage.

It is worth mentioning that, at each point in time where the maneuver sequence is generated or updated (i.e. when preparing for the de-orbiting, on the second day of each two-day cycle during phase 2 and before commencing the passivation of the propulsion subsystem), the predicted orbit will be checked against the orbits of all known operated spacecraft within the same orbital region. Also, results of the predictions of interferences with the rest of the Metop fleet will be provided to the spacecraft operations engineers.

3.1. Original approach

Taking into account the maximum duration of 1000 seconds allowed by the manufacturer for maneuvers during routine operations and the need to complete the de-orbiting of Metop-A in a short period of time, the original strategy chosen for the end-of-life maneuvers was to use double-burn maneuvers (i.e. maneuver commands including two burns each, consequently not needing the allocation of further uplink passes) in order to obtain the maximum benefit from each command while respecting the initial constraints.

Since the first objective to be met is clearing the operational orbit, the first command would include two maneuvers separated by half an orbit and executed at the apsides, with the intention to perform a Hohmann transfer to a lower, circular orbit. The rest of the commands during this phase would also include two maneuvers each, but separated by one complete orbit. The argument of latitude of the midpoint of these maneuvers would be selected to place and keep the perigee at the desired location while lowering its altitude until reaching the minimum selected for this phase, and to keep the apogee at the desired location while lowering its altitude afterwards, up to the point when the fuel amount threshold for starting phase 3 is reached. Figure 5 shows a scheme of the orbital evolution resulting from this strategy.

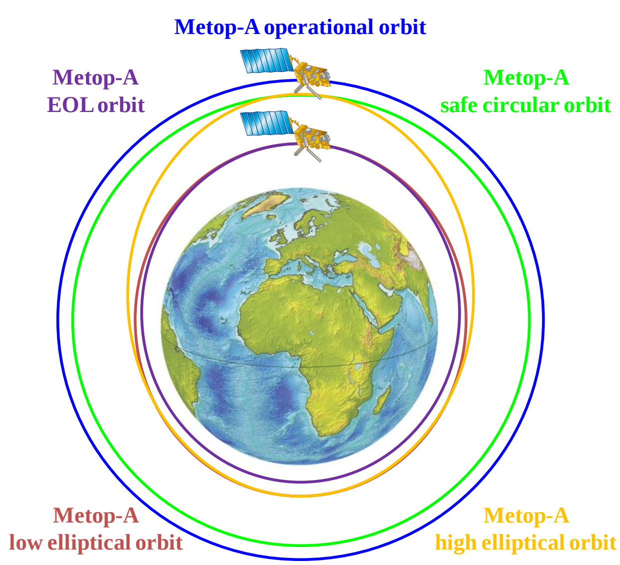

Figure 5. Original strategy for Metop-A de-orbiting maneuvers

Although from the flight-dynamics point of view this strategy is perfectly valid and meets the objectives while respecting most of the constraints imposed by the system, it has a major drawback. As stated in 2.2, one of the limitations of current EPS system is that in the case of double in-plane maneuvers no update is provided to the antenna pointing information for the period between maneuvers. Being the maneuvers of a relatively big size, to avoid a long duration of the de-orbiting operations, there is a risk that the satellite cannot be successfully tracked in passes between burns, especially when maneuvers are executed at the apogee, finishing shortly after the visibility of the Svalbard ground station. In this situation, the pass between burns would start almost one orbit after the first burn, meaning that its effect on the available antenna pointing information could be large enough to prevent acquisition of signal.

3.2. Revised strategy

In order to avoid the problem with the antenna pointing when commanding double maneuvers while attempting not to extend the duration of the end-of-life operations, two options can be considered:

- investigate ways of updating the pointing information for the period between burns, e.g. by creating intermediate products taking into account only the first burn before generating the final ones with the complete context; or

- modify the strategy in order to avoid double maneuvers, by increasing the size of the individual burns.

The first option would imply a significant complication of the already demanding and complex flight dynamics operations during the de-orbiting. The second option, however, would mean a relaxation of the procedures (it allows more time between maneuvers) and a simplification of the operations (all maneuvers are of the same type and executed around the same location). This would therefore be the preferred option, if allowed and compliant with the de-orbiting objectives.

