Feasibility of Metop-A Mission Extension on Drifting Local Time

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On 19th October 2006, Metop-A, Europe's first polar orbiting operational meteorological satellite, was successfully launched into its operational sun-synchronous orbit. After more than 10 years of operations, the satellite is still in excellent health and the data produced are still considered extremely useful by the users' community, who requested EUMETSAT to maintain the satellite operational as long as possible. However, very little fuel is available on-board for orbit maintenance as a large amount (close to 50% of the total available at beginning of life) is reserved for end-of-life operations. While in-plane maneuvers can still be executed to maintain the semi-major axis and perform collisions risk mitigation actions, fuel expensive out-of-plane maneuvers to control inclination cannot. Consequently, the Local-Time of the Descending Node will drift outside the design envelope of 09:30 +/-15 minutes. The survivability of the platform and the usefulness of mission data generated by the instruments outside this design envelope will ultimately determine the duration of the mission extension. In order to assess platform survivability and whether mission data can still be exploited, several analyses have been carried out jointly by the Flight Dynamics and the Metop Operations teams in EUMETSAT. These analyses show that it should be possible to extend the Metop-A mission without any major risk or significant loss of performance up to a local time drift of nearly 2 hours, permitting to reach the end of 2021.

Key Words: Mission extension, Drifting orbit, Power/Thermal balance

1. Introduction

Metop is the space segment of the EUMETSAT Polar System (EPS), Europe's first polar orbiting operational meteorological satellite system (Fig. 1).

EPS is the European contribution to a joint European-US polar satellite system called the Initial Joint Polar System (IJPS). On 19th October 2006, the first Metop satellite (Metop-A) was successfully launched from the Baykonur Cosmodrome by a Soyuz/Fregat launcher into its operational Sun-synchronous orbit. After more than 10 years of operations the satellite is still in excellent health.

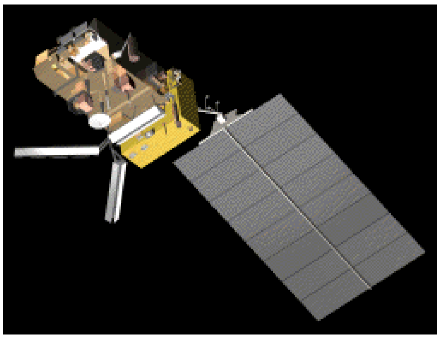

Fig. 1. Metop-A satellite

Since 2013, after the start of the operational phase of the second Metop satellite (Metop-B), the EPS mission is carried out by a dual-satellite system, with the two satellites on the same orbital plane and separated in orbital phase by around 180 degrees, as shown in Fig. 2. This ensures a much better coverage and therefore permits the implementation of more accurate meteorological products. The added value is such that the need of ensuring continuity of dual-satellite operations was made explicit by the meteorological users.

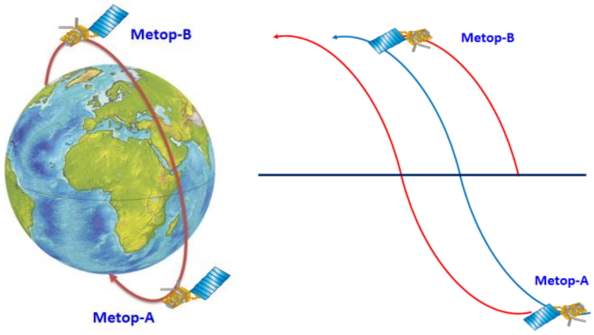

Fig. 2. Metop-A/Metop-B dual satellite configuration

To ensure continuity of the dual-satellite mission, Metop-A must be available at least up to the start of the operational phase of the third Metop satellite (Metop-C), whose launch is currently foreseen on the last quarter of 2018. In order to ensure in-orbit redundancy for the dual-satellite constellation and cope with possible failures on the two prime spacecrafts (Metop-B and Metop-CC), it is highly recommended to keep Metop-A in orbit even afterwards. Many users have also demonstrated interest in utilizing data from all three satellites, which should permit the development of new meteorological products.

Currently very little fuel is available on-board for orbit maintenance, as very a large amount (157kg of fuel out of the 315kg available at the start of the mission) is reserved for end-of-life operations; although not applicable to Metop due to its design age, EUMETSAT is making every effort to comply with ISO 24113 Space Debris Mitigation guidelines;

crucially, this means bringing the satellite down to an altitude permitting natural re-entry in the atmosphere within 25 years (as already explained in Ref. 1); that implies that inclination control (very fuel expensive), and consequently control of the Local Time of the Descending Node (LTDN, whose nominal value for Metop is 9:30), cannot be performed any longer and, therefore, the only way to extend the Metop-A mission is by letting the local-time drift toward earlier times.

