Normal Paper

Flight Dynamics Analysis of extended Lifetime for the Metop-A GOME-2 Instrument

Antimo Damiano [1], Pier Luigi Righetti [2] and Ruediger Lang [3]

[1] RHEA Group at Flight Operations Division, EUMETSAT, Eumetsat Allee 1, Darmstadt, 64295, Germany
[2] Flight Operations Division, EUMETSAT, Eumetsat Allee 1, Darmstadt, 64295, Germany
[3] Remote Sensing and Products Division, EUMETSAT, Eumetsat Allee 1, Darmstadt, 64295, Germany

Abstract

EUMETSATs Metop-A, launched on 19 Oct 2006, is the first flight model of the EUMETSAT Polar System (EPS). The Metop satellites share a sun-synchronous LEO orbit with a 29 days / 412 revolution cycle and Local Time of Descending Node (LTDN) of 09:30 local time. Together with Metop-B, launched in 2012 and Metop-C launched on 07 Nov 2018, they constitute the EPS space segment.
All Metop host the Global Ozone Monitoring Experiment–2 (GOME-2), a hyper-spectral Ultra Violet-Visible to Near Infrared spectrometer.
Daily Sun observations are mandatory for signal calibration. As Metop-A is approaching its end of life, Out of Plane (OOP) manoeuvre have been discontinued. The resulting loss of orbit inclination control leads to LTDN drift. The related orbital plane precession causes Sun visibility gaps lasting several days.
The first part of the paper deals with the link between the last OOP imparted, the LTDN evolution, and the comparison between expected and observed GOME Sun visibility in 2018.
As the gap characteristics depend on possible instrument mounting bias, the second part shows the analyses done to estimate these biases using actual Sun and Moon observations; a little platform bias in pitch indeed improves the Sun/Moon observation residuals and the signal timing w.r.t. predictions, although it introduces other geolocation problems.
The third part describes the Sun visibility gap predictions for December 2018-January 2019, the planned platform yaw-bias manoeuvres and their effects on the observations.

Introduction

The GOME-2 instrument calibration campaigns heavily depend on the capability to keep the Metop-A orbit LTDN under control. With dwindling fuel, the needed inclination manoeuvres have been discontinued after the last such manoeuvre conducted in August 2016.

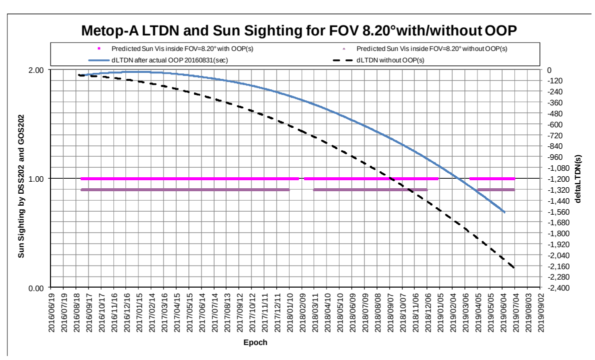

Figure 1 Metop-A LTDN after last Inclination Manoeuvre

The manoeuvre beneficial effect on the LTDN (cyan curve) w.r.t. to the LTDN without manoeuvre (black dashed curve) is shown in Figure 1 (upper graph). The same figure shows that the GOME-2 sun visibility (magenta bar) has no gap before February 2018, as expected.

GOME-2 is mounted on the Metop side facing the spacecraft flight direction. Apart from the window used for nominal grazing atmosphere measurements, a dedicated Sun slit is used for the daily calibration measurements, described in Figure 2.

The Sun slit nominal Field of View (FOV) as provided by the instrument documentation is 8.2 degrees. This dictates that the operational window for the Mean Local Solar Time (LTDN) of the Metop orbit must be 09:30 local time ±120 seconds.

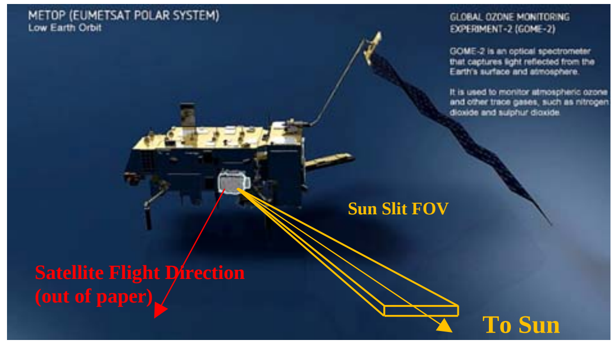

Figure 2 Metop Satellite, GOME and Sun Calibration Slit

Predicted Sun Visibility Gap in Winter 2018

This window has basically governed the mission for the past 12 years and has influenced the flight dynamics strategy for inclination manoeuvres, which are used to steer the LTDN. Close to the EOL, no more such manoeuvres are performed, thus leaving the LTDN naturally drifting towards smaller values. Based on the FOV value of 8.2 degrees, accurate predictions were drafted to see what happens to the Sun visibility after the LTDN would hit the 120s threshold.

