Flight Dynamics Support to extend Metop Instruments useful Lifetime

By Antimo Damiano[1*], Pier Luigi Righetti[2], Rüdiger Lang[2], Francisco Sancho[3]

[1] *RHEA Group at EUMETSAT,* [2] *EUMETSAT,* [3]*WGS at EUMETSAT*

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 UTC. Together with Metop-B, launched in 2012 and Metop-C slated for launch in 2018, they constitute the EPS space segment in Low Earth Orbit. Among the 13 instruments on board, the Global Ozone Monitoring Experiment–2 (GOME-2) is a hyper-spectral Ultra Violet-Visible to Near Infrared Spectrometer and it is used to get a detailed picture of the total atmospheric content of ozone and the vertical ozone profile in the atmosphere, as well as a large range of trace gas and aerosol products. For the measurements calibration GOME-2 needs to see the Sun in its sun slit field of view (FOV). As Metop-A is approaching its end of life no more Out of Plane (OOP) manoeuvre are conducted. The resulting loss of orbit inclination control leads to LTDN drift. This drift makes the orbital plane precess in such a way that the Sun visibility opportunities suffer a gap lasting many days. Failure to properly calibrate the measurements during more than very few days may invalidate the GOME-2 products. EUMETSAT responded to the challenge by optimizing the last feasible out-of-plane maneuver, by identifying a sun signal placebo for the GOME-2 instrument data processing chain and by developing techniques that periodically change the spacecraft attitude in yaw to allow GOME-2 to perform its sun-sighting.

Key Words: Local Time of Descending Node, Out of Plane Maneuvers, Instrument Sun-Sighting.

1. Introduction

The Metop mission is implemented on a repeatable sun-synchronous Low Earth Orbit (LEO). In order to be truly repeatable, the orbit inclination must be carefully controlled. At the end of fuel lifetime (which currently amounts to 11 years, against a nominal mission lifetime of 5 years) the limited amount of fuel is reserved to maneuvers which can ensure the control of the ground track and a de-orbiting compliant with international recommendations but not the precise inclination control anymore. With no inclination control the Local Time of Descending Node (LTDN), which must nominally stay in the corridor of 09:30 UTC ±120s, starts drifting away. The consequence is that the GOME-2 (Global Ozone Monitoring Experiment 2) instrument, one of the most successful instruments in the mission, looses visibility of the Sun in its Field of View (FOV), thus jeopardizing the quality of the scientific data. In order to further extend the instrument nominal mission EUMETSAT developed the strategies described in this paper.

2. Sighting the Sun

The GOME-2 instrument is mounted on each of the three Metop satellites on the satellite velocity vector side (as shown in Fig. 1). Once per day GOME-2 performs a Sun sighting through it sun slit to calibrate its daily measurements. As long as the LTDN is within the 09:30 UTC ±120s the Sun in the sun slit FOV is always within the Sun Slit FOV. As soon as the LTDN is left drifting naturally beyond the -120s the Sun results out of the FOV for many days in a row towards end of January / beginning of February every year. This is shown in Fig 2.

