MISSION ANALYSIS OF METOP-A END-OF-LIFE OPERATIONS

Pierluigi Righetti[(1)], **Jose Maria de Juana Gamo**[(2)] **and Richard Dyer**[(3)]
[(1)] *EUMETSAT, +4961518077670, pierluigi.righetti@eumetsat.int*
[(2)] *EUMETSAT, +4961518077352, jose.dejuana@eumetsat.int*
[(3)] *EUMETSAT, +4961518077460, richard.dyer@eumetsat.int*
EUMETSAT Allee, D-64295 Darmstadt

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 seven years of operations. This fuel can be allocated either to extend the satellite lifetime or to put the satellite in a faster-decaying orbit which will result in an earlier atmospheric re-entry of around 25 years. Several analyses have been performed by the EUMETSAT Flight Dynamics team to define possible end-of-life strategies that can ensure a proper balance between mission return and compliance with the international guidelines on space debris mitigation; some mission extension strategies have also been considered to increase as much as possible the mission duration but keeping at the same time the fuel consumption limited.*

Keywords: *End-of-life, Mission extension, Maneuvering strategy.*

1. Introduction

Metop (Fig. 1) is the space segment of the EUMETSAT Polar System (EPS), Europe's first polar orbiting operational meteorological satellite system. EPS is the European contribution to a joint European-US polar satellite system called the Initial Joint Polar System (IJPS).

On the 19th October 2006, the first Metop satellite (Metop-A) was successfully launched from the Baykonur Cosmodrome by a Soyuz/Fregat launcher.
The Metop mission requires that a repeat orbit of 412 revolutions every 29 days is followed within 5 km around the nominal ground-track and that the local time of the descending node is kept within 2 minutes of 09:30. Regular maneuvers are then required to maintain the operational orbit.

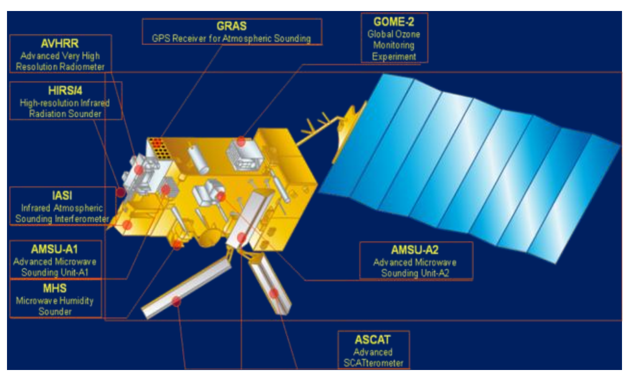

Figure 1. The Metop Satellite

Metop-A was loaded with approximately 300 kg of hydrazine at launch. This amount of fuel was budgeted for orbit maintenance, for correction of orbit injection errors following separation from the launcher and to maintain the satellite in a safe attitude in case of a major anomaly at platform level (and to re-acquire the operational orbit afterwards). No fuel was initially allocated to de-orbiting, since no End-of-life (EOL) disposal was imposed at design time (late 90's).

Thanks to a very accurate injection into the operational orbit, to a proper selection of the injection parameters (biased in inclination and local time of ascending node – LTAN – to obtain an initial post-launch 18 month maneuver free period) and to a close to optimal orbit maintenance strategy (out-of-plane maneuvers – OOP – executed close to the equinox and with full usage of the eclipse period, as described in [1]), together with the fact that no major anomaly at platform level (causing important fuel usage) has occurred, a large amount of fuel has been saved, in comparison with the design budget, in the first seven years of operations, as summarized in Tab. 1.

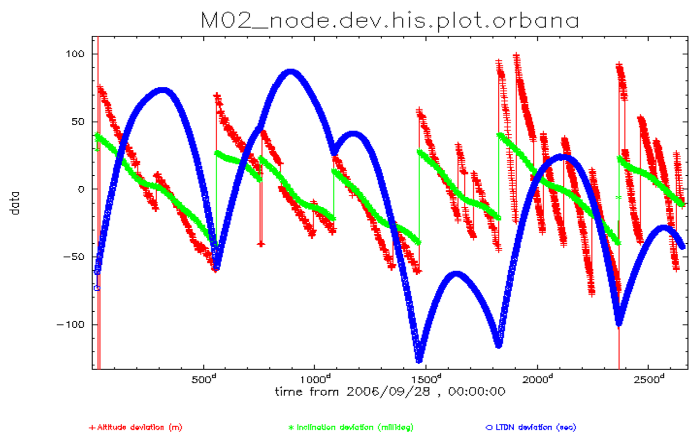

Figure 2. Inclination, semi-major axis and LTAN evolution of Metop-A orbit

Table 1. Metop-A real fuel budget versus design budget (kg)

Fuel	Design	Real
At launch	315	314.6
Acquisition	60	11.6
Routine ops	(20/year) 140	94.7
Contingency	(30/year) 210	0
Total left	<0	208.3
Margins	5	10
Available	<0	198.3

Even if we should have largely exhausted all the fuel according to the design projection (a nominal lifetime of 5 years was considered) around 208 kg of fuel are estimated to be still on-board at the beginning of 2014; out of these, 198 kg are considered to be still usable (5 kg of unusable fuel, 5 kg linked to estimation accuracy). This fuel can be either used to extend the satellite lifetime or to put the satellite in a faster-decaying orbit which will result in an earlier atmospheric re-entry; or a combination of both.

Currently two Metop satellites are operated by EUMETSAT (Metop-B has being launched on 17th September 2012, six years after the first one, and positioned on the same orbital plane and ground-track as Metop-A with almost 180 degrees of orbital separation, as explained in [2]); it has been recommended by the users to maintain this configuration, which provides optimal combined coverage and ensures hot redundancy at space segment level as long as possible, at least up to the end of the commissioning of Metop-C, currently foreseen for the second half of 2018. In addition to this, there is also the need to comply as much as possible with the international guidelines on space debris mitigation. Several analyses have been then performed at EUMETSAT to define possible mission extension and end-of-life strategies balancing between mission return and compliance with space debris mitigation requirements [3], taking into account the spacecraft design (not designed for de-orbiting), possible Metop-A contingencies that may still appear before EOL, and delays of the Metop-C mission. To increase as much as possible the mission duration minimizing the fuel consumption, some mission extension strategies have been considered, such as: overheating of the propellant tanks, reduction of the safety margins for the slew execution to allow partial execution outside eclipse, interruption of inclination control with uncontrolled LTAN drift, reduction of the semi-major axis.

In parallel to these analyses, a preliminary definition of the required operations for a reference end-of-life disposal has been performed and is currently being validated and the first OOP implementing some of the strategies above mentioned was executed successfully.

2. Metop-A Baseline Mission and possible Extension Strategies

The first analysis consists in defining baseline operational strategies until EOL (performing station keeping as per [1]) estimating for each one of them the available delta- velocity at EOL together with the re-entry orbit and decaying time that can be achieved with this delta- velocity.

When computing the achievable delta-velocity a the dry mass of 3770 kg, an ISP of 220 and a total efficiency of 92.4% (caused by thruster misalignments, thrusting efficiency and losses linked to attitude control thrusters activations during propulsion and stabilization) are considered; moreover, 10kg of fuel are not taken into account, as explained before.

To compute the achievable re-entry orbit a pure Hohmann transfer is assumed, together with a minimum apogee of 795 km (15 km below operational orbit) and a maximum perigee of 600 km (potential s/c design constraint, as explained in paragraph 4.4), both with respect to an equatorial radius of 6378 km; perigee is assumed at the South-pole (see paragraph 4.3).

The nominal re-entry time is computed using CNES STELA [4] with random average atmosphere (which means, insensitive to the de-orbit date and with 50% confidence of re-entering before the provided data) and random average drag surface of 34 square meters. A worst case re-entry time is computed too, using NASA DAS [5] (which implements a most pessimistic atmospheric profile) and considering a reduction of the drag surface by 10% (as observed by in flight data on the de-orbited SPOT satellites [6]).

2.1. Mission evolution with no OOP after 2013

The Metop-A mission evolution case assuming no more OOP after spring 2013 is presented as reference for further analysis.

Figure 3 presents the foreseen evolution in LTAN and inclination (2013 OOP visible): the 2 minutes dead-band is violated on 2014.35.

The 208.3 kg of fuel available permits to implement 101.7 m/s of delta-velocity, which are sufficient to bring the satellite to a perigee of 600 km and an apogee of 650 km.

A re-entry time of 17.7 years, compliant with the 25 years of the space debris guidelines, is computed (worst case of 27.8 years).

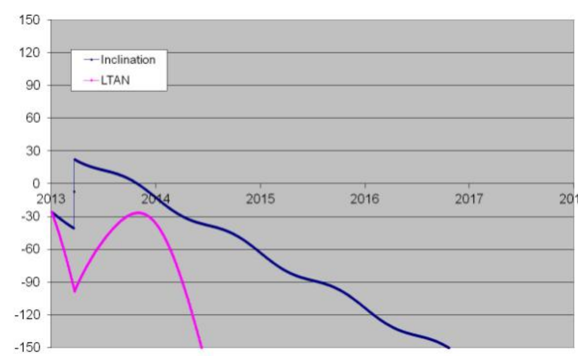

Figure 3. Foreseen inclination and LTAN evolution of Metop-A orbit; no OOP

2.2. Mission evolution with one OOP maneuver every year

From the figures presented in previous paragraph 2.1 some margin of fuel that can still be used for LTAN maintenance, while keeping compliance with the space debris mitigation recommendations. This margin is evaluated for the foreseen mission evolution considering the execution of an OOP every year for the next 3 years. All maneuvers are performed close to the spring equinox and with maximum usage of the eclipse to maximize their efficiency (as explained in [1]); maneuvers are segmented in two burns to respect the constraint of being fully executed in eclipse.

