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Debris Management in the frame of Long-term Space Sustainability Activities at EUMETSAT

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Abstract

EUMETSAT is strongly committed to contribute to the global effort to reduce as much as possible the generation of space debris, mandatory to ensure long-term sustainability of the space environment. This contribution is organised on two main directions:

- on one side, actively maintaining under control the risk of collision between an EUMETSAT space asset with either a space debris or another operated satellite; conjunction analysis (CA) operations have been carried out in EUMETSAT for nearly 15 years in line with the Space Debris Mitigation Guideline 3 of the Committee on the Peaceful Uses of Outer Space of the United Nation Office for Outer Space Affairs (UNOOSA) on all flying satellites, currently four Meteosat in geostationary (GEO) orbit and two Metop, two Sentinel-3 and one Sentinel-6 in low earth orbit (LEO);
- on another, ensuring that all satellites operated by EUMETSAT are removed from their operational orbit at the end of their operational lifetime according to the currently applicable ISO standards on Space Debris Mitigation: ISO 24113; end of life (EOL) operations were successfully carried out in 2021 on the first EUMETSAT Polar System (EPS) satellite, named Metop-A and, one year later, on the first Meteosat Second Generation (MSG) satellite, known as MSG-1 of Meteosat-8, as previously performed for the Meteosat satellites of the first generation.

Whereas EOL operations are described in detail in the above-mentioned ISO standard, that is not yet the case for CA operations; therefore, EUMETSAT developed its own operational practices based on what is performed by leading operators in the field, such as NASA, ESA and CNES.

These operations are continuously enhanced with lessons learned from real operational cases, as well as through ingestion of expertise from other operators, gathered at dedicated operator's workshop organized on alternate years by CNES in Europe and by SpaceNav in the USA. Furthermore, continuous adaptation of the CA operational practices is needed on one side to adjust to the evolving debris environment (e.g. increase of number of tracked debris) and to the latest technological solutions (e.g. alternative sources of data), on another to ensure compliance to the development of new international recommendations (e.g. new ESA requirements).

The first part of this paper describes the current conjunction analysis operational practices in EUMETSAT to manage the risk of in-orbit collision, as well as their expected evolution; since Metop is the EUMETSAT mission with the highest collision risk, due to its large size and orbital regime, its CA operations are taken as reference.

In the second part other activities currently carried out by EUMETSAT in the frame of long-term space sustainability are briefly addressed: in particular, in the frame of space traffic management (STM), as EUMETSAT was involved in several cases of conjunctions with satellites operated by other operators, including constellations, and to evaluate new potential alternative solutions for mission extension and EOL operations, taking into account, also in this case, the evolution of the available technology and of the international recommendations.

Keywords: conjunction analysis, end of life operations; space traffic management, risk management, technology evolution, space sustainability

Acronyms/Abbreviations

ADR: Active Debris Removal
ATP: Authorisation to Proceed
CA: Conjunction Analysis
CAM: Collision Avoidance Maneuver
CDM: Conjunction Data Message
CONANA: CONjunction ANAlysis SW
DoI: Depth of Intrusion

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EOL: End of Life
EPS: EUMETSAT Polar Satellite
EPS-SG: EPS Second Generation
FD: Flight Dynamics
GEO: Geostationary Orbit
HRE: High-Risk Event
LEO: Low Earth Orbit
LTAN: Local Time of Ascending Node
MD: Miss-Distance
MSG: Meteosat Second Generation
MTG: Meteosat Third Generation
O/O: Owner/Operator
OOP: Out-of-Plane (manoeuvre)
PoC: Probability of Collision
SDS: Space Defense Squadron (18th and 19th)
SP: Special Perturbations
Spacon: Spacecraft Controller
SPOUA: South Pacific Ocean Unmanned Area
STM: Space Traffic Management
SV: State Vector
TCA: Time of Close Approach

1. Introduction

Conjunction Analysis (CA) operations have been carried out by EUMETSAT for nearly 15 years for all operated satellites. Their aim is to ensure survival of the EUMETSAT operational assets (as an in-orbit collision may have a catastrophic outcome for the satellite involved) and, at the same time, to reduce the probability of accidental collision in orbit, in line with the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space of the United Nation Office for Outer Space Affairs, to limit the pollution of the operational orbits.

The currently available ISO standards on Space Debris Mitigation (ISO 24113), designed to reduce the growth of space debris, focus more on how to design, operate and dispose a satellite in a manner that prevents them from generating debris; therefore, they do not really address the specifics of the CA operational practice in a consolidated manner.

The operational practices here described have been developed by EUMETSAT based on what is performed by leading operators in the field, such as NASA, ESA and CNES, but further enhanced with lessons learned on improving risk detection, optimising the risk mitigation approach and ensuring an operational overview of the overall debris environment. Operational best practices on CA are discussed in dedicated operators’ workshops, organized on alternate years in Europe (by CNES) and United States (by SpaceNav), to which EUMETSAT attends not only as observer but also as internationally recognized contributor.

Regarding EOL operations, designed to ensure disposal of a satellite at the end of its operational lifetime, EUMETSAT always performed them fully in line with the above mentioned standard; an overview of past successful operations as well as of plans for future missions is provided, taking into account on one side the evolving standards, which reflect the increasing expectations from the space community, and on another the new technologies, such as active removal and in-orbit servicing, permitting new approaches to be considered.

2. Conjunction Analysis at EUMETSAT

EUMETSAT CA is based on the processing of Conjunction Data Messages (CDM) made available via the Space-Track web interface by the 19th Space Defence Squadron (SDS) of US Air Force, based on orbital solutions computed by the 18th SDS. CDM are generated whenever a conjunction between an operational satellite and a space debris is identified and contains all the data required to perform an assessment of the risk correlated with the event:

- Relative position and velocity of the debris with respect to the satellite at the Time of Close Approach (TCA), when the distance between the two is minimal, normally referred to as miss-distance (MD);
- Estimated position error for the debris and the satellite at TCA (expressed as an error ellipsoid in the own orbital frame of each participant);
- Auxiliary information for estimating the size of the debris (radar cross-section).

Based on this information it is possible to isolate those conjunctions representing a High-Risk Event (HRE) and thus deserving further attention. A software tool, called CONANA (from CONjunction ANAlysis), has been developed in-house to perform that processing.

Moreover, external support is provided by several external entities:
- CARA (NASA) for the Metop and Sentinel-6 satellites (described in paragraph 2.2);
- EUSST (European Union Space Surveillance and Tracking) for all the satellites (described in paragraph 2.3);
- SDA (Space Data Association) for the Meteosat satellites.

Further details on these services can be found in [1].

Since Metop is the EUMETSAT mission with the highest collision risk, due to its large size (~34 square meter in average of impact surface, much more than Sentinel-3, Sentinel-6 and Meteosat) and due to its orbital regime (debris density in LEO several order of magnitude larger than in GEO), CA operations for Metop are taken as the reference in the paper. Sentinel-3, Sentinel-6 and Meteosat CA operations are directly derived from Metop operations, with few adaptations, which are briefly described in paragraph 4.3.

2.1 EUMETSAT CONANA Software

CONANA was developed more than ten years ago to address the need for proper mitigation of the conjunction risks for the Metop mission and was then adapted for all the other missions; for its development the libraries of the operational Metop Flight Dynamics (FD) software have been re-used.

CONANA provides functionalities to automatically retrieve all CDM available in Space-Track for all the operated satellites and to process them to compute:
- Probability of Collision (PoC); a simplified, but still accurate, version of the standard 2D method developed by Akella and Alfriend is used;
- Depth of Intrusion (DoI); scale factor to be applied to the covariance of both objects to have them tangent; a small DoI, lower than one, means that the two covariance ellipsoids intersect (deep conjunction).

Details on how PoC and DoI are computed can be found in [2]. In case a high value of PoC or a low value of DoI or of MD is identified (configurable thresholds), an alarm is automatically generated and delivered via e-mail to the FD team.

CONANA also provides expert analysis functionality to support the decision of whether a mitigation action is needed and, in that case, the selection of the optimal mitigation action:
- Evaluation of the quality of the received data through analysis of consistency across consecutive updates; the changes in reported MD on two consecutive CDM shall be consistent with the covariance reported on the first CDM, otherwise, an error in the reported covariance shall be suspected;
- Analysis of risk sensitivity to debris covariance errors; as the covariance reported (mainly the one of the debris) may be affected by estimation errors it is advisable to evaluate how the risk changes assuming a larger or a smaller debris covariance than reported (as the PoC may change significantly for a small change); that is particular important if the previous analysis show that the reported covariance does not match properly the observed evolution of the MD;
- Optimal Collision Avoidance Manoeuvre (CAM) computation support: in case it is necessary to mitigate a HRE, computation of the residual PoC after CAM execution, as function of the remaining time to TCA and of the size of the manoeuvre (the impact of the expected execution error is also taken into account); more details on the three points above can be found in [3];
- Capability to perform next day risk predictions: it can be assumed that the changes in MD on the next CDM shall fall within the reported 3-sigma debris covariance and that the debris covariance shall reduce getting closer to TCA; if several possible changes of MD and covariance are considered, a statistical analysis on the probability of having a PoC above a certain threshold on the next future CDM can be performed, permitting to understand how stable the risk is; more details on this procedure can be found in [4].

2.2 External Conjunction Analysis Support: CARA

As stated above, external support is provided to the Metop CA operations by CARA (NASA CA service), though the partnership between EUMETSAT and NOAA.

CARA takes care of generating for Metop satellites CDMs from the 18th SDS orbital data, also known as Special Perturbation (SP) solutions, and of posting them on Space-track, on behalf of the 19th SDS; based on these CDMs CARA generates a daily CA Summary Report, containing:

- PoC computation for a standard impact surface (the worst-case radius of 4.5 metres is assumed); this is normally based on a full 2D approach (accurate integration of the risk density on the impact surface); a more accurate 3D computation is performed for particular cases requiring it (such as low velocity and very low DoI cases);
- PoC computation considering the Metop orbit as estimated by EUMETSAT, also known as Owner/Operator (O/O) Orbit, together with a model of covariance derived from historical data; that permits to assess if a routine manoeuvre creates or not any conjunction risk (if so, re-design of the routine manoeuvre may be necessary).

That CA summary report is delivered not only to the FD team, but also to the Spacecraft Controller (Spacon), on-duty 24 hours per day, 7 days per week, 52 weeks per year, who can therefore trigger the FD on-call engineer in case of late detection of a HRE.