From a users' perspective, that drift is not considered as detrimental for the tri-satellite mission, but rather as an opportunity to even further extend the products portfolio with new observation geometries: early morning LTDN data, Metop/NOAA overlaps opportunities outside the polar regions (described in Ref. 2), improved coverage for the Scatterometer ASCAT (already addressed in Ref. 3); moreover, the mission extension may represent an opportunity for performing special operations for further characterization of the instruments (described in Ref. 4).

However, to implement a local-time drifting mission with a satellite conceived for operations on a Sun-synchronous orbit is not straight forward as several problems arise when the local time diverges from the nominal design value.

2. LTDN Drift Feasibility Analyses

The last inclination maintenance maneuver for Metop-A was performed the 31 of August 2016; no further inclination correction is possible, due to the limited fuel on-board available for orbit maintenance (more details can be found in Ref. 5); the resulting long-term LTDN evolution is presented in Fig. 3.

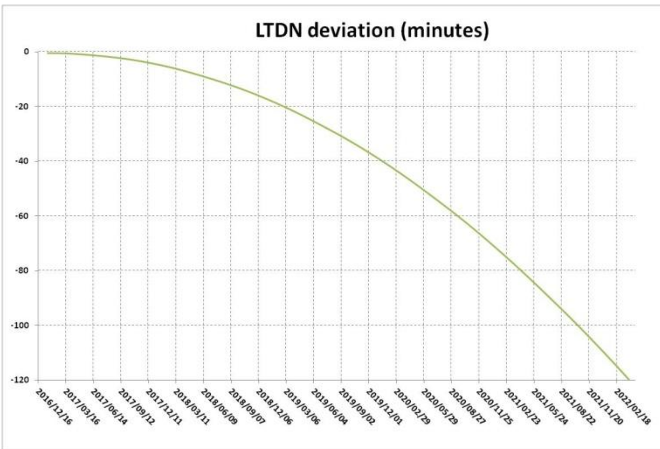

Fig. 3. Metop-A LTDN foreseen evolution

It can be observed that the LTDN deviation will reach one hour (LTDN of 8:30) around mid September 2020 and 2 hours (LTDN of 7:30) around beginning of April 2022.

The impact of such a large LTDN deviation on a satellite designed for operations on a Sun-synchronous orbit within an envelope of +/-15 minutes is not negligible. In order to assess if a mission extension in drifting local time is really feasible, several analyses have been carried out by the Flight Dynamics and the Metop Operations teams in EUMETSAT.

2.1. Impact on the AOCS Sensors

The Metop satellites make use of a Digital Earth Sensor (DES) to nearly continuously monitor the pitch and roll pointing of the platform and of a Digital Sun Sensor (DSS), to ensure attitude control in yaw.

The DSS Field of View (FOV) is a slit normal to the radial direction with semi-angle of ~21 degrees and a off-pointing (with respect to the orbital velocity) of ~36 degrees toward port-board (to be aligned with the mean Sun nominal direction for nominal LTDN of 9:30); the Sun is observed once per orbit, close to the northernmost position, (when the Sun enters into the satellite's zenith hemi-space, as in Fig. 4), and the deviation between that observation and the expected one is used first of all to reset the yaw error to zero and then to calibrate the gyroscopes to ensure accurate yaw commanding during the entire following orbit.

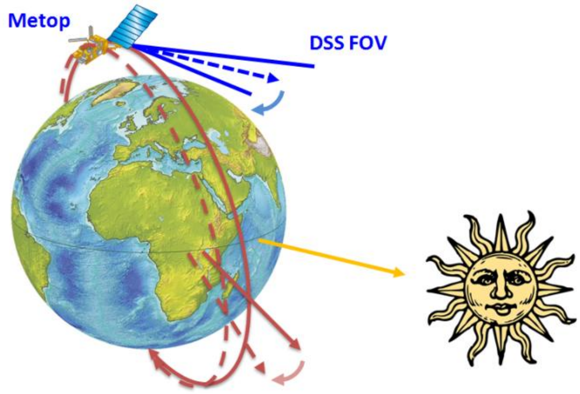

Fig. 4. Metop DSS geometry evolution with LTDN drift

Due to the deviation in LTDN, the angle between the Sun direction and the orbital plane increases, causing a displacement of the Sun in the DSS FOV toward port-board. For large enough deviations in LTDN, the Sun is no more visible in the FOV. The first Sun visibility gap is expected to happen at the end of 2020 and last around 3 months (the Sun re-enters the FOV in spring thanks to the yearly East/West movement of the Sun around its mean direction). The Sun is expected to disappear permanently from the FOV in mid September 2021.