Table 2 summarizes the results obtained in terms of the main parameters used to evaluate the EOL performance: those already presented in 2.1 for the case without any maneuver are also included as reference. For those cases where nominal re-entry in more than 25 years is computed (considering the limitation in perigee altitude presented above in chapter 2), the value of the EOL perigee (and apogee) needed to achieve 25 years is also presented.

Table 2. Metop-A EOL performance parameters for yearly OOP

Last OOP year	2013	2014	2015	2016
2 minutes LTAN violation	2014.35	2015.46	2016.56	2017.78
Available fuel (kg)	208.3	191.7	176.1	161.2
Available delta-velocity (m/s)	101.7	93.4	85.5	78
EOL Perigee (km)	600	600	600	600
EOL Apogee (km)	650	682	712	740
Nominal re-entry time (y)	17.7	21.6	**25.3**	29.5
Worst case re-entry time (y)	27.8	31.7	35.9	38.9
25 years EOL Perigee (km)	N/A	N/A	592	556
25 years EOL Apogee (km)	N/A	N/A	718	791

From the above table it can be observed that it is still possible to perform 2 OOP maneuvers (one in 2014 and one in 2015), still remaining compliant with the 25 years nominal decaying orbit. Moreover, even if currently the limit of the perigee altitude is set to 600 km, it is still to be confirmed if reaching a lower value is possible; analyses are being carried out by the satellite manufacturer to confirm this (see paragraph 4.4).

To perform a further maneuver in 2016 would however degrade the EOL performances (re-entry time getting very close to 30 years); an important reduction of the perigee over the currently considered limits would be needed.

<u>On the basis of this analysis it was recommended to perform nominally no more than two further OOP maneuvers with Metop-A</u>; the foreseen evolution of LTAN and inclination in this case is presented in Fig. 4.

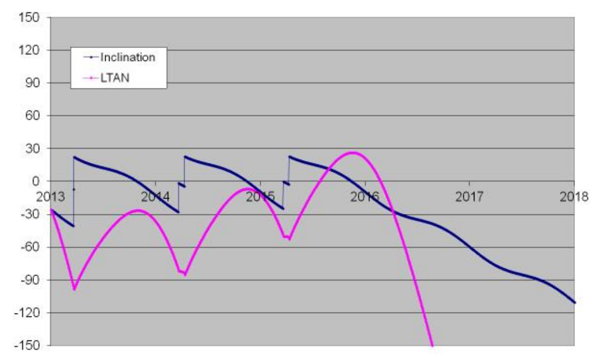

Figure 4. Foreseen inclination and LTAN evolution of Metop-A orbit; OOP till 2015

2.3 Mission Extension Strategies

The above proposed strategy however is not ensuring continuity of operations till the end of the commissioning of Metop-C, currently foreseen in the second half of 2018, as exit from the 2 minutes LTAN dead-band occurs around 2 years before that. Two mission extension strategies have been taken into account, to ensure dual Metop mission continuation, even if with some degradation of instrument performances:

- Reduce the satellite orbit altitude to implement a further LTAN cycle; that solution is similar to what performed with ENVISAT, which was lowered by 25 km in 2010 to remain within the nominal LTAN for 3 years longer [7];

- Leave the LTAN drift outside the 2 minutes nominal dead-band; that solution is similar to what performed by some NOAA satellites, which are free drifting in a very large LTAN control window, not having any propulsion capability to control the LTAN evolution [8].

Figure 5 presents the predicted LTAN evolution assuming a semi-major axis (SMA) reduction of 20.2 km shortly before the 2 minutes are violated (time window shifted one year to show the full evolution within the dead-band). Violation is postponed by nearly two years to 2018.51, so compliant with the foreseen start of Metop-C operations.

This SMA reduction is well within the specification of the platform and of the instruments (no limitation at satellite level identified).

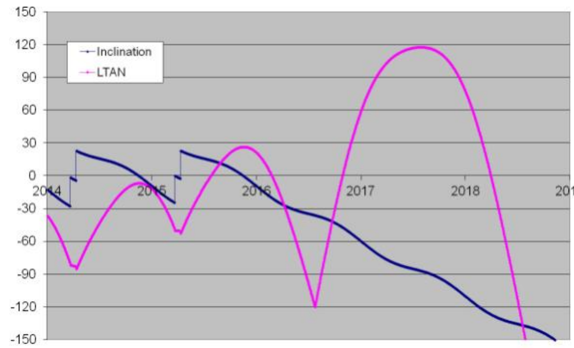

Figure 5. Foreseen inclination and LTAN evolution of Metop-A orbit; SMA reduction

The main drawback of that solution is that, due to that reduction of SMA, a large relative drift (of around 22.5 degrees per day) is created between the two satellites and then Metop-A overtakes Metop-B every 16 days, with several undesired operational consequences:

- Being the S-band transponder identical on the two spacecraft, regular long telemetry (TM) interferences periods are observed (as explained in [2]); similarly shorter X-band interferences, may be observed; very long ranging interferences are also to be expected;
- Whenever the separation of the two satellites, in terms of ascending node crossing time, is too short, it is no more possible to operate both satellites using a single antenna, as currently performed;
- Whenever the field-of-view (FOV) of the radar scatterometer (ASCAT) on board of the two satellites is overlapping (for conditions to the one on the previous bullet) then large degradation of the data from both instruments is observed;
- As the nominal ground-track cannot be maintained anymore, then the coverage figures of the dual mission degrades significantly (nearly same regions observed when the two satellites are very close).

Figure 6 presents the predicted LTAN evolution assuming a drift of the LTAN up to 30 minutes (time window shifted one year and LTAN scale expanded to show the full evolution); violation is postponed by nearly two years to 2018.52, so compliant with the foreseen start of Metop-C operations.

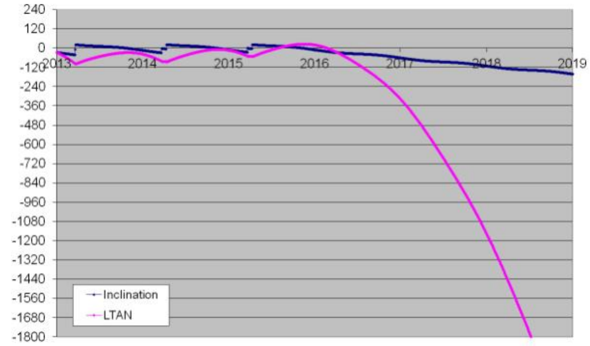

Figure 6. Foreseen inclination and LTAN evolution of Metop-A orbit; LTAN drift

It is however necessary to ensure that this large LTAN drift, which implies a relatively large change of the Sun direction with respect to the orbital frame, is acceptable both at platform and at instrument level:

- Digital Sun sensor (SSD): it is necessary that the Sun is visible in the SSD at least once per orbit; considering the instrument FOV size, the yearly oscillation of the Sun around its main direction and the maximum expected attitude deviation of the platform, sufficient margin is available to absorb up to 50 minutes of LTAN deviation;
- Digital Earth sensor (STD): it is necessary to mask via telecommand the reading of the STD measurement whenever a Sun blinding event is predicted; no masking is performed during the expected eclipse duration (assuming nominal LTAN); it is therefore necessary to adjust the mask telecommand to take into account the reduction of the eclipse duration with the LTAN drift, as shown in Fig. 7, (case with no more OOP executed after spring 2013 is presented);

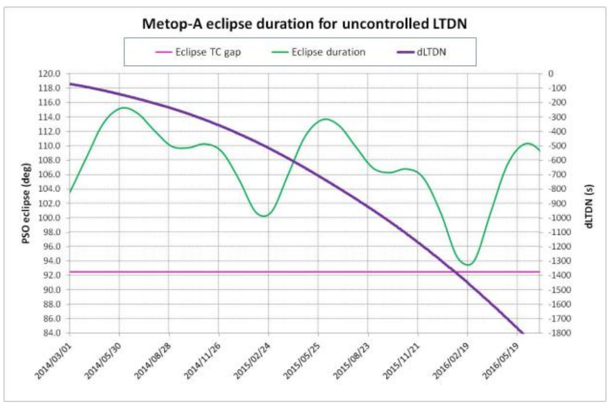

Figure 7. Eclipse duration evolution for uncontrolled LTAN

- Thermal control: it is estimated that a marginal increase of temperature is caused by the shorter eclipse duration and by the change of Sun direction, still well compliant with the satellite margins: up to 50 minutes of LTAN drift could be accepted before any problem;
- Power availability; it is estimated that the marginal reduction of power caused by the change of Sun direction is compensated by the equivalent decrease of the eclipse time;
- GOME instrument: that instrument requires daily Sun calibration and therefore proper maintenance of the Sun direction to ensure presence of the Sun in the calibration FOV (LTAN maintenance requirement is coming from here); however Sun unavailability once having abandoned the nominal LTAN is estimated to happen only around end of February (lasting ~4 months for 30 minutes of LTAN drift); during that period it is however possible to perform cross calibration with the equivalent instrument on board of Metop-B, for which Sun calibration is still possible;
- Other instruments; those with NOAA heritage (AVHRR, AMSU, HIRS, MHS) have been already operated on a very large LTAN band with no major problems on board of the NOAA satellites; the radar scatterometer (ASCAT), the infra-red sounder (IASI), the

radio occultation sounder (GRAS) and the spectrometer (SEM) are insensitive to the Sun illumination conditions.

