THE METOP-A ORBIT ACQUISITION STRATEGY AND ITS LEOP OPERATIONAL EXPERIENCE

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ABSTRACT

Europe's first polar-orbiting weather satellite, METOP-A, was launched by a Soyuz launcher from Baikonur Cosmodrome on the 19th of October of 2006. The routine operations of METOP-A are conducted by EUMETSAT (European Organization for Exploitation of Meteorological Satellites) in the frame of the European Polar System mission (EPS). The METOP-A Launch and Early Orbit Phase (LEOP) operations have been performed by ESA/ESOC.

The Flight Dynamics Orbit Determination and Control team (OD&C) at ESOC was in charge of correcting the S/C orbit as delivered by the launcher in such a way that EUMETSAT would be able to acquire the reference orbit with a drift-stop manoeuvre approximately two weeks after a LEOP of 3 days and Hand-Over to the EUMETSAT Control Centre (EUMETSAT-CC) in Darmstadt, Germany.

The various strict constraints and the short amount of time available for ESOC operations made this task challenging. Several strategies were prepared before launch and analysed during LEOP based on the achieved injection orbit.

This paper presents the different manoeuvre strategies investigated and finally applied to acquire the operational orbit, reporting as well the details of its execution and final achieved state.

1. INTRODUCTION

METOP-A (METeorological OPerational) was launched by a Soyuz launcher equipped with a Fregat upper stage from Baikonur Cosmodrome on the 19th of October of 2006. METOP-A, Europe's first polar-orbiting weather satellite, is the first of a series of three S/C which comprise the space segment of the EPS mission. EUMETSAT is in charge of running the EPS mission and controlling the routine operations. The METOP-A LEOP operations have been performed by ESA/ESOC.

The strategy chosen by EUMETSAT to control the METOP-A orbit is based on a Sun synchronous reference orbit with a repeat pattern of 412 orbits in 29 days and with a local time of the ascending node (LTAN) of 21:30 hrs. The deviation of the S/C orbit from the reference orbit is measured in terms of perpendicular distance in ground-track and in deviation of the LTAN.

Table 1. Reference orbit

METOP-A reference orbit	
Type	Near Polar Sun Synchronous Repeat Ground-track Frozen Eccentricity
LTAN	21:30 h
Cycle length	412 orbits
Cycle duration	29 days

The orbit control is achieved by the execution of two types of manoeuvres in order to keep the distance to the ground-track and the LTAN within a predefined dead-band:

- In-plane (IP) manoeuvres to change the semi-major axis (and eccentricity) which allow to control the ground track deviation from the reference orbit at the Earth Equator.

- Out-of-plane (OOP) manoeuvres to correct the inclination, allowing to control the deviation from the reference ground-track at high latitudes as well as the drift of the ascending node and its local time.

The OD&C team at ESOC was in charge of preparing a manoeuvre plan to correct the S/C orbit as delivered by the launcher. Since no large manoeuvres were foreseen during the commissioning phase by EUMETSAT, this plan should aim to correct completely the inclination error and adjust the semi-major axis in order to acquire the reference ground-track in two weeks after Hand-Over. At this time EUMETSAT-CC was supposed to perform a small IP manoeuvre to stop the drift.

METOP-A LEOP was characterized by a tight schedule of the FD activities, which affected in particular the OD&C team. The foreseen LEOP duration was just three days with only two possibilities for manoeuvering on the third day. Of great importance was the prompt assessment during the LEOP of the feasibility of accommodating a manoeuvre plan in a nominal LEOP duration.

Additionally, the following constraints had to be taken into account:

- The OOP effect of an IP manoeuvre and vice versa. The thrusters of METOP-A are aligned to minimize potential contamination of the S/C payload by the exhaust plume and not for the needs of orbit control.

- The maximum change in inclination that can be achieved with one OOP manoeuvre was not enough to correct the 3-sigma dispersion of the launcher (see Table 2).