The AOCS shall ensure stable behavior in yaw using only the gyroscopes during these periods. The long term stability of the gyroscopes is monitored routinely by Flight Dynamics and the measurement drift observed since the beginning of the mission is presented in Fig. 5.

From this, it can be observed that the long term stability is excellent (~2E-5 degrees per second in 10 years), while the medium term is affected by a not negligible seasonal effects (6 months pulsation of ~3E-5 degrees per second, on the gyro axis controlling the yaw, in green). A maximum drift of ~3E-5 degrees per second can therefore be expected in the three months of gap, which would lead to a yaw deviation of ~0.03 degrees (expected yaw deviation can be computed from the gyro drift divided by the orbital pulsation, ~1E-3 radians per second for Metop). Such a deviation is considered more than acceptable for fulfilling the mission goals.

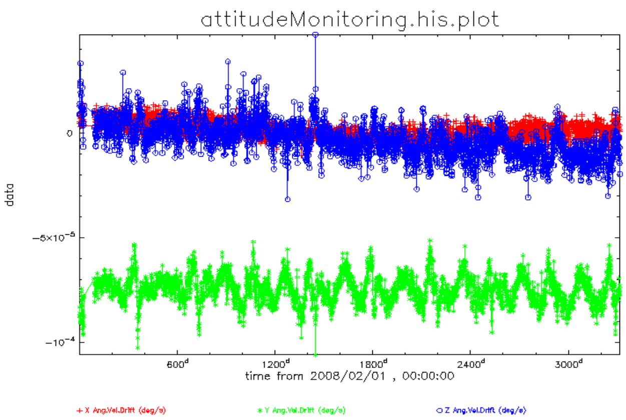

Fig. 5. Metop-A gyroscopes measurement drift history

In order to verify that the yaw deviation remains acceptable, above all if operations continue later than end 2021, it is possible to observe it making use of time measurements of the signal transmitted by the on-board active instrument (the Scatterometer ASCAT) and received on the ground by calibration antennas (located in Anatolia); as it is possible to measure with a good accuracy (below 0.1 second) the time of reception of the ASCAT pulse and as the instrument foot-print gets to more than 1000 km away from the ground-track in cross-track direction, a yaw deviations larger than 0.04 degrees shall be well observed from the difference between observed and expected time of reception (Fig. 6); in case such a deviation is observed, compensation is possible by actively biasing the satellite in yaw in the opposite direction; this same yaw error observation procedure was used operationally to confirm proper orientation of the satellite; the large drift observed in yaw (green curve in Fig. 5) could then be associated to a mounting bias of the gyroscopes of around 0.07 degrees.

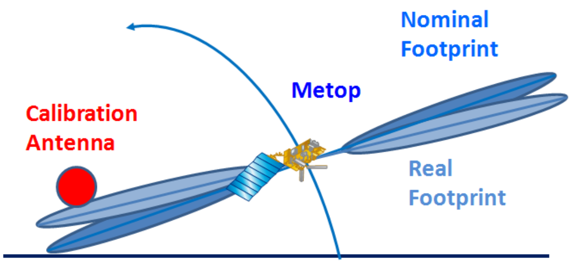

Fig. 6. Metop ASCAT footprint change for yaw deviation

Marginal performances degradation shall also be expected in pitch and roll, being also the DES affected by the LTDN deviation, as the infra-red shape of the Earth changes; the tables used to compensate for that, optimized for the nominal local time, become then inaccurate; dynamic adaptation of these tables to the current LTDN is however not considered necessary.

More serious is the problem caused by the reduction of the duration of the eclipse when the local time drifts; the DES is masked to avoid blinding of the sensor whenever the Sun falls into the FOV (Fig. 7), from around the southernmost point (when the Sun enters into the satellite's nadir hemi-space) to start of eclipse and then from end of eclipse around the northernmost point (when the Sun exits from the satellite's nadir hemi-space).