To maintain the optimal coverage figures for the dual mission it is necessary however to keep ground-track control of the Metop-A satellite at the Equator while the LTAN is drifting; as a consequence the separation of the two satellites, in terms of ascending node crossing time, decreases by exactly the same value; as the two satellite are operated with a single antenna, a separation of at least 20 minutes have to be kept, which limits the LTAN drift to a maximum of 30 minutes, being the initial separation of the order of 50 minutes, as presented in Fig. 8.

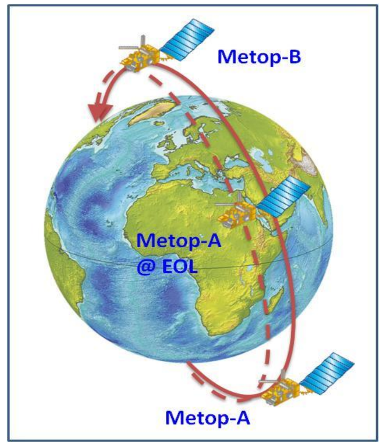

Figure 8. Metop-A/B EOL configuration

Based on this analysis, it was recommended to implement a mission extension for Metop-A after execution of the 2015 OOP through a LTAN drift of 30 minutes with ground-track maintenance.

This strategy permits to operate Metop-A till mid 2018, which is compatible with the foreseen start of Metop-C operations. Moreover, thanks to the remarkable displacement of the Metop-A satellite from its nominal orbital location, it is possible to position Metop-C directly on its target location, the same currently occupied by Metop-A, without any interference with Metop-A itself.

3. Metop-A OOP Enhanced Mission Extension Strategy

The baseline EOL strategy for Metop-A described in chapter 2 is however not supporting any delay in the Metop-C launch.

Two options have been considered to squeeze out the required few months more from the EOL strategy, impacting as little as possible the EOL disposal capabilities:

- Further optimize the maneuvering strategy, to increase the satellite lifetime till reaching the 30 minutes of LTAN drift, minimizing the extra fuel consumption;
- Consider allowing a larger drift of the LTAN up to 50 minutes (still compatible at satellite level, as shown in paragraph 2.3).

3.1 Refinement of the maneuvering strategy

Several options have been analyzed to achieve additional extension with as minimum as possible fuel consumption:

A. Execute a 2 burns OOP in spring 2014 and a 2 burns OOP in spring 2015 (as in the baseline strategy presented in chapter 2) plus a 1 burn OOP maneuver in spring 2016;
B. Execute a 2 burns OOP in spring 2014 and a 3 burns OOP in spring 2015 (with no full eclipse usage to avoid violation of the LTAN dead-band afterwards);
C. Execute a 3 burns OOP in spring 2014 (with no full eclipse usage) and a 2 burns OOP in autumn 2015; due to the larger inclination change provided by first OOP it is possible to implement a 18 month LTAN cycle and move the second OOP to the following equinox;

D. Execute a 2 burns OOP in spring 2014 with increased duration of the propulsive phase and a 2 burns OOP in spring 2015, also with increased duration of the propulsive phase; from analysis of the yaw de-pointing evolution during the slew rotation after the propulsive phase (which should be performed fully in eclipse), it seems possible to execute the final part of it (up to 3 minutes) outside the eclipse, being the de-pointing already very close to zero (as shown in Fig. 9); that permits to increase the duration of the propulsive phase and, as for case B, an 18 months LTAN cycle can be implemented between the two OOP maneuvers;

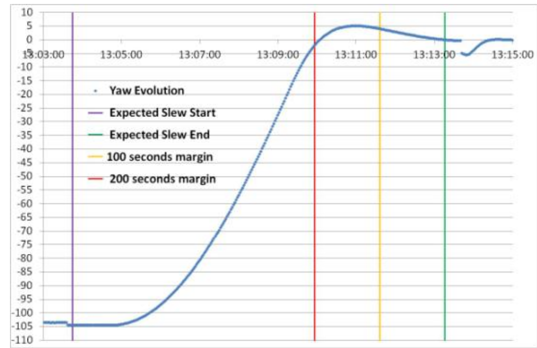

Figure 9. Yaw de-pointing during 2013 Metop-A OOP slew-back

E. As for the previous case plus increasing the temperature of the tanks; Metop-A is currently operated in a rather cold configuration (around 15 degrees), to minimize the thermal noise in the instrument; it is however acceptable to increase for a short time period the temperature of the tanks (up-to 25 degrees, so ~3% more) to increase the pressure and then the propulsive force provided by the thrusters; a larger inclination change (also of the order of 3%) can be then implemented in the same propulsion time;
F. As previous case plus further enlargement of burns duration by reducing the slew rotation in yaw required before execution of the OOP maneuver (and so the slew time), to increase the propulsion time (and so the achieved inclination change); a remarkable in-plane (IP) component is generated by the inaccurate yaw pointing, which needs to be limited (to a couple of degrees), to avoid a too large ground-track drift (it has to be ensured that the satellite remains in the nominal 5 km dead-band at least a couple of days after the OOP); moreover an IP correction (of the same size of the IP component above mentioned), has to be performed before exiting the dead-band, which causes an important fuel penalty.

To evaluate these options the benefit in terms of extra mission duration (at 30 minutes LTAN deviation) versus the extra fuel required (taking as reference the baseline strategy presented in paragraph 2.3) is computed; the impact in the re-entry time at EOL and on the perigee required to achieve a 25 years re-entry is also presented; the obtained results are summarized in Tab. 3 (a conservative value of 100 seconds of slew outside eclipse is considered for cases *D* and *E*).

Table 3. Metop-A OOP maneuvering strategy comparison

Strategy	*A*	*B*	*C*	*D*	*E*	*F*
Fuel penalty (kg)	7.2	5.6	6.9	5.2	**6.3**	8.3
Life gain (years)	0.44	0.39	0.53	0.40	**0.53**	0.60
Cost per year (kg/year)	16.3	14.4	13.1	13.0	**12.0**	13.8
Re-entry time (y)	27.3	26.9	27.3	26.8	**27.1**	27.6
25 years EOL Perigee (km)	575	578	575	579	**577**	572

From the table above is appears clearly that the optimal strategy, to gain the desired 6 months more of extra life with minimal cost and no significant impact on the disposal capabilities at EOL, is *E* (presented in Fig. 10); that thanks to the fuel saved not having to perform an extra slew (in comparison with cases *A*, *B*, *C*) and to the higher propulsive performances of the hotter tanks; moreover, the execution of a further OOP burn would have meant an extra data outage and then a degradation of mission availability, compared with the baseline case.

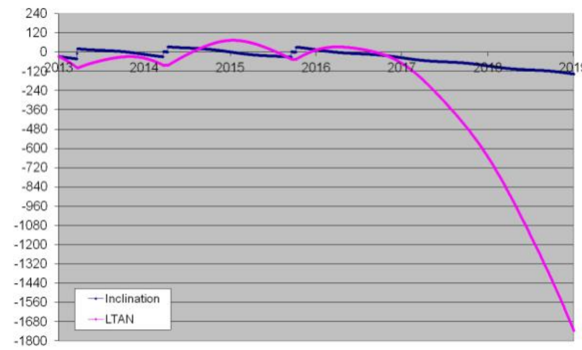

Figure 10. Foreseen inclination and LTAN evolution of Metop-A orbit; E option

The option of reducing the slew to gain propulsion time permits to gain some extra margin, but increasing significantly the yearly cost as well as the operational complexity (in-plane maneuver to execute shortly after each out-of-plane burn) and risk (large ground-track violation in case the in-plane correction is delayed); therefore it is not recommended to have that option considered.

Based on this analysis, <u>strategy E was retained for operational implementation.</u>

3.2 Extending LTAN drift phase

As explained in paragraph 2.3, the maximum LTAN drift of Metop-A on one side allowing to keep the nominal ground track and on the other permitting to operate both satellites with a single antenna, is 30 minutes. However, from a pure satellites point of view larger deviations, up to 40 to 50 minutes should be possible.

Taking as baseline the option E in paragraph 3.1, EOL is then postponed to:

- 2019.45 (0.40 years later) for 40 minutes of LTAN deviation
- 2019.82 (0.77 years later) for 50 minutes of LTAN deviation

It is however necessary to abandon ground-track control, to avoid conflict in the antenna usage, which would imply an important degradation of the mission return whenever also N19 has to be supported and its visibility period overlaps with the ones of both Metop satellites (estimated to happen during one to two days every week). Figure 11 depict this triple visibility conflict case; the separation between Metop-A and Metop-B in terms of ascending node crossing time is below the desired 20 minutes (so LTAN deviation larger than 30 seconds with ground-track control kept) and the NOAA 19 ascending node crossing time falls between these two times.

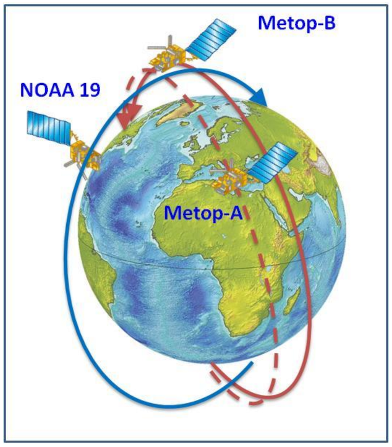

Figure 11. Triple visibility conflict

As explained in [2], there are 29 relative positions between Metop-A and Metop-B ensuring over-flight of the same ground-track (one every 1/29th of the orbit for the same LTAN, being the repeat cycle of Metop of 29 days); that implies that it is possible to absorb a LTAN drift of 1/29th of the orbital period (~3.5 minutes) just by drifting Metop-B into the next possible orbital location having the same ground-track, 1/29th of an orbit apart (~12.4 degrees). To extend the LTAN deviation of Metop-A to 40 minutes without creating any antenna conflict it is then sufficient to drift Metop-A position by 3/29th of an orbit (~37.2 degrees, permitting to gain ~10.5 minutes of LTAN); 50 minutes of LTAN deviation can be achieved with a 6/29th drift.