Table 2. Separation orbit parameters (True Of Date)

Parameter	**Value**	**3-sigma**
Semi-major axis (km)	7188.64	± 12
Eccentricity	0.00245	± 0.001
Inclination (deg)	98.74[1]	± 0.12
RAAN (deg) [2]	-	± 0.12
Argument of perigee (deg)	107.80	± 12

There was, at the same time, a degree of freedom introduced by shifting the reference orbit. This means that in fact only the sequence of sub-satellite longitudes at node-crossings was fixed, but the crossing times were allowed to change (keeping unaltered the LTAN). The requirement on these longitudes stems from the location of devices on ground needed for calibration of the payload.

Due to these constraints and the short amount of time available for ESOC operations, several manoeuvre strategies were identified and analysed before the launch, covering nominal and contingency cases. The objective of these preparations was to speed up to the maximum extent the analysis of the manoeuvre strategy during LEOP, after having available the information of the achieved injection orbit.

2. PREPARATION OF THE MANOEUVRE STRATEGIES

A reference orbit having the characteristics mentioned in Table 1 was generated at EUMETSAT-CC during the pre-launch activities and sent to ESOC.

The two objectives set by EUMETSAT regarding the optimisation of a manoeuvre strategy were:

- To initialize an LTAN control cycle for ca. eighteen months between 21:28 and 21:32 hours to avoid executing OOP manoeuvres during this period.

- To allow EUMETSAT-CC to freeze the eccentricity when performing an IP drift stop manoeuvre with a Delta-V below 20 cm/s.

The analysis of the possible manoeuvre strategies was agreed to be presented to EUMETSAT at Mission Elapsed Time (MET) 32:30 hrs. This presentation should include a complete analysis of the orbit status after injection and the feasibility of fulfilling the orbit control requirements in a 3 days LEOP. An initial rough estimation of the Delta-V sizes required for this purpose could be quickly achieved through simple first order models. The cases described in the next subsection were foreseen to be analysed and presented to EUMETSAT.

2.1 MANOEUVRE STRATEGIES ANALYSED

Noncontingent acquisition of the reference orbit

Three of the strategies analysed (cases A,B and C) represent a non-contingency LEOP. The objectives mentioned in section 2 are achieved in each case by:

- An OOP manoeuvre to correct the inclination to be performed on the third day of LEOP, at 50:20 MET. This manoeuvre was required to be performed within visibility of the ground stations of Kerguelen (Indian Ocean) and Malindi (Kenya). The target for the inclination

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[1] The injection value is 0.035 degrees above the inclination of the reference orbit. This difference allows to start a LTAN cycle of ca 18 months.

[2] Value depends on launch date.

was 35 mdeg above the inclination of the reference orbit (see Table 1). This target inclination should result in the desired LTAN cycle of 18 months.

- An IP manoeuvre to start a drift of 14 days to an adequately resynchronized reference orbit. This manoeuvre had to be executed the third day of LEOP, with an execution window going from 61:40 MET to 63:20 MET. A drift-stop manoeuvre was foreseen to be performed by EUMETSAT-CC in order to acquire the target ground-track.

The three cases have the OOP manoeuvre in common. The difference between cases A, B and C is the optimisation of the IP manoeuvre and the reference orbit considered.

The only constraint on the reference orbit required by EUMETSAT is to fly over a sequence of longitudes at Earth Equator crossing, respecting at the same time the required LTAN. Therefore it was possible to resynchronize the reference orbit, such that the acquisition of the reference orbit could be made in the most convenient way.

Case A. No IP manoeuvre to start the drift is executed during LEOP. In this case it is assumed that the semi-major axis after injection starts a gentle drift with respect to the reference orbit. Under this assumption it is possible to resynchronize the reference orbit in such a way that it can be acquired with a small drift-stop manoeuvre only.

Case B. An IP manoeuvre is executed during LEOP to adjust the drift towards an adequately resynchronized reference orbit. The resulting drift should be gentle and should also lead to an opportunity to acquire the resynchronized reference orbit exactly 14 days after Hand-Over. An IP manoeuvre to stop the drift is performed by EUMETSAT-CC as in case A.