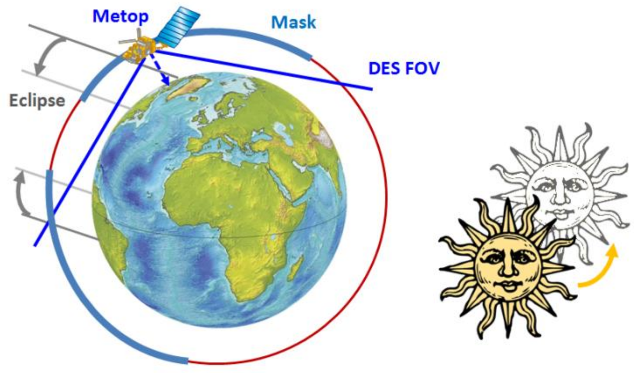

Fig. 7. Metop DES masking evolution with LTDN drift

As the Sun masks for the DES are computed on-ground by Flight Dynamics considering the shortest eclipse expected for nominal LTDN, these masks need to be enlarged accordingly, to avoid blinding of the DES and consequently entry into safe mode; as the percentage of unavailability of the DES signal in the AOCS gets then higher, the performances in pitch and roll pointing are expected to further degrade. Once the LTDN gets below 8:40 (second half of 2020), the Sun shall always remain sufficiently far away from the FOV of the STD not to be necessary anymore any masking.

2.2. Impact on the Instruments

Due to the drift in LTDN, the direction from which the Sun light impinges on the instrument changes significantly, as can be observed in Fig. 8.

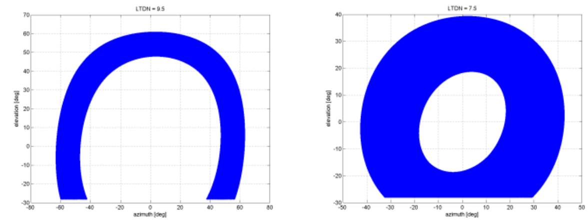

Fig. 8. Yearly evolution of the Sun vector direction from Metop satellite for nominal LTDN (9:30) and for 2 hours LTDN deviation (7:30)

While for the nominal LTDN the Sun is visible in two azimuth windows around 25 degrees wide, located approximately at azimuth +/-50 degrees (only negative elevations are meaningful, as for positive values the Sun is in the zenith hemi-space, so not visible from instruments looking at nadir, as is the case for Metop), for a deviation of 2 hours in LTDN the Sun is observed during the year in any azimuth value between approximately +/- 45 degrees; that exits significantly from the specifications and may lead to stray-light phenomena, potentially affecting the quality of the acquired data.

For important LTDN deviation, moreover, the satellite does not enter Earth eclipse during large periods of time (for LTDN 8:00, the entire month of February, as shown in Fig. 9), which makes calibration using internal sources (as done for the GOME-2 spectrometer) ineffective. Also for GOME-2, the Sun no longer enters the FOV of the Solar Calibration port at certain times of year (similarly to the DSS), further degrading the data quality (detailed analysis is provided in Ref. 5).

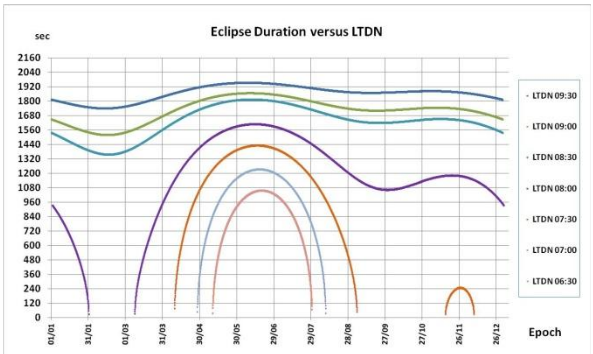

Fig. 9. Yearly evolution of the eclipse duration for different LTDN

2.3. Impact on the Energy balance

The energy collected by the solar array can be in first approximation computed from the angle between the orbit plane and Sun direction (Beta-Angle, whose evolution for different LTDN is depicted in Fig. 10), corrected taking into account the 22 degrees of mounting bias of the solar array (observable in Fig. 1) to obtain the Sun incidence angle (between Sun direction and solar array normal), the duration of the eclipses (presented in Fig. 9) and the distance from the Sun (with minimum close to the winter solstice).

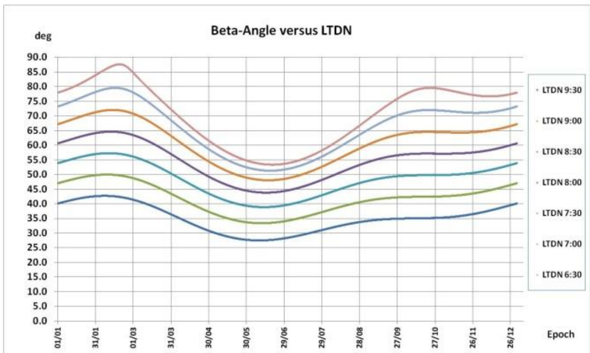

Fig. 10. Yearly evolution of the Beta-Angle for different LTDN

The result of the above mentioned computation presents, after calibration of the solar array efficiency (~13%), a quite good agreement with the flight data collected during routine operations, as presented in Fig. 11.