Moreover, CARA provides several added-value services and products in case of HRE:

- Management of the request of increased tracking, in case of poor estimation of the debris orbit, to better characterize the debris orbit and increase the confidence on the obtained result; whenever increased tracking is received a new CA Summary Report is generated and delivered;
- PoC computation using a brute force Montecarlo approach, in case a large mismatch is observed between the results provided by the 2D and 3D methods above mentioned;
- Provision of auxiliary support products (HRE support package), permitting to validate the results provided by CONANA:
    - PoC decrease as function of CAM parameters (similar to what provided by CONANA, as reported in paragraph 2.1) considering all the events identified after the CAM (not only the event mitigated, as done by CONANA);
    - PoC variability as function of impact surface changes, to permit to cross-correlate CARA results with CONANA PoC estimation (which is based on an accurate evaluation of the impact surface, as explained in paragraph 4.1).
- Auxiliary information, whenever available, for decision making support:
    - on the next possible tracking opportunities on the debris before TCA;
    - on the confidence of the provided debris covariance (if accurate or over/underestimated);
    - on the probability and impact of a large change in solar activity (affecting strongly the debris orbit);
    - on the potential consequence of the collision (if catastrophic or not).

2.3 External Conjunction Analysis Support: EUSST

External support is provided to the Metop CA operations also by EUSST, a CA service being developed by the European Union in support to European assets; the same support is also provided to all the other EUMETSAT missions (Sentinel-3, Sentinel-6 and Meteosat).

The EUSST Prime support is provided by the Spanish Space Surveillance and Tracking Operations Centre (called S3TOC); the main features of that support are:

- Automatic processing of available CDM via Space-Track;
- Capability to consider the O/O orbit (plus a model covariance derived from historical data) in the computation of the risk, for post-manoeuvre assessment;
- Capability to generate CDM based on the SP catalogue from the 18th SDS (useful in support to special operation, such as EOL or relocation) as well as on the orbital data posted to space-track by other operators (as for instance OneWeb);
- Capability to generate CDM based on the data collected by European tracking assets (good coverage currently is provided in GEO via optical means);
- Computation of PoC making use of an automatically computed azimuth dependent impact surface (based on a database delivered by EUMETSAT for each satellite);
- Computation, under the same assumptions, of the so called extended-PoC (worst case PoC when scaling the covariance for both objects in function of the observed changes in position across consecutive CDMs);
- Alarms provided to the satellite operator via e-mail and telephone in case of HRE detection (extended-PoC above a defined threshold), together with detailed reports delivered via a dedicated web portal;

- Expert support for design of the mitigation strategy; that includes CAM computation for complex cases with several risky events present on consecutive orbit and/or with different debris;
- Coordination among operators serviced by EUSST in case of conjunctions involving two operational satellites;
- Data relay between EUMETSAT and CARA (delivery of orbital information to EUSST in text format and further distribution after conversion to standard format).

In case of unavailability of the S3TOC support, backup support is ensured in hot redundancy by the French CA operation Centre (CAESAR, the CNES CA service).

2.4 Conjunction Analysis Data Flow

Figure 1 here below depicts the CA data flow for the Metop case, as described above in this chapter.

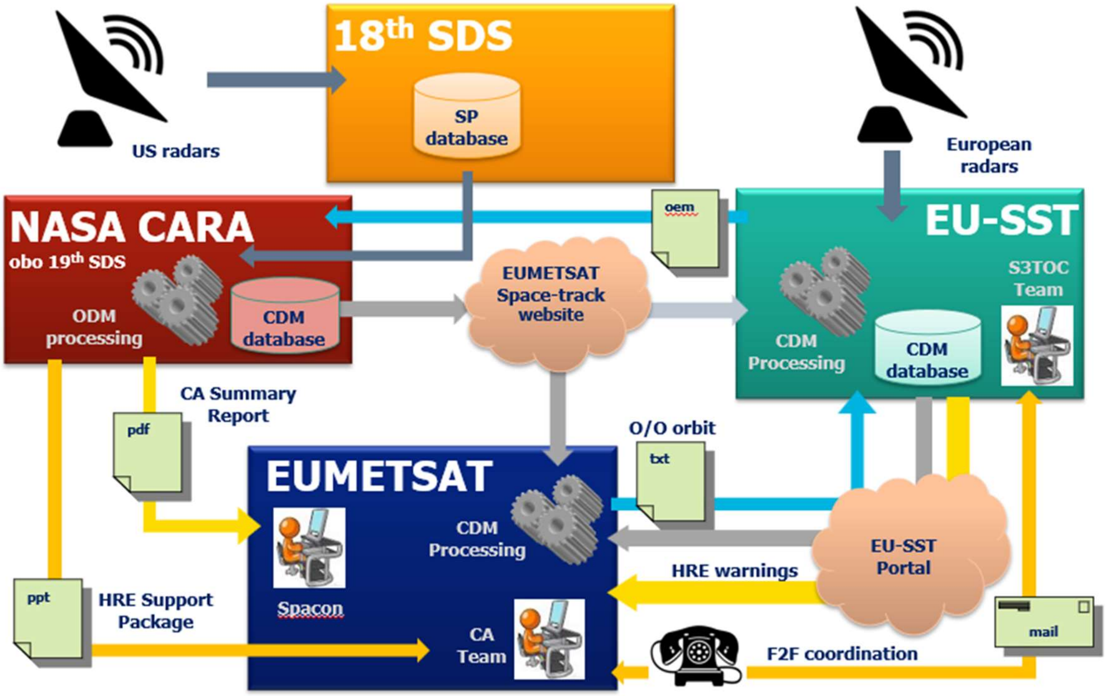


Fig. 1. CA data flow (Metop)

3. Conjunction Analysis Operations at EUMETSAT

Apart from the routine monitoring of CONANA results, CA operations are started by the FD team whenever a HRE event is detected, either by an external service provider or directly by the internal CONANA SW (most of the time by all of them); the Spacon can also trigger the process via the received CA Summary Report from CARA.

3.1 Conjunction Analysis Standard Operations

A conjunction is normally detected several days before the conjunction itself, as CDM generation span covers several days in the future (5 in LEO and 7 in GEO); whenever it is identified as HRE, which may then lead to the execution of a mitigation action, operations management is informed.

If the high risk is confirmed at around 24 hours before the event, an escalation meeting, involving satellite and ground operations management, takes place (possibly during working hours), in order to:

- Decide if the event really deserves mitigation;
- If that is the case, select the most adequate mitigation strategy (mainly, if it is better to wait, in the hope the risk vanishes, or to intervene as soon as possible);
- To select the optimal mitigation manoeuvre, in terms of execution time, size and direction, to mitigate the risk;

- Depending on the above and on the needed time to finalize the preparation and uplink of the manoeuvre, to select the last point in time where a final decision of executing the manoeuvre is taken (the so-called Go-No-Go time).

The escalation meeting can be brought forward to a working day if the risk (and the related mitigation) materializes during the weekend or a holiday period.

If the high risk is confirmed as requiring mitigation at the Go-No-Go time, and after formal endorsement of the operations management on a dedicated Authorisation to Proceed (ATP) meeting, a CAM is prepared in line with the decision taken at the escalation meeting (with size eventually adjusted to the latest received data), sent on-board (normally as late as possible, taking into account the opportunities available to contact the satellite and after proper evaluation of the resulting orbit versus possible future conjunction events by the external support providers) and executed.

3.2 Conjunction Analysis Compressed Operations

If the risk is detected only at the last minute (i.e. less than 22 hours before the event), then compressed operations have to be implemented:

- The Spacon calls in the FD engineer on duty (also during the night);
- The escalation meeting provides also the ATP for a CAM, if needed;
- If needed, the FD operation are streamlined by removing the manoeuvre optimization steps (a standard manoeuvre of 0.1 m/s half orbit before the event, considered sufficient to mitigate any risk by radial separation, is implemented); the need of a complete post manoeuvre orbit analysis may also be waived, if not enough time available (CONANA can perform it, even if not as accurate as the external support providers);
- The back-up pass, normally considered for uplink of the manoeuvre, can be removed;
- The thruster pre-heating time, required to ensure optimal execution, can be reduced in duration by more than 50%;
- The manoeuvre can be brought even closer to the event than half orbit (up to around one third of an orbit).

Last minute risk detection is normally due to a major solar storm, strongly affecting the orbital evolution of a light debris; even if such cases are quite unlikely, EUMETSAT had to make use of this process already several times, to mitigate risks reported less than 6 hours before the event, as reported in [5].

3.3 Conjunction Analysis Operations Timeline

Figure 2 here below depicts the CA operations timeline for the Metop case, as described above in this chapter.

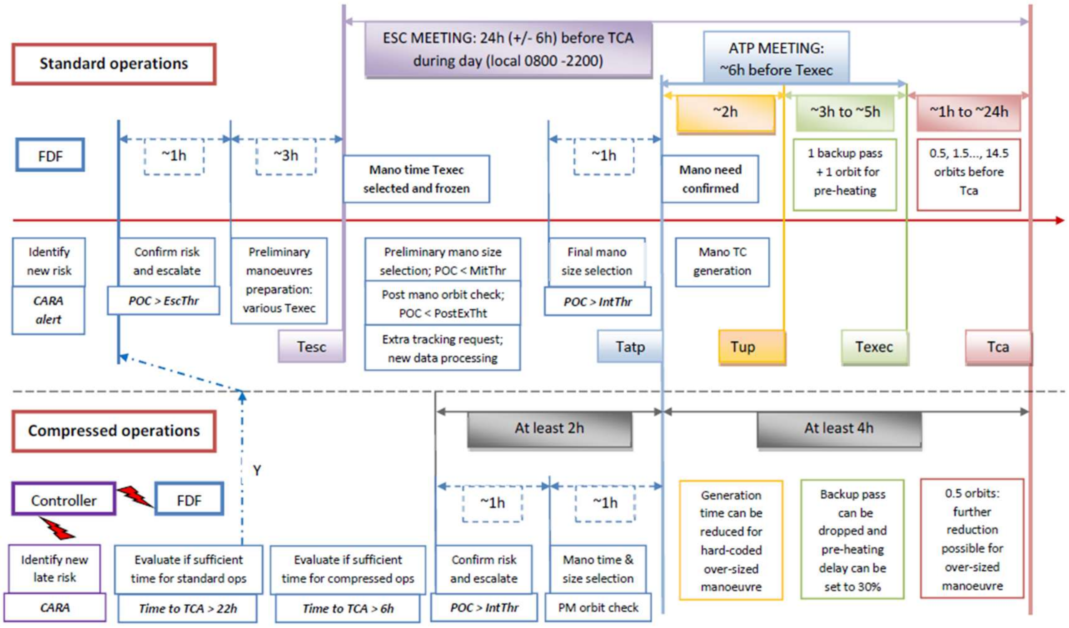


Fig. 2. CA timeline (Metop)

4. Operational lessons learned at EUMETSAT

4.1 Risk Detection

To reduce the number of false alarms (estimated risk higher than real, leading to unnecessary effort for mitigation) and, even more critically, to avoid missed conjunction detections (risk estimated lower than real, leading to an unacceptable not mitigated collision risk), it is important to perform a computation as accurate as possible of the actual PoC.