Case C. An IP manoeuvre is executed during LEOP to adjust the drift towards the reference orbit (without any resynchronization). Another IP manoeuvre to stop the drift is performed by EUMETSAT-CC as in case A.

Acquisition of inclination and semi-major axis only

This case (case D) covers the possibility of not attempting the acquisition of the reference orbit, but simply correcting the dispersion of semi-major axis, eccentricity and inclination by executing an OOP and an IP manoeuvre.

2.2 FURTHER ANALYSIS

In addition to the four cases mentioned in the previous subsection, the following analysis was also prepared to cover the occurrence of a contingency situation.

Large inclination correction

The Attitude and Orbit Control System (AOCS) allows the execution of an OOP manoeuvre with a maximum size of 7 m/s. This together with the already mentioned fact that only one OOP manoeuvre was nominally foreseen in a 3 days LEOP implied that it was not possible to correct for the 3-sigma dispersion in inclination given by the launcher (Table 2) with one of the four nominal strategies. For such a case, the following alternatives were foreseen to be analysed:

- To request an extension of the duration of the LEOP. This would allow ESOC to carry out the inclination correction in two OOP manoeuvres, making it possible to calibrate the thrusters between the two manoeuvres. This would translate into an increase of the accuracy of the final achieved inclination. However a LEOP extension had to be as far as possible avoided.

- No LEOP extension requested and to carry out the inclination correction in two OOP manoeuvres, having a calibration of the thrusters in-between. This option would mean that there is no possibility to execute an IP manoeuvre during LEOP and therefore EUMETAT would have to perform a large IP manoeuvre 14 days after Hand-Over to acquire the reference orbit.

- No LEOP extension requested and to carry out the inclination correction by two OOP manoeuvres at successive node crossings without calibration in-between. This way an IP manoeuvre can also be performed during LEOP, but the final inclination achieved is likely not to be very accurate.

- No LEOP extension requested and to carry out the maximum inclination correction possible by one OOP manoeuvre leaving the correction for the remaining inclination error to EUMETSAT-CC. This strategy allows to perform the IP to start the drift during LEOP. As a drawback the duration of the first LTAN cycle would be less than 18 months.

Performance of the thrusters

An inefficient performance of the thrusters in the execution of the OOP manoeuvre could have a significant impact on the LTAN cycle. Representative cases of ± 10% performance were analysed.

The OOP effect of an IP manoeuvre and vice versa

METOP-A uses a hydrazine propulsion system with two redundant branches, each made up of a tank and eight thrusters. The thrusters are grouped together into propulsion plates located on the S/C faces +Y, -Y, +Z, -Z, with +Y being the face pointing into the flight direction. Due to the biases of the plates with respect to the S/C axes and the fact that the thrusters are tilted with respect to their plates, the execution of an IP burn has a parasitic component in the OOP direction and vice versa.

A procedure was defined and trained during the LEOP preparations in order to cope with this alignment of the thrusters. This procedure was based in the execution of several iterations between the OD&C software in charge of the manoeuvre optimisation and the command generator. The latter uses the Delta-V sizes optimised by the OD&C team to generate the thruster pulse pattern and to derive from it a realistic acceleration profile prediction (preparing previously a sensible guess of the applicable tank pressure and taking into account the constraints on the platform).

After a complete iteration, the effect on inclination due to the IP manoeuvre can be taken into account when optimising the OOP manoeuvre in the next iteration and vice versa.

3. LEOP ACTIVITIES

After a series of 3 unsuccessful launch attempts in July 2006 the launcher had to be refurbished and a new campaign started in October 2006. Finally METOP-A was launched on the 19th of October at 16:28:13.2 UTC and separated from the upper stage at 17:36:57.2 UTC.

The achieved orbit after the separation of METOP-A had a semi-major axis approximately 4.8 km above the reference nominal value and an inclination offset wrt the reference orbit value of +0.029 degrees, i.e. only -0.006 degrees wrt the launcher target. The good injection managed by Soyuz/Fregat made it clear from the first hours after injection that an extension of the LEOP duration would not be necessary. From this point onwards the OD&C team activities diverged from the preparations described in section 2, since there was no need to further analyse any contingency cases.

