OPERATIONAL LOCAL TIME AND ECCENTRICITY MANAGEMENT FOR METOP-A

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ABSTRACT

Metop 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 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 kept within 5 kilometres around the nominal ground-track. Moreover the local time of the ascending node (LTAN) has to be maintained within 2 minutes around 21:30, to ensure the correct geometry for sun-calibration of the Global Ozone Monitoring (GOME) instrument, and frozen eccentricity conditions have to be kept, to accurate calibrate the data collected by the Advanced Scatterometer (ASCAT) instrument, very sensitive to height variation with respect to the nominal profile. Regular manoeuvres are then required to maintain the operational orbit and carefully control the eccentricity vector.

Most of the fuel budget foreseen for orbit maintenance (more than the 95%) is spent to maintain the orbital inclination close to the sun-synchronous value, to ensure that the LTAN does not drift away from the nominal value. A careful review of the long term inclination and LTAN maintenance strategy is therefore needed not only to minimise the fuel consumption but also to reduce the operational complexity while limiting the service outages. Constraints at satellite level, as the need of performing the entire out of plane manoeuvre (OOP) in eclipse, and the evolution of the propulsive system performances are considered in this activity.

Due to the offset of the thrusters mounting with respect to the satellite frame, the execution of a large OOP manoeuvre has as consequence the generation of a remarkable radial parasitic thrust (of the order of 5% of the OOP thrust itself) which leads to the disruption of the frozen eccentricity conditions and then to a large deviation of the satellite height evolution from the reference one. That problem was already presented in the ISSFD 2005 by Oscar Luengo.

Therefore it is necessary to re-acquire the frozen eccentricity conditions as soon as possible after the execution of an OOP manoeuvre by executing a double IP manoeuvre. The problem of selecting of the optimal eccentricity target for the correction manoeuvre revealed itself more complex than expected, due to the observed instability induced by seasonal effects; seasonal targets are then to be defined to have the eccentricity stable in the short period. The active reduction of the eccentricity deviation implies the minimisation of the height error across cycle; however the error within different orbits of the same cycle cannot be actively reduced through manoeuvres. Therefore it is necessary to identify the orbit within a cycle that minimise the height error with all other orbits and have it considered as reference for the ASCAT processing.

1. METOP-A, MISSION AND ORBIT CONSTRAINTS

Metop-A is the first European operational satellite for meteorology flying in a Low Earth Sun-Synchronous Orbit, and the first satellite operated by EUMETSAT in this type of orbit. It is the first of a series of three satellites which should ensure 15 years of continuity of mission operations.

Its repeat cycle is 29 days and 412 orbits, corresponding to an approximate altitude of 826km. A dead-band of ±5km around the reference ground-track and frozen eccentricity conditions must be maintained to ensure optimal observation conditions for the calibration and the following exploitation of the on-board instruments, mainly the Advanced Scatterometer (ASCAT). In plane manoeuvre are thus needed for dead-band maintenance and eccentricity control.

The mission LTAN is 21h 30min and must be maintained within 2 minutes. This constraint is imposed to maintain sun-calibration geometry for the Global Ozone Monitoring Experiment (GOME) instrument and derives in the need to perform active orbital inclination control around the nominal Sun-Synchronous inclination of 98.7 degrees.

The satellite Service Module (SVM) is directly derived from the one used for SPOT, ERS and ENVISAT (Fig. 1). Automatic attitude control is based on one Digital Sun Sensor, one Digital Earth Sensor and two bi-axial gyros.

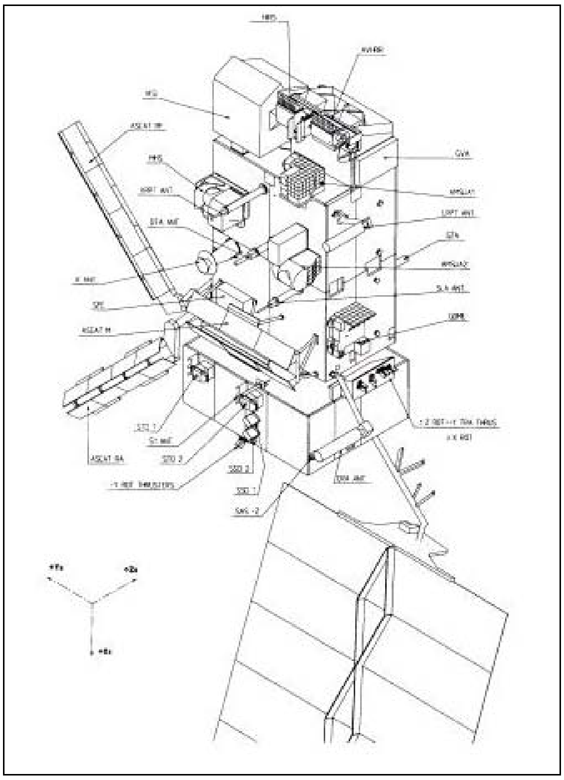

Fig. 1 Metop Satellite

Orbit control is performed by hydrazine thrusters (two plates, each with one pair for propulsion and yaw control and two pairs for roll and pitch control). The location of the thrusters on the Metop platform imposes the need to rotate the spacecraft by approximately 90 degrees around its yaw axis (slew) before performing the out-of-plane manoeuvre itself. A second rotation in inverted direction (slew-back) is needed after the manoeuvre to return to the nominal pointing.

Instrument illumination conditions impose a constraint to the manoeuvre: the satellite can only be slewed within eclipse conditions. This effectively means that the maximum time available for the manoeuvre thrust is quite limited and depends on the time of the year (see paragraph 2.1)

The Payload Module (PLM) of the satellite carries 13 instruments for meteorological observation. Among those, the ones of particular interest for the flight dynamics operations are:

- GRAS (GNSS Receiver for Atmospheric Sounding): provision of precise navigation data;
- ASCAT (Advanced Scatterometer): constraint in repeat cycle and frozen eccentricity maintenance;
- GOME (Global Ozone Monitoring): constraint in LTAN maintenance.
- AVHRR (Advancer high resolution radiometer): constraint in the geo-location accuracy.

2. THE LTAN AND INCLINATION MAINTENANCE PROBLEM

For sun-synchronous satellites, the secular change of the orbital inclination is mainly due to the Sun gravity fields and depends on the Mean Local Solar Time of the orbit. For the Metop orbit that perturbation is close to the maximum and causes an inclination decrease of around 50mdeg per year.