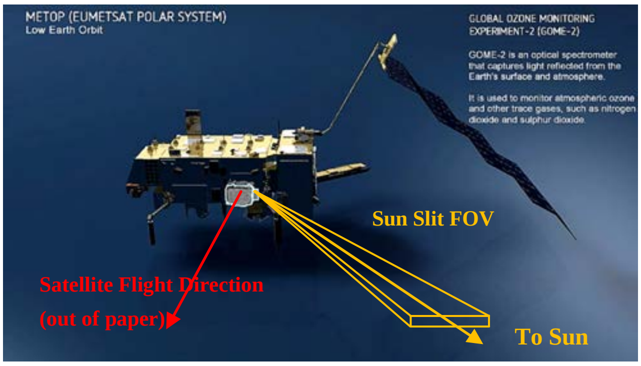

Figure 1 Metop and GOME-2

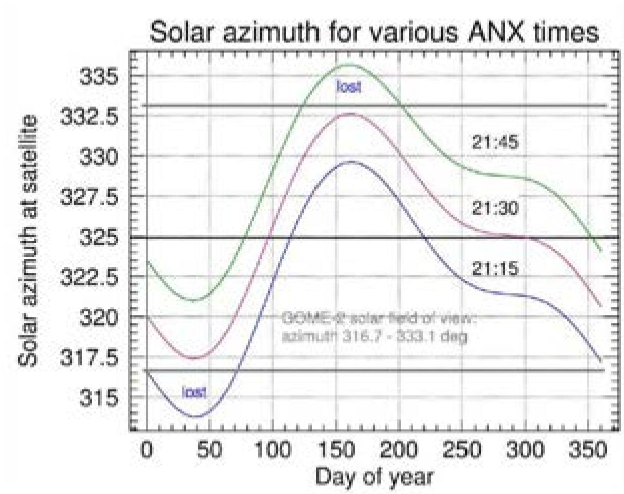

Figure 2 Sun Azimuth in GOME-2 Sun Slit versus Day of Year for different LTDN Values (Ref. 1)

It can be observed that year-long visibility is ensured for LTDN 09:30 +/- 120s. A negative LTDN violation (of 15 minutes) involves the loss of Sun visibility in the first 2 months of the year. In addition to the Sun slit official FOV semi-angle of 8.20°, two artificial fields of view were considered for the GOME-2 sun slit width semi-angle: 7.95° and 8.45°, adding and removing the Sun radius from the nominal value (as shown in Fig.3). This is due to the fact that the FDF computes events taking into account the Sun centre position, therefore:

- The reduced FOV ensures visibility of the entire Sun disk inside the sensor;
- The extended FOV permits to identify when the Sun starts entering the sensor.

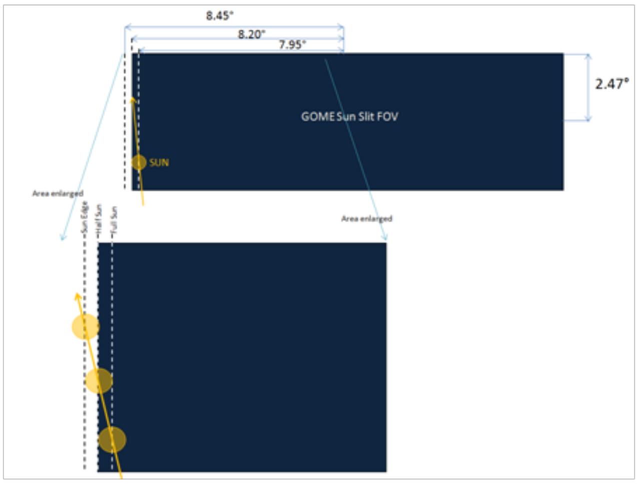

Figure 3 Nominal and Auxiliary FOV for GOME-2 Sun Slit

3. Determining the Manoeuvre Fuel Budget

The natural way to keep the LTDN under control is to steer it by changing the orbit inclination. This is achieved through an Out of Plane (OOP) manoeuvre. The last Out-of-Plane maneuver was performed in late summer 2016 to induce such an orbital plane shift that sun visibility by GOME-2 is granted until February 2018. At the same time the manoeuvre must leave enough fuel as to ensure EOL de-orbiting operations such that the satellite re-enters the atmosphere within 25 years.

As the fuel evaluation errors are affected by statistical errors and the amount of unusable fuel is also affected by a statistical uncertainty, it is possible to provide the answer to the question of "how much fuel is available" only if a statistical confidence is defined (e.g. available with a 95% probability). It is assumed that the fuel estimation error has a Gaussian distribution and that the unusable part of fuel can be equally modeled by a Gaussian distribution on top of a mean fuel value.

Three different methods are used for the Metop mission: PVT (Pressure, Volume, Temperature), pulses count, and a hybrid model developed by CNES (see Ref. 2). The first two methods deliver a similar sigma of the estimation error at EOL of ~6kg; it is reasonable to consider the average of the two solutions and consider as sigma the RMS of the two sigma values (for 50% of the total fuel); that leads to a value of 4.2kg. This same value is assumed as sigma for the CNES hybrid method. Again, being the CNES and the EUM standard solutions of equivalent quality, it is possible to average them; the same applies to the sigma, which results ~3kg.

From the satellite documentation 3.4kg of fuel is surely unusable, as trapped in the propulsion system; on top of that there are 5.4kg of fuel that may not be usable due to fluid-dynamics phenomena and 3.8kg that may not be usable due to filling unbalance among the various tanks. Therefore the unusable fuel is modeled as having a mean value of 8kg and a sigma value of 1.1kg (4 sigma assumed between mean and max values of unusable fuel).