The results are presented in Figure 3. The predictions have been done for the nominal 8.2 degrees and for a conservative value of 8.05 degrees. This ensures that whenever the Sun centre reaches that value, almost the whole Sun disk is inside the Sun slit FOV. It can be seen that the LTDN is parabolically drifting off and that therefore the Sun sweeps the FOV towards the FOV edge until it cannot be seen any longer in the Sun slit. For a FOV of 8.2 degrees this happens between 2018/01/27 and 2018/02/18 (orange line). The concept of Sun visibility gap comes into play because any Sun visibility shorter than a given threshold (30 seconds) is discarded by the instrument data processing chain.

The Sun visibility duration is displayed in Figure 4 for a FOV of 8.05° and 8.20.The Sun visibility gap is evident. Based on these predictions a series of studies was conducted to mitigate the effect of the Sun Visibility gap.

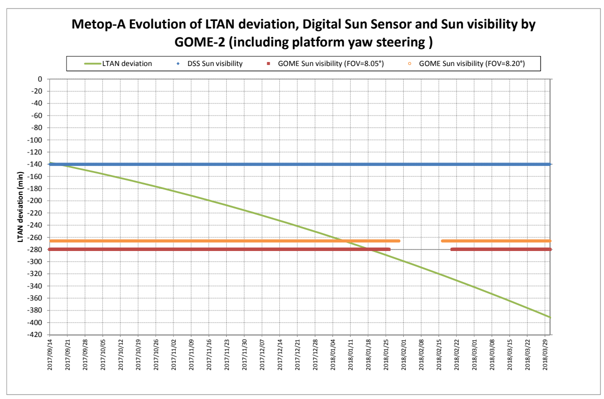

Figure 3 Sun Visibility vs. Time for a drifting LTDN deviation

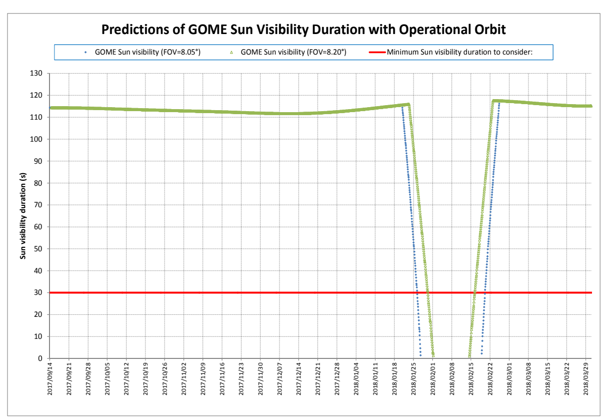

Figure 4 Sun Visibility Duration vs. Time in Winter 2017/2018

The most complex effort was to model an artificial solar signal in order to keep GOME-2 generating nominally calibrated measurements under any condition. The artificial solar signal is used for measurements calibration purposes for the periods during which the Sun is temporarily not visible in the FOV.

This Sun model was developed by the CGI Inc. company under EUMETSAT contract EUM/CO/15/4600001614/RL. The model is essentially a forecast model and is modelling the expected evolution of the solar signal based on the latest nominally processed solar mean reference spectra (SMR). This model uses input parameters like solar angle azimuth, solar distance, temperature and parameters describing the solar variation (like F10.7 and MgII indices) either taken from external databases or derived from GOME-2 measurements taken by Metop-B. The model was extensively tested and successfully validated with operational data. For details see [2].

The operational concept foresees that the Sun model is used in the instrument data processing chain whenever the Sun Aspect Angle Azimuth (SAA) in the Sun slit FOV reaches 8.2° because the calibration curves are limited to this value. Until winter 2017/2018 it was thought that at 8.2 degrees also the geometrical Sun image would get out of the slit, therefore the two events (limit of calibration curves validity and Sun visibility gap) would occur at the same time.

Observed Sun Visibility Gap in winter 2017/2018

GOME-2 downlinks the SAA numerical value for the Sun sighting. Examining the long-term SAA profile from 2006 to 2019 (Figure 5) one sees that the SAA “sags in” precisely during the times in winter 2017/2018 predicted by Flight Dynamics.

Zooming into the period 2017/2018 (Figure 6) one can see that the SAA effectively violated the 8.2 degrees threshold between 2018/01/14 and 2018/02/18, thus forcing the use of the solar model. The red markers highlight the effect. It should be stressed that the reason why the solar model kicked in was not the absence of Sun signal, rather the fact that the SAA exceeded the limit of 8.2 degrees for calibration curve validity. The validation of the flight dynamics predictions was thought to be straightforward: by carefully observing the time when the Sun visibility gap begins or ends, a good estimate of any time bias would have been achieved. But there has been no evidence that the Sun signal was ever lost in the Sun slit between 2018/01/14 and 2018/02/18.

At this point we set out to determine why the predicted gap has not been observed.