The following assumption where made at mission analysis level when defining the initial inclination and LTAN maintenance strategy:

- due to the quite large dead-band available in inclination (+/-40mdeg, corresponding to around 4.5km of ground-track deviation at the pole), it is sufficient to perform a very large inclination correction of around 75mdeg every 18 months;
- being the inclination evolution centred on the nominal sun-synchronous inclination, the LTAN evolution would remain bounded to around +/- 60 seconds (linear inclination drift assumed), well within the required 2 minutes margins.

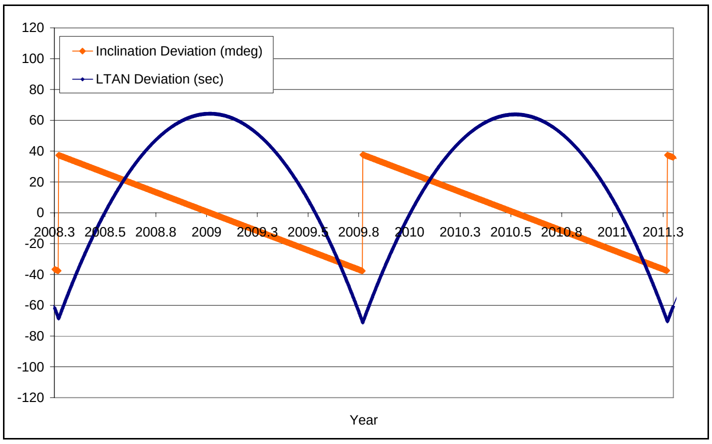

Fig. 2 Inclination and LTAN evolution (MA case)

In Fig. 2 the expected evolution in inclination and LTAN is presented.

However, considering the quite large mass of the satellite (more than 4 tons), the very limited thrusting level available (around 40 Newton at beginning of life - BOL) and the very large impulse to be provided (nearly 10 m/s), nearly 17 minutes of continuous propulsion would be required (assuming perfect efficiency of the manoeuvre and no reduction of the thrusting level during the manoeuvre itself). Even larger propulsion times are needed on later stages of the mission as the thrusting level decreases with the reduction of the tank pressure (nearly 35 minutes of thrust needed at end of life (EOL), being only 20 Newton of thrust available).

Due to the satellite constraints of performing the entire manoeuvre phase in eclipse (thus around the ascending node - ANX) and taking into account the time needed for: slewing the platform before the manoeuvre, to align the thrusters, normally aligned with the velocity direction, with the out-of-plane direction (a bit more than 11 minutes); slewing it back into the nominal attitude afterwards (a bit less than 11 minutes); between 7 and 10.5 minutes of thrusting time are available for a single burn (depending on the eclipse duration that changes with the time of the year). Segmentation in several burns – 2 at BOL, 3 at mid of life (MOL) and up to 4 or even 5 at EOL – is then required.

The baseline strategy of performing one large correction each 18 months appears therefore operationally sub-optimal, due to the complexity of performing multiple burns in sequence (see [1]). Also from the fuel usage point of view that strategy seems not to be optimal, due to partial usage of the eclipse period (for instance if 24 minutes of thrusting are needed and 10 are available in the eclipse, 3 manoeuvres have to be performed instead of 2.4, each with an usage of 80%). More manoeuvres are then needed, with a net penalty deriving from the slew cost (around 1.3 kg per manoeuvre at BOL).

Finally, the real evolution of the inclination and LTAN in one year is not as smooth as presented above, due to the non-linearity of the inclination drift during one year caused by the oscillation of the real-sun position around the mean-sun.

Therefore larger decays are observed on winter (around 150% or the yearly average) and smaller on summer (around 50% of the yearly average). The resulting evolution is then affected, as shown in Fig. 3 (same initial condition and same manoeuvres as in Fig. 2).

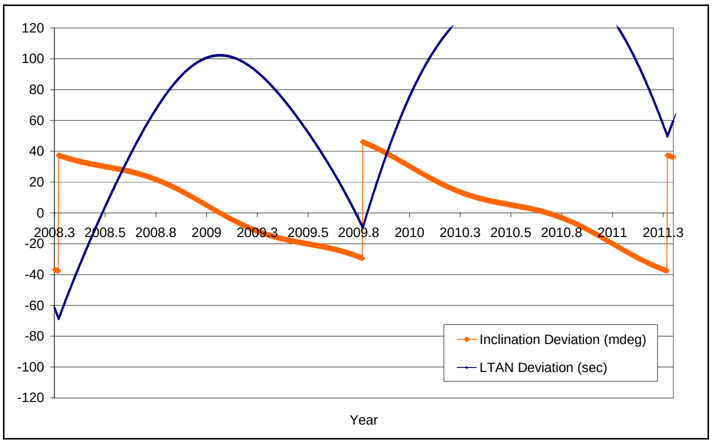

Fig. 3 Inclination and LTAN evolution (real case)

Therefore, a complete review of the long term strategy is performed to identify the best strategy permitting to:

- optimize the fuel usage (to increase the satellite lifetime);
- minimize the number of burns performed during the satellite life (with positive impact both at fuel and operation level);
- reduce as much as possible the number of manoeuvre campaigns (to reduce the overall outage caused by that activities);
- minimize the number of burns in each manoeuvre campaign (to keep operations simple, no more than two burns per campaign should be performed);
- maintain as far as possible a repetitive operational scheme (to ease the long term planning).

To achieve that, an accurate selection of the best dates for performing OOP manoeuvre and an optimal usage of the eclipse period are needed. Several possible operational strategies are then identified and analysed in terms of the above presented merit figures. The final optimal OOP strategy, which combines the best characteristics of the analysed strategies, is then derived and selected for operations.

2.1 OOP Manoeuvre Efficiency and Specific Cost

The orbital position (position sur l'orbite; PSO; angle between ANX and current satellite position measured on the orbital plane) when an OOP manoeuvre can be executed changes as function of the day of the year (DOY), due to the change of the eclipse location within the orbit. As a consequence change also the overall inclination efficiency that can be achieved when the entire available arc is used (as product of the non impulsive efficiency, deriving from the spreading of the burn around its mid point, and of the displacement efficiency, deriving from the displacement of the burn mid point from the ANX location).