The discrepancy observed in February (~2%) is due to the fact that yaw steering mode is not modeled, which further aligns the solar array normal to the Sun direction at the descending node; the impact on the collected energy is larger around February as the Sun incidence angles on the solar array (directly linked to the Beta-Angle) is larger; whenever the eclipses vanishes the benefit on the descending node is compensated by an equal penalty on the ascending node.

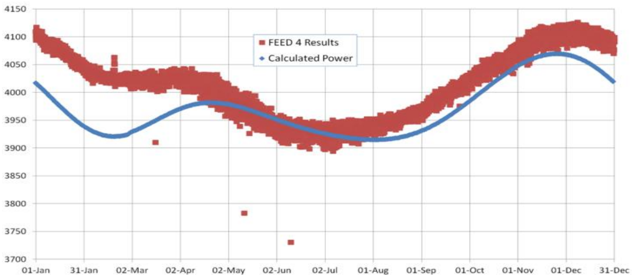

Fig. 11. Yearly evolution of mean orbital power for nominal LTDN

What can be observed is that reductions of the Sun incidence angle on the solar array are compensated by reductions of the eclipse duration, leading to a nearly flat orbital energy availability profile. This same phenomenon can be observed till a LTDN of around 8:00. At this point eclipses start to disappear around February, as shown in Fig. 9. As the Beta-Angle then increases further, the generated orbital energy falls significantly (the compensation provided by the reduction of the eclipse duration gets saturated). This effect can be observed in Fig. 12.

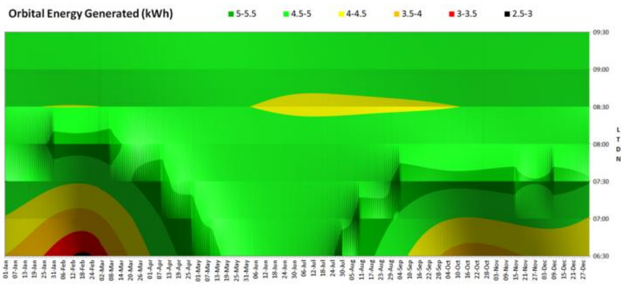

Fig. 12. Available orbital energy as function of Day of Year and LTDN

To evaluate how the orbital energy margins (which must be positive to continue the mission) evolve, it is necessary to also have an idea of how the orbital energy consumption of the platform and payload evolves, to keep temperature within limits. Reference data were provided by ESA-ESTEC for different LTDN in February. This is when the Beta-Angle is maximum, are and therefore the worst case. These data are presented in Fig. 13.

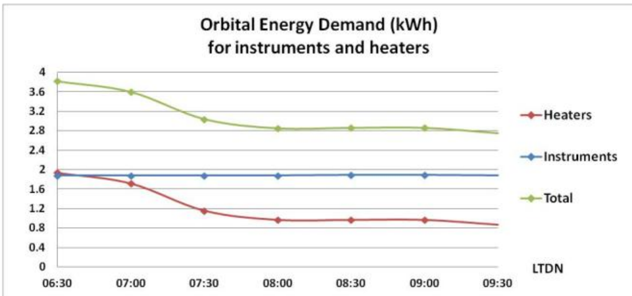

Fig. 13. Orbital Energy Demand for different LTDN

A fast increase of the heater energy demand is observed for LTDN lower than 8:00. That is linked primarily to shadowing of the satellite body by the solar array with decreasing LTDN; the larger the deviation in LTDN the larger is the percentage of the satellite body in shadow, as illustrated in Fig. 14.

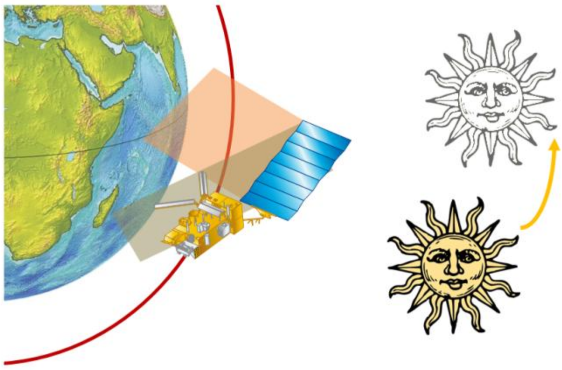

Fig. 14. Shadowing of the solar array on the satellite body

A dedicated finite elements study was run by GMV for EUMETSAT (Ref. 6) to analyze in detail the percentage of the satellite body put in shadow by the solar array for different LTDN and dates. Results for February (to ensure consistency with ESTEC data) were used, to compute the satellite body surface illuminated by the Sun, considering or not the effect of the solar array shadowing. The results for the case with LTDN 6.50 is presented in Fig. 15; the important effect of the shadowing, reducing the illuminated surface for the satellite faces (mainly the one where the array is mounted) is evident.