The elements having the largest importance in the final PoC computation are the combined impact surface (derived from the impact surface of the asset and, normally to a lesser degree, of the debris) and the combined covariance (derived from the covariance of the debris and normally, to a lesser degree, of the asset).

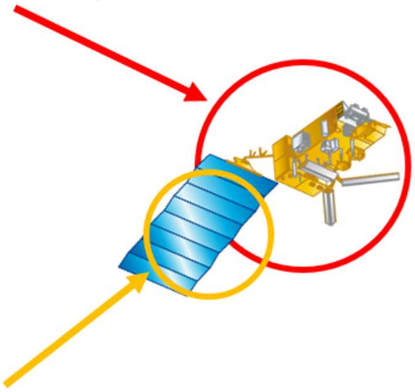


Fig. 3. Dependence of impact surface estimation from impact direction

To ensure an accurate estimation of the impact surface of the asset (normally overestimated, leading thus to false alarms) it is important to properly consider the impact direction and the attitude of the satellite in its orbital frame, as well as the orientation of the solar panel at TCA, as shown in figure 3. The estimation of the impact surface of the debris is in most of the cases less critical, since the size of the debris is normally much smaller than the one of the asset; in such a case, a rough estimation is normally enough.

A sufficiently good value can be derived either from the radar cross-section reported in the CDM (considering a proper amplification factor, as normally that value underestimates the real size) or from the reported covariance (a large value of the covariance implies bad observability and thus can be correlated with a small object). In case of large debris, their size is normally available in public databases, such as the ESA-DISCOS.

Even more important is to have accurate information of the covariance of the debris and of the asset (normally less important, mainly in case of a conjunction with a relatively small debris). For the debris, it is therefore important to ensure that the value reported in the CDM for the covariance is coherent with the observed data evolution.

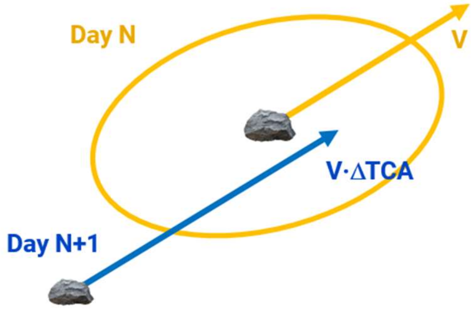


Fig. 4. Debris displacement in its orbital frame across consecutive updates

In other terms, we need to ensure that the changes observed in the state vector (SV) across consecutive updates (between day N and day N+1, both estimated at TCA for day N) are compatible with the covariance reported at day N, as illustrated in figure 4.

If that is not the case and large discrepancies are observed, an adjustment of the covariance of the debris to the observed changes in SV (applying an adequate scale factor) is recommended; the worst case PoC computed within the window of potential scale factors (defined extended-PoC, as mentioned in paragraph 2.3) shall be then considered.

The covariance of the asset can normally be derived from historical data; since that value is normally smaller than that for the debris, its impact in the final PoC computation is smaller

However, if the debris size, and thus its covariance, is comparable with the one of the asset, more care is needed, as an over-estimation of the covariance of the asset may lead not only to false alarms, but even to missed risk detections, due to dilution of risk caused by the large combined covariance. It is also important to consider in the estimation of the asset covariance the impact of the execution error of manoeuvres foreseen in the analysis arc (mainly for the post-manoeuvre assessment).

Before taking any decision on a risk mitigation it is necessary to ensure that the information used to compute the PoC is actually the actionable one; several cases were observed by EUMETSAT where that was not always clear:

- whenever the age of the last received CDM is far in the past (more than two days) it can be observed in the CARA report, described in paragraph 2.2, that, most of the time, the object had left the reporting volume (that happens above all during high solar activity); this can be verified making use of the SP catalogue (not available however to normal operators); therefore, CDMs older than two days are considered as not-actionable by EUMETSAT;
- sometime it can be observed that the date of the last observation on the latest delivered CDM is before the date of last observation on the previously delivered CDM; in other terms the latest delivered CDM does not consider the latest available observation; it is understood that this may happen whenever the latest observations are degraded and thus are rejected in the generation of the latest CDM; however it cannot be excluded that the latest observations were wrongly excluded from the generation of the latest CDM; in case of mismatch in the reported PoC between these two CDN, a possible way to select which one shall be trusted is to compute for both the PoC setting the MD to zero (the so called zero-MD PoC); as this value is expected to increase when the quality of the CDM increases, then the CDM with higher quality can be selected; alternatively, the CDM with highest risk shall be used for decision taking (ensuring however that a mitigation action mitigates also the risk represented by the other CDM);
- the PoC computed from the CDM based on the asset orbit estimated by the 18th SDS and estimated by EUMETSAT are sometimes significantly different: that is most of the time caused by a missing manoeuvre in the orbit from the 18th SDS, in which case it shall be discarded; however, sometimes the difference is present even in absence of any manoeuvre, and is simply caused by the difference in propagation models; as it is believed that the propagation models used by the 18th SDS are more accurate than the standard available to operators, their solution shall be thrusted if the TCA is far in the future; however, for short propagation the EUMETSAT solution shall be preferred, as the determination of the orbit is more accurate (based on GPS instead of radar measurements);
- few cases where observed when multiple conjunction events were reported with the same debris on consecutive orbits; while the risk may not be observable on any individual CDM, the aggregation of all individual risks together may be above the intervention threshold: how to compute correctly this aggregated risk is however not clear, as a large correlation among these events is present and therefore a standard summation of the PoC may not be adequate.

4.2 Risk Mitigation

For Metop, the operational rule to trigger a mitigation action (normally a CAM) is if the observed risk (computed normally as PoC, but in some cases as extended-PoC on a proper adjustment window, as mentioned above in paragraph 4.1) is above the so-called Intervention Threshold of 1E-4 (1 out of 10000).

However, initial activities in preparation of a potential mitigation, including the escalation to the management, start already when the risk gets above the so-called Escalation Threshold of 6.6E-5 (2/3 of the Intervention Threshold), as an increase of 50% in the risk on subsequent updates is considered normal.

Normally a mitigation action is not triggered as soon as a risk above the Intervention Threshold is identified, as the operational experience shows that most of the time a risk vanishes on its own when the debris covariance shrinks the closer we get to TCA, since the propagation arc between estimation time and TCA gets shorter (as depicted in figure 5). The operational baseline is therefore to wait as long as possible for a risk to vanish on its own.

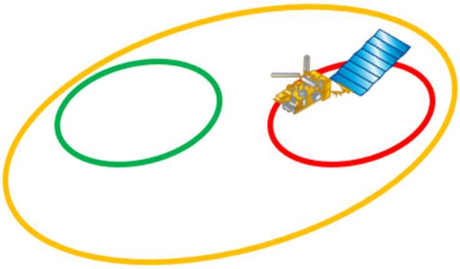


Fig. 5. Debris covariance shrinking on consecutive updates (yellow, initial covariance, red and green, potential updates)

On the other hand, it can be observed that the size of a CAM increases the closer it is executed to TCA, as the orbital dynamics has less time to build up a change in MD in the in-track direction; that is relevant only if the impact is not frontal, in which case a change in the in-track direction brings limited mitigation of the risk and an increase in radial separation is needed instead.

Therefore, the option to bring forward a CAM (above all for non-frontal cases, as above explained) deserves to be considered whenever:

- the impact on the orbit evolution is negligible; in other terms, if an early CAM can be used as routine orbit maintenance manoeuvre (the size of a late CAM is normally not compatible with that);
- the probability of receiving before TCA fresh information on the debris orbit is considered small (for instance if the next tracking opportunity reported by CARA is after the Go-No-Go time);

- the next day risk analysis (described in paragraph 2.1, and visualized in figure 6) shows a high probability of persistence of the high risk or even of a large increase (in that case an earlier manoeuvre may permit to save fuel);
- the impact on the satellite operations to wait before executing a CAM is high (if there is a potential conflict with other critical activities);
- the availability of the personnel for execution of a late CAM is limited (for instance if the CAM preparation would fall during a weekend or during the night).

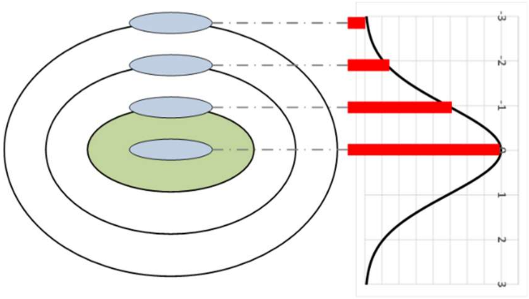


Fig. 6. Next Day Risk Analysis

The CAM size selection is such to achieve a reduction of the residual risk below 6.6E-6 (Mitigation Threshold, ten times more stringent than the Escalation Threshold). That target is considered robust even in case of an important change in the conjunction MD occurs between the time of uplink on-board and the actual TCA (event normally linked with an important solar event) or in case of a manoeuvre execution error significantly larger than the one assumed in the computation of the residual risk (resulting in a CAM significantly smaller than planned).

It is important to remark that this same Mitigation Threshold is considered not only for the event requiring mitigation, but for all events in the first day after the CAM, to exclude the need of any further intervention in that time window. For those events after the 24 hours a minimum mitigation target to 6.6E-5 (the Escalation Threshold) is also imposed, to avoid having to start an escalation the day after the execution of a CAM. These same rules are considered applicable not only for a CAM but for any orbital manoeuvre.

In case it is not possible to ensure compliance to these rules for all the events reported in the post CAM screening, scenario currently not observed very often (actually, only once by EUMETSAT) but expected to be more and more frequent in the future with the expected increase in number of objects in the catalogue (as described in paragraph 5.2), then two options are possible:

- select the solution providing the minimum total post event risk, cumulating the PoC derived from each individual event observed; this information can currently be provided by CARA;
- relax the Mitigation Threshold for those risk presenting the lower energy (the number of light debris is expected to increase with the increase of the on-ground detection capabilities), therefore having a lower likelihood to result into a catastrophic outcome, both in terms of impact on the mission itself (probability of losing the mission) and on the space environment (probability of creating a large cloud of debris).

When several options are available (normally, for Metop, it is possible either to implement a CAM in the flight direction or against it), the one minimizing the impact on the mission (i.e. requiring a minimum number of manoeuvres afterwards to re-start a nominal ground-track control cycle) is preferred; in case of late CAM execution however the direction maximising the radial separation is normally more efficient for risk mitigation.

Fuel is normally not considered as a major driver, as the cost of these manoeuvres is normally negligible in comparison with the yearly budget (~50 grams each CAM versus 16 kg per year of nominal fuel consumption).