That effect is presented in Fig. 4. It can be observed that whereas the manoeuvre arc is maximum in summer (around DOY 230) and minimum in winter (around DOY 60), the efficiency presents two maximum, one close to the spring equinox (around DOY 70) another to the autumn one (around DOY 280), thanks to the lower displacement of the burn mid point from the ANX. When however the specific cost of a manoeuvre is analysed (defined as number of grams of fuel per millidegrees of change in inclination) then the situation is slightly modified by the non linearity introduced by the fixed penalty of performing the slew manoeuvre. Fig. 5 presents the evolution during the year of the maximum achievable inclination change, of the fuel spent and of the specific cost (BOL conditions assumed). The maximum inclination change presents a minimum in correspondence of the minimum manoeuvre duration and the cost present two minimum points in close to the maximum efficiency dates (DOY 80 and 280); it is interesting however to notice that the autumn minimum is more advantageous than the spring one due to the longer manoeuvre that can be performed (diluting thus the slew cost).

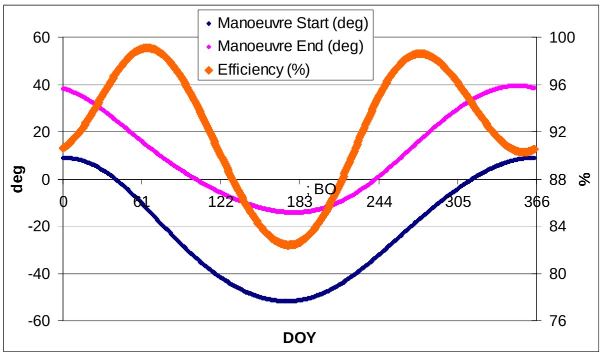

Fig. 4 Manoeuvre efficiency

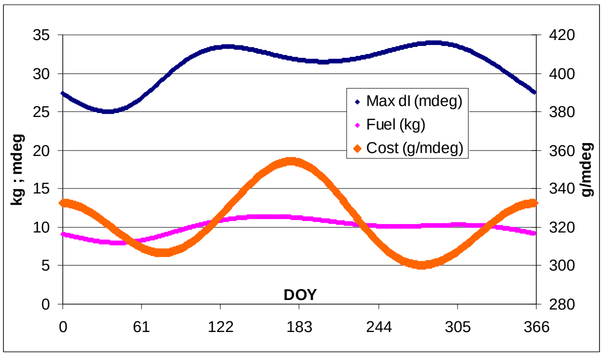

Fig. 5 Manoeuvre specific cost

The situation remains basically unchanged for MOL and EOL conditions.

When the eclipse usage is reduced, then the specific cost decrease for bad performance dates (summer and winter) and increase for good performance dates (spring and autumn).

- In the first case, the increase of efficiency linked with the reduction of the thrusting arc and with the reduction of the displacement of the burn mid point from the ANX, is quite big, compensating the increased impact of the slew cost (final inclination change is reduced in any case).
- In the second case the efficiency increase is limited, as the burn is already quite well centred on the ANX location. Therefore the loss of cost caused by the slew is predominant.

Fig. 6 depicts the evolution of the specific cost in case of usage of only the 80% of the eclipse.

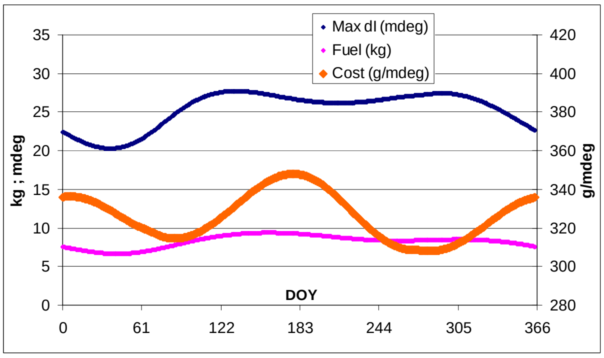

Fig. 6 Manoeuvre specific cost
(80% eclipse usage case)

From these preliminary analyses it can be concluded than, in order to minimise the manoeuvre cost, full usage of the eclipse during the autumn slot is recommended; that ensure at the same time maximum change in inclination, permitting thus to minimise the number of the manoeuvres. Usage of the spring slot is also acceptable, even if lower inclination changes are achieved (more manoeuvres are then required).

2.2 Long Term Inclination and LTAN evolution Analysis

Several LTAN strategies were analysed in detail through full long term simulations, based on simplified but still quite representative models of the eclipse (same as used on the previous paragraph), of the orbital evolution (inclination and LTAN deviation only considered) and of the satellite (mass, fuel, pressure, specific impulse and thrusting level modelled using real satellite database values and calibrated with real satellite flight data).

Simulations start in April 2008, time when the first OOP manoeuvre was executed by EUMETSAT (inclination and LTAN bias implemented at LEOP permitted to have an 18 month manoeuvre free period practically at zero cost) and last till end on 2020 (14 years of mission!).

The first considered case is the mission analysis strategy, above already mentioned: LTAN deviation kept between +/- 60 sec and inclination deviation between +/- 40 mdeg; OOP performed whenever the LTAN dead-band is reached to generate an as long as possible LTAN cycle.

The performances of that strategy, described in Fig. 7, can be summarised as follow:

- Number of campaign: 9
  (regular distribution each 17 months)
- Number of manoeuvres: 31
- Max number of manoeuvre per campaign: 4
- Total inclination change: 645 mdeg
- Average eclipse usage: 87%
- Average manoeuvre efficiency: 0.94
- Total fuel used: 238 kg
- Specific cost: 369 g/mdeg

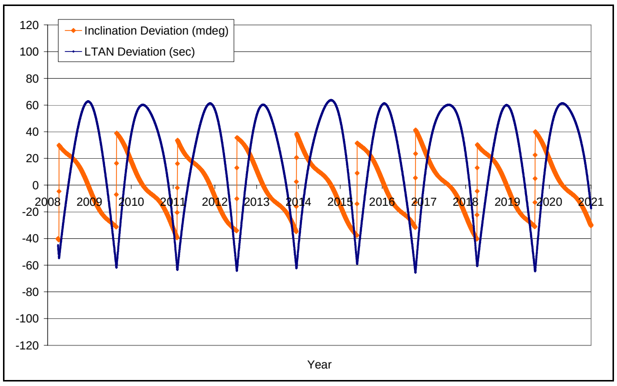

Fig. 7 MA strategy

Due to the fact that the manoeuvre date shifts, suboptimal dates are used, with impact on the efficiency and consequently on the specific cost, which is very high. Moreover, being the inclination change to be provided quite large (between 70 and 75 mdeg), the number of inclination manoeuvres in a campaign increases a lot when the satellite gets older (and even on the first years, due to the pour efficiency of the manoeuvres).

Eclipse usage is also not optimal, due to the constrained inclination change to be provided. However it can be observed that maximising the eclipse usage, by allowing smaller LTAN cycle, does not produce a big advantage in terms of fuel (suboptimal dates are used in any case), increasing the number of needed campaigns (which are now closer in time).