3.1 ANALYSIS USING FIRST ORDER MODELS

After the second orbit determination at MET 18:00 the injection orbit was analysed using simple first order models. This quick analysis provided the OD&C team with the necessary figures to start the optimisation of the manoeuvre strategy. The orbit after the initial attitude acquisition and the output of this analysis were the following:

- Difference in semi-major axis wrt the nominal reference orbit of +4.8 km. This difference translates into +6.1 seconds difference in orbital period. Consequently, the Position Sur l'Orbit (PSO) drifts backwards 5 degrees per day wrt the nominal reference orbit.
- Inclination offset wrt nominal mean inclination of +0.029 degrees.
- Mean eccentricity: module 0.00097, argument of perigee 83 degrees versus target 0.00115, argument of perigee 91 degrees (frozen orbit).
- LTDN[3]: 09:28:58 hrs. Violation of the 120 second dead-band in 14 months (See Figure 1).
- The approximate distance of two consecutive nodes of the reference ground track is close to 100 km (412 nodes along the Earth equator). The analysis of the injection orbit shows that the natural drift wrt the nominal reference orbit leads to the crossing of a ground track node every two and a half days approximately (See Figure 2). This is the time that the ground track deviation at 0 degrees (ascending or descending leg) takes to increase by approximately 100 km.

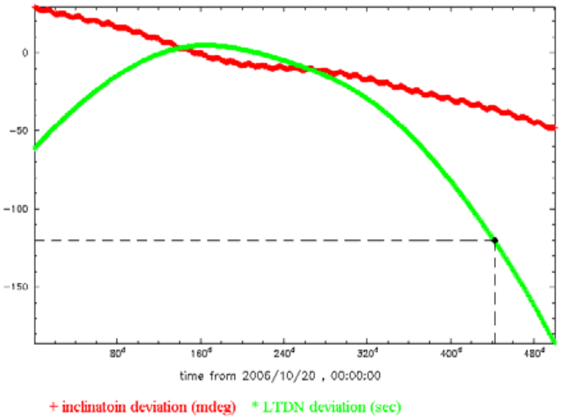

Figure 1. Evolution of the inclination and LTDN deviations after injection.

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[3] Local time of descending node, i.e. LTAN + 12 hrs. This is the figure that will be displayed in the following plots.

Out-of-plane manoeuvre

In view of the good accuracy of the injection inclination the possibility of not executing an inclination correction at all was considered. EUMETSAT decided to discard this option, since there was a large interest on executing an OOP manoeuvre in order to validate the platform and the procedures as well as to calibrate the thrusters. The availability of the whole project, industry and ESOC teams constituted the optimum frame to carry out this validation exercise.

A Delta-V of 0.701 m/s was needed to change the inclination from 0.029 to 0.035 mdeg above the reference orbit inclination.

However, EUMETSAT requested via fax a new target inclination of 0.040 degrees above the reference inclination of the reference orbit, instead of the nominal value of 0.035. “This arrangement ensures that the OOP has a reasonable size and meets the target of having 18 months inclination cycle”. This change was expected since the value of 0.035 deg above the reference was derived for the previous launch date in summer 2006. Due to seasonal effects the actual launch date lead to a different inclination evolution during the first 18 months after launch.

A Delta-V of 1.350 m/s was needed to achieve the new inclination shift.

In-plane manoeuvre

The nominal window for the IP manoeuvres was 61:40 – 63:20 MET, or equivalently 2006/10/22-06:08:13.2 – 2006/10/22-07:48:13.2 UTC.

Two cases were analysed for the IP manoeuvre, each of them based in a different resynchronization of the reference orbit.

The time and the longitude of a node crossing of the injection orbit close in ground-track to a node crossing of the reference orbit were set as an input for the resynchronization. The resynchronization changes the times at which the equatorial nodes are crossed, in such a way that the node crossing of the reference ground-track which is closest in longitude to the one given as an input will be also the closest in crossing time to the input one.