The (mean) available fuel is therefore computed as difference between the (mean) fuel estimation and the (mean) unusable fuel. The overall sigma uncertainty of the available fuel is computed from the RMS of the estimation sigma and of the unusable part sigma, which results ~3.2kg. Figure 4 describes graphically that model.

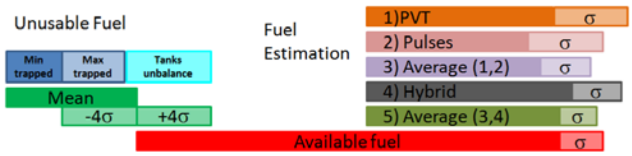

Figure 4 Metop Fuel Model

In statistical terms, that means that a 1.6 sigma reserve is needed on top of the mean unusable fuel to ensure 95% of confidence; in conclusion, 13.1kg is the safety margin, including fuel unusable as trapped in the tanks and pipelines or due to tank unbalance effects and measurement errors, to ensure with 95% of probability of having the minimum required fuel for EOL operations, estimated to be 144kg, (CNES STELA software with standard average atmosphere used for the EOL re-entry time computation, (Ref. 3). This determines the mass budget for all maneuvers until 2022 as given in Table 1.

Overall Fuel (kg)	Fuel to reach EOL orbit (kg)	Error on Fuel (kg)	Remaining Fuel for Maneuvers until 2022 (kg)	
168.0	144.0	13.1	10.9	
			In-Plane (kg)	Out-of-Plane(kg)
			1.3	9.6

Table 1 Metop-A Fuel Allocation at EOL

As there is a not negligible level of uncertainty in the amount of fuel available, also the final re-entry time is uncertain; in Figure 5 the probability of achieving an EOL orbit leading to a certain re-entry time is presented; it can be observed that even if less fuel is available than expected (so if we are in the unlikely case to be in the excluded 5% of the available fuel distribution), then the re-entry time will increase, but never above 30 years; similarly, the probability of achieving a much faster re-entry is quite large (around 50% of re-entry in ~22 years).

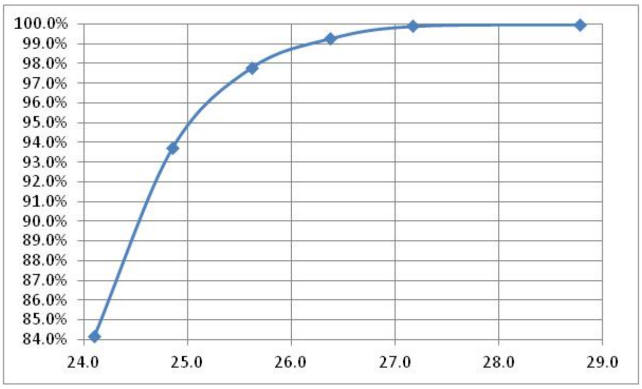

Figure 5 Probability of successful Re-orbiting after N Years

4. Designing the Final Out-of-Plane Maneuver

At beginning of 2016 a quite long (around two months) Sun visibility gap was predicted for winter 2018 on the Metop-A GOME-2 instrument. To cancel it out, or at least to have its duration reduced significantly, the decision was taken to execute a final OOP maneuver in summer 2016, making use of the available 9.6kg identified above.

The Metop satellite can execute OOP maneuvers only if in eclipse, to respect the illumination constraints of the platform and the payload, as shown in Figure 6.

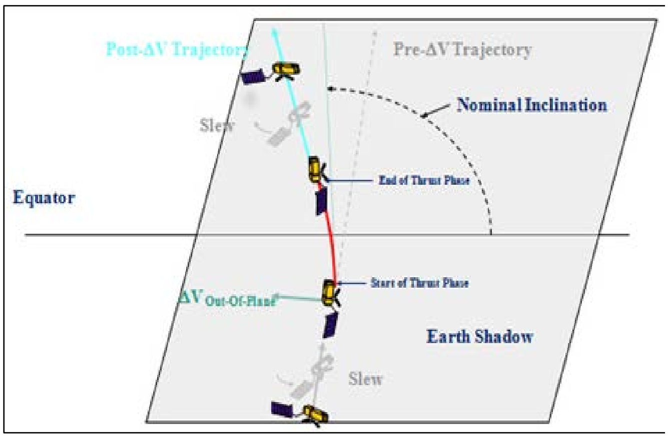

Figure 6 Metop OOP Maneuver and Earth Eclipse

Because of the large extra fuel cost caused by the slew required to align the platform with the target thrust direction (executed with thruster, due to the large size of the satellite), the optimal efficiency is achieved when the maximum possible percentage of the eclipse duration is occupied by the burn (as shown in Ref.4).