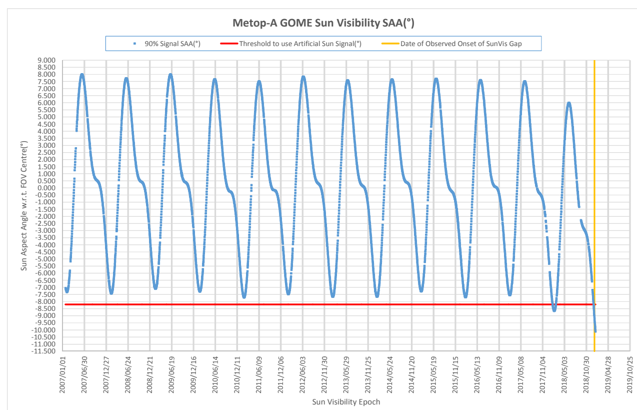

Figure 5 Long-Term Sun Azimuth Angle Observed in the GOME-2 Sun Slit

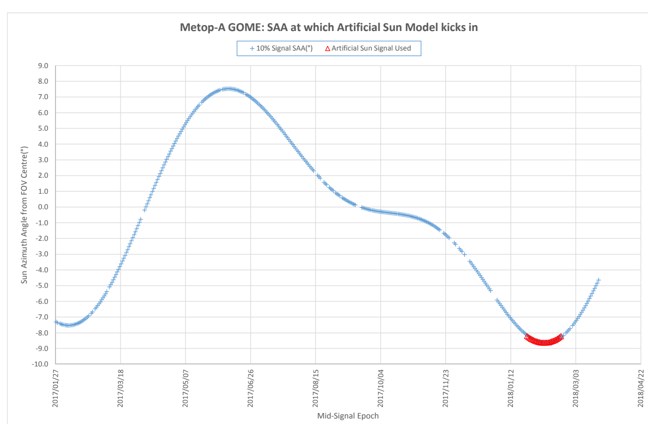

Figure 6 Sun Aspect Azimuth in the GOME-2 Sun Slit with highlighted Sun Model Activation in Winter 2017/2018

Influence of Instrument Bias

A possible cause of the absence of Sun visibility gap can be an un-modelled bias in the instrument mounting. In this scenario the instrument is sighting the Sun at a slightly different angle from the angle used by the event prediction software. It can therefore occur that the software thinks that the Sun is marginally out of the FOV, whereas the Sun is actually still inside the FOV, although by a narrow margin. As a diffuser element is in the instrument optical path downstream of the Sun slit, a small decrease in Sun signal intensity may equally go unnoticed.

We therefore compared the start/end time of Sun visibility predicted by the flight dynamics system with the start/end time of Sun visibility downlinked in the instrument telemetry (TM). The deviations has a biased behaviour (blue data points in Figure 7). Determining the bias value was straightforward: the timing differences between predictions and measurements would get to a well-behaved zero-average distribution if a Sun slit mounting bias in pitch of 0.368°was introduced, see Figure 7, showing an excerpt of the full dataset used. This pitch bias causes a time delay on the Sun acquisition of 6.17s. As the event occurs with a time-offset, the platform yaw-steering, at the typical rates observed when the Sun-sighting takes place, differs from its nominal value by 0.025deg. This is about one-twentieth of the Sun diameter on the GOME Sun sensor, which is insufficient to explain the observed behaviour.

It was also seen that the same value of pitch bias allows a better agreement between predictions and acquired Moon signal during the periodic Moon calibration sessions. Figure 8 shows that almost 80% of the differences reduce to within ±2s using this pitch bias.

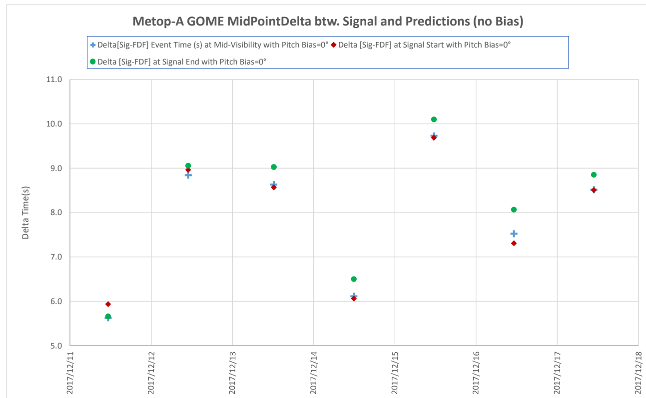

Figure 7 Excerpt of GOME-2 Sun Visibility Timing Comparison btw. Predictions and actual Measurements in Winter 2017/2018; no Bias is applied

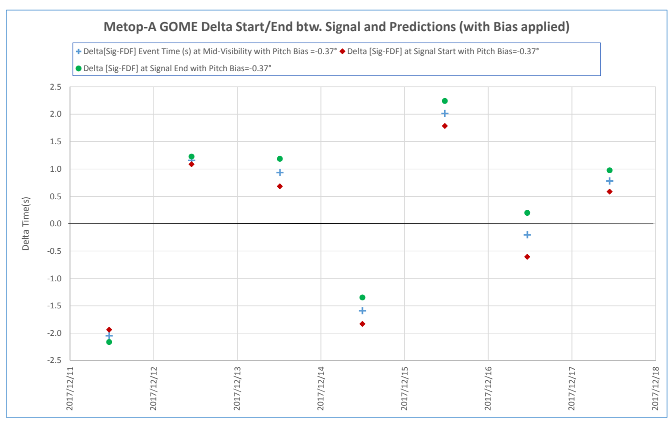

Figure 8 Excerpt of GOME-2 Sun Visibility Timing Comparison btw. Predictions and actual Measurements in Winter 2017/2018 after applying the estimated Pitch Bias

However although the pitch bias leads to better agreement between Sun and Moon predictions and measurements, it should also introduce some large offsets in the GOME geolocation, in the order of magnitude of some kilometres. This is too a high value and it would have immediately been visible in all geolocation products, which is instead not the case. It was therefore decided that a mounting pitch bias in the Sun slit is not the culprit of the missed Sun visibility gaps.