Therefore a simulation was performed forcing the manoeuvres to be executed only close to the equinoxes (equinox strategy), so on optimal dates (around DOY 80 or DOY 280), and with full eclipse usage. Same LTAN and inclination dead-band as on the mission analysis case considered, but no maximisation of the cycle duration requested (impossible as full eclipse usage is imposed).

The performances of that strategy, described in Fig. 8, can be summarised as follow:

- Number of campaign: 15
  (once per year, twice on two years)
- Number of manoeuvres: 27
- Max number of manoeuvre per campaign: 3
- Total inclination change: 644 mdeg
- Average eclipse usage: 100%
- Average manoeuvre efficiency: 0.98
- Total fuel used: 222 kg
- Specific cost: 345 g/mdeg

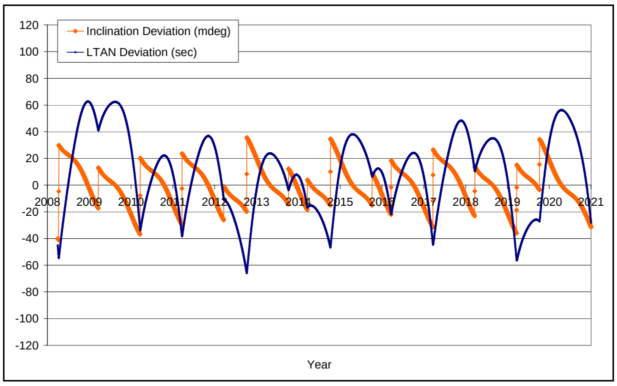

Fig. 8 Equinox strategy

Due to the fact that the manoeuvre dates are fixed to optimal cases the efficiency is very high and consequently the specific cost is much smaller than in the mission analysis case (7% better). Moreover, being the inclination change to be provided much more limited, as not the full dead-band is used, the number of manoeuvres in a campaign remains quite limited (less than 2 on the first 8 years).

In order to further improve the manoeuvre efficiency and also the operational behaviour, the stringent (and artificial) requirement of LTAN and inclination maintenance were relaxed to +/-100 seconds and +/- 45 mdeg respectively.

It is then possible to define a strategy when manoeuvres are performed every 18 month (<u>18-month strategy</u>), around optimal dates. No full eclipse usage is however possible, as a constraints is imposed in the manoeuvre dates and in the maximum LTAN evolution.

The performances of that strategy, described in Fig. 9, can be summarised as follow:

- Number of campaign: 9
  (every 18 months)
- Number of manoeuvres: 28
- Max number of manoeuvre per campaign: 4
- Total inclination change: 660 mdeg
- Average eclipse usage: 94%
- Average manoeuvre efficiency: 0.97
- Total fuel used: 230 kg
- Specific cost: 349 g/mdeg

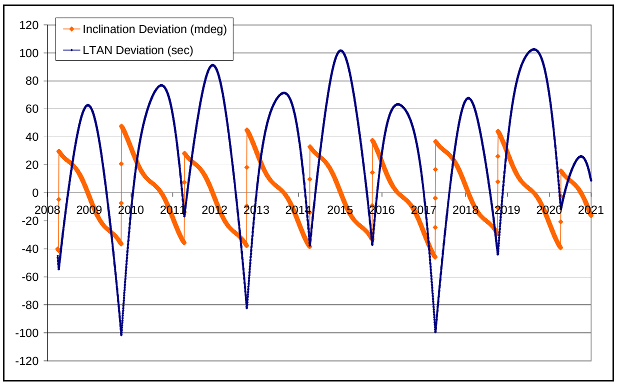

Fig. 9 18-months strategy

As no full eclipse is used, a marginal increase in the specific cost is observed with respect to the equinox strategy; the cost remains in any case very limited. Moreover, the number of campaign is minimised, permitting to minimise the mission data outages. However, due to the large inclination change to be provided, the number of manoeuvres per campaign is quite high (already 3 manoeuvres needed on the second campaign).

To limit the number of manoeuvres per campaign (higher segmentation is observed in spring, due to the smaller inclination change that can be implemented), a further simulation was performed when manoeuvring campaigns are executed only in the autumn slot, around DOY 280 (<u>autumn strategy</u>). Furthermore the number of manoeuvres per campaign is limited to 2. In order to avoid dead-band violation at EOL, the option of performing extra campaigns in spring is considered.

The performances of that strategy, described in Fig. 10, can be summarised as follow:

- Number of campaign: 15
  (once per year, twice on two years)
- Number of manoeuvres: 26
- Max number of manoeuvre per campaign: 2
- Total inclination change: 664 mdeg
- Average eclipse usage: 100%
- Average manoeuvre efficiency: 0.98
- Total fuel used: 227 kg
- Specific cost: 341 g/mdeg

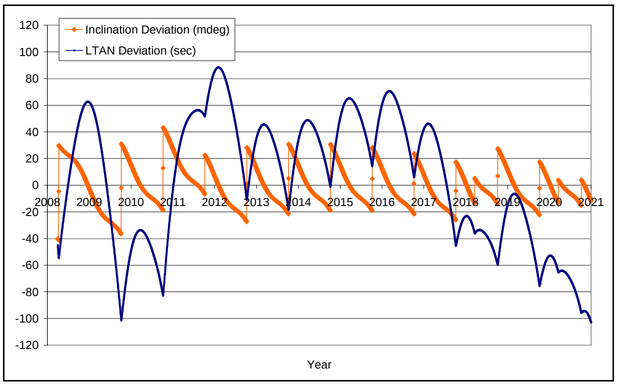

Fig. 10 Autumn strategy

The strategy presents the highest efficiency (8% better than the mission analysis case) as full eclipse usage is always achieved (thanks to the dead-band extra-margin) for the very optimal date (13 times). No need to use the spring slot is identified in the first 10 years of simulation (only one manoeuvre is sufficient in these cases), which provides to the strategy a very good operational repetitive pattern. Because of that, the autumn strategy was recommended for implementation in operations.

2.3 Operational Long Term Inclination and LTAN Maintenance

The autumn strategy presents, after the first OOP campaign in spring 2008, an 18-month period during which no manoeuvre is executed, followed by a big double-burn. The LTAN deviation at time of this double burn (autumn 2009), as well as its rate, is quite high; any delay in the implementation of the manoeuvre may result in fast violation of the dead-band. Taking into account also the complexity of performing a double OOP manoeuvre, it appears clearly that this strategy is quite challenging, if not dangerous, from an operational point of view. The operational complexity can be reduced by performing a first small burn 6 month after the first OOP campaign (Autumn 2008) and then another big burn 12 month later (Autumn 2009).