By doing that however the track of Metop-A does not fall anymore in between the two tracks of Metop-B but get much closer to one of the two. That deviation however is small enough not to affect significantly the coverage figures of the passive instruments, thanks to their large cross-track FOV (just little gaps observed for 6/29th of drift), and may even results in an improvement for the ASCAT scatterometer, because of the peculiar shape of its FOV (presenting a large gap around the nadir direction), as shown in Fig. 12; thanks to the drift of 6/29th of an orbit the left footprint of the FOV of Metop-A falls in between the left and the right footprints of the FOV of Metop-B, instead of overlapping with the right one, as it happens for the nominal configuration.

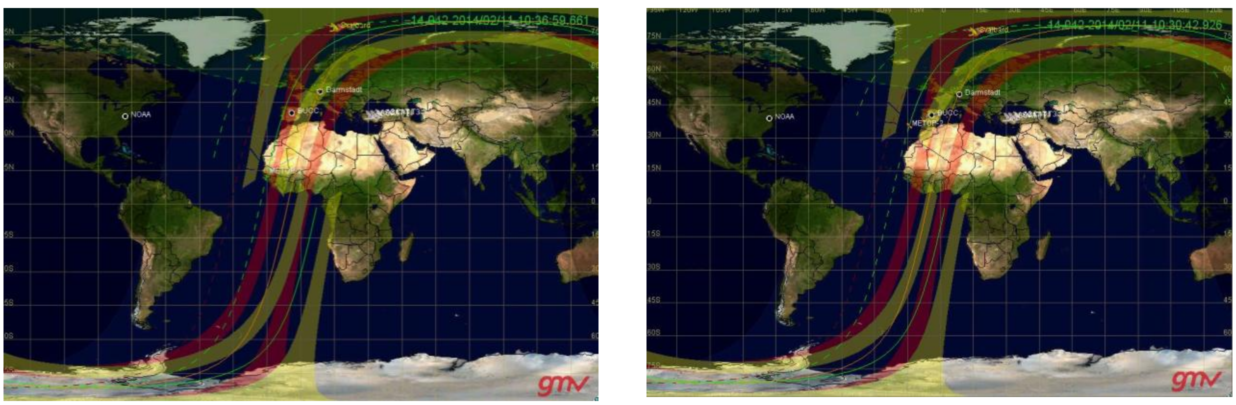

Figure 12. Metop-A/B ASCAT FOV for nominal (left) and shifted (right) configuration

In case a further extension of the Metop-A well above beginning 2019 is required (to cope with further delays in Metop-C launch date) it is therefore recommended to implement LTAN drift up to 50 minutes abandoning ground-track maintenance for LTAN over 30 minutes (maintaining at the same time the possibility of positioning Metop-C on the previous Metop-A location)

4. Additional analyses

4.1. EOL strategy robustness versus platform contingencies

In order to evaluate the robustness of the proposed strategy to platform contingency, the remaining performance margins for carrying out EOL operations after one occurrence of such an event are computed; the Metop satellites dispose of two contingency modes, depending on the severity of the contingency:

- The Fine Acquisition Mode 2 (FAM2), to cope with low criticality contingencies; in this case the satellite starts maintaining earth pointing attitude using thrusters; due to the large torques the satellite have to cope with (because of the satellite shape and inertia), the fuel consumption in this mode is quite high (1 to 2 kg per day); an overall estimation of the fuel consumption for such a mode, up to recovery to the nominal attitude mode and to the nominal orbit (important orbital degradation is caused by the thrusters) is of ~12 kg.

- The Safe Mode (SFM), to cope with high criticality contingencies; in this case the satellite performs a transition into Sun pointing mode and maintain that pointing; as all these operations are performed using thrusters the fuel consumption is very large, not only for the maintenance of the sun pointing mode (similar to FAM2) but also for performing the mode transitions (to Sun pointing and back to Earth pointing once the contingency is recovered) and to re-acquire the nominal orbit (large orbital degradation is caused by these transitions); considering that the expected duration of a SFM is much larger than for a FAM2, an overall fuel consumption of ~55 kg is estimated.

The following cases are then analyzed and the resulting EOL performances, in terms of lifetime and best achievable re-entry time, are presented in Tab.4 here below, together with the performances of the baseline case *E* (presented in Tab. 3):

a. FAM2 happening after 2014 OOP and 2015 OOP maintained
b. FAM2 happening after 2015 OOP
c. SFM happening after 2014 OOP and 2015 OOP cancelled
d. SFM happening after 2014 OOP and 2015 OOP maintained
e. SFM happening after 2015 OOP

Table 4. Metop-A contingency scenario performances

Strategy	*E*	*a*	*b*	*c*	*d*	*e*
Remaining fuel (kg)	169.7	158.4	157.7	133.8	117.5	114.7
30 minutes LTAN violation	2019.05	2018.99	2019.05	2017.78	2018.81	2019.05
Re-entry time (y)	27.1	30.3	30.5	37.2	47.9	49.9
Best re-entry time (y)	25.0	25.0	25.0	34.3	45.1	47.1
Perigee / Apogee (km)	577/749	549/805	548/808	581/810	612/810	617/810

The cases of contingency before the 2014 OOP are not presented as the maneuver was already carried out (as presented in chapter 6) and therefore of no interest anymore.

For the computation of the best re-entry time the constraints of minimum perigee (above 600 km) and maximum apogee (below 795 km) have been relaxed; as limit apogee the value of the operational orbit perigee (810 km, at North-pole) has been taken.

It can be noticed that in case of a FAM2 event it is still possible to be compliant with the 25 years re-entry time target, assuming that the perigee and apogee limits considered can be violated; even if that were not possible, the degradation in re-entry time remains acceptable, as well as the reduction of the lifetime up to violation of 30 minutes of LTAN deviation.

For the SFM case the situation is more critical, as a single occurrence of the contingency would make impossible to be compliant anymore with the 25 years target re-entry time target; in order to limit that violation it is necessary to cancel the final OOP maneuver in 2015, if the contingency happens beforehand; in case the final OOP maneuver is carried out a much larger violation of the re-entry time, with degradation moreover of the mission lifetime is observed.

It is now necessary to point out that a reduction of the lifetime after EOL to ~50 years, as achieved in case of a SFM occurrence, provides already a very large mitigation when compared with the re-entry time in case of no EOL operations are performed (~185 years) or if the orbit is just lowered by 15 km, bringing the North pole altitude to the desired 795 km (~160 years).

As shown by an ESA study [10], to reduce the orbital lifetime to ~50 years reduces the integral collision risk of the satellite during the re-entry from nearly 50% to around 1%. Being the 25 years lifetime recommended limit linked to the need of mitigating the proliferation of orbital debris caused by fragmentation of un-operated satellite (mainly because of collisions), it is then clear that the risk mitigation achieved is in any case more than satisfactory.

On another hand, the benefit of reducing the perigee altitude below the current 600 km limit (by ~50 km), to mitigate the negative impact on the re-entry time of a FAM2 event, is clear.

<u>The analysis here presented shows that the proposed strategy presents a good robustness versus platform contingencies.</u>

4.2. Impact of LTAN drift on the satellite operations

As already presented in paragraph 2.3 the local time drift outside the 2 minutes dead-band causes an important impact on the satellite, which requires the implementation of special operations during this phase:

- STD mask has to be updated regularly, to cope with the reduction of the eclipse size, as already explained in 2.3;
- The Earth IR shape, used as reference for correcting the pitch and roll de-pointing measurements from the STD, has to be updated regularly to take into account the changes caused by the new viewing angle with respect to the Sun direction;
- For large LTAN deviations, it could be necessary to implement a degraded yaw control algorithm robust to temporal unavailability of SSD measurements, to avoid a transition to contingency mode when the Sun exit the SSD FOV due to a marginal yaw de-pointing;
- For large LTAN deviation, it could be necessary to implement an improved monitoring of the thermal and power conditions, to be able to identify degradations in the performances as soon as possible; depending on the outcome of that monitoring it may be necessary to anticipate the start of the EOL operation to ensure their feasibility;
- Modification of instrument set-up, to cope with the different illumination conditions, is not to be discarder, together with tuning/re-calibration of the on-ground processing of the received data.

<u>The analysis here presented shows that several modifications on the satellite operations is required before allowing the LTAN drift to take place.</u>

4.3. EOL perigee location selection

The selection of the EOL perigee altitude and location is driven by the need on one hand to minimize the re-entry time and on another to ensure safe execution of the EOL operations.

According to an ASTRIUM study (see [9]) the minimum altitude at which the Metop satellite can be safely operated without any change on its on-board system is 620 km over the Earth surface; at a lower altitude the observed size of the Earth gets so large that the STD is no more able to properly identify the Earth to deep-space transitions within the measurements range. In Fig, 13 is depicted how the apparent size of the Earth increases at the perigee; transitions are detected with a much larger de-pointing angle with respect to the zenith (red lines) than for the nominal case (yellow lines).