Instrument Field of View

A second hypothesis which can explain why the flight dynamics predictions identify Sun visibility gaps which are not observed is that the GOME Sun slit FOV modelled in the flight dynamics system is smaller than it is in the real world.

Indeed after some detailed (archaeological) researches in the Sun slit manufacturer documentation it was found that FOV is 8.67° (see black line Figure 9), whereas the GOME mission documentation defines the FOV as 8.2° (red line in the same figure). Note that 8.67° a hardware (baffle) limit. The 0.47° are there to ensure a margin which takes into account Sun size, mounting errors and thermal deformation.

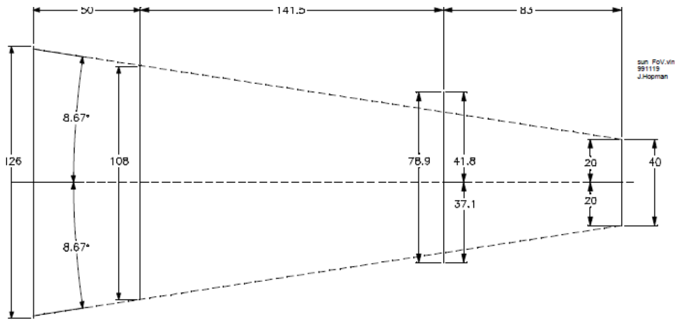

Figure 9 Manufacturer Specifications of the Sun Slit FOV.

The SAA measured in Winter 2017-2018 in the vicinity of the Sun visibility gap season evolved as shown in Figure 10. It can be seen that the SAA values went down to a minimum of 8.63°, which just skimmed the 8.67°baffle limit by a narrow margin.

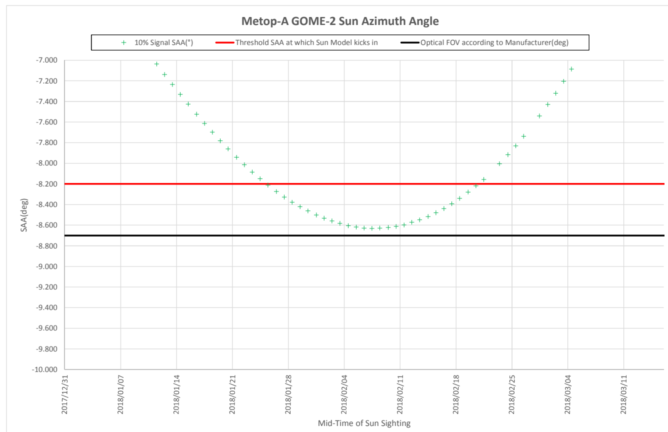

Figure 10 GOME-2 Downlinked SAA in Winter 2017/2018 vs. the mission documentation limit and the Sun slit manufacturer baffle limit

In our opinion this is the reason why no Sun visibility gap was observed in GOME-2 during Winter 2017/2018.

Predicted Sun Visibility Gap in winter 2018

This hypothesis can be tested during the upcoming Sun visibility gap season in Winter 2018/2019, which will be longer than the previous one, as the LTDN has further drifted off the nominal value in the meanwhile. This is shown in Figure 11 for two representative values of the FOV. The corresponding dates for the visibility gaps are given in **Error! Reference source not found.**

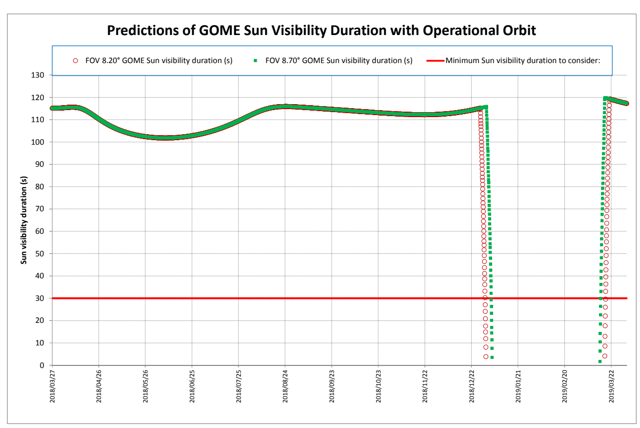

Figure 11 Sun Visibility Duration vs. Time in Winter 2018/2019.

Table 1

Sun Slit FOV (°)	Last Sun Visibility yyyy/mm/dd	First Sun Visibility yyyy/mm/dd	Dur. (days)
8.2	2018/12/31	2019/03/17	76.6
8.7	2019/01/04	2019/03/14	69.5

It was therefore expected that in the Sun visibility gap season the Sun signal will effectively go missing.
The artificial Sun signal was activated manually on 2018/12/26, to have a few days' margin w.r.t. the "Last Sun Visibility" date reported in
.