The performances of that strategy, described in Fig. 11, can be summarised as follow:

- Number of campaign: 16
  (one more than on previous case)
- Number of manoeuvres: 26
- Max number of manoeuvre per campaign: 2
- Total inclination change: 655 mdeg
- Average eclipse usage: 99.8% (max 105%)
- Average manoeuvre efficiency: 0.98
- Total fuel used: 224 kg
- Specific cost: 342 g/mdeg

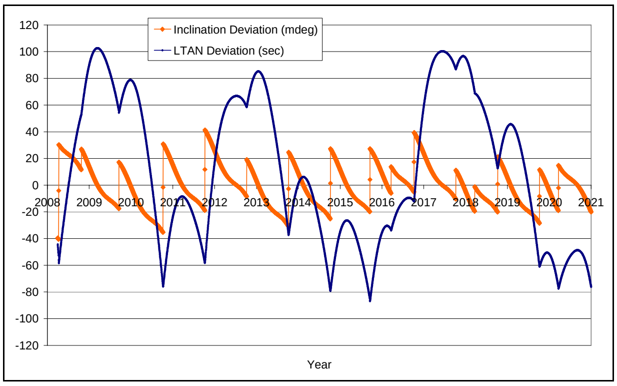

Fig. 11 Operational strategy

The characteristics of that strategy are basically unchanged with respect to the autumn one.

As the burn in autumn 2008 is not using the full eclipse duration (around 50%), then it is necessary to overcharge the following manoeuvres (eclipse usage for campaigns 3, 4, 5, 7, 8, 9 around 104%) to compensate for the loss in inclination change. Eclipse usage up to 110% have been observed as possible in the execution of the first double manoeuvre in spring 2008 (post manoeuvre margin considered in this analysis seems to be too conservative), so it should not represent any problem.

Fig. 12 presents how the autumn strategy was implemented; the foreseen effect of the incoming OOP in autumn 2009 as well as the evolution before the OOP in spring 2008 are also included.
Due to little differences in manoeuvre execution with respect to the a-priori strategy, the evolution according to the <u>model</u> (considering the real manoeuvres) diverges slightly from the <u>a-priori</u>. The <u>real</u> evolution follows however quite well the model. Further eclipse overload (110%) is then foreseen in autumn 2010 to recover the observed LTAN bias with the a-priori evolution.

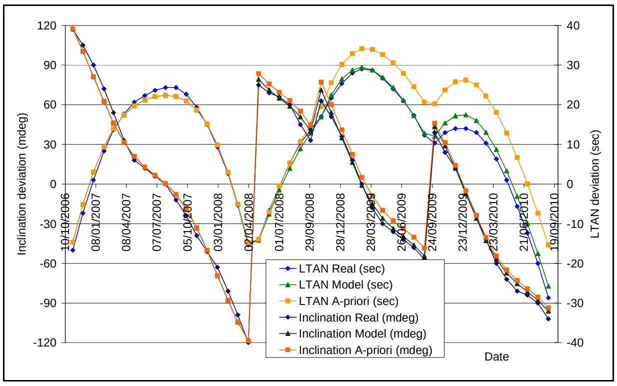

Fig. 12 Real evolution

3. THE FROZEN ECCENTRICITY MAINTENANCE PROBLEM

The ASCAT data processing chain assumes a fixed reference geodetic height for a given PSO to calibrate the data. Height accuracies up to about 250m are needed to achieve high quality processing.

However, a significant satellite height scattering can be observed for a given PSO when the eccentricity vector differs significantly from the eccentricity vector of the orbit used for generating the fixed reference geodetic height profile. At the beginning of the mission the ASCAT data calibration software relied as reference on the nominal Metop orbit from mission analysis. During the first year of operation that nominal orbit was replaced by the operational one. In order to achieve the needed height accuracy it is therefore necessary to maintain the eccentricity as close as possible to the value of the orbit selected as reference for the ASCAT data calibration. That is normally achieved by the so called frozen orbit conditions.

Moreover, a not negligible scattering at a given PSO was also observed within a repeat cycle even when the eccentricity vector was close to the frozen eccentricity.
That is linked to the natural short term evolution of the eccentricity vector, shown in Fig. 13 where the eccentricity averaged on 71 revolutions (one orbital sub-cycle for Metop) is compared with the orbital average.
That effect cannot be cancelled out but only minimised by proper selection of the orbit used as reference for ASCAT.

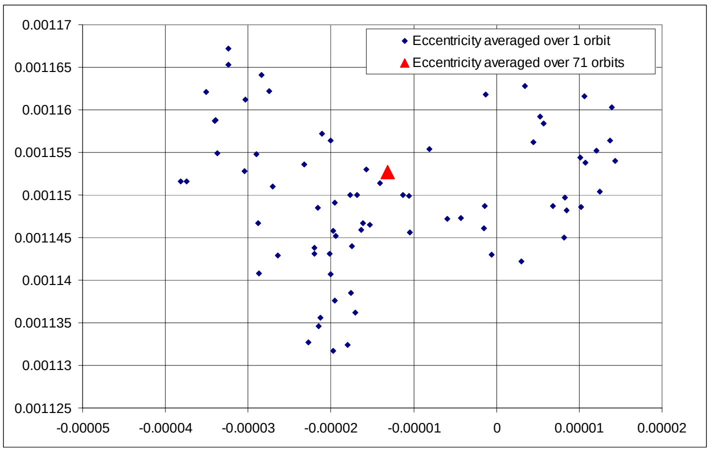

Fig. 13 Eccentricity scattering on one sub-cycle

3.1 Characterisation of Contributions to Height Scattering

As above discussed, two components of the height scattering must be considered:

➢ Height scatterings at same PSO within the 29 days repeat cycle.

The behaviour of that component is shown in Fig. 14.

The height (at ANX) scattering with respect to the average height within the same cycle is shown for frozen and non-frozen eccentricity cases (0.00005 away from frozen value; averaged on 71 orbits). About 300m peak to peak are observed, relatively independently from the eccentricity conditions. Some very limited additional drift exists for the non-frozen eccentricity case due to the eccentricity drift.