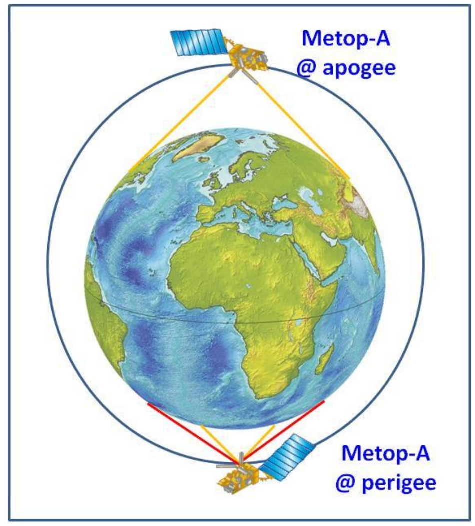

Figure 13. Increase of apparent Earth size at perigee crossing

It is necessary to notice that the value of 620 km over the Earth surface is equivalent to different altitude values with respect the fixed reference of the Earth equatorial radius (used for defining perigee altitude in STELA, the reference SW used for re-entry time computations by EUMETSAT), depending on the location of the perigee:

- 620 km for the perigee at the Equator (obviously);
- 600 km for the perigee on the poles (being the polar radius 20 km smaller than the equatorial radius); that value is used as limit in the analysis presented in that paper.

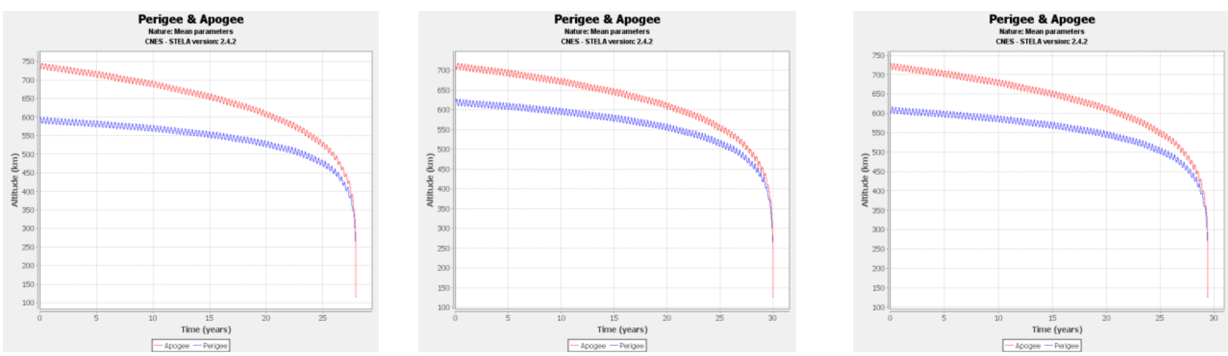

Figure 14. Perigee and apogee evolution for initial perigee at South-pole (1), Equator (2) and North-pole (3)
EOL orbit: 600 km – 730 km for cases 1, 3; 620 km – 710 km for case 2

To select the perigee location the following criteria have been considered:

1. Minimization of the re-entry time; a location at the South-pole provide a better re-entry time, as shown in Fig. 14 here above, where equivalent cases at South-pole, Equator and North-pole are compared; when the initial perigee is located at the South-pole not only its initial altitude with respect to the equatorial radius can be reduced safely by ~20 km (as explained above) but, moreover, the natural eccentricity evolution brings it to further

reduce when the perigee rotates toward the Equator (as explained in [1]); as a consequence the altitude when the perigee crosses the Equator is around ~27 km lower than for case with initial perigee at the Equator; a benefit of ~10% in the re-entry time can be observed; for the case with initial perigee at the North-pole the altitude increases due to the eccentricity rotation, removing part of the benefit of the lower initial altitude.

2. Maximization of the duration of the passes for the final passivation (see paragraph 5.1); when the final end-of-life orbit is achieved it is necessary to fully passivate the satellite; as these operations require as long as possible visibilities, and as the stations used for doing that are both located close to the North-pole (in Svalbard and Fairbanks), a South-pole location is clearly recommended, above all when the number of long combined passes (the most useful for the passivation) are considered; in Fig. 15 it can be observed that a perigee at the South-pole provides more than the double of such opportunities.

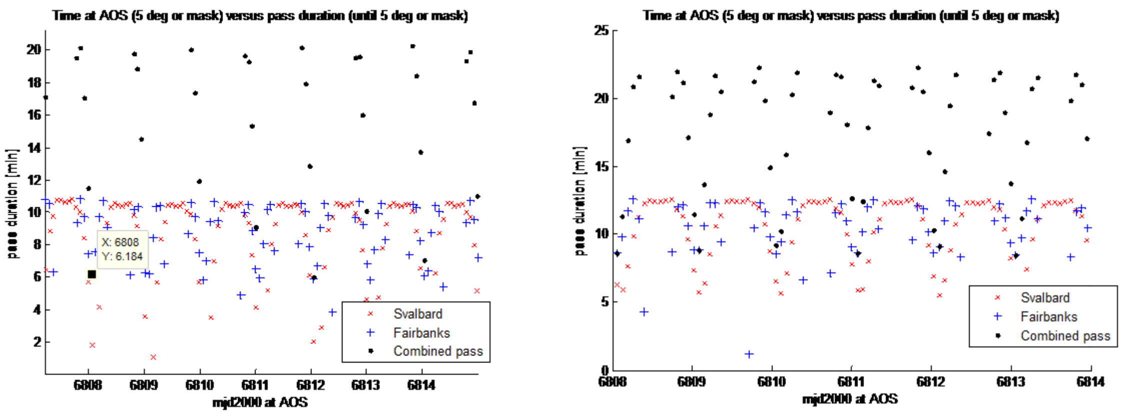

Figure 15. Pass duration for perigee at South-pole (left) and North-pole (right) EOL orbit: 600 km – 795 km

3. Minimization of the drag torque load on the perigee; as it is foreseen to maintain the solar panel pointing toward the sun during the entire de-orbiting operations, the maximum drag torque is expected to be experienced at the Poles (solar panel normal to the orbital velocity) and the minimum at the Equator (solar panel aligned with the orbital velocity); therefore it would be recommendable to have the perigee at the equator; however, as the de-orbiting is foreseen to happen in a low solar activity season, the torque load resulting even for a perigee at the South-pole should be well within the capacity of the wheels (preliminarily internal analysis seems to confirm that); the option of blocking the solar panel in a configuration aligned with the orbital velocity can also be considered (the reduction of power availability should have no impact, as during EOL the instruments are switched-off and the power demand decreases significantly).

<u>Based on the above considerations the decision to locate the perigee at the South-pole was taken (at least in the scope of this analysis).</u>

4.4. Perigee altitude reduction

As already presented in paragraph 4.3, currently a minimum perigee value of 620 km over the Earth surface is considered. However the option of reducing that value deserves to be deeply analyzed, as it would permit on one side to make the current selected EOL strategy (presented in paragraph 3.1) fully compliant with the 25 years re-entry time and on another to mitigate the effect of any contingency at satellite level (as explained in paragraph 4.1) on the re-entry time.

Several issues need to be however considered before being able to further reduce the perigee without risk for the platform:

- The measurements range of the STD needs to be enlarged in order to properly detect the Earth to deep-space transition from a lower altitude (bigger sire of the Earth disk); that can be done up to a certain level by SW patch on the STD; however an HW limit is also present which cannot be over-run, which defines the absolute limit in altitude the platform can be safely lowered; the satellite manufacturer is performing an analysis to confirm that HW limit and define the procedure for the SW limit upgrade.
- Being the pitch guidance of the satellite commanded from ground, based on a model adapted for circular orbits, the error of this guidance increases remarkably (by nearly two order of magnitude) when the eccentricity of the orbit increases, as shown in Fig. 16; that can lead to serious problems on the pitch pointing accuracy above all on exit of a STD mask event (during which the STD signal is not used for pitch control and only the guidance law is applied), which may cause entry of the satellite into a contingency mode; relaxation of the pitch pointing accuracy (affecting the performances only in routine) is needed to avoid that to happen; that problem is currently being analyzed by EUMETSAT.

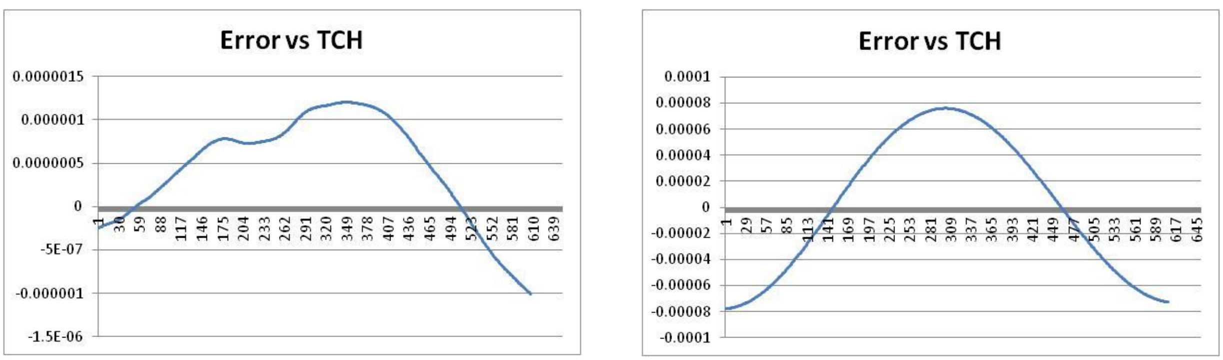

Figure 16. Pitch guidance error for circular (left) and elliptical (right) orbit

- The load on the wheels increases exponentially when reducing the altitude, due to the large increase of the atmospheric density at perigee; mitigation measures, as blocking the solar array in a configuration minimizing the drag torque, may need to be put in place to reduce that effect and avoid wheel saturation and consequent entry of the satellite in contingency mode; the satellite manufacturer is performing an analysis to evaluate the minimum altitude the wheel can cope with the drag torque and define mitigation actions.