The data processing in the real-time ground segment used the artificial Sun signal, while the alternative ground segment data processing used the actual Sun signal.
On 2019/01/14a re-processing of one-month worth of data showed that the difference between the actual and artificial Sun signal jumped to a clearly different level: starting from approximately 2019/01/05 GOME was not observing the actual Sun through the Sun slit. The effect continues to be seen as of today. See Figure 12

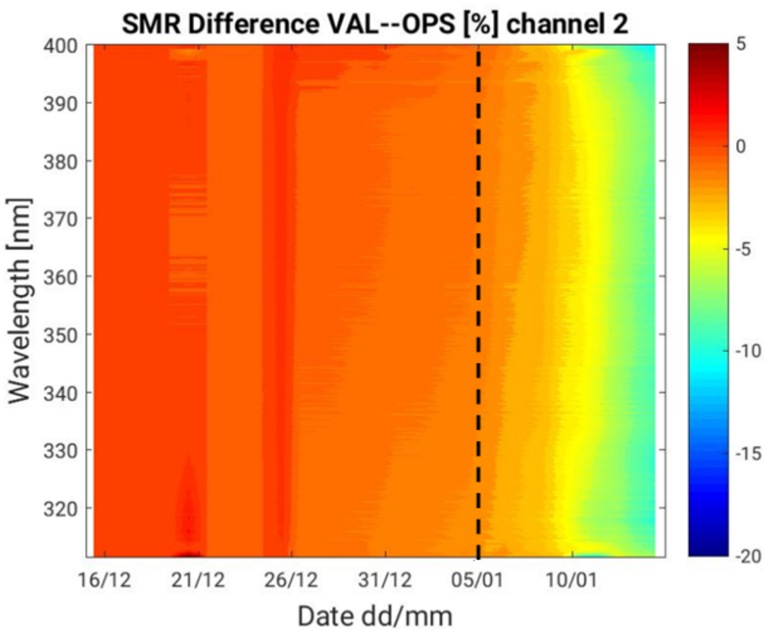

Figure 12 First GOME Observation of Sun Visibility Gap

The effect is very wavelength dependent. It is prominent in GOME channel 1 and 2 (the upper part of channel 2 is in the violet part of the visible spectrum), likely due to scattering of the diffuser element in the light path.
The observed SAA on 2019/01/05 was -9.2°, which is beyond the -8.7° limit recently found in a very specific documentation of the GOME baffle and surely beyond -8.2° mentioned in the overall mission documentation. It means that GOME can be used quite beyond the operational limits considered so far; this has a big impact on the mission and on the overall Metop manoeuvre strategy for Metop-B and Metop-C.

Similar re-processing of data in January 2018 are in progress and they may also show that the predicted gaps actually took place one year ago, around the dates predicted by flight dynamics.
The next step is to check the measured start/end times of Sun visibility and to compare them with the respective predictions to better characterise the actual Metop-A GOME Sun slit FOV size. The additional assumption is that there are some discrepancies between the FOV size

reported in the documentation (and considered by the flight dynamics predictions) and the actual FOV size. This task is useful also for the two remaining Metop missions.

Impact of this Analysis on actual Satellite Operations

The Metop series is composed of three identically built Metop-A, Metop-B and Metop-C. Metop-B is using the Metop-A experience, in that the Metop-B inclination manoeuvres in 2018 were already conducted beyond the old ±120s threshold in LTDN deviation (blue curve) and now its value is around -150s, see

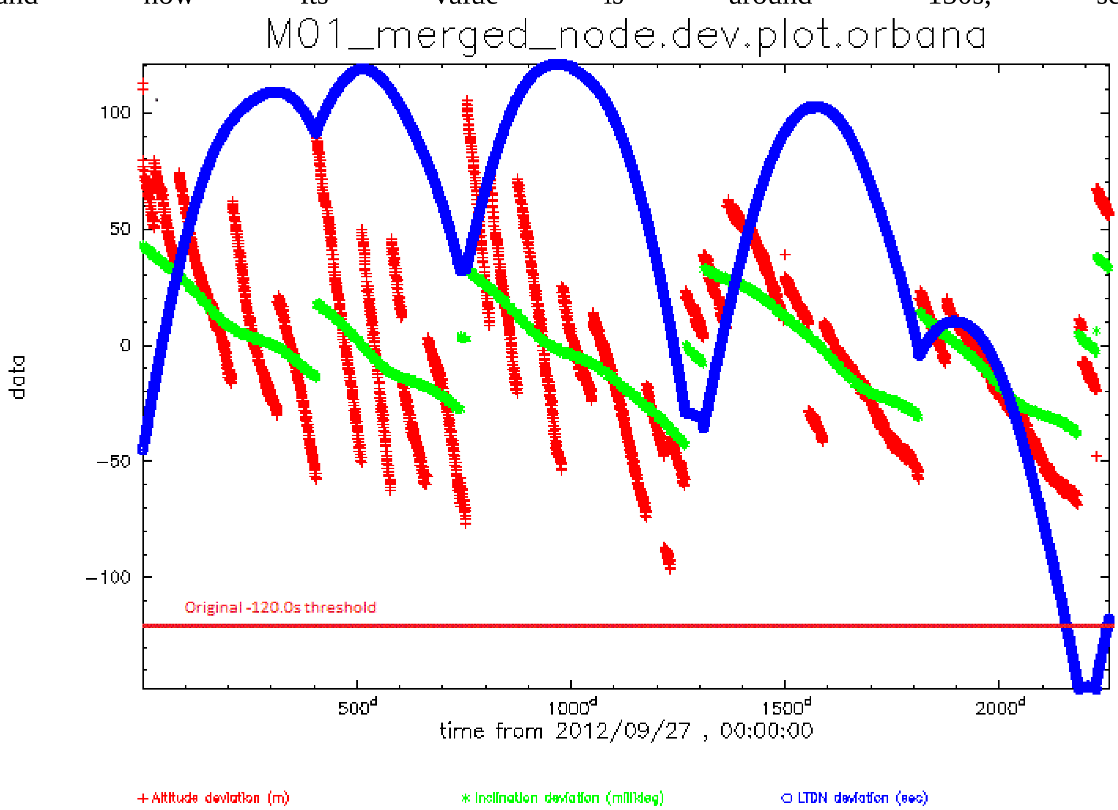

Figure **13**. (Metop-B is also defined as M01).