Therefore all options explored for designing the final Metop-A maneuver considered a maximum usage of the eclipse time. These options are presented in Table 2.

#	Date	Fuel (kg)	Gap (days)	OOE (sec)	Tanks heaters	FOV
A	*2016/08/10*	*9.965*	*22.2*	*175*	*Off*	*8.20°*
B	***2016/08/24***	*9.579*	*24.4*	*175*	*Off*	*8.20°*
C	*2016/09/07*	*9.489*	*24.6*	*175*	*Off*	*8.20°*
B	*2016/09/21*	*9.480*	*25.0*	*175*	*Off*	*8.20°*
E	*2016/10/05*	*9.524*	*26.3*	*175*	*Off*	*8.20°*
F	**2016/08/24**	9.900	21.7	**205**	Off	8.20°
G	**2016/08/24**	10.128	19.8	**205**	**On**	8.20°
H	**2016/08/24**	10.128	0.0	**205**	**On**	**8.45°**

Table 2 OOP Maneuver Options

Cases A to E were used to analyze how the performances of the maneuver evolve (in terms of fuel consumption and gap duration in 2018) when changing the execution date. It can be observed that the gap is strongly reduced from the initial two months to around 3 to 4 weeks.

The operationally optimal date is identified to be around the end of August 2016 (case B), as shown in Figure 7, where the change in Sun visibility gap duration and of fuel is depicted; it can be observed that to anticipate the maneuver causes an unacceptable fuel increase, well above the available amount of 9.6kg; to postpone the maneuver on another hand does not reduce significantly the fuel consumption, while the gap duration increase significantly.

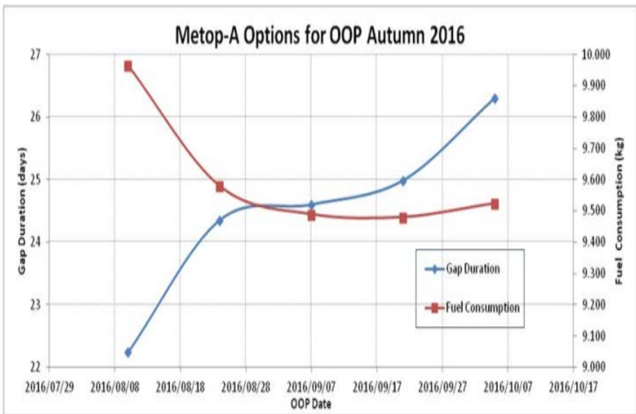

Figure 7 Optimal Maneuver Date selection

Cases F, G and H show how the maneuver performances increase (optimal case B taken as reference) when further optimizations are conducted at maneuver design, propulsion and FOV levels (see also Ref. 3):

- an increase of the out-of-eclipse (OOE) portion of the slew back (from the nominal 175 seconds to 205 seconds) permits to reduce further by ~3 days the gap (at a cost of a slight increase of fuel spent and a bit larger risk at exit of eclipse, being the yaw angle a bit larger than for the nominal case);
- an increase in temperature of the tanks by 8 Kelvin permits to reduce further by ~2 days the gap (at a cost of a further slight increase of fuel spent);
- an increase of the FOV by 0.25deg (Sun radius), permits to cancel completely out the gap, which means that there will not be any total loss of the Sun signal in the FOV (as explained in Par. 2, to increase the FOV is equivalent to say that a gap is identified only if the entire Sun exit the FOV)

In conclusion, it seems possible to fully cancel out the gap in 2018 (if we consider a gap whenever the full Sun signal is lost), but that would imply a fuel consumption a bit higher (0.5kg) than assumed available.

5. Implementing the Final Out-of-Plane Maneuver

Due to operational resource conflicts (refurbishment of the TTC antennas), it was not possible to execute the final OOP before the 31 of August (which reduced a bit the reference fuel consumption with respect to the 24 of August).