4.3 Sentinel and Meteosat missions

The operations above described have been developed initially for Metop and then adapted for Sentinel (3 and 6) and Meteosat satellites; therefore, some adaptations have to be implemented to cope with the peculiarities of these missions:

- CARA is not providing any service for Sentinel-3 and Meteosat; therefore, CDMs are posted on Space-track for these missions directly by the 19th SDS;
- In order to ensure a satisfactory mitigation of the collision risk the Intervention Threshold for the Sentinel missions is set to 3E-5 (a factor 3 more conservative than for Metop); the same is done for all the other thresholds;
- The Sentinel missions present limited S-band access opportunities of only 2 passes per day (while Metop can be accessed once per orbit), with optional extra passes on request. It is therefore operationally recommended to upload a CAM with a certain anticipation (normally immediately after the escalation meeting) and use an optional pass to cancel it if before the event if no more needed (note that these platforms permit to suspend easily a manoeuvre on-board, while this operation is quite complex, and therefore not recommended, for Metop);

- The ground-track control band for the Sentinel missions is much smaller than for Metop (1km versus 5km); therefore, a CAM has normally to be executed as a double-burn, being a routine in-plane manoeuvre too small to be used as a CAM. On another hand, many OOP manoeuvres are needed for Sentinel-3 (none for Sentinel-6), which can then be used as a CAM (in that case the optimal execution time is 1/4 of an orbit before TCA, to build-up enough cross-track separation);
- Due to the large dilution of the risk density observed in GEO (very large covariance ellipsoids), the DoI is used as threshold for Escalation (DoI < 3), and geometrical criteria for Intervention (MD < 1.0km AND radial component < 0.5km) and Mitigation (MD < 20km);
- For GEO missions too it is possible to consider an OOP for risk mitigation (mainly for MTG, performing routinely an OOP every 6 weeks, while only one per year for MSG).

4.4 Special Operations

The efficacity of standard CA operations, based on PoC estimation, is at least questionable in case of special operations requiring very large manoeuvres, as for instance in case of EOL for a LEO satellite: due to the very large manoeuvre execution errors the post manoeuvre covariance of the asset increases so fast that, also for a conjunction resulting in a null MD (which means that a collision is expected in case of perfect execution of the manoeuvre and perfect propagation of the debris), the computation may provide a null PoC (the so called dilution problem).

Therefore, geometrical criteria, based on a minimum acceptable value of the MD, are preferred: the issue in that case is that, if all objects present in the database are considered, it is nearly impossible in LEO to find a compliant manoeuvre; that’s why only a limited subset, containing the operated satellites and the very large debris, is considered; that ensures mitigation of those risks with higher impact, as affecting another operator (diplomatic impact) and causing a catastrophic degradation of the environment (reputational impact).

In the case of Metop-A EOL, described in paragraph 7.1, the minimum MD to identify an HRE was set to 5 km and the subset of objects to analyse to all the operated satellites and to all object with a radius larger than 1 meter. EUSST was tasked to analyse the operational orbit provided daily by EUM, containing all the future planned manoeuvres, versus the SP catalogue to confirm the fulfilment of these conditions before proceeding the implementation.

For MSG-1 EOL, described in paragraph 7.2, a similar process was set-up, considering all objects available in GEO (as all objects visible at this distance are big enough to have a catastrophic impact) and 50 km of minimum MD (10 times larger than in LEO as the debris density is much lower in GEO).

A similar approach will be used for the post-launch phase of the next two satellites to be launched by EUMETSAT in the second half of 2025:

- for MTG-S1, the first sounder satellite of the Meteosat Third Generation (MTG) mission, to be launched by Space-X Falcon-9 in July 2025, the ascent trajectory up to separation is assessed by NASA; however, the first orbit afterward, and mainly the first perigee, needs also to be analysed before launch, as the satellite is not yet manoeuvrable up to the following apogee; also in this case EUSST will perform this analysis versus the reduced SP catalogue for each integer minute within the launch window; the minimum MD parameters to be taken into account are being consolidated by EUMETSAT, to ensure that something outside the exclusion volume for the nominal orbit cannot get to a zero MD (so a collision) under the nominal injection error conditions; a single set of values shall be enough, as the time spent around the perigee is small in comparison to the time from separation to perigee crossing. As the launch will be performed on a super-synchronous inclined orbit, no interference is expected with objects close to the GEO ring, which therefore do not need to be taken into account. All the minutes in the launch window when no violation is identified are then flagged as acceptable for launch by EUMETSAT.
- for EPS-SG-A1, the first satellite of the EPS Second Generation (EPS-SG) mission, to be launched by Ariane-6 in August 2025, the ascent trajectory up to separation is assessed by CNES; however, also in this case it is necessary to have analysed the orbit after separation up to when the satellite is expected to be manoeuvrable (around 7 orbits); also in this case EUSST will perform this analysis versus the SP catalogue for the nominal launch time; to minimize the risk of having to postpone by one day the launch in case a no-go condition is detected, the analysis shall be repeated also for an anticipated and a delayed launch time by around 5 seconds, enough to ensure the conjunction is solved, but as less as possible to minimise the impact on the post separation LTAN; the minimum acceptable MD parameters are being consolidated by EUMETSAT with a similar approach as for MTG, taking into account however that these value increase in time significantly orbit after orbit.

The final approach, to be followed for all further foreseen launches of EUMETSAT satellites, will be derived from the lessons learned acquired during the execution of the operations above described.

5. Future Evolutions

5.1 Evolution of accuracy of debris orbits

Since 2020 the new US space-fence entered operations; this enhanced observation capability was expected to increase in a significant manner the accuracy of the debris available in the catalogue. The impact can be observed in figure 7, where the along-track covariance of all objects reported in CDM received for Metop is plotted versus the time to TCA on 2019, 2020 and 2024; from the first two plots it can be observed that the accuracy of the tracked objects improved clearly thanks to the enhanced observability, with an important reduction of objects remaining badly determined close to TCA. That results in a simplification of the CA operations, as a reduction of the covariance when approaching the event permits better to determine if a risk deserves being mitigated or not.

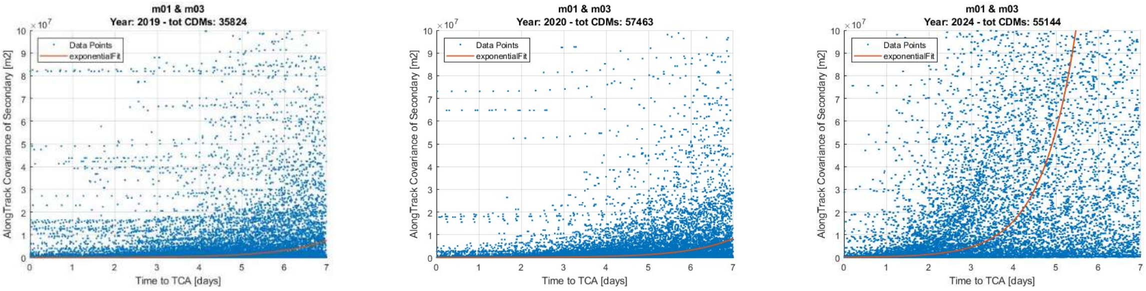


Fig. 7. Along-track covariance versus time to TCA in 2019 (left), 2020 (centre), 2024 (right)

Looking however at the result for 2024, an important degradation of the quality of the orbit determined for the considered objects can be appreciated; a correlation with the increase in solar activity is considered to be the cause of that, as a higher solar activity implies a bigger uncertainty in the atmospheric density, impacting the propagation accuracy and thus resulting in a larger covariance at TCA; the benefit of the new US space-fence is still observable, as covariances still converge the closer we get to TCA, but much later, as shown by the exponential fit.

CA operations become therefore more challenging, as a reliable estimation of the covariance for the debris, permitting take action on the event, is achieved much later, leading often to the need of compressed operations.

Worth to observe that the relative evolution of the covariance versus TCE (in terms of reduction with respect to an initial reference, taken at around 5 days from TCE) is to a certain extent systematic as shown in figure 8.

The covariance decreases by a factor 1000 in the 5 days with a dispersion of around 1 order of magnitude, which corresponds to a daily reduction of around a factor 4 with a 50% of dispersion; these values are taken into account to implement the next day risk analysis procedure described in paragraph 4.2.

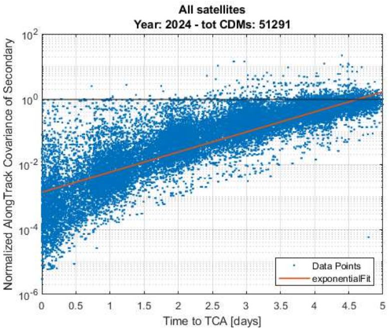


Fig. 8. Relative evolution of the along-track covariance versus time to TCA

5.2 Increase of number of tracked debris

Another expected consequence of the entrance in operations of the new US space-fence was a very large increase of catalogued objects leading to an equivalent important increase of events and thus of HRE; moreover, it was expected that these new objects, being smaller, would have been less observable and more difficult to propagate accurately, leading to significantly larger covariances, with increased operational complexity.

However, this large increase of objects did not really materialise, nor the degradation in accuracy.

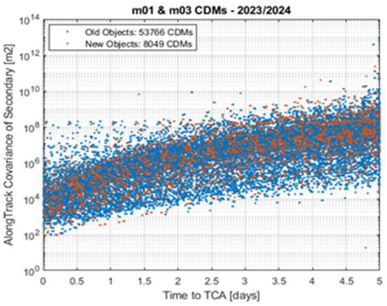


Fig. 9. Along-track covariance evolution for new (red) and old (blue) objects

That is shown in figure 9, where the evolution of the covariance versus TCA is presented for all objects observed in all CDM received in 2023 and 2024, differentiating between those included in the catalogue before (old objects, in blue) and after (new objects, in red) beginning of 2020, when the new US space-fence entered operations.

Nearly 1500 events have been observed in these 2 years; around 15% of those can be related with new objects. In terms of covariance evolution, no statistically significant difference can be observed. The impact on operations is therefore still quite moderate.

5.3 Increase of number of missions

The increase of number of missions has multiple impacts on EUMETSAT CA operations: on one side, the increase of the number and type (with the introduction of low-thrust satellites to the fleet) of satellites to be operated will imply a proportional increase of operational workload for CA activities; on another, the presence of many more satellites, mainly those belonging to the mega-constellation being currently deployed (Starlink and OneWeb) and planned to be in the near future (such as Amazon Kuiper and the Chinese Guowang and Qianfan), will cause an exponential increase of the number of events involving two operated satellites.