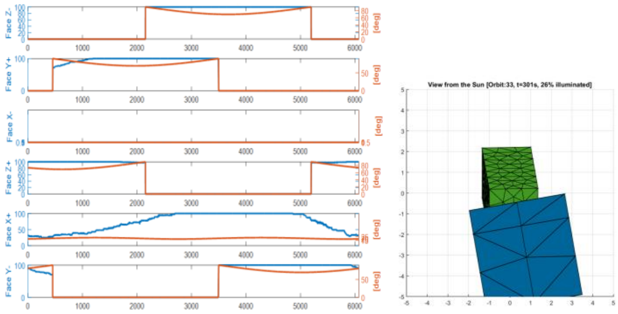

Fig. 15. Satellite faces illumination conditions for LTDN 6:50

As shown in Fig. 16, the loss of illuminated surface is negligible for LTDN larger than 8:00 and then increases fast, reaching nearly 20% for LTDN approaching 7:00.

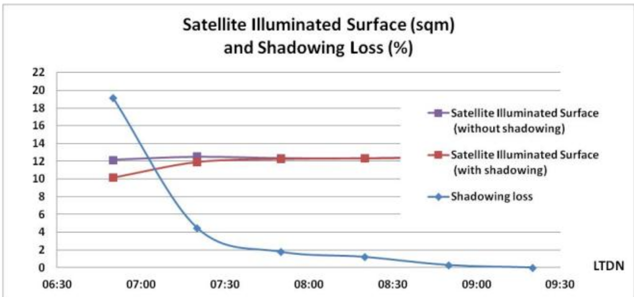

Fig. 16. Satellite body illuminated surface for different LTDN

It is now possible to compare the increase of energy spent by the heaters and the loss of Sun illumination energy reaching the satellite body due to shadowing of the solar array; the correlation, shown in Fig. 17, is quite strong, confirming the origin of the increase on energy demand.

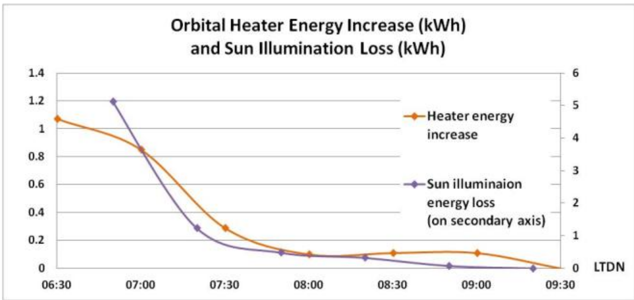

Fig. 17. Heater energy demand increase and Sun illumination energy loss for different LTDN

To obtain a rough estimation of the energy margins it is then sufficient to remove from the available orbital energy, presented in Fig. 12, the energy demand presented in Fig. 13, applying, for a given LTDN, the same worst case value for each day of the year. The obtained result is presented in Fig. 18, which also includes the LTDN trajectory for Metop-A for the next years, from Fig. 3.

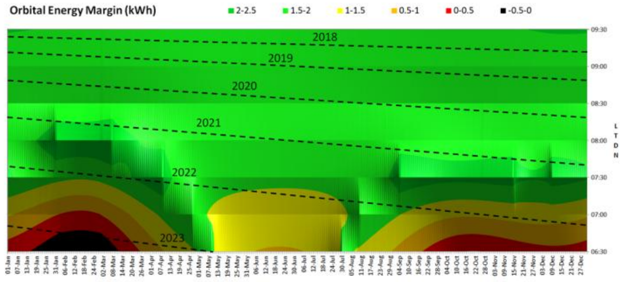

Fig. 18. Energy margin as function of Day of Year and LTDN

It can be observed that positive margins are available till beginning of 2023. As worst case energy demand values are considered, margins outside the reference month (February) are even larger. In the first quarter of 2023 the combined effect of the decrease of the available energy and of the increase of energy demand leads to an unsustainable balance.

The option of switching off some of the instruments to save energy does not bring any significant benefit, as they normally generate a significant amount of heat; so by switching them off, the duty cycle of heaters would simply increase to compensate. The option to apply an attitude bias in yaw, to reduce the Sun incidence angle, may permit to acquire the extra energy needed to pass over the critical season.