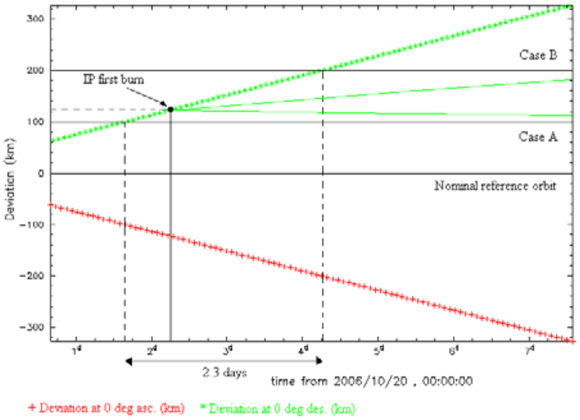

Figure 2. IP manoeuvre strategies.

Case A. Reverse the drift towards the closest node of the reference ground-track

In case A the reference orbit is resynchronized to the closest node of the reference ground-track at the execution time of the manoeuvre. This resynchronized orbit was used to optimise (first order models) the IP manoeuvre. A Delta-V of 2.558 m/s applied against the flight direction is needed to reverse the drift towards the new reference orbit (See Figure 3)

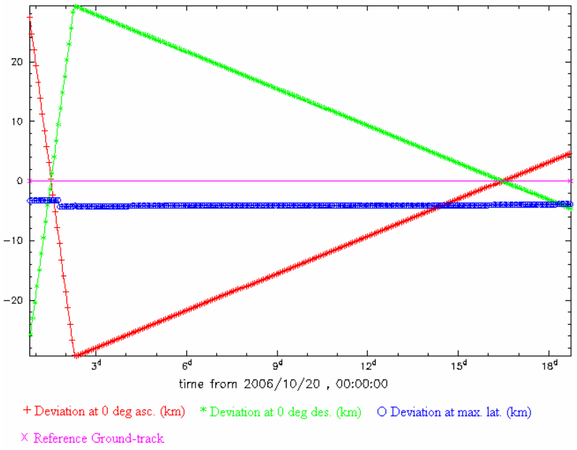

Figure 3. Case A: ground-track evolution.

Case B. Slow down the drift towards the next node of the ground-track

In this case, the next node crossing to the one targeted in case A (2.3 days later) was the target for the resynchronization. The Delta-V needed to adjust the drift towards the new reference is 2.129 m/s to be applied against the flight direction (See Figure 4).

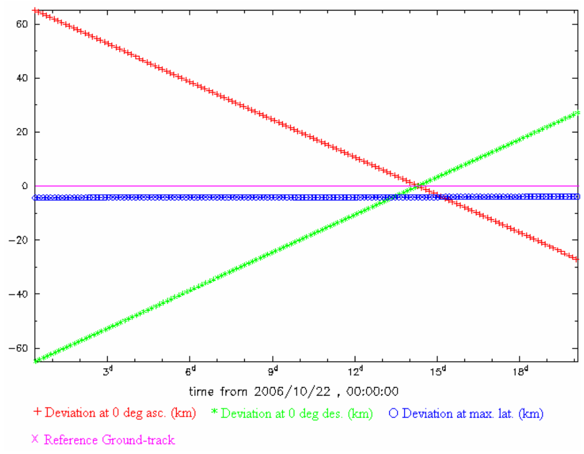

Figure 4. Case B: ground-track evolution.

3.2 FINE OPTIMISATION OF THE MANOEUVRE SEQUENCE

Once a clear picture of the possible manoeuvre strategies had been reached, the next step was to optimise the manoeuvre sequence using a full force model at least for one of the cases before presenting the results to EUMETSAT.

Out-of-plane manoeuvre optimisation

The target for the OOP manoeuvre was to shift the inclination +0.011 deg from 0.029 to 0.040 deg above the reference inclination. It was foreseen to take into account the non-impulsivity of the burn. Once the pressure of the tanks had been determined after the end of the attitude acquisition firings, the duration of the burn could be estimated and a correction for the non-impulsivity could be added to the final size. However, this effect was lower than 0.1 % due to the small size of the OOP manoeuvre and therefore it was neglected.