While the CA operations here presented are fully adequate for debris conjunctions and can easily expanded for future missions (CONANA is designed as a multi-mission element and thus scalable by design; with some evolution that may be needed to cope with low-thrust operations), significant adaptations may be needed to cope with conjunctions with operated satellites; initial experiences in this directions are presented later in chapter 0.

5.4 Evolution of standards

As mentioned in chapter 1, EUMETSAT operations are currently full in line with the applicable ISO standards as well as with the UN Space Debris Mitigation Guideline. However, these standards and guidelines are continuously evolving, which may imply the need to adjust the CA operations to increase compliance.

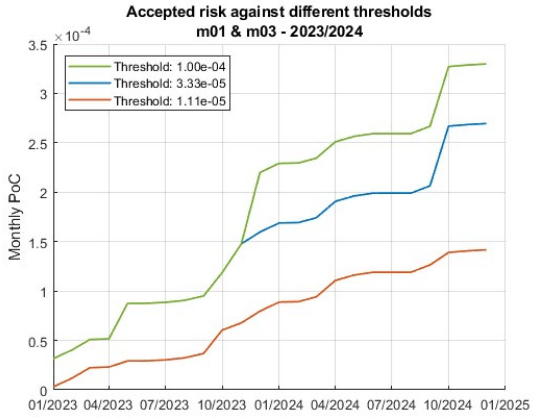
To make an example, in the latest years the concept of ensuring that the residual risk with known debris is kept controlled below a certain threshold during the mission execution is taking momentum in the Space Debris community. Depending on the agreed threshold, that may lead, together with the expected increase of tracked objects mentioned in paragraph 5.2, to an increase of number of CAM required, and thus to the operational workload.

To verify the efficacity of its CA strategy EUMETSAT performs a continuous monitoring of the residual accepted collision risk, computed as accumulation of each not mitigated individual risk (PoC) derived from last received CDM for each event; if the last CDM is older than 2 days it is assumed that the object had left the monitoring window, as explained in paragraph 4.1, and the related risk is set to zero.

The evolution in the last two years, during which all HRE with PoC above an Intervention Threshold of 10E-4, have been mitigated, is presented in figure 10.

It can be observed that the execution of 6 CAM permitted to mitigate nearly 95% of the total observed risk of nearly 0.6%, leaving not mitigated a residual risk of less that 1E-4 per satellite per year in average.

If a better mitigation is required (e.g. reducing by a factor 2 the level of residual accepted risk), it is necessary to reduce the intervention threshold by one order of magnitude, which would result in more than the double of number of CAM.



m01 & m03 - Risk 2023/2024						
Threshold	CAMs	Observed	Mitigated		Accepted	
1.00E-04	6	5.97E-03	5.64E-03	94.47%	3.30E-04	5.53%
3.33E-05	7	5.97E-03	5.70E-03	95.48%	2.70E-04	4.52%
1.11E-05	13	5.97E-03	5.82E-03	97.62%	1.42E-04	2.38%

Fig. 10. Accepted risk for Metop mission

6. Management of conjunction with operated Satellite

6.1 Summary of operational cases

During the last years EUMETSAT was involved in several cases of conjunctions with satellites operated by other operators, which permitted to acquire a certain level of experience on these topics:

- HRE between Metop-A and RESOURCESAT-2A, operated by ISRO, on 21 April 2021: the event was identified when assessing the post manoeuvre orbit resulting from a CAM being planned by EUMETSAT; ISRO, after having been contacted, reported that a routine manoeuvre for their satellite was planned for the same date; coordination was needed to ensure that the CAM of EUMETSAT, anticipated by 6 hours, was safe with respect to RESOURCESAT-2A; the post-CAM orbit was then provided to ISRO who could safely execute their manoeuvre, postponed by 6 hours, taking this information into account.
- HRE between Metop-C and JPSS-2, operated by NOAA, on 22 November 2022: the event was identified when assessing the post manoeuvre orbit resulting from a CAM being planned by EUMETSAT; as the satellite was still in commissioning (having been launched 2 weeks before) no regular provision of orbital data to EUMETSAT was implemented yet; NOAA provided EUMETSAT with their latest estimated orbit, which confirmed that the observed risk was on truth a false alarm, linked to the still pour tracking on their satellite.
- HRE between Metop-C and RESOURCESAT-2 on 7 June 2023; the event was identified five days before the TCA; ISRO, after having been contacted, reported that a routine manoeuvre for their satellite was planned two days before TCA and could be used to mitigate the risk; post manoeuvre orbital information provided to EUMETSAT confirmed that.
- HRE between Sentinel-3B and Shiyan-20C, classified, operated by an unknown Chinese operator, on 9 September 2023; the event was identified two days before the TCA; as no point of contact was available, pertinent information was provided to the Chinese representative in the committee of the International Symposium on Space Flight Dynamics (ISSFD); a CAM was prepared by EUM but never executed, as a sudden risk reduction was observed before uplink; a-posteriori analyses could demonstrate that Shiyan-20C was manoeuvred away.
- HRE between Sentinel-3B and (again) Shiyan-20C on 31 January 2024; the event was identified five days before the TCA and disappeared the day after, as Shiyan-20C was manoeuvred away before any internal escalation or attempt of coordination was needed.
- HRE between METOP-B and WSF-M, operated by US Department of Defence, on 9 August 2024; the event was identified four days before the TCA and disappeared the day after, as WSF-M was manoeuvred away before any internal escalation or attempt of coordination was needed.
- HRE between Sentinel-3A and GJZ-02, classified, operated by the China Aerospace Corporation, on 12 February 2025; the event was identified four days before the TCA and disappeared the day after, as GJZ-02 was manoeuvred away before any internal escalation or attempt of coordination was needed.

6.2 Lessons learned and on-going activities

For events involving partner organisations, as NOAA and ISRO, the main issue was the late identification of the risk, reducing the time available for a bilateral discussion; this kind of risks are normally identified only quite close to the TCA, as the algorithms defined for debris are used; improvement on this direction should be possible by improving the used algorithms (e.g. geometrical detection) and making proper usage of orbits provided by the operators themselves. Once the risk was detected, it was relatively simple to initiate a bilateral discussion leading first to the confirmation of the need of mitigating it and then to the definition of an agreed mitigation plan.

The same cannot be said for the cases involving a Chinese satellite; the main difficulty in these cases is, once the risk identified and flagged as deserving mitigation, to start a communication with the operator, as no point of contact is available in the space-track repository; without knowing what the other satellite is doing it is difficult even to proceed with a mitigation, which may be either useless or even leading to a more risky situation (e.g. if both operators implements the same mitigation).

As EUMETSAT belongs to the committee of the ISSFD a message can be sent in these cases to the Chinese representative in the committee, who at least can ensure that some basic information is passed over to the correct operational team, even if normally no feedback is received. Another potential communication channel with Chinese operators could be implemented via the Coordination Group for Meteorological Satellites (CGMS), to which EUMETSAT belongs; discussions are ongoing within the group to better define what could be achieved in this way.

Several HRE were also observed with OneWeb satellites; in these cases, however, the risk normally disappears the day after its appearance, well before any action is needed from EUMETSAT side, as OneWeb takes care of modifying the manoeuvre plan of the involved satellite (as in ascending phase when crossing EUMETSAT operational orbits) to implement a quite large, and thus safe, separation.

This same behaviour, to disappear as soon they are involved in a conjunction, was also observed several times in the last couple of years, for events involving classified Chinese satellites, as well as with a satellite operated by US Department of Defence.

6.3 Contribution to Space Traffic Management initiatives

As it can be seen, many of these cases could be handled individually through direct interaction with the concerned operators and a face-to-face discussion; however, that may not be always possible (e.g. one operator may refuse to accept the risk as deserving mitigation and therefore consider a waste of time the definition of a joint mitigation plan) and a more consolidated framework for STM seems necessary.

Currently EUMETSAT is supporting several activities in the STM frame, either triggered by the European Commission (as expert operator) or as part of the activities of the Coordination Group for Meteorological Satellites (CGMS, to which EUMETSAT belongs).

The goal of these activities is to define the operational approach to be followed in cases of conjunctions involving two operated satellites; several factors are taken into account to define which operator, once the risk properly identified (as reported above, there are still margins of improvement) and once agreed that the situation requires mitigation (not always trivial, as not all operators have the same appreciation of the risk, as above mentioned), shall be responsible for the implementation of the needed operation:

- manoeuvrability: if only one of the two satellites is not manoeuvrable, it is expected that the operator of the other satellite assumes the responsibility; however, to define if a satellite is actually manoeuvrable is not a trivial activity, as low thrust solutions may not provide enough acceleration for an efficient mitigation;
- mission type: it is current practice that constellations (such as Starling and OneWeb) take care of adjusting their routine manoeuvring plan to keep safe distance from other operated satellites, as reported in paragraph 6.2;
- mission phase: to implement a mitigation action for a satellite in routine operations may represent a service disruption; therefore, if one of the two satellites is on a different mission phase, not providing any service (e.g. relocation, backup), it is expected to take over the responsibility;
- mission goal: institutional satellites, as providing public services (for instance meteorological observations) shall be given priority versus commercial satellite, which shall implement the mitigation; that is standard practice in on Earth, where a private car is not expected to be driven on traffic lines reserved to public transportation;
- data sharing: whoever is not willing to share their data to permit another operator to define a mitigation action, is expected to take responsibility of implementing the mitigation (as observed in paragraph 6.2, it seems already to be the case).

Of course, coordination among the operators is needed before any action is taken, on one side to avoid that both operators perform a mitigation manoeuvre, which may result in a further conjunction, on another as the operator having priority may decide to take over the responsibility, as able to perform the mitigation as part of a routine operation.

It is also very important to ensure that, whenever orbits generated by the operators are used in the risk analysis, these are based on compatible drag models; differences in the decay rate may result in important difference of the radial distance at TCA, causing quite large changes in the estimated PoC, which may lead to either false alarms or even to missed detections; as normally operators have a quite accurate knowledge of the current position of their assets, but limited propagation capabilities, the availability of a certified service ensuring optimal propagation based on the latest most accurate models for atmospheric density would be quite welcome (EUMETSAT already proposed this solution to the 18th SDS, the current provider of SP orbital solutions).

7. End of life approach in EUMETSAT: past activities

Since its creation in 1986 EUMETSAT took care of ensuring proper EOL operations for all its satellites. In particular, all satellites of the METEOSAT first generation were successfully de-orbited fully in line with the applicable international recommendation:

- Meteosat-2 in 1991 to an altitude above GEO of around 440 km
- Meteosat-3 in 1995 to an altitude above GEO of around 960 km
- Meteosat-4 in 1996 to an altitude above GEO of around 910 km

- Meteosat-5 in 2007 to an altitude above GEO of around 520 km
- Meteosat-6 in 2011 to an altitude above GEO of around 360 km
- Meteosat-7 in 2017 to an altitude above GEO of around 560 km

In the last years also the first LEO satellite operated by EUMETSAT, Metop-A, and the first Meteosat satellite of the second generation, MSG-1, also known as Meteosat-8, have been removed from their operational orbit, also fully in line with the applicable international recommendations; a brief summary of these operations is presented in the remaining of this chapter.