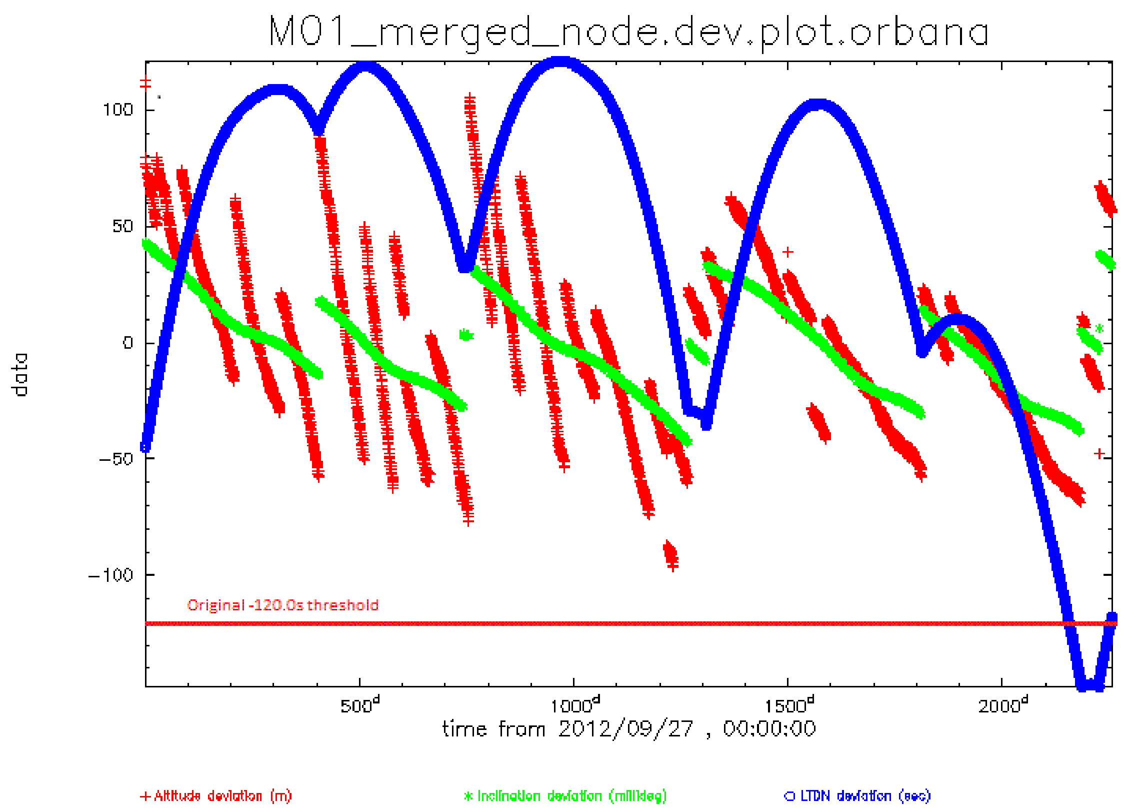

Figure 13 Consequences of the Metop-A GOME Analysis: Metop-B relaxed LTDN corridor

Metop-C, launched in November 2011 is using the Metop-A experience, as the spacecraft handover conditions from LEOP were relaxed, as the violation of -120s threshold was authorised by EUMETSAT around autumn equinox, see for example the discussion in [1].

Fuel Savings predicted by this Analysis

This analysis has shown that the original LTDN mission corridor can be relaxed from -120s to at least -150s.

As reported in [3] the operational manoeuvre strategy until now have included an Out-of-Plane manoeuvre campaign composed by two manoeuvres performed two weeks apart; this solution allows to perform one such campaign every 1.5 years. Two manoeuvres are needed because the entire inclination change cannot be performed in a single manoeuvre; in fact the constraints of performing the manoeuvre in the Earth-eclipse period must be fulfilled. With decreasing tank pressure, the time for the necessary slew and back-slew manoeuvres (see Figure 14) increases to such an extent that the central boost phase is too short to deliver the whole DV needed to change the orbit inclination.