In-plane manoeuvre optimisation

The IP manoeuvre was optimised after the generation of the first acceleration profile containing the OOP manoeuvre by the command generator. The IP manoeuvre consisted of two burns separated by half an orbit in order to correct for the eccentricity (See Table 3).

Table 3. Optimised IP manoeuvre for case A

Manoeuvre execution time	Size(m/s)	PSO(deg)
2006/10/22-06:32:13.466	-1.65005	297.992
2006/10/22-07:22:52.970	-0.90329	117.992

The effect of the IP manoeuvre on the inclination (See Figure 5) was a decrease of 0.0007 deg, therefore the inclination correction had to be readjusted to 0.0117 deg to compensate for it. The Delta-V needed to achieve this inclination shift was 1.428 m/s to be performed at the ascending node.

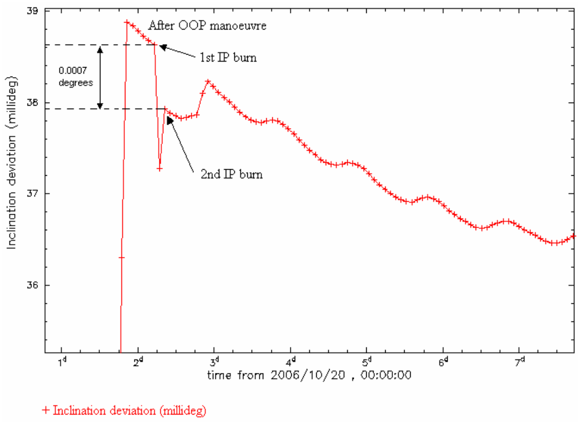

Figure 5. Effect of the IP manoeuvre on the inclination.

Presentation to EUMETSAT

All the results obtained during the optimisation of the strategy were collated in a presentation that was shown in a meeting held at ESOC at MET 32:30, together with the FD, Flight Control teams and EUMETSAT project.

Both cases, A and B, did not imply major operational risks. In terms of fuel consumption option B was cheaper, but as far as the drift-stop manoeuvre was concerned, option A was more suitable, since the size of the manoeuvre was smaller than for option B. Option A was finally selected. Thrusters on the +Y face were agreed to be used for the OOP and IP manoeuvres. The reasons being that it’s the natural choice for the IP and they are the ones that will be used operationally by EUMETSAT for future inclination corrections.

3.3 EXECUTION OF THE INCLINATION CORRECTION MANOEUVRE

All OD&C tasks related to the implementation of the inclination correction manoeuvre were planned to be finished at MET 43:00, in order to start the generation of commands at MET 43:30 while giving half an hour to the Tests & Validation team to verify the optimisation and implementation of the manouevre. The final objective of the OOP was a shift of +0.012 deg in inclination.

Manoeuvre implementation

Since time permitted it, the analysis of the effect of the IP manoeuvre on the inclination was carried out anew. In this occasion, as the decision on the plates to use for the OOP had been already made, +Y was selected as input for the command generator. -Y had been used during the preparation of the presentation.

The final optimisation gave a Delta-V of 1.56 m/s leading to a commanded manoevre as given in Table 4.

Manoeuvre calibration

The calibration of the OOP manoeuvre started right after the retrieval of the first passes after the manoeuvre execution. At MET 53:30 a final orbit determination for the OOP calibration showed a 1% overperformance. The output of this orbit determination was used to optimise again and implement the coming IP manoeuvre.

Table 4. Calibration of the OOP before the implementaion of the IP manoeuvre.

Mid-burn execution time 2006/10/21-18:58:08.261	Commanded	Calibrated
Radial (m/s)	-0.1111	-0.1262
Along-track (m/s)	0.0000	-0.1263
Cross-track (m/s)	1.5605	1.5453
Pointing error (deg)	--	4.7

3.4 IN-PLANE DRIFT-START MANOEUVRE

Manoeuvre implementation

The re-optimisation of the IP manoeuvre started right after the calibration of the OOP manoeuvre.