7.1 Metop-A EOL operations

Metop-A was launched in 2006 and its orbital plane was actively controlled till 2016, date when the last Out-of-Plane (OOP) manoeuvre, needed for inclination correction, was executed; no further OOP manoeuvre was possible afterwards as the remaining fuel (around 50% of the initially loaded on the satellite) was reserved for EOL operations.

The decision to bring to the end the operational phase of Metop-A in 2021 was due to the resulting very large drift in Local Time of Ascending Node (LTAN) of nearly two hours, which would have brought the satellite above 70 degrees the angle between the orbital normal and the Sun direction, the so-called beta angle (as shown in figure 11), and therefore in marginal thermal conditions, dangerous for the propulsion system (as described in details in [6]).

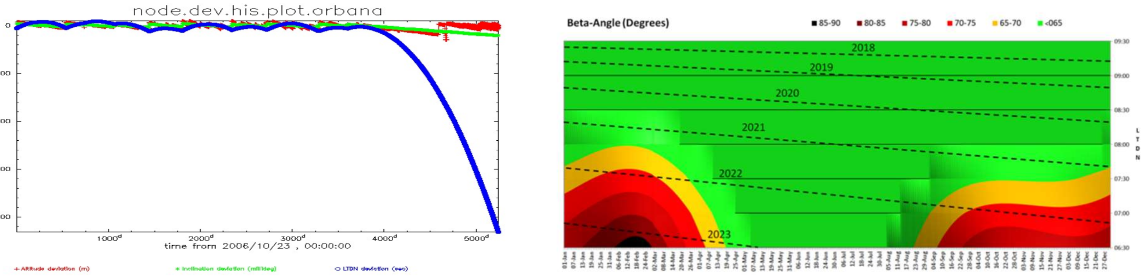


Fig. 11. Evolution of LTAN during Metop-A mission (left) and related evolution of beta-angle (right)

The target for the EOL operation was an elliptical orbit with low perigee, permitting to re-enter the atmosphere within 25 years with 90% of confidence; at the same it was necessary to reduce the apogee below the perigee of the other Metop operational satellites, to avoid any future risk of collision.

To achieve at the same time both these targets the orbital altitude was reduce through 15 very large (with a duration of around 18 minutes) anti-velocity manoeuvres at the north pole, forcing the perigee at the south pole (more efficient in terms of re-entry time and ensuring better visibility conditions from the ground stations in Svalbard) and, at the same time, reducing sufficiently the apogee altitude at the north pole, thanks to the dispersion of the manoeuvres around the apogee.

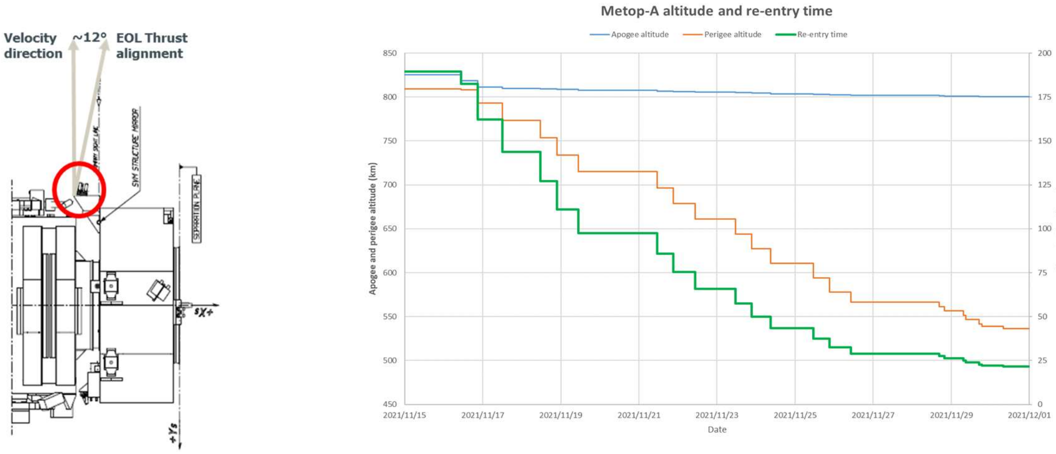


Fig. 12. Thrusters alignment on Metop-A (left) and orbital parameters and fuel evolution during EOL (right)

In order to further increase the efficiency of the manoeuvres, the large misalignment of the thrusters (12 degrees, as shown in figure 12/left) to the anti-velocity direction was corrected via a yaw bias of 8 degrees (sufficient to reduce the correlated fuel penalty, of more than 2%, by around the 90%).

Once executed these manoeuvres, the achieved orbit was nearly compliant with the EOL target of 25 years; the remaining fuel was spent through a series of long thrusts fully in visibility, to be able to passivate the satellite whenever fuel exhaustion was detected in telemetry; 8 of such thrusts were executed (the last only partially, before divergence of the platform due to thrust imbalance), permitting to achieve a final orbit with less than 22 year of re-entry time (as can be observed in figure 12/right).

The actual EOL operations were carried-out between15 November and 01 December 2021; more details can be found in [7]

7.2 MSG-1 EOL operations

MSG-1 was launched in 2002 and its inclination was actively controlled till 2010, date when the last correction was executed; no further inclination maintenance was possible, leading to a constant drift of the inclination reaching the value of 8 degrees in 2022; in order to avoid further degradation of the images (due to the north-south displacement of the satellite sub-satellite point with respect to the optimal equatorial location) and as MSG-2 had already taken over the MSG-1 service over the Indian Ocean, the decision was taken to being to an end the operational phase of MSG-1.

The target for the EOL operations was to achieve an orbit at least 245 km above the GEO ring; however, as the reliability of the tangential thruster (designed to execute in-plane manoeuvres and thus to carry out the EOL operations) was too low, due to the unavailability of the back-up chain, it was necessary to ensure compliance also using, as back-up solution, the axial thrusters (designed to execute out-of-plane manoeuvres, as depicted in figure 13/left); a back-up strategy, foreseeing to align the axial thruster to the anti-velocity direction via a 30 degrees slew before each burn, was therefore prepared; this strategy (shown in figure 13/right), however, much less efficient than the nominal (due to the thrust not properly aligned to the orbital plane and to the cost for the slew), required to reserve around three times more fuel than the nominal one.

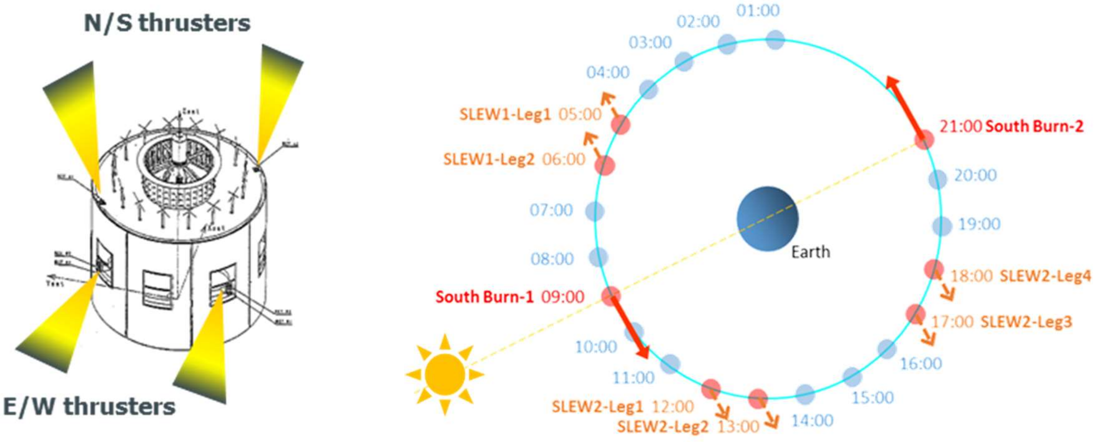


Fig. 13. Tangential (E/W) and axial (N/S) thrusters mounting on MSG-1 (left) and back-up EOL strategy (right)

This extra fuel could be used to achieve a second target to reduce significantly the spin of the satellite (from the operational 100 revolutions per minute to 20), in line with recommendation to reduce ad much as possible the on-board stored energy.

Therefore, two initial large burns were executed with both tangential thrusters, generating a large altitude change, sufficient to achieve very fast the minimum altitude required, but no spin reduction. Afterwards, 7 thrusts were executed making use of only one tangential thruster, permitting to further increase the altitude and at the same time to reduce the spin, as shown in figure 14/right.

Finally, once the target spin achieved, the remaining fuel was spent through two further burns with both tangential thrusters, permitting to achieve a final altitude above the GEO ring of more than 600km; the last residuals were expulsed with a final burn with the axial thruster; the overall strategy is presented in figure 14/left here below.

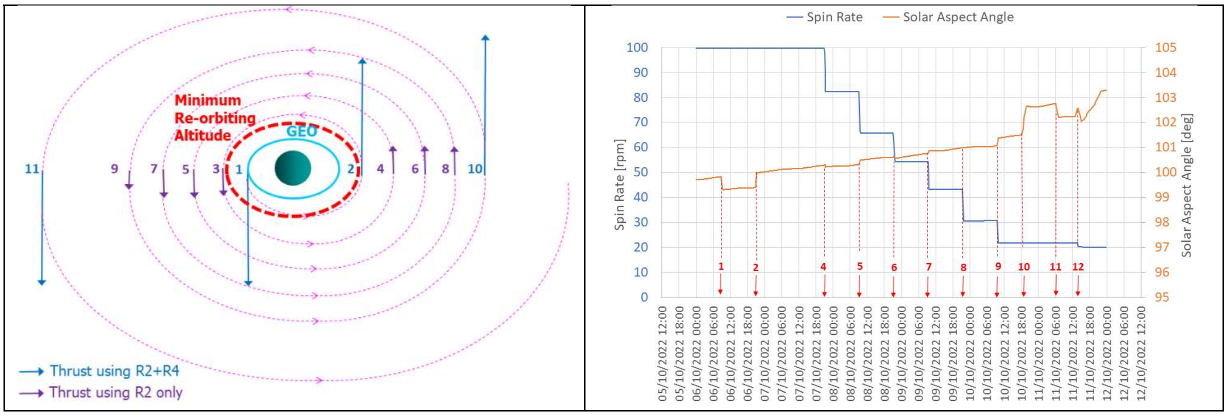


Fig. 14. EOL strategy for MSG-1 (left) and spin parameters evolution (right)

The actual operations were executed between the 6 and 12 October 2022; more details can be found in [8].