Consequently, consultation with the manufacturer is started, and after some analysis on their side the conclusion is that during end-of-life maneuvers of up to 2300 seconds can be executed, since at this stage long-term damage of the thrusters is no longer a concern. With this updated constraint, the analysis is triggered on EUMETSAT’s side to determine whether this modified strategy is valid in both scenarios listed in 2.3, i.e. whether it can lead to clearing the operational orbit in the early stages, as well as to acceptable re-entry times, without affecting the overall duration of the operations. Figure 6 shows a scheme of the orbit evolution resulting from this strategy, where all maneuvers are executed at the apogee and, due to their spreading, lower both apogee and perigee.

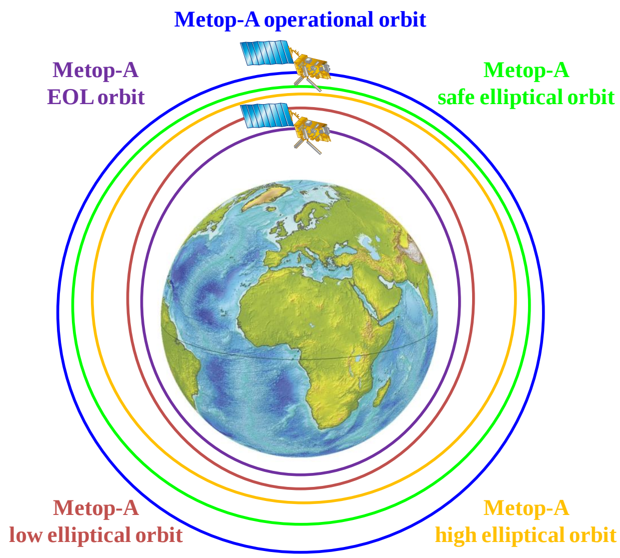

Figure 6. Revised strategy for Metop-A de-orbiting maneuvers

As a first approach for the validation of the new strategy, the same duration of the maneuvers is considered for both scenarios. The chosen duration is 1800 seconds, which is below the maximum allowed duration and corresponds to double the size of the maneuvers that were being considered in the double-burn strategy. If the target de-orbiting conditions can be achieved with this duration, the new strategy can be considered valid, and fine tuning of this and other parameters can be performed at a later stage.

4. Analysis and results

The different strategies and scenarios are analyzed with a dedicated, configurable Matlab program that uses Matlab mission analysis libraries available at EUMETSAT. These, in turn, use Orekit (see [4]) as underlying space dynamics low-level library. The resulting tool provides propagation and thrust models which results are very much in line with the ones obtained with the operational flight dynamics system used for EPS operations, thoroughly validated and consistent with the real behavior of the Metop satellites and their environment.

Regarding the estimations of re-entry times for the different orbital conditions, these have been performed using CNES's STELA (see [5]).

For both the original and the revised strategy, and for each of the two possible de-orbiting scenarios, following results are provided:

- altitude of the apogee after the initial Hohmann transfer in the case of the original strategy and after the first and second maneuvers in that of the revised one, in order to give an indication of how far Metop-A would be from the operational orbit in case a contingency at the beginning of end-of-life operations prevented the execution of the rest of the de-orbiting sequence;

- number of maneuvers needed in phase 2 (i.e. before reaching an estimated fuel mass of 22kg);

- duration of the last maneuver in phase 2, as an indication of how much margin there is for reducing the duration of de-orbiting maneuvers without increasing the total number of maneuvers needed, or how much the duration of previous maneuvers has to be increased in order to perform one maneuver less;

- orbital conditions at the end of phase 2, in terms of altitude of the perigee and expected re-entry time;

- minimum fuel needed during phase 3 in order to achieve a re-entry time of 25 years, in case this is not achieved at the end of phase 2; and

- estimated fuel mass left on board once the perigee altitude limit (525km) is reached, in order to give an indication of whether it is expected to need positive maneuvers to avoid the violation of that limit during end-of-life operations.

Besides, plots are also provided including the evolution for each of the considered scenarios of the perigee and apogee altitude and of the estimated fuel mass.

In the following, all apogee and perigee altitudes are mean values with respect to the Earth’s equatorial radius. This is consistent with the convention followed by the spacecraft manufacturer when providing the minimum allowed perigee altitude.

4.1. Original strategy

Table 2 shows the main output values obtained for the original strategy for each of the analyzed scenarios, while Fig. 7 shows the evolution of the perigee, apogee and fuel mass.