The drift-stop manoeuvre to be performed by EUMETSAT was confirmed to be on the 2006/11/05. EUMETSAT emphasized that by that time the ground-track deviation at the Equator should had entered by all means a 5 km dead-band, in such a way that the drift-stop manoeuvre could be performed to acquire the target reference ground track.

The strategy for the IP manoeuvre was then revisited (See Figure 6). A safe approach was adopted to guaranty the fulfillment of the request from EUMETSAT. In principle, the IP burns had been optimised to lead to a 14 days drift towards the target reference orbit. By reducing this drift to 12 days, it was observed that the deviation at the equator (descending leg) wrt the reference ground track after 14 days was close to 5 km, which is the most favorable position to start a long control cycle. In the event of an under-performance close to 1% in the execution of the IP burns, the deviation at the equator after 14 days would be close to zero, which would allow EUMETSAT-CC to execute an IP manoeuvre without any major risk. In case an over-performance occurred, the deviation at the equator (descending leg) after 14 days would be greater than 5 km, but still would allow EUMETSAT-CC to start a control cycle.

The final optimisation took place at 55:40 MET with the following result.

Table 5. Final IP manoeuvre optimisation

Manoeuvre execution time	Size(m/s)	PSO(deg)
2006/10/22-06:32:08.952	-1.56542	297.854
2006/10/22-07:22:48.527	-0.87734	117.854

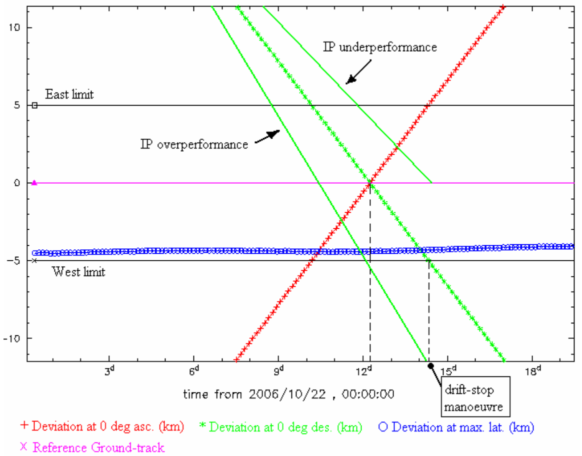

Figure 6. Ground-track evolution for a 12 days drift IP manoeuvre

Manoeuvre calibration

The first attempts to calibrate the IP manoeuvre did not show any anomalous behaviour. It was possible to calibrate the two burns separately, since there were passes over Hawaii, Alaska and Esrange between the burns. The retrieval of data continued over the next two orbits. At this point (2006/10/22-11:45:00 UTC) the final calibration of the IP manoeuvre showed a performance of +1.2% and +2.6% for the first and second burn respectively. This overperformance impacted the duration of the drift towards the target. As it can be noticed in Figure 7, the deviation at zero degrees (descending leg) was exiting the dead-band in 11.5 days.

Table 6. Calibration of the first IP burn.

Mid-burn execution time 2006/10/22-06:30:42.774	Commanded	Calibrated
Radial (m/s)	-0.1139	-0.0616
Along-track (m/s)	-1.5656	-1.5809
Cross-track (m/s)	-0.3400	-0.3712
Pointing error (deg)	--	2.1

Table 7. Calibration of the second IP burn.

Mid-burn execution time 2006/10/22-07:21:59.704	Commanded	Calibrated
Radial (m/s)	-0.0638	-0.0348
Along-track (m/s)	-0.8773	-0.8983
Cross-track (m/s)	-0.1907	-0.2094
Pointing error (deg)	--	2.1

4. HAND-OVER TO EUMETSAT

The nominal orbit control activities continued after the calibration of the complete sequence of manoeuvres. The last orbit determination took place at MET 66:00. Following this orbit determination the control of the S/C was handed over to EUMETSAT-CC on the 22nd of October of 2006.