8. End of life approach in EUMETSAT – future activities

EUMETSAT is preparing EOL operations for its entire fleet; operations for next Metop and Meteosat satellites will be based on the experience acquired with the first satellite of each family. For other missions currently being operated, namely S3 and S6, preliminary analyses have been carried out, showing that, due to the very large amount of fuel on board, it could be possible to implement even a faster re-entry than the currently required 25 years; as international recommendation are evolving toward reducing the re-entry time to 5 years, that is a good trump in the hands of EUMETSAT.

Regarding the new generation of EPS, EPS-SG, a controlled re-entry strategy was selected, which at the same time minimises the time in orbit after end of mission and ensures reduction of the on-ground casualty risk.

8.1 Sentinel-3 EOL preliminary analysis

In the frame of the last regular lifetime review for the Sentinel-3 mission (currently implemented via two satellites, Sentinel-3A and 3B, launched respectively in 2016 And 2018, being the launch of the third satellite, 3C, foreseen in 2026) a preliminary operations plan was drafted to demonstrate feasibility of EOL operations with both the nominal and the backup thrusters and identify the amount of fuel still usable for routine operations (and thus the maximum residual lifetime).

One of the main differences of the Sentinel-3 satellites with respect to the Metop ones is the much lower propulsive force (less than 1/10 at EOL); being the Sentinel-3 satellites mass around one third of the one of Metop, that leads to the need of a much larger propulsion time (nearly 4 times more) to achieve an orbit satisfying the same target re-entry times of 25 years.

Considering a maximum thrust duration for each burn of 30 minutes, to maintain the spreading losses acceptable, around 40 burns are needed to achieve the target EOL orbit using the nominal thrusters; however, being the reliability of the nominal thrusters not sufficient to ensure their availability at end of mission to execute the EOL operations, it is necessary to reserve enough fuel to be able to achieve the target orbit also with the backup ones.

While on Metop the nominal and backup thrusters have nearly exactly the same mounting, so the same efficiency, that is not true for Sentinel-3. Only the nominal thrusters are well aligned with the anti-velocity direction, ideal for EOL operations; the back-up ones are aligned with the velocity direction and presents a very large canting angle; therefore, if these have to be used for EOL operations, a slew of 180 degrees needs to be performed before each burn and an important fuel penalty (of around the 35%) has to be taken into account due to the canting; as a consequence the number of burns to be executed raises to around 60.

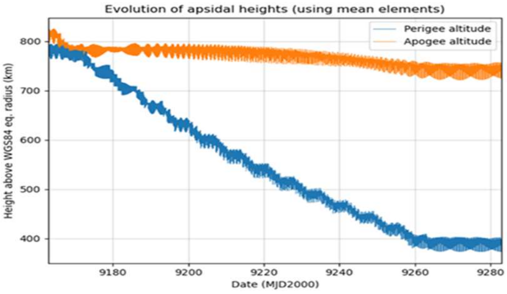


Fig. 15. Orbit evolution during EOL for Sentinel-3

It can be observed that, if the fuel reserved for EOL operations with backup thruster is used with the nominal thrusters, a much lower orbit can be reached (as shown in figure 15) leading to a re-entry time close to 5 years; it is still to be analysed, however, if the large torques expected at this very low perigee (at around 400 km) is sustainable by the platform attitude control system.

It is worth pointing out that, even if this latter approach is taken, the fuel available on bord shall still permit to further operate the Sentinel-3A and 3B satellites until 2037, way longer than the nominal 12 years of mission. The easiest approach to implement these operations would be to make use of the routine manoeuvring procedure, thus implementing one manoeuvre per working day; that would requires however very long operations of nearly three months; to increase the manoeuvring rate to two burns per day should be relatively simple, just adapting the CAM procedure presented in paragraph 4.3; that would already reduce the overall duration of the operations to a more acceptable value of one month, if working also during the weekend. Further reductions are also possible: implementing four manoeuvres per day would permit the operations to be carried out in a couple of weeks, or even in only one, if double burns are implemented, but it may require an important re-design of the satellite operations.

8.2 Sentinel-6 EOL preliminary analysis

Also for the Sentinel-6 mission (currently implemented via the satellite Sentinel-6A, being the launch of the second satellite, 6B, foreseen in last quarter of 2025) some preliminary computations were performed to evaluate various options for the EOL operations.

The main differences of the Sentinel-6 satellites with respect to the Metop and the Sentinel-3 ones is that the orbit not sun-synchronous, therefore it is not necessary to control its inclination; moreover, the altitude of Sentine-6 is significantly higher than the one of the other two missions, making its orbit much less subject to atmospheric drag.

Those elements, together with the quite large amount of fuel still available and the relatively light weight of the satellite, make it possible to implement a practically infinite mission duration (being the yearly consumption negligible) and still to be fully compliant with the EOL recommendation even selecting a circular orbit as target.

By implementing around 50 manoeuvres of a bit more than 20 minutes (executed alternatively at apogee and perigee) a circular orbit well below 600 km can be reached, as shown in figure 16/left; that results in a re-entry time lower than 20 years.

Alternatively, it is possible to achieve an elliptical orbit with perigee below 300 km by executing the last third of the manoeuvres at the apogee, as presented in figure 16/right; the resulting re-entry time is then below 5 years.

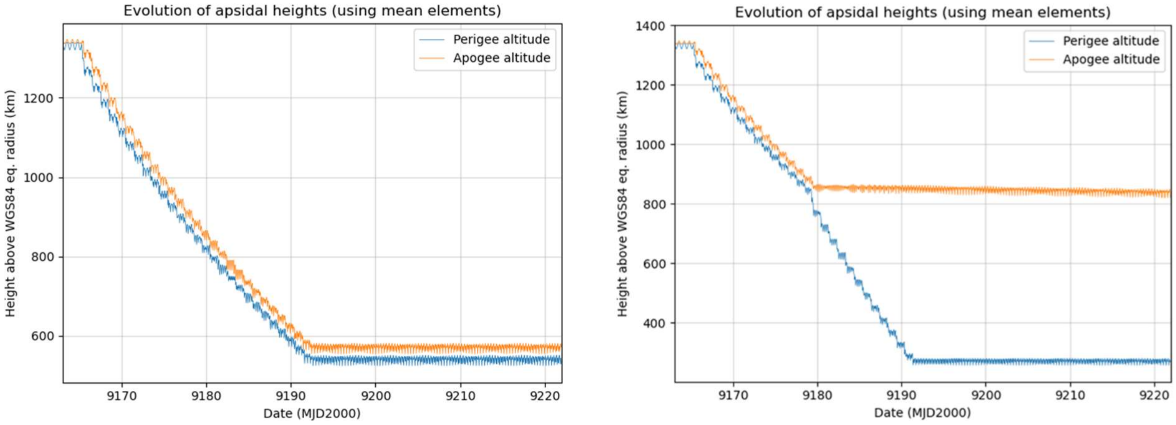


Fig. 16. EOL options for Sentinel-6: circular (left) and elliptical (right)

Comparing both solutions, even if the second one presents a shorter re-entry time and a lower probability of collision, and thus fragmentation, during re-entry, probably the second should be preferred in terms of long term space sustainability, as presenting a shorter dwelling time in the high density orbital shell between 700 and 900 km; in case of collision in this shell leading to fragmentation (possible only if the second solution is selected), then the impact on the environment caused by the generated debris is probably much larger than if a collision happens on a circular orbit below 600 km.

8.3 EPS-SG EOL preliminary operations

For the second generation of LEO satellites, named EPS-SG, planned to be launched in the second half of 2025, the decision was taken at design level to rely on a controlled re-entry strategy, to mitigate the casualty risk posed by the very massive satellite (a similar problem is present for the first generation and is addressed in paragraph 9.1); that required the integration of a dedicated very high thrust engine to perform the final re-entry burn.

The operational concept developed during the design is the following: after having freed the operational orbit with the nominal thrusters (via a Homan transfer), the perigee is lowered to 400 km with two burns of the very high thrust engine; afterwards a final 30 minutes burn, mostly in visibility, is executed with the very high thrust engine, to implement the controlled re-entry over the South Pacific Ocean Unmanned Area (SPOUA), as described in figure 17.

In case of not availability of the high thrust engine, the perigee is lowered with the nominal thrusters to 250 km and then the final burn is implemented using together the nominal and the back-up thrusters (having similar mounting).

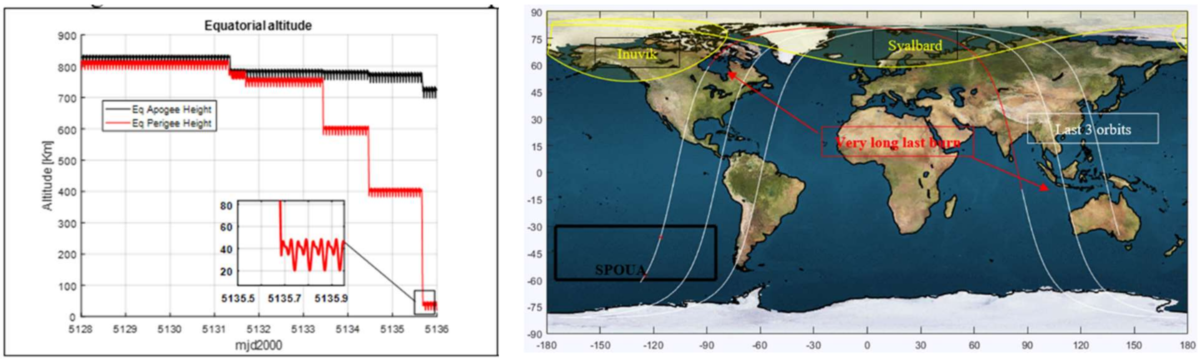


Fig. 17. Orbit evolution during EOL for EPS-SG (left) and detailed view of final burn (right)

More details can be found in [9].

9. End of life approach in EUMETSAT: options from new technologies

In the last years new technologies started being developed, to provide end-of life support to defunct satellites or in-orbit service to operational satellites. EUMETSAT started therefore looking with interest in this direction to evaluate if these could provide interesting options on one side to improve the way EOL operations are carried out, on another to further optimise the lifetime of its assets; at the end, to increase the lifetime of satellites has a positive impact not only in terms of return of services, but also for space sustainability, as less objects need to be deployed to ensure the continuity of these services; of course, due care is needed to ensure that, in any case, the satellite are properly removed from their operational orbit at the end of their life.

9.1 Active removal for Metop

As explained in paragraph 7.1, Metop-A was deorbited in 2021 and is expected to re-enter the atmosphere between 2040 and 2045; however, due to the large mass of the satellite, the size of the expected footprint on ground of the re-entering debris is very large, leading to a casualty probability well above (more than 7 time larger than) the maximum of 10-4 appearing in the international recommendations: that pose a potential liability issue on EUMETSAT, which would be better to have solved.