<u>None of the point above presented seems to indicate that a further reduction of the perigee is not feasible </u>(at least up to 570 km geodetic, equivalent to 550 km with respect to the equatorial radius at the South-pole, where other satellites of the same family have been de-orbited [6]).

4.5. Comparison with circular de-orbiting option

The hypothesis of selecting a circular orbit as target for the EOL operations was analyzed, as considered potentially simpler to implement. With the fuel available after the foreseen execution of the 2015 OOP maneuver (according to strategy *E* presented in paragraph 3.1), it is possible to reduce circularly the orbit by ~155 km.

When comparing the performance of that solution with those of strategy *E,* the following can be observed:

- The re-entry time is relatively higher (30.3 years versus 27.1 years assuming 600 km of perigee limit and 25 year assuming a marginal violation of that limit);
- The robustness versus contingencies is also reduced (for instance, assuming a FAM2 event after execution of 2015 OOP maneuver, case *b* in paragraph 4.1, the re-entry time increases to 35.5 years);
- The risks deriving from reducing the perigee height and increasing the eccentricities, presented in 4.7, are reduced (risks in any case considered acceptable);
- Much larger maneuvers (theoretically lasting even the entire orbit) can be used to lower at the same time the perigee and the apogee (no losses due to finite execution), with a potential gain in terms of time for implementing the EOL operations; however that would imply a major (and thus risky) change in the satellite operations;
- A circular de-orbit target would ensure than both perigee and apogee are below the 700 km altitude, the most populated in terms of operational satellites as well as of debris; that may permit to reduce the risk of collision in this region of high operational interest; however, such a criteria is not yet taken in consideration by the mitigation regulation [3].

Based on the above considerations the decision to consider as target for the EOL operations an eccentric orbit was taken (at least in the scope of this analysis).

4.6. Fuel estimation accuracy

In chapter 1 it is stated that 5 kg of the estimated fuel cannot be considered in the computation of the achievable EOL orbit, due to uncertainties in the fuel estimation itself.

Two methods are currently used for fuel estimation:

- Pressure-Volume-Temperature (PVT) method, based on evaluating the volume occupied by the pressurizer (helium) present in the fuel tanks from pressure and temperature measurements and then derive the volume (and thus the mass) occupied by the fuel (hidrazyne);
- Pulse book-keeping (PBK) method, based on evaluating the fuel spent by each commanded thrust pulse relying on the available information of force and specific impulse (ISP) of the thruster providing the pulse.

The results provided by the two methods match in the order of a couple of kg as shown below in Fig. 17 (first 15 and last 20 days; PVT on red curve, PBK on blue constant line).

To further validate that result, data collected during a tank heating exercise (to prepare for the OOP execution with hot tanks, according to strategy *E*, presented in 3.1) were processed (25 days in the middle in Fig. 17); the large oscillation in the PVT results observed are due to a thermal delay on the temperature transducers (larger relative pressure increment observed).

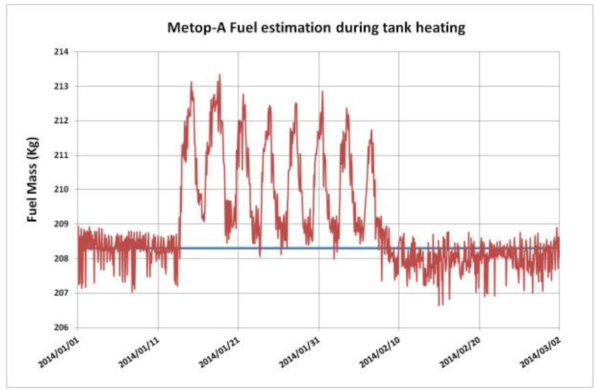

Figure 17. Metop-A PVT and PBK fuel estimation during tank heating

It is however interesting to notice that the lower limit of these oscillation (shortly before the bang-bang temperature controller triggers the tank heaters on, so after having provided enough time to the satellite to stabilize thermally) is very close to the PBK value, even if slightly higher; it is therefore believed that the fuel estimation with PVT on nominal thermal conditions is slightly underestimating the remaining fuel.

Reviewing the PBK algorithm implemented it was also found out that the reference force used for the computation is the nominal one, and not the observed one, slightly lower (due to the thruster efficiency); also in this case therefore it can be concluded that the method provide and underestimation of the remaining fuel (being the consumption overestimated).

Based on the above analysis, being the amount of fuel available most probably larger than the estimated value, the margin of 5 kg currently considered for fuel estimation error could be safely reduced (improving the EOL performances).

5. Preliminary EOL operations plan

The main goal of this activity was to define, based on the outcome of the analyses presented above in chapter 4, a maneuvering strategy permitting to achieve the target end-of-life orbit, minimizing the duration of the operations, and so their cost, but still keeping them properly under control; as the risk of not being able to bring the full maneuvers sequence to completion cannot be excluded, the selected strategy shall also permit to achieve as soon as possible a safe configuration versus the operational satellites and a reasonable re-entry time. At the same time the operations to be performed on the satellite to minimize that risk and on ground to cope with the changes of Metop-A orbital status (mainly the period) are identified.

5.1. EOL operational sequence overview

The following high level sequence of operations was identified (depicted in Fig. 18, not in scale):

1. Decrease the orbit by at least ~15 km below the nominal altitude, with a standard double-burn maneuver, to free the Metop-B and C operational orbit (safe circular orbit); this altitude reduction, which brings the altitude at the North-pole below the desired 795 km

for the EOL perigee, ensures that, even if no more operations are performed afterwards, the eccentricity evolution will never bring back the apogee to the operational altitude, cancelling out any collision risk with the operational Metop satellites and reducing the risk of long term pollution in case of fragmentation of Metop-A. That first maneuver also reduces strongly the LTAN drift (by nearly the 50%) and induces a very large relative drift with respect to the others Metop satellites (requiring therefore management of the deriving radio-frequency interference, as explained in paragraph 5.3).

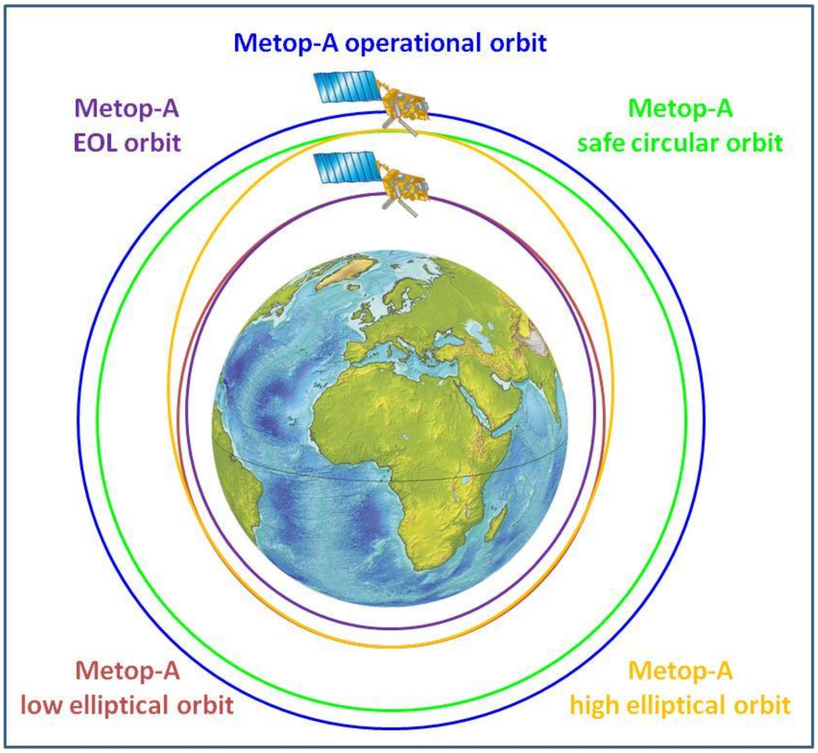

Figure 18. Metop-A orbital evolution during EOL operations

2. Bring down the perigee by ~200 km to ~10 km above the target value at the South-pole of 600 km, with a series of maneuvers at the North-pole (high elliptical orbit); this perigee reduction ensures that, even if no more operations are performed afterwards, a large fraction of lifetime reduction is achieved (to ~38 years); the little margin kept with respect to the target value ensures that no violation of the perigee constraint occurs during the final fuel passivation operations described in point 4 below; during this phase the LTAN drift is reverted (already when the perigee is lowered by ~40 km) and special operations at satellite levels have to be carried out, as described in paragraph 4.4, to ensure operability on the high eccentric orbital conditions.
3. Bring down the apogee at the North-pole up to when ~10 kg of fuel are estimated to be on board (5 kg to take into account for the estimation error, as explained in 4.7 and 5 kg as unusable fuel) with a series of maneuvers at the South-pole (low elliptical orbit); for the fuel estimation during that phase, the PBK method only will be used, due to the degradation of the PVT results for low pressure, as large fuel changes cause only marginal changes in the pressure; during this phase the apogee shall reach the target altitude of ~725 km.

4. Deplete all the remaining fuel performing long burns at the North-Pole during long combined visibility passes of Svalbard and Fairbank (presented in Fig. 15); the first burn is executed in the anti-velocity direction to reach the limit altitude of 600 km and then, if further burns are required, alternatively in the velocity and anti-velocity direction, to avoid violating the altitude limit (EOL orbit); the size of these alternate burns is reduced to keep the perigee always close to the 600 km; whenever fuel depletion is detected, full electrical and radio-frequency passivation is carried out.