In agreement with the satellite manufacturer, EUMETSAT decreased the interval between end of the platform back-slew and exit from earth shadow, thus extending the main thrust phase by 30sec. Also the tanks were heated, to increase their pressure and then the maneuver efficiency; it is however to be noticed that the achieved pressure was below the one expected in design phase, being the observed initial pressure before tank heating lower than the one expected (yearly cycle); so, practically speaking, the heating was just recovering that loss.

The OOP maneuver provided 4.6m/s and caused an increase of inclination of 34.5mdeg (see Fig. 8). Its overall consumption, including attitude stabilization effects, was 9.7kg (~0.4kg less than reference case G, due to the combined effect of the 1-week postponement, the lower initial pressure observed and a consumption of the slews lower than expected). 9.7kg, even if marginal more than the allocated 9.6kg, can be considered an excellent result, which does not endanger in any manner the EOL capabilities of the platform (0.1kg being well below the noise of the fuel model used).

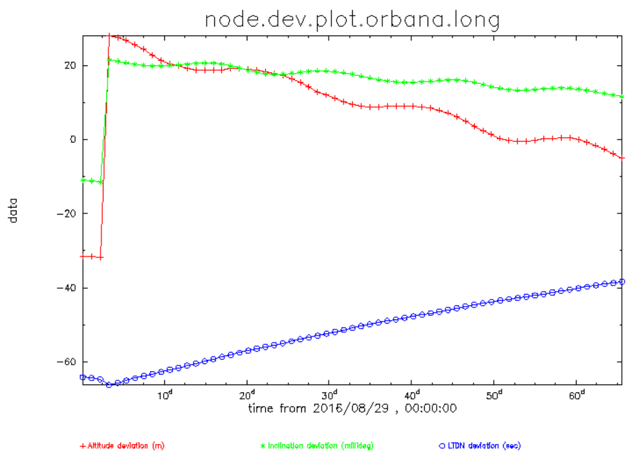

Figure 8 Effects of the actually performed OOP Manoeuvre

The manoeuvre beneficial effect on the LTDN (cyan curve) w.r.t. to the LTDN without manoeuvre (black dashed curve) is shown in Figure 9 (upper graph). The same figure shows that the GOME-2 sun visibility (magenta bar) has no gap before February 2018, as expected.

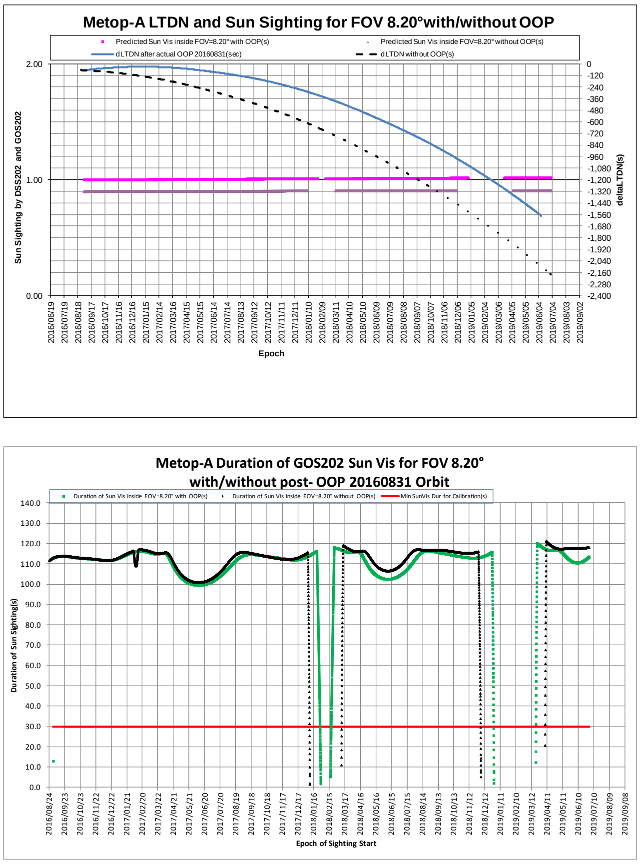

Figure 9 Sun Visibility Gaps with and without OOP

The corresponding post-maneuver prediction of GOME-2 sun visibility duration in seconds is given in Fig. 9 (lower graph, green curve with manoeuvre, black curve without manoeuvre). The GOME-2 sun slit must see the sun for at least 30s at each orbit for the calibration to be classified as successful.