Moreover, due to the large size of the satellite, the risk of collision during the relatively long re-entry phase is quite high too, also in this case well above the target of 1E-3 currently considered as adequate (and expected to become standard in the future) by the space community to ensure long term space sustainability. In case of a catastrophic collision the satellite may become source of a debris cloud causing a significant degradation of the orbital environment with a corresponding increase in risk of secondary collisions and related fragmentations (which is the mechanism of the well-known Kessler syndrome). Also in this case, a potential reputational impact on EUMETSAT is clear, deserving due attention. It is important to remember that these have been the main arguments leading to the decision of implementing a direct re-entry strategy for EPS-SG, as described in paragraph 8.3.

Therefore, in the last years EUMETSAT have been looking at solutions which could permit to tackle at the same time the two issues above described; that led to the decision to start assessing the level of technological maturity of the space market in providing Active Debris Removal (ADR) services; such a service foresees a servicer spacecraft capturing the target object (normally a defunct satellite, but could even be a still active one) and bringing it into a trajectory re-entering on Earth in a safe manner (normally, in the SPOUA).

Another not negligible benefit of an ADR mission is that it permits to extend a mission even in case a major failure, reducing the satellite reliability for EOL operation below the 90% value dictated by the international recommendation, is suffered; normally such an event would imply a mission termination; however, even if the satellite itself is no more able to perform autonomously EOL operations, these can still be carried out by the ARD service; de facto, operation to failure becomes an option, with a large potential increase of the mission return (as no fuel has to be reserved for EOL operations, nominal operations can be carried out for basically the double of the nominal duration, as further discussed in paragraph 9.2) as well as clear benefit in terms of space sustainability (as explained above, in the introduction to this chapter); therefore, this technology, initially considered for the defunct Metop-A, becomes attractive also for the still operated Metop-B and C satellites.

Currently several space companies are working to develop the technologies required for active removal mission; the first operational demonstration mission is expected within few years. On another hand also ESA is quite interested in this topic, as it would permit to remove from space the ticking bomb represented by ENVISAT, which was lost in orbit in 2012.

EUMETSAT has discussed the concept with some companies, to get a better understanding of the maturity of the required technology and operations and supported an initial design exercise for a reference ADR mission, ERASE (whose logo can be admired in figure 18), with ESA, based on a similar exercise performed for ENVISAT and described in [10]; the option of having a single mission to remove the three Metop satellites was also analysed.

Even if the cost of such a mission is high, the benefits deriving from it, not only in terms of mission return, but also as mitigation of on-ground casualty risks related with the current situation, as above explained, may make it sustainable.

Fig. 18. Erase mission’s logo

More initiatives, to further proceed in the definition of such a mission, are therefore foreseen; as a next step, ESA and EUMETSAT have recently launched an Industrial Request for Information for the Metop ADR to assess industrial capabilities. It is intended to launch Pre-Phase A studies in the near future; the decision of whether or not to proceed with more steps toward the full implementation of such a mission will be based on the results of these studies

9.2 Mission extension for Metop-B

As above explained, the availability of an ADR service would permit to extend further the lifetime of the flying Metop satellites, releasing for operation the fuel reserved for EOL. For Metop-B the case of spending part of this fuel, which would permit to achieve an orbit with a re-entry time similar to the one of Metop-A (around 22 years, as shown in paragraph 7.1) has been analysed in detail from a mission analysis point of view.

Currently the LTAN of Metop-B, for which the last OOP manoeuvre was performed in 2022, is drifting away from its nominal value, similarly to what observed for Metop-A, and shall reach illumination conditions requiring mission termination at end of 2028 (6 years after the last OOP manoeuvre, one more than for Metop-A, due to an improved management of the fuel resulting in a more advantageous LTAN evolution).

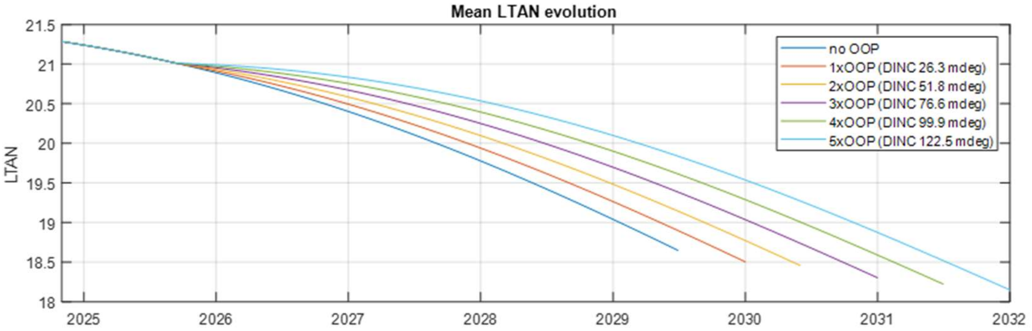


Fig. 19. Impact in Metop-B LTAN evolution of the execution of an increasing number of OOP manoeuvres

The performed analysis aimed to quantify on one side the benefit, in terms of mission extension, of executing an increasing number of OOP manoeuvres in autumn 2025, on another the impact of the resulting reduction of the available fuel on the performances, estimated as increase in the re-entry time, of the EOL operations. As it can be observed, in figure 19, around 4 to 5 months of lifetime (assuming 19 hours as minimum acceptable LTAN value) can be gained for each extra manoeuvre. Therefore, the end of mission can be postponed from end of 2028 to end of 2030 if 5 OOP manoeuvres are executed.

This increase of lifetime would be quite welcome by the operational meteorological community, to ensure continuity of the EPS mission, which will be taken over by the second generation around in 2027: a relatively large overlap between the two generations is needed to ensure a proper cross-calibration of the instruments for climatology. Moreover, the option of having the first and second generation flying together on different LTAN, something possible if in 2030 the remaining fuel on Metop-B is spent to stop its LTAN at around 19.5, may permit the development of new multi-sensor products of large added value.

On another hand, each manoeuvre causes a not negligible increase of around 4 to 5 years in the re-entry time; that means that the re-entry time achievable at the end of the 5th OOP manoeuvre would be around 45 years; the related risk of collision during the re-entry would raise significantly too, from a bit more than 1% to nearly 3%, making the ADR option more than just an option.

9.3 In-orbit servicing for MTG

As explained in paragraph 7.2, mission extension for the Meteosat Satellites is normally achieved by leaving the inclination drift (foreseen to reach 10 degrees for MSG-2 at its expected EOL time in 2027) while controlling only the longitude within the allocate slot; however, the efficacity of this solution for MTG is strongly questioned, due to the more limited flexibility in the observation geometry, constraining the maximum inclination to 2.5 degrees.

The MTG nominal mission is designed for 8.5 years with fuel resources permitting 2.2 years of mission extension. Assuming then a drift in inclination up to the maximum acceptable value, another couple of years can be gained, bringing the total life to around 13 years. Even if this result seems satisfactory, that is well below the around 20 years reached by MSG-1 and expected to be reached by all flying MSG satellites.

To extend even further the lifetime of MTG in-orbit servicing options are currently being analysed in EUMETSAT:

- Active removal: similarly to what explained in paragraph 9.1 for Metop, the burden of bringing the satellite into the graveyard orbit could be delegated to one of the companies currently developing these technologies; however, while for a LEO mission this option, even if expensive, may result quite attractive, as providing a large increase in the mission duration (doubling the nominal lifetime), that is not true for a GEO mission, as the saved fuel, permitting to just a couple of months of mission extension, is rather marginal.
- AOCS takeover: this option implies that a servicer spacecraft is physically connected to the serviced satellite and performs all AOCS functions of the coupled system, including orbit maintenance; this solution seems very attractive for a telecommunication satellite, allowing to make commercial use of a working payload even with a no more operational platform, but it is most probably not good enough for the MTG mission; the mechanical coupling of the two satellites makes very challenging, if not impossible, to achieve the very high performances needed in terms of attitude control accuracy and stability, which are needed for accurate observation of the Earth from the GEO ring; while for a telecommunication satellites several tens of kilometres of accuracy on the sub-satellite points location are acceptable, that is not the case for a mission targeting to achieve geolocation accuracy below the kilometre.
- Refuelling; the option of having a servicer spacecraft re-fuelling the serviced satellite would permit to extend the mission by a much larger extent (in theory, up to as much the spent lifetime), also allowing to remain always within the optimal observation conditions (inclination kept below 1 degree); however, the complexity of this operation, requiring heavily intrusive activities to reach the fuel tanks and inject in them the needed fuel, is very large and the risk involved is much higher than for the other options presented above.
- Relocation: this option implies that a servicer spacecraft is physically connected to the serviced satellite and either relocates it into another longitude slot or performs a change of its inclination, before releasing it. As a maximum inclination of 2.5 degrees is still acceptable for MTG, even if with slightly degraded performances, a possible scenario could be that, at the end of the mission, the inclination is initially left drifting during more than two years up to reach the maximum value.

At this point a relocation service performs a 5 degrees correction (providing around 250 m/s of change of velocity) to bring the inclination vector into the symmetrical location with respect to the zero inclination (so just a node rotation); from here the inclination is left drifting again for more than 5 years up to reaching the maximum value, as visualized in figure 20. This second drift phase would result on a net gain in mission lifetime (actually, bit less, as some fuel would be in any case needed to perform regular longitude maintenance and wheel off-load manoeuvres).

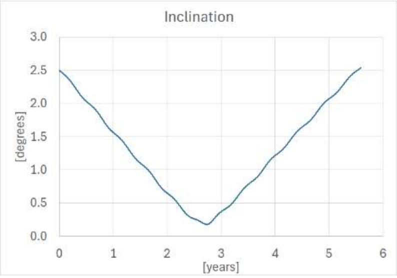


Fig. 20. Inclination evolution after node rotation

As for the ARD services, EUMETSTAT is actively monitoring the industrial ecosystem, following up with interest the development of these services for a future potential usage in around 10 years (when the fist MTG satellite will have reached EOL conditions in terms of available fuel).

10. Conclusions

After nearly 15 years of CA operations EUMETSAT can be considered one of the leading organization in Europe on this field. Lot of work was done in these years to ensure optimal protection to the operational assets as well as a sustainable space environment and more is to be done to maintain the operational approach in line with a continuously evolving environment.

It is worth mentioning that in the near future the responsibility to provide civil operators with reliable information for CA operations will be transferred from US Department of Defence (the 18th and 19th SDS) to Department of Commerce (the NOAA's Office of Space Commerce, which will take over also the role of CARA); how that will impact EUMETSAT CA operations is still under analysis; the outcome of these activities will be presented to the Space Sustainability community in due time.

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