5.2. Maneuvers implementation and orbit management

The size of the maneuvers that can be implemented (and thus of the orbital correction achieved) during the EOL operations is limited by a design limitation in the the duration of the propulsion phase (below 1000 seconds) and by the low pressure (well below 10 Bars) still available in the tanks (which can be increased by ~3 percent by tank heating); reduced maneuver duration ensures a negligible impact of the efficiency losses due to finite versus impulsive execution.

Several maneuvers are then needed:

- 2 on step 1 (both of at least ~3.5 m/s to implement the desired 15 km altitude reduction).
- 12 on step 2 (~50 m/s to be provided to reach the high elliptical orbit)
- 4 on step 3 (~15 m/s to be provided to reach the low elliptical orbit)
- 2 to 4 on step 4 (the first one of ~2.5 m/s, to reach the 600 km perigee and consuming ~5 kg of fuel; the remaining ones of half size and alternate sign, to keep the perigee below 605 km, each consuming around 2.5kg of fuel; two of those are needed to exhaust the foreseen remaining 5 kg; one more or less may be needed to cope with the estimation inaccuracy)

The standard operational approach of performing orbit determination after each maneuver to apply the obtained calibration results for the planning on the following maneuvers (leading to a standard rate one maneuver per day) is found not optimal since it would lead to nearly 3 week of operations. Instead, to speed up the acquisition of the final target orbit, maneuvers are executed as a sequences of 3 double maneuvers (with 1 orbit time de-correlation for step 2 and 3 in paragraph 5.1) separated by around 5 orbits without maneuver, as shown in Fig. 19 (orbits with maneuvers are identified in red); 6 maneuvers are provided in a time window of around one day (15 orbits), followed by around one day (13 orbits) without maneuver, during which to perform orbit determination (OD) and plan accordingly the next sequence of 6 maneuvers.

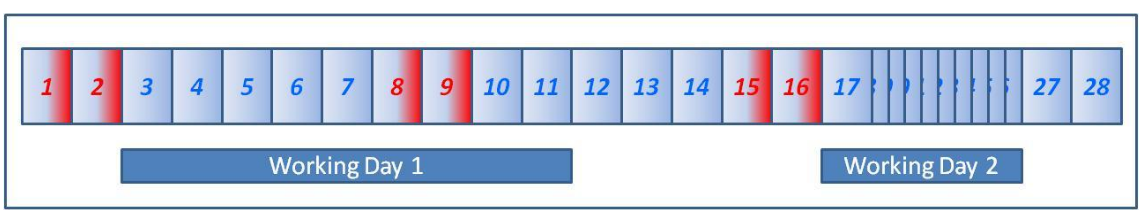

Figure 19. Metop-A EOL maneuvers sequence definition

The first burns of each sequence are executed on the two last opportunities before start of the working day (so at around 5:00 UTC); no OD is required within a maneuver sequence as monitoring of the time offset value (TOV, difference in signal acquisition time at the ground-station, proportional to the in-plane orbital deviation) with respect to the foreseen one and its synchronization, if needed, is sufficient to ensure ground-station acquisition capabilities; as a TOV of 2 seconds can be accepted by the used stations, whenever a TOV drift higher than 1 second is observed (a loss of visibility on one orbit is assumed) the maneuvers sequence is suspended, an OD is carried out to refresh the orbital knowledge (and the maneuvers calibration factors) and a new sequence is computed; 1 second of TOV drift per orbit corresponds however to a very large execution error of nearly 0.5 m/s, so this latter scenario is considered quite unrealistic, even if it cannot be excluded (due to possible degradation of the thrusting performances at very low pressure).

It is then possible to compress the entire EOL operations, in only 3 sequences (circularization and 4 perigee lowering maneuvers in the first, 6 perigee lowering maneuvers in the second and 2 perigee lowering and 4 apogee lowering maneuvers in the third), permitting to achieve the low elliptic orbit in less than week, as shown in Fig. 20;

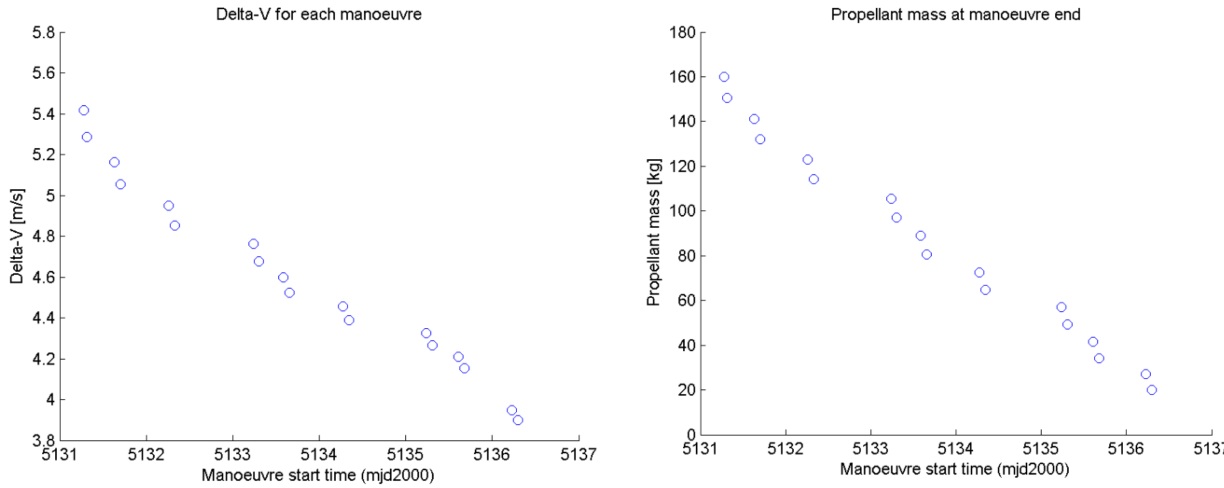

Figure 20. Metop-A EOL maneuvers size (left) and associated fuel evolution (right)

A high fidelity emulator of Metop-A propulsive and orbital behavior was developed by EUMETSAT to be able to perform in a detailed and agile manner these EOL analyses (figures from 20 to 22 are generated using that tool); an operational usage of this same tool is also foreseen to generate the reference maneuvers plan to be implemented by the FD operator and to refresh it after each OD based on the re-estimated orbit; this approach was validated operationally in the last EOL simulation executed in the past winter.

The evolution of the most interesting orbital parameters is presented in Fig. 21 here below, where it can be appreciated that the strategy properly ensures that the limit of 620 km of geodetic altitude is respected.

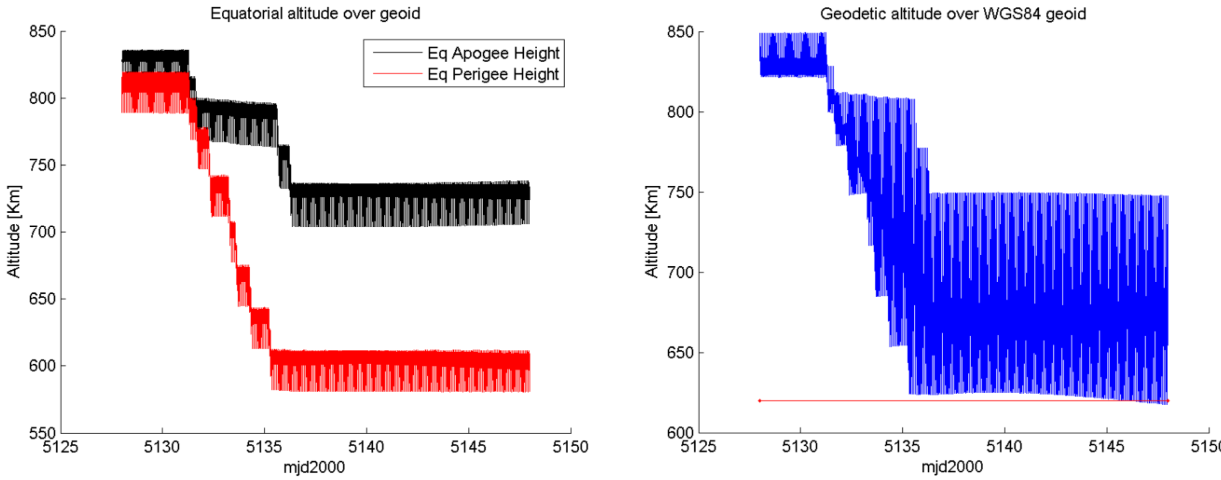

Figure 21. Metop-A EOL perigee/apogee (left) and altitude (right) evolution

5.3. Interference management

Because of the lower orbital altitude of Metop-A as soon as the first EOL maneuvers are executed, a large (and steadily increasing) drift in orbital position with respect to the other flying Metop satellites (Metop-B for sure and Metop-C most probably) is created.

As all the Metop satellite share exactly the same radio-frequencies (RF) both for telemetry, telecommand and ranging (S-band) as well as for scientific data download (X-band), as described in [2], regular RF interferences are expected whenever the orbital separation is below few degrees as presented in Fig. 22.