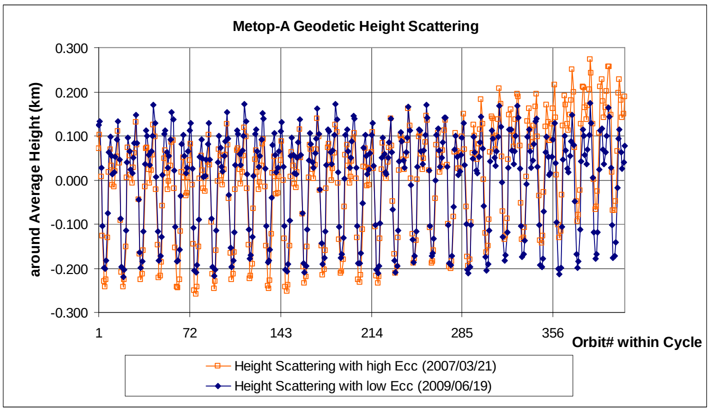

Fig. 14 Height scattering within one cycle

This can be minimised by selecting as reference orbit for ASCAT the one having minimum height separation with all other orbits in the cycle.

- Height scatterings at same PSO and same orbit# across two cycles.

The behaviour of that second component is seen in Fig. 15.

The difference in height (at ANX) between two cycles is shown for very similar eccentricity vectors (frozen case) and very different eccentricity vectors (non-frozen case; 0.00005 of difference; averaged on 71 orbits). Up to 350m of difference are observed in the non frozen eccentricity case. The difference is proportional to the eccentricity separation between the two cycles and the orbital semi-major axis (350m ~ 7000km x 0.00005).

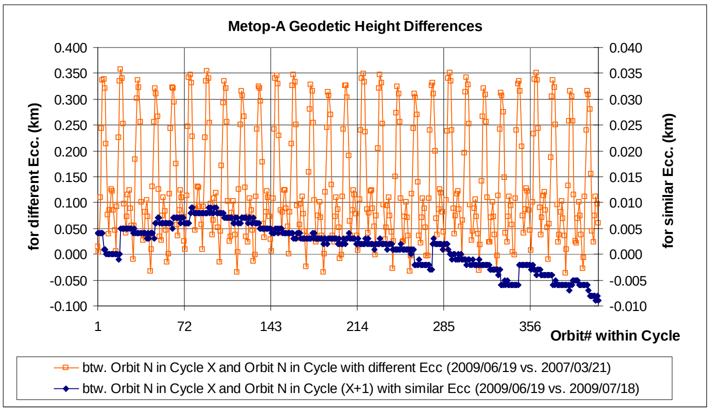

Fig. 15 Height differences across two cycles

This can be limited by appropriate eccentricity control, as demonstrated by the frozen eccentricity case, where much smaller differences are observed; below 10m. The short-term (daily) swings of the height difference are due to the rotation of the relative orbital average eccentricity vector.

3.2 <u>Identification of the ASCAT Reference Orbit</u>

In order to define an adequate reference orbit for the ASCAT instrument data processing, the orbit in a cycle with statistically lower height separation with the other 411 orbits must be identified. The method is the following:

- Consider 1 full orbital cycle (412 orbits) which is manoeuvre-free.
- In order to eliminate possible tesseral resonances, take 1 orbit every 45 orbits (around 3 days, 5 days being the repetition sub-cycle).
- Consider orbits 1, 46, 91, 136, 181, 226, 271, 316, 361, 402.
- For each orbit, compute the Earth-fixed geodetic height with a 60sec sampling interval.
- Compare height for orbit 1 versus orbits 46, 91, 136, 181, 226, 271, 316, 361, 402. Fig. 16 shows the measured height differences for this case.
- Build heights RMS for each comparison and average these values.
- Compare orbit 46 vs. 1, 91, 136, 181, 226, 271, 316, 361, 402.
- Build heights RMS for each comparison and average these values.
- Repeat the procedure for the remaining considered orbits (91, 136, 181, 226, 271, 316, 361, 402).
- Take the lowest RMS. Fig. 17 shows the evolution of the RMS for all the considered orbit.

The corresponding orbit (in our case #136) is the one which least differs in height from the others with and average RMS of 113m (from around 150m of mean RMS). It is interesting to note in Fig. 16 that orbit 136 (yellow-coloured curve) presents very little separation from orbit 1 and provides a further validation to the obtained result.

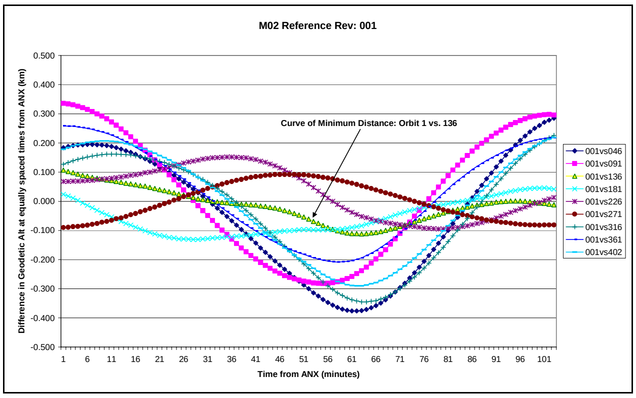

Fig. 16 Difference in height between orbits

Fig. 17 Minimisation of height average RMS

3.3 Eccentricity Control

The second component of the height scattering is driven by the eccentricity variations during different cycles. Eccentricity is mainly perturbed by the significant radial component during OOP manoeuvres (5% of the overall DV) due to thrusters mounting (see [2]).

A mean geodetic height scattering is observed as soon as the eccentricity drift away from the value considered when the ASCAT reference orbit was generated. For a difference of 0.00003 a scattering of 200m is observed which, added to the scattering within a cycle above described, may lead to the violation of the ASCAT calibration requirements (250m).

Either a new ASCAT reference orbit should computed each time the eccentricity moves more than 0.00003 or the natural evolution of the eccentricity shall be bounded within 0.00003 around the ASCAT reference orbit value. In both cases minimisation of the eccentricity excursion is required.

A short description of the manoeuvre history shows the pitfalls involved in identifying the correct strategy to minimize the eccentricity evolution.

3.4 OOP Manoeuvre and Eccentricity History

In the context of the below presented data, mean eccentricity indicates an eccentricity vector averaged on 71 orbits (or 5 days, which is the orbital repeat sub-cycle for the Metop 29-day cycle).
Fig. 18 provides a graphical description of the eccentricity history here-below.