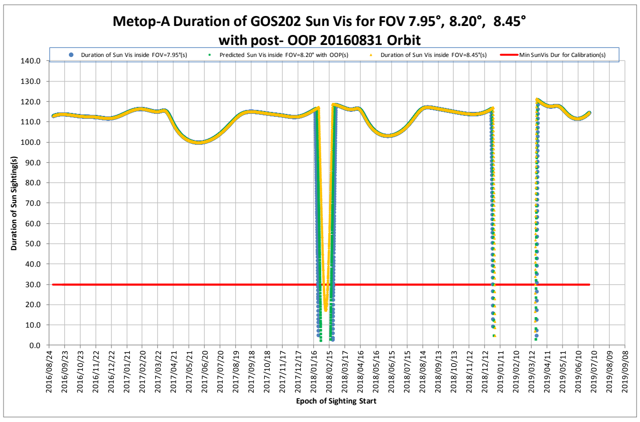

Figure 10 GOME-2 Sun Visibility Duration for different FOV Sizes (i.e. different usable Sun Disk Sizes)

As shown in Figure 9, the gap at the beginning of 2018 still marginally exists, but it is stamped as gap only because of the 30-second official threshold. Performing the OOP causes the gaps to shrink by about 15 days on either side. If it can be observed that calibration are possible with less than 30s of sun visibility, this corresponds to a no-gap situation (in line with the predictions as shown in Tab. 2, case H).

6. Sun Model.

We use a GOME-2 sun slit FOV of 8.05° including some margins, which are applied for the processing of solar data in order to avoid stray-light contributions from the sun-port baffle. For this FOV of the GOME-2 sun-port the beneficial effects of this manoeuvre on the LTDN will last only until February 2018. In order to keep GOME-2 generating nominally calibrated measurements beyond that date, a modeled solar signal will be 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 (see Ref.6). The model is essentially a forecast model and is modeling 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-B previous measurements.

By comparing model data to measurements for the same period of time, the model accuracy can be assessed. As an example, the following figure shows that the instrument determines basically the same NO2 density in the atmosphere with the actual sun signal and with the sun model for a specific day in 2015.

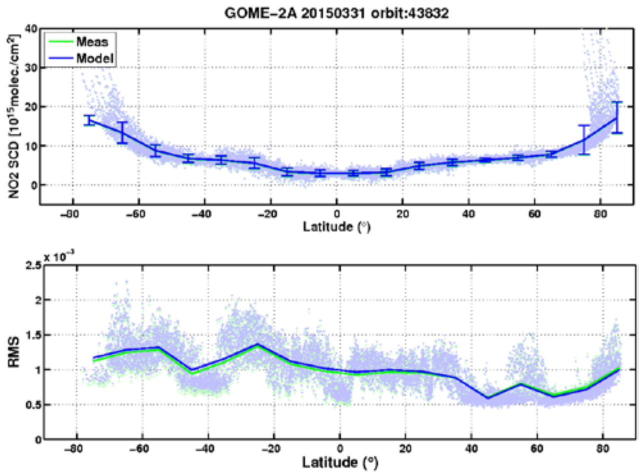

Figure 11 Determined NO2 Density (and its RMES) using Actual Measurements and using Sun Model for a Case Study in 2015

It can be seen that the model closely reproduces what the actual sun spectrum did in 2015. The model also showed to be able to predict the sun signal well, if fed with good solar radiation index forecasts. The sun signal modeling procedure strongly depends on the instrument past and present characteristics; the properties of the GOME-2 hardware on-board of Metop-A are different from the properties of the hardware flown on Metop-B (lens/screen aging effects). Possible instrument aging effects must be built-in into the model if it has to be used to predict future SMR.

In its simplest form, the procedure for GOME-2 sun calibration foresees that the actual sun signal is used as long as possible. When the sun visibility gap starts, the predicted sun signal is used. When the gap ends, the use of the actual sun signal is resumed.

7. Platform Attitude Biasing Operations

The effects of the last OOP are going to last until spring 2018. Afterwards, the otherwise unavoidable set in of Sun visibility gaps can be counteracted by periodically tilting the platform around the yaw axis yaw so that GOME-2 can achieve sun sighting for at least 30 seconds (see Figure 12).