Table 2. Summary of results with the original strategy

	Scenario A	Scenario B
Last out-of-plane maneuver	Fall 2015	Fall 2016
Estimated fuel mass at start of de-orbiting (kg)	172	164
Duration of de-orbiting maneuvers (per burn) (s)	900	900
Apogee after initial Hohmann transfer (km)	807.1	807.1
Number of double maneuvers during phase 2	10	10
Duration of last maneuver in phase 2 (per burn) (s)	798	189
Apogee before PFTs (km)	785.9	786.2
Perigee before PFTs (km)	547.1	562.6
Re-entry time before PFTs (years)	22.6	26.4
Additional fuel needed for reaching 25 years (kg)	N/A	3
Estimated fuel mass at 525km perigee (kg)	10	1

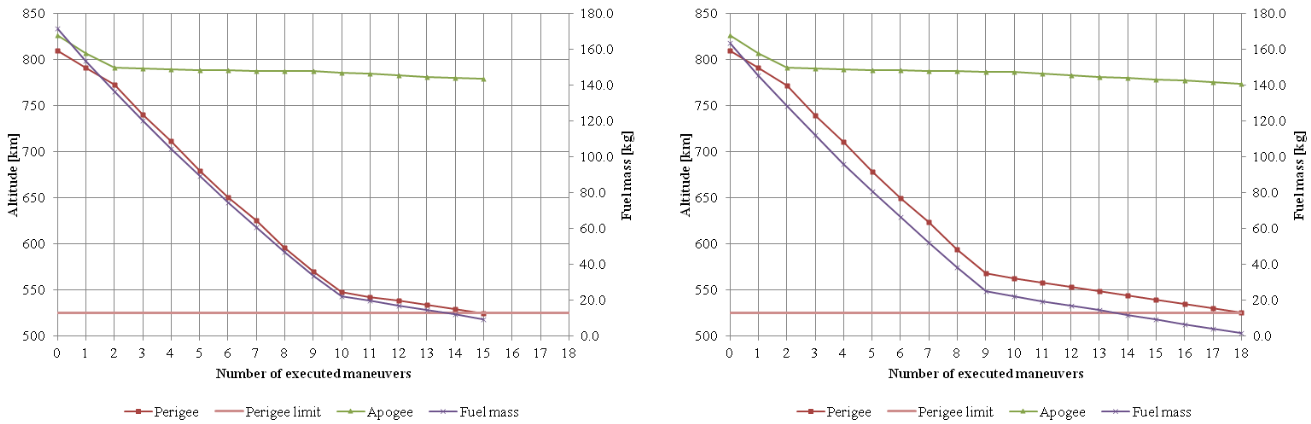

Figure 7. Evolution of perigee, apogee and fuel mass with the original strategy for scenarios A (left) and B (right)

4.2. Revised strategy

Table 3 shows the main output values obtained for the revised maneuver strategy for each of the analyzed scenarios, while Fig. 8 shows the evolution of the perigee, apogee and fuel mass.

Table 3. Summary of results with the revised strategy

	Scenario A	Scenario B
Last out-of-plane maneuver	Fall 2015	Fall 2016
Estimated fuel mass at start of de-orbiting (kg)	172	164
Duration of de-orbiting maneuvers (s)	1800	1800
Apogee after first de-orbiting maneuver (km)	808.3	808.3
Apogee after second de-orbiting maneuver (km)	805.2	805.2
Number of maneuvers during phase 2	10	10
Duration of last maneuver in phase 2 (s)	1568	351
Apogee before PFTs (km)	788.1	789.3
Perigee before PFTs (km)	545.5	560.2
Re-entry time before PFTs (years)	22.5	26.0
Additional fuel needed for reaching 25 years (kg)	N/A	2
Estimated fuel mass at 525km perigee (kg)	11	3