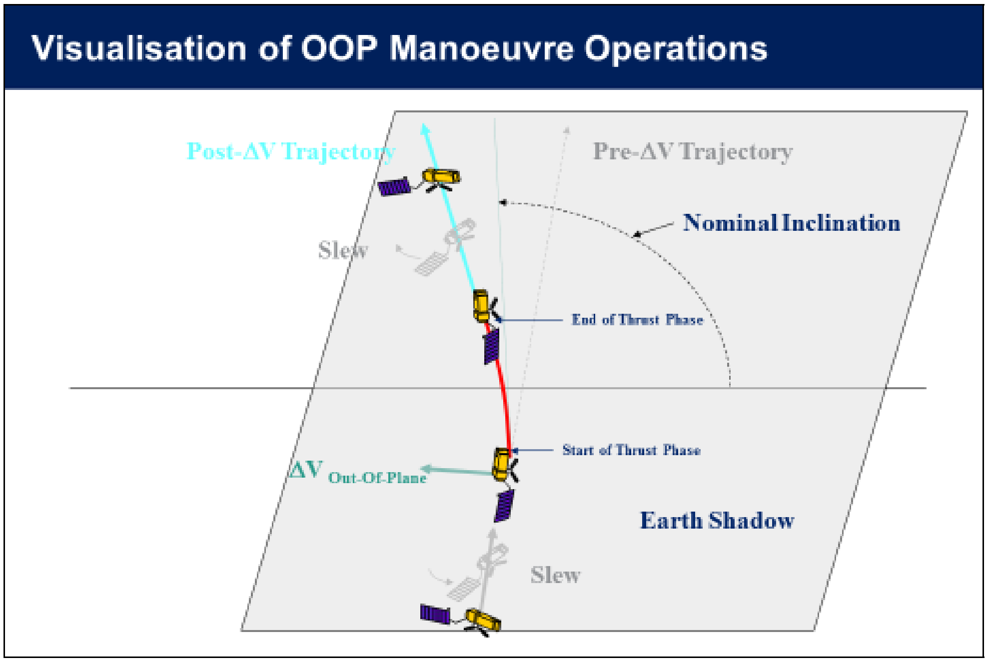

Figure 14 Visualization of OOP Manoeuvres

Considering the time between the first OOP manoeuver with the new strategy, September 2017 and beginning of 2023, at which time Metop-B phase of inclination control will be as long as the Metop-A phase of inclination control, one can either:

A. keep the old strategy with the original LTDN lower threshold of -120s and perform 2 burns every 1.5 years. It requires 10 burns.
B. relax the LTDN lower threshold to -150s and perform an alternated sequence of 2 burns every 1.5 years followed by 1 burn 1 year afterwards, followed by 2 burns after 1.5 years and so on. It requires 9 burns, 1 less than option A (see Figure 15).

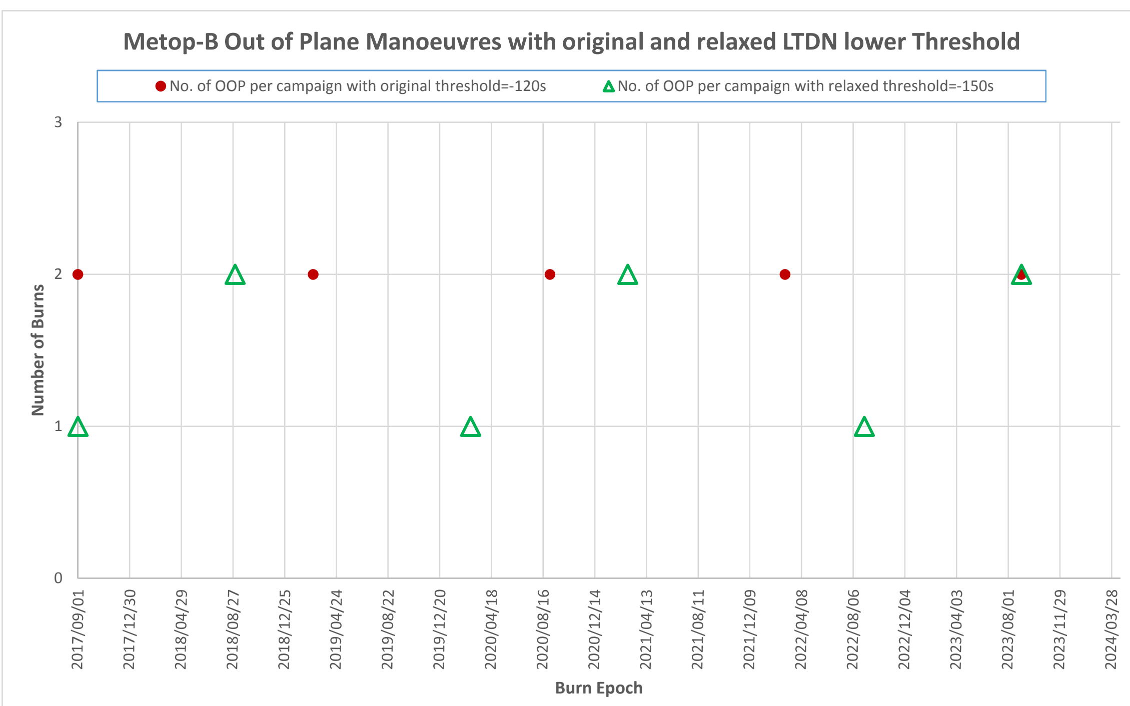

Figure 15 Number of Inclination Burns for original and relaxed LTDN lower Threshold

The actual saving on fuel is in the slew and ant-slew manoeuvres, namely about 1.3 kg for each saved inclination manoeuvre. As the satellite will not be manoeuvred in inclination any longer after that date, only the ground-track is controlled within its operational corridor. As about 0.3 kg of fuel is needed for groundtrack-only control in one year, the Metop-B lifetime with groundtrack control can be extended by around 4 years of operations thanks to this analysis. Moreover, as each OOP implies a large outage in terms of mission return, that reduce the foreseen outage by nearly 15%.