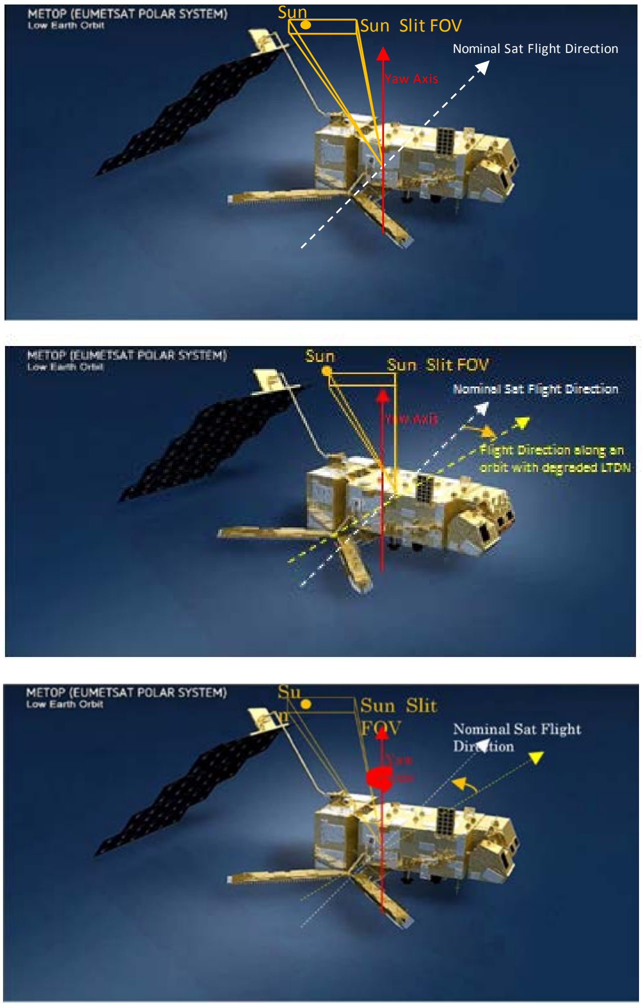

Figure 12a.b.c. Biasing the Platform to correct Sun-Aiming

The requested yaw biasing is calculated for each case as shown in Fig. 13.

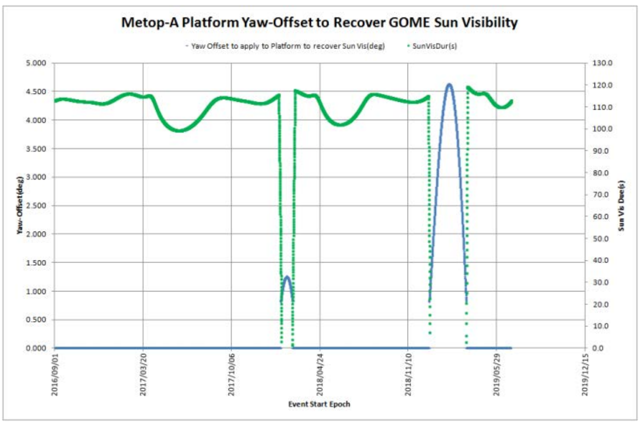

Figure 13 Platform Yaw Offset to recover Sun Visibility.

Some Metop simulator runs for this manoeuvre type are on-going. Fig. 14 shows the platform behavior during one of the runs (Ref. 5).

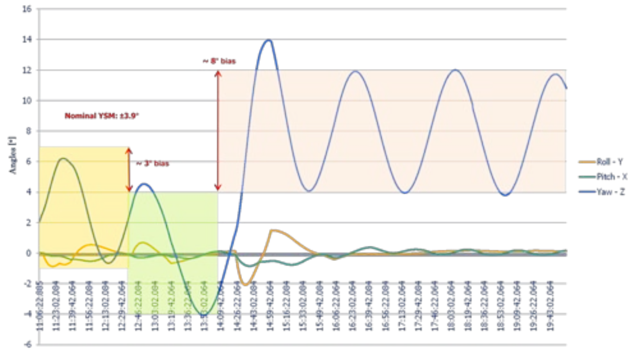

Figure 14 Metop Simulator Run showing the Introduction of a Platform +8° Yaw Bias to recover Sun Visibility.

Note the expected ±3.9° yaw-steering evolution centered about +8°, once the transient is over. Also, the attitude starts stabilizing after the Sun visibility event, where the sun sensor yaw off-pointing measurement is also used and taken into account in the control loop. The periodicity of these maneuvers is still under analysis. It could be envisaged to perform the yaw off-pointing once every few days (if so decided by EUMETSAT), with the off-pointing being kept for one or two orbits each time.