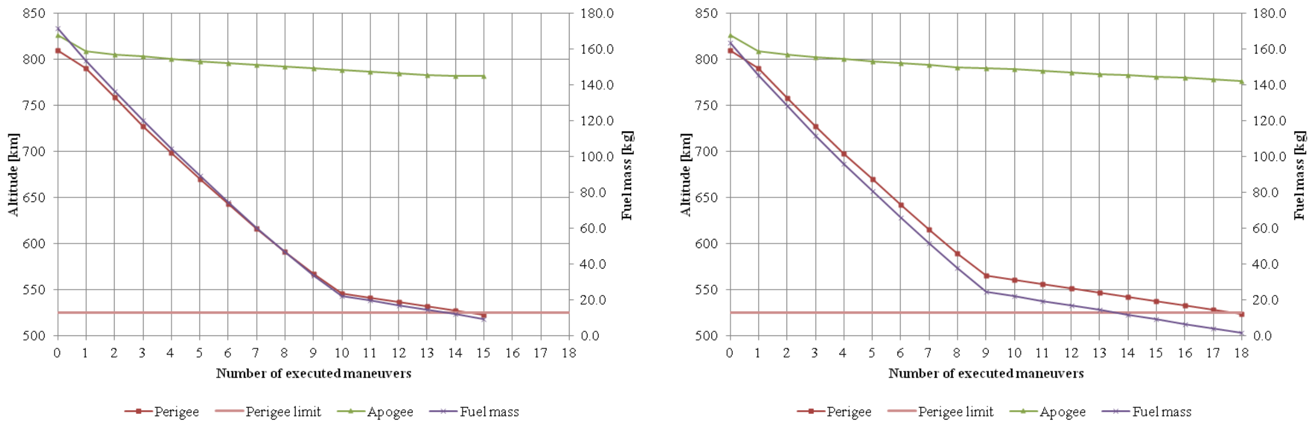

Figure 8. Evolution of perigee, apogee and fuel mass with the revised strategy for scenarios A (left) and B (right)

5. Conclusions and recommendations

From the above results it can be concluded that the revised strategy (very large, single in-plane maneuvers during the de-orbiting phase of the Metop-A end-of-life operations) is compliant with the desired objectives, and provides very similar results to the original one.

The proposed maneuver size is valid for both scenarios. In case the last out-of-plane maneuvers executed are the two in Fall 2015, the altitude of the perigee before starting the PFTs is slightly above the one chosen as minimum for the end of phase 2 (545km), which means that there is no need to perform larger maneuvers during this phase in order to lose efficiency and avoid reaching that altitude. Larger maneuvers could be considered in this scenario, however, if an advantage is seen in executing one maneuver less and the penalization in re-entry time is considered acceptable.

For scenario B, it is also seen that there is margin for decreasing the duration of maneuvers without penalization in the total number of burns, in case more efficiency is desired in order to reach a lower perigee and get closer to (maybe even below) the 25 years of re-entry time at the end of phase 2. Or just the opposite: a minor increase in maneuver duration would result in one less maneuver without a large impact on the re-entry time, which could be considered advantageous.

The figures and plots above show a very similar evolution of perigee and apogee during the first maneuvers: delaying the end-of-life until after an out-of-plane maneuver in 2016 does not have a negative impact on the apogee altitude reached during the initial maneuvers. Moreover, the lowering of the apogee with these large maneuvers is very similar to the one achieved with the original strategy after the initial two double-burn maneuvers executed for lowering the orbit maintaining its eccentricity.

From the above information it can also be concluded that the probability of requiring positive maneuvers during the PFTs is rather high in the first scenario. This may be one more argument in favor of extending the duration of the maneuvers during phase 2, since having to perform perigee-raising maneuvers complicates the operations.

In view of these results and conclusions, it was recommended to adopt the revised strategy of performing very large, single in-plane maneuvers as baseline for the Metop-A end-of-life operations, independently of which is the last out-of-plane maneuver performed. This recommendation was indeed taken into account and is the one considered as baseline in current version of the Metop-A end-of-life operations implementation plan.

Further analyses will be carried out closer the time of the de-orbiting, and once the initial conditions and all operational preferences are known, in order to fine-tune the duration of the phase 2 maneuvers in order to optimize their number vs. the achieved final orbital conditions.

6. References

[1] Sancho, F., Lázaro, D. and Righetti, P. L, "Out-of-plane maneuver campaigns for Metop-A: planning, modeling, calibration." Proceedings of the 21st International Symposium on Space Flight Dynamics – 21st ISSFD, Toulouse, France, 2009.

[2] Damiano, A., Righetti, P. L., Soerensen, A., "Operational Local Time and Eccentricity Management for Metop-A." Proceedings of the 21st International Symposium on Space Flight Dynamics – 21st ISSFD, Toulouse, France, 2009.

[3] Righetti, P. L, de Juana Gamo, J. M. and Dyer, R. "Mission Analysis of Metop-A End of Life Operations." Proceedings of the 24th International Symposium on Space Flight Dynamics – 24th ISSFD. Laurel, Maryland, USA, 2014.

[4] Orekit, https://www.orekit.org/, CS Systèmes d'Information and others, France, 2015.

[5] "STELA User's Guide." https://logiciels.cnes.fr/sites/default/files/Stela-User-Manual_0.pdf, CNES, France, 2014.