Yaw-Bias Manoeuvres to Sight the Sun

Procedures have been developed in 2017 to slew the Metop platform around the Z (yaw) axis to allow GOME to sight the Sun for part of an orbit, in case the satellite LTDN drift becomes so large that the Sun slit cannot see the Sun, see Figure 16. The procedure has been successfully validated against the satellite simulator. The actuators are the reaction wheels, thus no fuel consumption is involved. This is reported in [4].

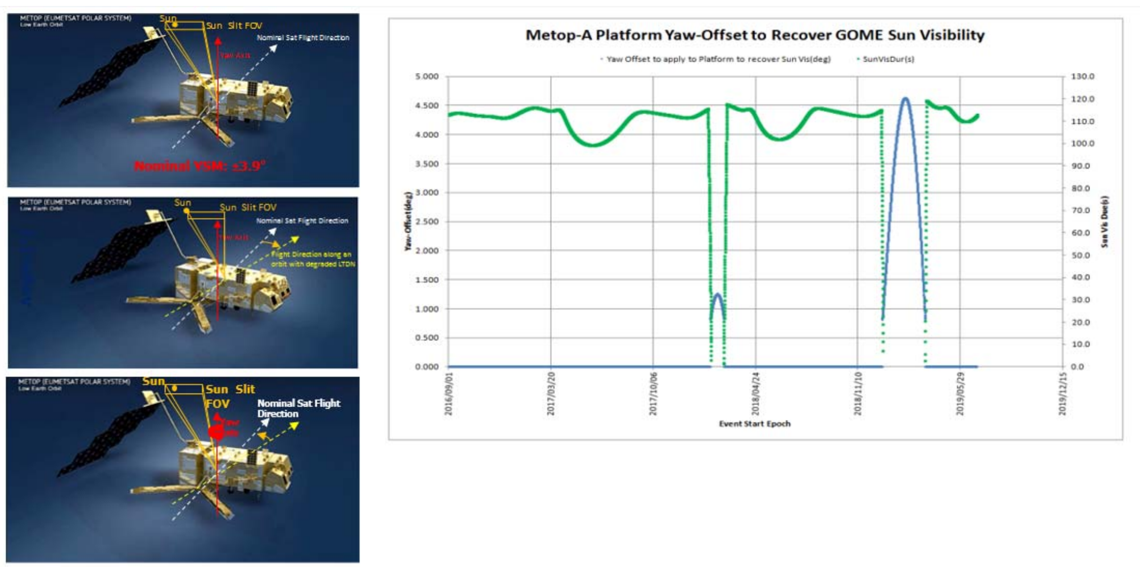

Figure 16 Concept of Yaw-Biasing the Attitude to allow Sun Sighting.

Conclusions

Since 2006 the GOME Sun slit FOV size has governed the Metop inclination manoeuvre strategy imposing a LTDN of 09:30 ±120s to ensure the Sun visibility inside the Sun slit FOV. After the Metop-A inclination manoeuvres have been discontinued due to low fuel mass, GOME Sun visibility gaps have been predicted but not verified in 2018. This led the flight dynamics team to assume that the GOME Sun slit FOV is larger than previously thought. This has been corroborated by some instrument documentation. This assumption can be further checked during the Sun visibility gap season in December 2018-March 2019.

The first Sun visibility gap to be observed by GOME channel 2 was recorded on 2019/01/05, just 5 days off the flight dynamics predictions, which, considering the inconsistencies found in the instrument technical documentation for the GOME baffle FOV, can be considered a success.

The baffling absence of the predicted Sun visibility gaps in winter 2017/2018 has spawned in 2018 an analysis of the extent of possible LTDN lower threshold relaxation. This was eventually quantified in -150s or 25% more than the original value, which allows to extend Metop-B operations by around 4 years after the end of inclination manoeuvres.

The recently launched Metop-C had its LEOP manoeuvres trimmed to use the -150s LTDN lower limit, which allowed to save on costly LEOP inclination manoeuvres, thus extending its operational lifetime.

References

1. Righetti, P.L., De Juana Gamo, J. and Sancho, F., EUMETSAT, “Metop-C deployment and start of 3-satellite operations “, ISSFD 2019, Melbourne.

2. Damiano, A., RHEA Group at EUMETSAT, Righetti, P.L., EUMETSAT and Sancho, F., WGS at EUMETSAT, “Flight Dynamics Support to extend Metop Instruments useful Lifetime”, ISSFD 2017, Matsuyama.

3. Damiano, A., RHEA Group at EUMETSAT, Righetti, P.L., EUMETSAT and Soerensen, A., EUMETSAT: “OPERATIONAL LOCAL TIME AND ECCENTRICITY MANAGEMENT FOR METOP-A”, ISSFD 2009, Toulouse.

4. Sancho, F., WGS at EUMETSAT, Fischer J., Jade Aerospace at EUMETSAT and Tarquini, S., “Non-Nominal Attitude Manoeuvres during Metop-A Extended Lifetime”, ISSFD 2017, Matsuyama.