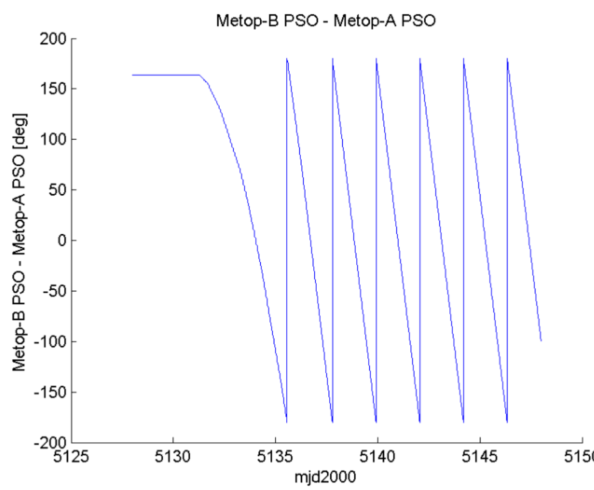

Figure 22. Metop-A relative position (wrt Metop-B) during EOL

During EOL operations it is foreseen to switch-off the Metop-A instruments; therefore there is not real need of keeping the X-band on (excepted may be to download GPS data, coming from the radio occultation – RO – instrument , which could be useful to increase the orbital knowledge of the satellite); therefore, in case an X-band interference is predicted, priority will be given to the operational satellites (Metop-B or Metop-C) and X-band will be muted on Metop-A (if not already off).

On another hand, the availability of the X-band ensure also full availability of the S-band (multiplexed to it); as a consequence the operational satellites (Metop-B or Metop-C) have little need of continuous S-band data for telemetry; ranging is also not mandatory thanks to the availability of GPS data from the RO instrument and commanding can be concentrated in few daily passes (out of the available 14); therefore, in case an S-band interference is predicted, priority will be given to Metop-A, to ensure full operability, and on the operational satellites (Metop-B or Metop-C) S-band will be muted.

<u>In any case it is recommended to execute fast EOL operations to minimize the number of RF interferences occurrences,</u>

5.4. Space debris conjunction monitoring

On what concerns monitoring of conjunction with space debris, very little can be done due to the large number of executed maneuvers, their large size (making any post maneuver prediction very unreliable) and their high frequency.

More than 12 hours are needed to determine a proper post maneuver orbit, provide it to JSpOC [11] and receive a feedback based on it and nearly the double if JSpOC is asked to determine the post maneuver orbit on its own; that makes useless to assess the status after the first two maneuvers in a sequence as any warning would be received after execution of the next maneuver in the same sequence; that rational on one side permits to discard the need of performing orbit determination between maneuvers in a sequence, on another shows that the best way to reduce the risk is to perform the maneuvers in a sequence with an as little separation as possible, overlapping so post-maneuver time periods during with the debris assessment is very unreliable.

The only useful monitoring could be after the third maneuver of each sequence, when a fresh orbit is available; also in this case however only events before the start of the next sequence, so within 24 hours after the end of the previous maneuver, would be of interest and they would be received around 12 hours after it, so with a very (too) little reaction time available (between zero and 12 hours); to implement any mitigation action in these conditions, also considering the not operational orbit where the satellite is, could be more dangerous than simply accept that risk.

Even if post maneuver predictions are very unreliable, as stated above, it is in any case recommended to perform a screening for conjunctions with operated satellite that could be found at lower altitude (a short list of these could be prepared prior to starting de-orbiting), taking large safety margins (of the order of 100 km) as done for the launch of a new satellite, and slightly modify the maneuvers plan in case such an event is identified.

6. Metop-A spring 2014 OOP execution

The Metop-A OOP foreseen in spring 2014 was carried out successfully, with a first burn on the 26th of March and a second burn two weeks later on the 9th of April: fuel tanks were heated by ~9 degrees over the nominal control point.

Based on the analysis presented in paragraph 3.1 (Fig. 9), it was decided to allow 120 seconds of the slew back to happen outside eclipse (penumbra event taken as reference); however the satellite expert, together with the satellite manufacturer, recommended to reduce that value by 45 seconds, to take into account the error between the foreseen and the real end of the slew back maneuver (clearly observable in Fig.9; the real slew-back end is visible as a jump, due to the TM gain change at mode end).

For the second maneuver the 45 seconds margins were considered not necessary, provided that the umbra event was taken as reference for the computation (time between umbra and penumbra considered sufficient to absorb potential delay in the end slew-back).

The inclination correction implemented was sufficient to initiate a LTAN cycle of more than 18 month (shown in Fig. 23), which shall permit execution of the next OOP maneuver in autumn 2015 (2 minutes LTAN violation around the 20th of October), as foreseen in scenario *E* (in paragraph 3.1).

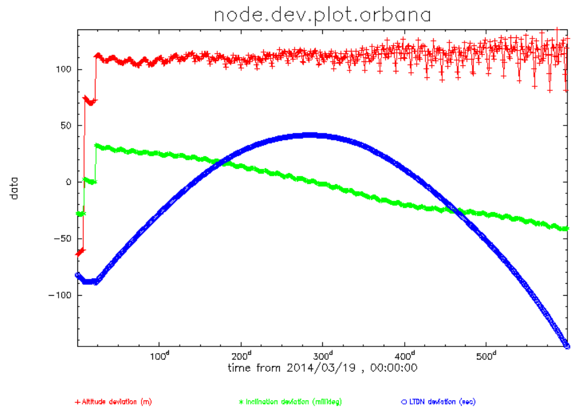

Figure 23. Foreseen inclination and LTAN evolution of Metop-A orbit after 2014 OOP

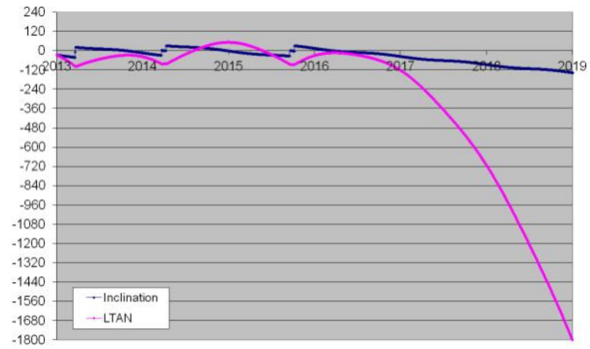

Figure 24. Foreseen inclination and LTAN evolution of Metop-A orbit including effect of 2015 OOP

For the next OOP maneuver it is foreseen to use the same margins of the second burn of the spring 2014 maneuver for the end of the slew-back but to reduce the margins for the start of the slew, as during the first ~20 seconds the platform has not yet acquired an important deviation.

The resulting LTAN evolution is shown in Fig; 24; the 30 minutes LTAN deviation limit is reached at the end of 2018 and nearly 6 months more are available if up to 40 minutes of LTAN deviation are accepted (as explained paragraph 3.2), which should ensure availability of the Metop-A satellite up to the start of operation of Metop-C even in a very pessimistic scenario (large delay of Metop-C launch).

Due to the reduction of the thrusting time for the spring 2014 OOP, a little more fuel shall be available on board after execution of the autumn 2015 OOP: 170 kg (0.3 kg more), which leads to very marginal improvement of the EOL performances (0.1 year faster).

7. Conclusions

The paper presents the current status of preparation of the EOL strategy and of the related operations for the Metop-A satellite, showing how it is possible to maximize the operational return of a mission behind his operational lifetime without impacting in a remarkable manner its performances in terms of compliance with the international space debris mitigation guidelines (even if the satellite was not designed for that). Being the EOL operations quite complicated, several issues have to be carefully considered in their preparation and execution, requiring good coordination between the FD and the satellite experts and support of the satellite manufacturer.

8. Acknowledgements

The authors would like to thanks the LEO FD team not only for the support to the execution of many of the analyses presented in this paper (in particular Antimo Damiano), but also for the excellent preparation and execution of the spring 2014 OOP maneuver (coordinated by Francisco Sancho) and for validation of the FD operations for EOL (prepared by David Lazaro).

Thanks also to the Metop satellite operations team (namely to Tatiana Paulino), for the effort put in consolidating with the satellite manufacturer the optimal safety margins for the spring 2014 OOP execution and the various options for EOL presented in this paper.

7. References

[1] Operational local time and eccentricity management for Metop-A
A. Damiano and P.L. Righetti, EUMETSAT; 21st ISSFD, Toulouse, France, 2009

[2] Metop-B orbit acquisition operations; preparation and execution
P.L. Righetti, F. Sancho and T. Paulino, EUMETSAT; 23rd ISSFD, Pasadena, CA, USA, 2012

[3] Space Systems, Space debris mitigation requirements
ISO 24113, 2011

[4] STELA SW user's guide
CNES, 2010; http://logiciels.cnes.fr/STELA/fr/logiciel.htm

[5] DAS SW user's guide
NASA, 2012; http://orbitaldebris.jsc.nasa.gov/mitigate/das.html

[6] SPOT-2 EOL Orbital Operation
A. Moussy and G. Beaumet, CNES; Debrief on SPOT-2 EOL, Toulouse, France, 2012

[7] 2010 and beyond – the ENVISAT mission extension
J. Frerick, B. Duesmann and M. Canela, ESA; Envisat Symposium, Montreux, Switzerland, 2007

[8] NOAA Weather Satellites information System
http://noaasis.noaa.gov/NOAASIS/ml/genlsatl.html / Polar-Orbiting Satellites

[9] Analysis in case of large error at injection orbit
S. Garces and P. Ghivasky, ASTRIUM; EUMETSAT study, 2011

[10] Metop-A End-of-Life Disposal Analysis
H. Krag, B. Bastida and S. Lemmens, ESA/ESOC; EUMETSAT study, 2011

[11] Evolution of EUMETSAT LEO Conjunctions Events Handling Operations
D. Lazaro and P.L. Righetti, EUMETSAT; 12th SpaceOps, Stockholm, Sweden, 2012