- 14 days after end of LEOP (2006/11/02), a one-burn manoeuvre was executed to stop the LEOP residual drift. The eccentricity at this point of time was (-0.000015, 0.001116); the target was set to the reference orbit target (-0.000000, 0.001154). The resulting mean eccentricity (0.000018, 0.001174) showed a 0.00003 deviation w.r.t. the considered target value. The mean eccentricity evolution followed a circular path of radius 0.00005, as expected.

- A relatively big double-burn manoeuvre was executed on 2007/04/19 to bring the eccentricity to the centre of the observed eccentricity evolution in the previous 5 months (-0.000016, 0.001144). Execution errors, linked to stabilisation pulses, affected marginally the achieved eccentricity as explained in [3]. The resulting evolution still followed a nearly circular path of radius around 0.000015 (three times smaller than previously). However the path centre drifted essentially along Ey starting from around (-0.000014, 0.001150), during the first six months, downwards to around

(-0.000015, 0.001135) for the following six months. Therefore the eccentricity vector tip path did not close upon itself as expected. A seasonal dependency on the location of the eccentricity evolution centre is suspected.

- The first OOP was executed on 2008/04/08. Due to the sizable radial components of the OOP the condition of frozen eccentricity was lost and a deviation of 0.00007 w.r.t the target eccentricity above considered is observed, too large to be acceptable.

- Quite a big double-burn manoeuvre was executed on 2008/04/24 to bring the eccentricity back to reasonable frozen conditions. As target the centre of the evolution observed during the six month before the OOP was taken (-0.000015, 0.001137). As for the previous case, execution error affected marginally the achieved eccentricity and the resulting evolution followed a circular path initially around the eccentricity point (-0.000014, 0.001150) of a radius around 0.000015. This behaviour is very similar to what observed after the double manoeuvre in 2007/04. Again, the eccentricity vector path started drifting towards more negative Ey after some month, which confirmed the hypothesis that the eccentricity evolution centre seems to show a seasonal dependency.

- The second OOP was executed six months after the first OOP, on 2008/10/23. Due to the sizable radial components of the OOP the condition of frozen eccentricity was lost again and a deviation of 0.00003 with respect to the target eccentricity above considered is observed, again too high to be acceptable.

- A relatively big 2-burns manoeuvre was executed on 2008/10/30 to bring back again the eccentricity toward frozen conditions. This time as target the centre of the foreseen evolution in the following six months (assuming no correction is performed) is selected: (-0.000015, 0.001140). That choice permits to minimise eccentricity variations in following six months. As for the previous double burns, execution errors affected marginally the achieved eccentricity. The resulting evolution follow now quite an unusual evolution, first rotating during 4 months around an apparent centre of around (-0.000015, 0.001135) with a very limited amplitude of around 0.000004 (nearly four times smaller than what observed before), then drifting upwards in Ey during two months and finally rotating around a centre of around (-0.000014, 0.001150) with very small amplitude (of the order of 0.000002) in the last four month.

3.5 <u>Eccentricity Behaviour</u>

Comparing that evolution with the other previously observed, it becomes evident that the centre of the eccentricity periodically drifts upwards and downwards in the Ey space between two locations:

- In winter the eccentricity rotates around a “lower” centre located at (-0.000015, 0.001135);
- In summer the eccentricity rotates around a “higher” centre located at (-0.000014, 0.001150);
- In autumn and spring the eccentricity drifts from one centre to the other.

Fig. 18 shows the eccentricity evolution from November 2006 to September 2009 when the third OOP (17 September) is foreseen; the large eccentricity perturbations are due to OOP and the related eccentricity corrections double-IP manoeuvres

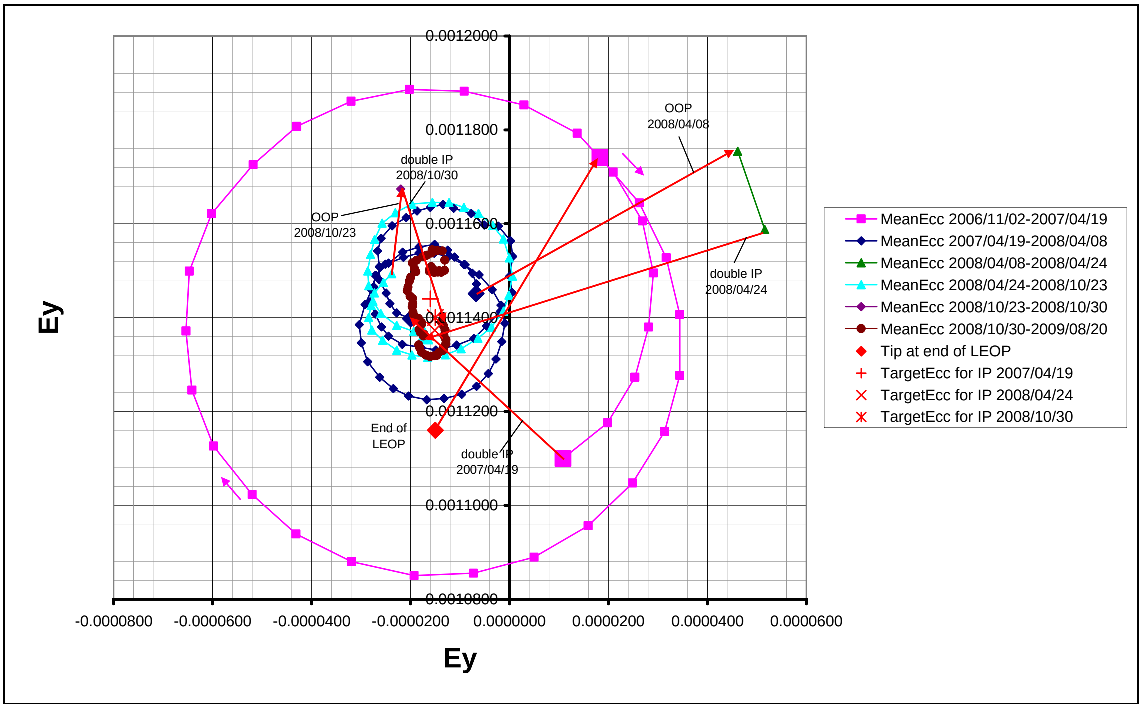

Fig. 18 Eccentricity Evolution

The zoom-in of the eccentricity plot (Fig. 19) permits to better appreciate the seasonal displacement in Ey of the centre of the eccentricity evolution.