According to the final orbit determination the ground-track deviation at 0 deg (descending leg) was entering the dead-band at around 2006/10/30-06:00, the deviation was exactly 0 km at around 2006/11/02-12:00 and it was going to exit the dead-band on the 2006/11/02-12:00 (see Figure 7).

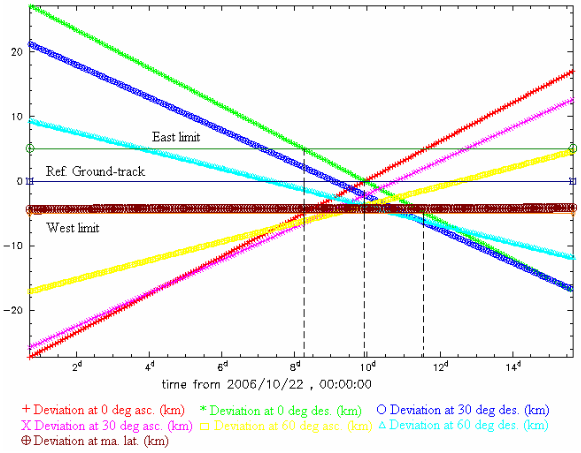

Figure 7. Final ground-track evolution at Hand-Over

Regarding the inclination cycle, the requirement of an 18 moths cycle without any inclination correction was perfectly satisfied as it can be seen in the plot of the evolution of the inclination and LTDN deviations after Hand-Over (see Figure 8).

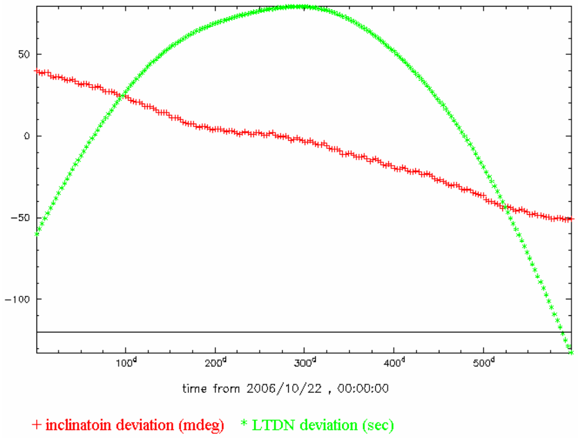

Figure 8. Evolution of the LTDN and inclination deviations after Hand-Over.

The orbital elements of METOP-A at 16:30:00 UTC on the day of Hand-Over are given in Table 8.

The state of the orbit at Hand-Over was accepted by EUMETSAT without reserve and the orbit control activities for the LEOP of METOP-A at ESOC were considered as closed.

Figure 9. Artist impression of METOP-A satellite

Table 8. The orbital elements of METOP-A at 16:30:00 UTC on the day of Hand-Over.

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State Vector Report                            ESOC/FDD
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 Satellite Name: MET2
 Satellite ID  : 2006044

 Reference frame: J2000.0

 Epoch: 2006/10/22-16:30:00.000

               Actual            Reference            Difference

       X     -943.077262676        -948.065987620           4.988724944 km
       Y     1203.748858532        1194.773943509           8.974915023 km
       Z    -7042.080165754       -7043.443701575           1.363535821 km
    Xvel        7.310626786           7.313346812          -0.002720026 km/s
    Yvel       -0.711631818          -0.680508092          -0.031123726 km/s
    Zvel       -1.101089730          -1.100305424          -0.000784306 km/s

 S/M Axis    7186.778427895        7187.076372700          -0.297944805 km
 Eccentr.       0.002702741           0.002730043          -0.000027302
 Inclin.       98.735971504          98.696363212           0.039608292 deg
 Asc.Node     353.120286127         353.370959240          -0.250673114 deg
 Arg.Per.      82.502660271          82.694273935          -0.191613664 deg
 Tr.Anom.     178.874043302         178.689661551           0.184381751 deg

                              Radial            -0.501011212 km
                              Along-track        3.888124336 km
                              Cross-track       -9.587866451 km
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