8. Future Development: In-Flight Characterization of GOME-2 Sun Slit

The FOV size of the GOME-2 sun slit is known from the instrument documentation, but the observation of actual time of loss of sun signal, expected in spring 2018 can be used to characterize the actually usable size of the instrument sun slit FOV without interference of the baffle from shadowing or stray-light effects. Basically a lookup table is computed which allows to determine the slit size by observing when the sun visibility gap actually begins and ends. The ultimate scope of this piece of information is not limited to Metop-A or Metop-B: instead it is used to gauge the LEOP injection target for Metop-C, foreseen to be launched in autumn 2018, so that a more favorable LTDN and inclination bias can be imparted at the beginning of the Metop-C mission. The related additional fuel associated to this bias will thus be spent by the launcher/upper stage, thus saving the Metop-C own fuel and further extending this satellite fuel lifetime.

9. Future Development: Needed Sun Size for Calibration

The initial, conservative indication from the GOME-2 instrument team was that the full sun diameter must be visible in the sun slit for at least 30s daily in order for the calibration to be considered valid. It is being investigated whether the calibration may still be successful if the full sun is visible for 20s and half sun is visible for 10 more seconds. This would extend the number of days with successful calibration. A second investigation deals with a scenario where the full sun is seen for 10s, followed by 10s of half sun and 20 more seconds of a smaller sun image (ideally down to a small edge of the sun disk); if confirmed, this could also constitute a valid calibration. Figure 4 illustrates the concept. Needless to say, all of this must be validated in-flight and is part of the next step of an interesting activity which bundles Flight Dynamics, Satellite and Instrument operations.

10. Conclusions.

The generic problem of extending the nominal flight envelope of the highly successful GOME-2 instrument on an aging Metop-A required first a statistical analysis of the fuel available on-board using three different methods, then the careful assignment of fuel to maneuvers specifically designed to extend the instrument nominal operations. This paper presented the three interleaved solutions developed at EUMETSAT to solve the above-mentioned problem:

1. Design and implement a maneuver optimized both at flight dynamics and satellite operations level to ensure at least 1.5 additional years of nominal orbital geometry.
2. The problem of sun visibility gaps was also attacked by the instrument data processing team generating an artificial, reliable sun signal for the times when sun gap visibility will be unavoidable.
3. Satellite operations are being developed and rehearsed to periodically tilt the platform to restore the sun visibility events to temporarily allow a nominal sun calibration of the data taken by the instrument even when the effects of the last OOP manoeuvre will have vanished.

Acknowledgments

The authors wish to thank all members of the EUMETSAT LEO FD team, of the satellite flight control team and the GOME-2 instrument engineers for their suggestions, ideas and discussions aimed to find a reliable method to solve the problem of extending the lifetime of a major EPS instrument on a platform which has vastly exceeded its nominal lifetime.

References

1) Corpaccioli E.: *GOME-2 Instrument Operations Manual*, European Space Agency, MO-MA-ESA-GO-0304, issue 7, November 2008, p. 324
2) CNES, *Méthode de bilan d'ergols mise en œuvre pour les manœuvres de fin de vie des satellites des filières SPOT & HELIOS*, DCT/TV/PR 2016.0000876, issue 1, January 2016
3) Righetti, P.L, de Juana, J., Dyer, R.: *Mission Analysis of Metop-A End of Life Operations* 24th ISSFD, May 05 – 09, 2014, APL, Maryland, USA
4) Damiano, A, Righetti P.L., Soerensen, A.: *Optimal Eccentricity Maintenance for LEO Flight Operations: the Metop-A Case*, 21st ISSFD, September 28, October 02, Toulouse, France
5) Sancho, F. Fischer, J., Tarquini, S.: *Non-nominal Attitude Manoeuvres during Metop-A extended Lifetime*, 26th ISSFD, June 06-09, 2017, Matusyama, Japan
6) Krijger. M., Raettig, N., Yu, H., Latter, B.: *Mitigating the Loss of Solar Visibility on GOME-2-2 Reflectance Data Quality after the End of Metop-A Orbit Inclination Maintenance*, V.1, CGI Deutschland Ltd.& Co KG, EUMETSAT Contract EUM/CO/15/4600001614/RL led by Lang, R., EUMETSAT, presented to EUMETSAT on 2016/11/04 , Darmstadt, Germany