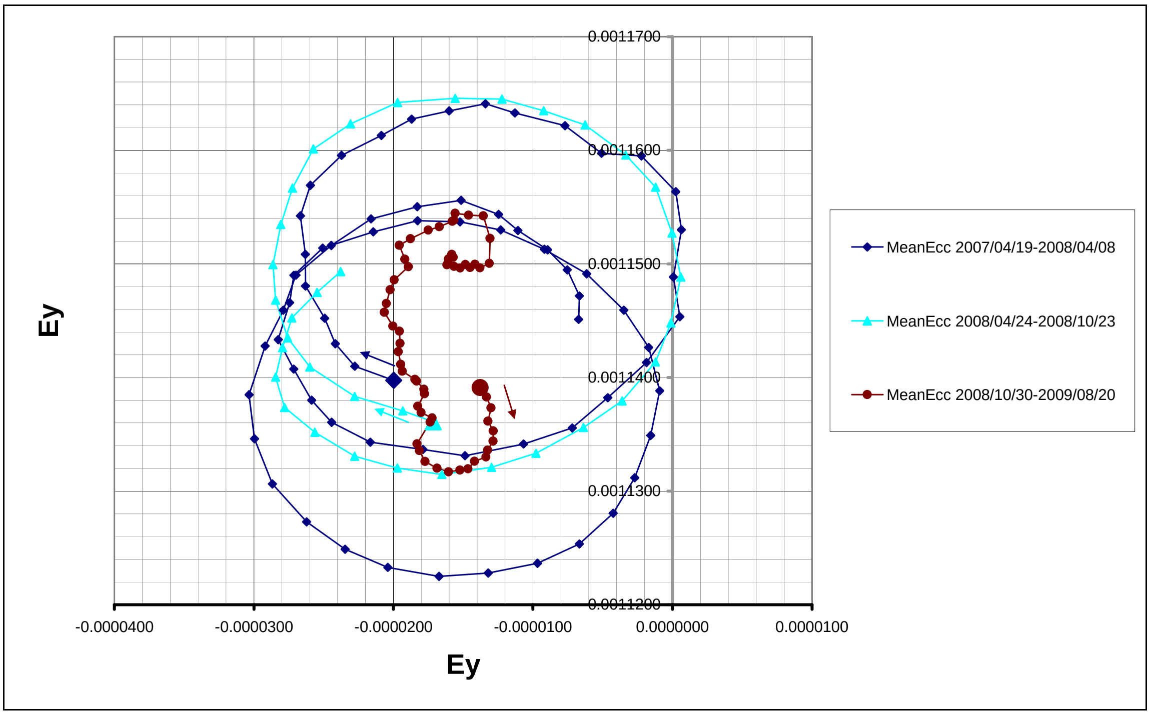

Fig. 19 Eccentricity Evolution Zoom-In

In order to further demonstrate the seasonal character of the eccentricity evolution the following test was done (see Fig. 20); the eccentricity evolution is computed from same initial eccentricity at different initial dates six month apart.

- The brown-coloured curve shows the situation if starting in winter.
- The red-coloured curve shows the situation starting in summer.
- The blue-coloured curve shows the situation in the same initial conditions as the other two cases but eliminating the solar pressure effects.

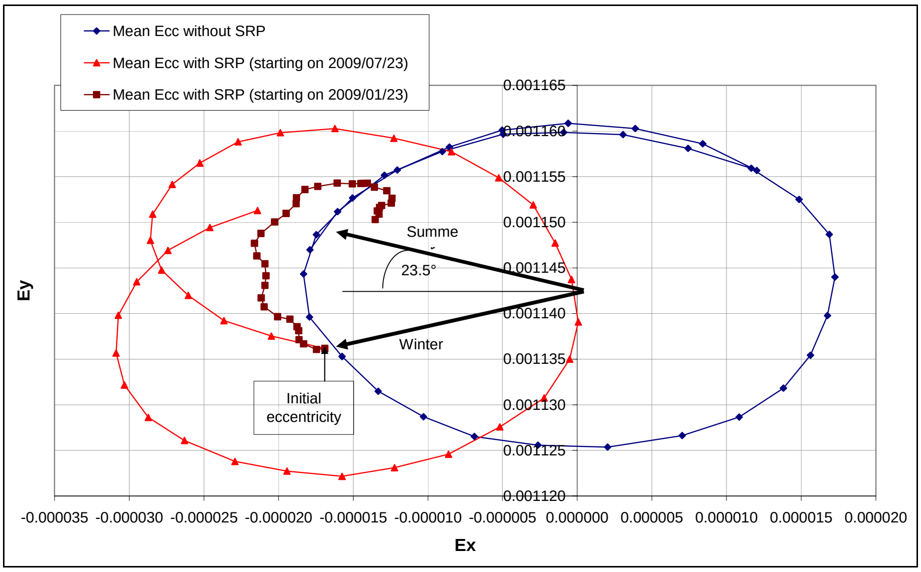

Fig. 20 Eccentricity Evolution vs. Season

It is readily seen that the target around which the eccentricity rotates is not unique. Rather, the eccentricity rotation centre drifts upwards in summer and downwards in winter:

- The direction of seasonal displacement is along Ey, with amplitude around 0.000014;
- Ex remains fixed at around -0.000017.

If the solar radiation pressure is intentionally omitted from the eccentricity evolution, the eccentricity centre is placed around Ex=0 and does not move. The direction of the target with no solar pressure and the seasonally varying targets is aligned with the sun direction about the equator (±23.5 degrees), which induces us to attribute the eccentricity drift behaviour to the seasonally changing sun declination.

The solar pressure acts on the orbit in such a way that the eccentricity centre seasonally reverts its path. Due to this dynamics, it is therefore incorrect to define as eccentricity target the point around which the eccentricity revolved in the past few months. If the manoeuvre takes place in spring and its effect must last 6 months, then the correct target must be the one corresponding to the summer conditions.

4. CONCLUSIONS

A complete review of the long term strategy was performed to identify the best strategy not only to optimize the fuel usage but also to minimize the number of burns performed during the satellite life while at the same time keeping operations as simple as possible (no more than two burns per campaign should be performed and campaign performed at regular frequency).

A large save in fuel was possible (nearly 8%) with respect to the original strategy proposed at mission analysis level, at the cost of an increased number of campaigns (with marginal increase of the operational outages).

The eccentricity vector undergoes a seasonal oscillation around the nominal location during a tropical year. The amplitude of this oscillation is around 0.000014, mainly in the eccentricity vector y-direction and it is likely due to perturbations triggered by seasonal changing direction of solar radiation.

The altitude change caused by that eccentricity displacement, in the order of 100m, can be cancelled out by providing different reference orbit to the ASCAT data processing, depending on the season and controlling the eccentricity of the orbit around the corresponding seasonal target.

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