2.4. Impact on Thermal balance

The fact that the energy balance is positive, however, does not imply that the thermal equilibrium inside the satellite is respected. ESA-ESTEC also provided worst case (February) temperatures for different values of LTDN and different equipment, as summarized in Fig. 19.

It can be noticed that for a LTDN of 8:00 problems may be observed for the temperature on the Fuel Control Valves (FCVs), which may lead to hydrazine freezing. This would have catastrophic effect on the mission, as well as on the capability to de-orbit the satellite at the end of the mission.

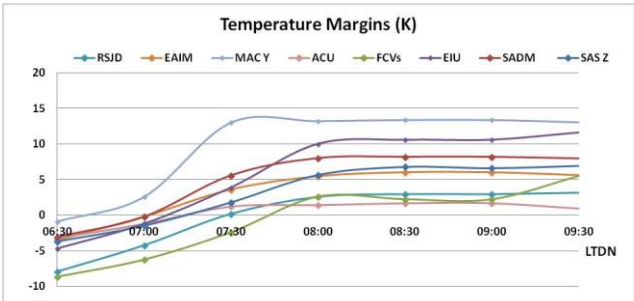

Fig. 19. Temperature margins

2.5. Power/Thermal Summary

Given the inherent uncertainty in thermal modeling, it is crucial to have a qualitative understanding of the effects of the decreasing LDTN. In summary, we observe that as long as we still have eclipses and there is no significant shadowing from the array, i.e. up to a beta angle of 65 degrees, there is no overall impact. After this, the energy margins and temperatures can drop quickly.

Figure 20 describes how the Beta-Angle evolves in function of the LTDN and the Day of the Year (same information as in Fig. 10); the LTDN evolution of Metop-A is also depicted.

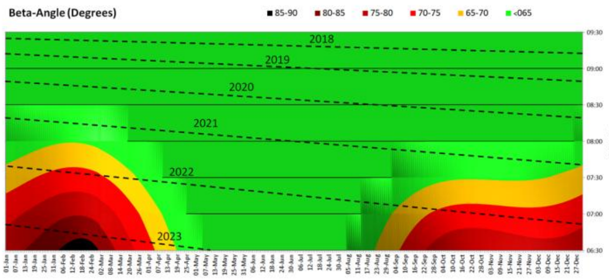

Fig. 20. Beta-Angle as function of Day of Year and LTDN

It can be noticed that even if the first occurrence of a Beta-Angle of 65 degrees is observed for a LTDN of 8:00, Metop-A will not reach this until an LTDN of nearly 7:30 (end 2021) due to the trajectory of the LTAN.

3. Agreed long term strategy for Metop-A

From the above presented analysis the follow limits for the mission extension of Metop-A can be identified:

- AOCS: end 2021: DSS signal loss
- Instrument: none (just degradation of data)
- Energy: beginning 2023
- Thermal: end 2021

Based on these results the decision was taken to extend the Metop-A mission till end of 2021, when the LTDN will have reached a deviation of nearly 2 hours.

Even if degradations on the AOCS pointing accuracy and on the instrument data quality (both affecting the quality of the final meteorological products) are expected, the benefits of the mission extension, presented in paragraph 1, are still considered relevant enough to justify the mission extension (and the related extra cost to have it implemented).

Continuous monitoring of the available energy and thermal margins is needed, to ensure that these are in line with the predictions. In case of significant deviations, leading to margins decreasing much faster than expected, the capability of de-orbiting the Metop-A satellite on short notice shall be ensured (EUMETSAT is already working on this, as explained in Ref. 1).

On what concerns the implementation of the mission extension, the user requested that the nominal ground track is kept as long as possible. This implies, as explained in Ref 3, that Metop-A will get closer and closer to Metop-B in orbital phase. In mid 2019, once a separation in orbital phase of around 25 minutes is achieved (minimum required to ensure safe operations of both satellite with a single ground station), ground-track control will have to be abandoned and Metop-A will start being controlled in orbital phase with respect to Metop-B. This will cause westward drift of the ground-track (also explained in Ref. 3).

The westward ground-track drift will permit implementation of alternative coverage configurations. This is particularly interesting for ASCAT because the shape of its footprint causes a large coverage gap around the ground-track nominally (see Fig. 6). By allowing the ground track to drift, Metop-B will nearly completely fill the gap from Metop-A after circa 45 minutes of LTDN drift, improving significantly the overall coverage figures, as shown in Fig. 21

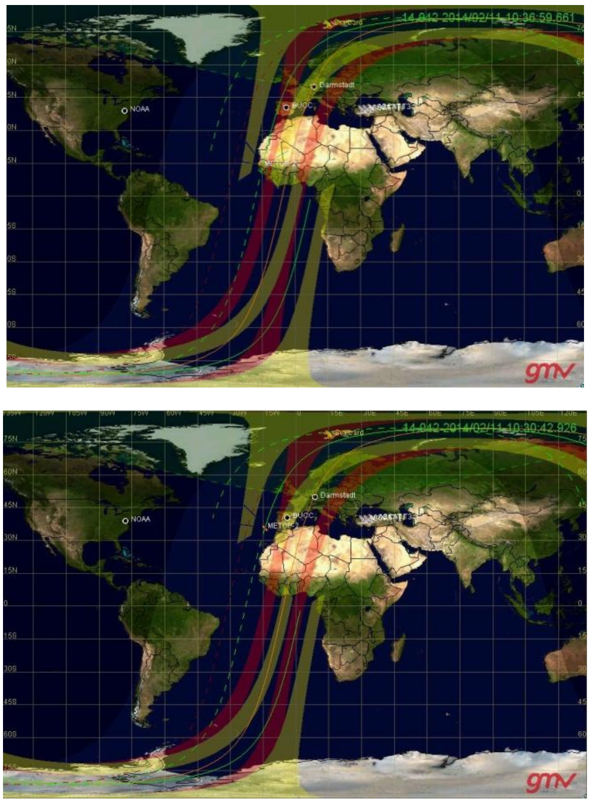

Fig. 21. Metop-A/Metop-B ASCAT swats coverage for nominal LTDN and after ~45 minutes of LTDN drift

Metop-C is foreseen to be launched in the last quarter of 2018 with its commissioning carried out on a location around

1/3 of orbit in front of Metop-B, to avoid interferences with Metop-A, still controlled in its ground-track. Once commissioning is completed, and ground-track control is abandoned on Metop-A, it will be possible to move Metop-C into the operational location occupied by Metop-A during routine operations. This scenario is described in Fig. 22.

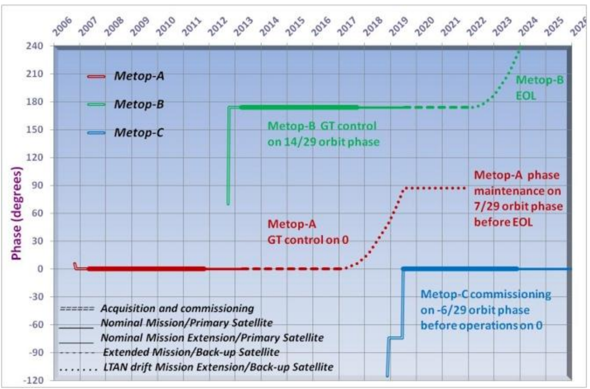

Fig. 22. Evolution of the Metop constellation; nominal scenario

An alternative scenario is also considered: the Metop-C satellite, after the end of its commissioning, is kept on its commissioning location also for operations and Metop-A is brought back (slowly) to a position half way between the two other satellites, implementing a more equally spaced constellation. This option is described in Fig. 23.

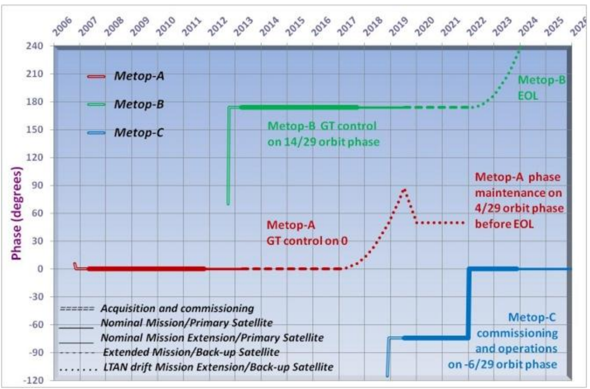

Fig. 23. Evolution of the Metop constellation; alternative scenario

The selection of which configuration to implement for the three-satellite constellation is driven by several factors, including operability (both at satellite support and data processing level), data continuity with previous dual-satellite operations, scientific return of the data.

Detailed analysis on that direction are currently been carried out in EUMETSAT to select the optimal configuration for the three-satellite operational phase; a final decision has to be taken before end of Metop-C commissioning, so in the first half of 2019.

4. Conclusion

The analysis preformed did not show any issue preventing EUMETSAT to extend the operational mission of Metop-A on drifting LTDN till the end of 2021. Marginal degradation of the performances, both at satellite and instrument level, is expected, which however is not expected to affect significantly the usefulness of the meteorological data.

Data from Metop-A, Metop-B and Metop-C will be available to the users during nearly 3 years; afterward, Metop-A will be de-orbited into a 25 years re-entry orbit.

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