METOP-B ORBIT ACQUISITION OPERATIONS; PREPARATION AND EXECUTION

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Abstract: *The 17th of September 2012 the second Metop satellite (Metop-B) was successfully launched from the Baikonur cosmodrome by a Soyuz/Fregat launcher. After three days of LEOP (Launch and Early Operations Phase), performed by ESOC, the satellite was handed over to EUMETSAT, who since then has being taking care of all satellite operations, including SIOV (System in Orbit Verification) of the platform and of the 11 instruments on-board. In order to acquire the orbit selected for operations a simple strategy was developed by ESOC and EUMETSAT; details on that strategy can be found in an ESOC paper presented on this same conference. Few challenges were identified on the foreseen SIOV operations for 5 possible launch dates starting from the 17th of September, which required more detailed analyses by EUMETSAT. This paper presents the outcomes of these analyses focused on: characterization of the propulsive system efficiency, acquisition of frozen eccentricity in case of large injection error and management of radio-frequency interferences between the two Metop satellites. A summary of the Flight Dynamics operations performed by EUMETSAT during Metop-B SIOV to acquire its operational orbit is also provided, to show how the outcome of the pre-launch analyses is applied in the real operations.*

Keywords: *Metop, orbit acquisition, thruster performances, radio-frequency interferences.*

1. Introduction

Metop constitutes the space segment of the EUMETSAT Polar System (EPS). The EPS is the European contribution to a joint European-US polar satellite system called the Initial Joint Polar System (IJPS). EUMETSAT has the operational responsibility for the morning orbit, where the Metop-A (launched in 2006) and Metop-B satellites are currently located, while its US counterpart, the National Oceanic and Atmospheric Administration (NOAA), is responsible for the afternoon orbit, covered by the NOAA-18 and NOAA-19 satellites.

In the frame of the EPS program an in-orbit phasing separation between the two Metop satellites of ±173.8deg is selected for the operational phase; that accounts for the given EPS system constraints (on data acquisition, processing and distribution) and requirements (same reference ground-track), which ensures at the same time maximization of data exploitation by the users. Moreover, in order to be able to launch at any date with no collision risk between the two satellites, an injection orbit 16km below the final operational one (the same where Metop-A satellites is currently flying) was selected for Metop-B.

This difference in altitude provides a large relative drift in in-orbit phasing between the two Metop satellites, which can be used to bring Metop-B into its target orbital location. As the orbital phase drift required to acquire the final in-orbit location is different for different launch dates (same in orbit-position at injection for Metop-B, while Metop-A positions changes every day within the 29 days repeat cycle), the duration of the drift phase depends on the launch date itself as well as on the injection error (a larger drift is induced by a lower injection altitude due to a launcher underperformance, the opposite for an overperformance). An adjustment of the drift may therefore be required during LEOP to make sure that the target in-orbit location is reached between 5 and 14 days after hand-over of operations to EUMETSAT, as required not to conflict with critical SIOV operations (service module routine commanding initialization and attitude bias removal; instruments switch-on, out-gassing and decontamination); once the target is reached a drift-stop maneuver is executed during SIOV, followed by a touch-up maneuver on the following day to compensate for execution error of the drift-stop.

2. Metop-B operational orbit acquisition strategy

In order to achieve the proper local time Metop-B has to be launched exactly when the launch site location (Baikonur) crosses the target orbital plane; that happens once a day at ~16:28:40 UTC. Injection takes place ~69 minutes after launch, so at ~17:37:45 UTC, close to the southernmost point of the orbit (Ref. [4]). As Metop-A flies on an orbit with 29 days of repeat cycle for 412 revolutions (14+6/29 orbits per day), then its in-orbit position changes depending on the selected launch date (with a repletion pattern of 29 days, obviously). Being the two target in-orbit positions possible for Metop-B at ±173.8deg with respect to Metop-A position, then the angular separation between injection and targets position for Metop-B also changes depending on the selected launch date.

Metop-B is injected in an orbit lower (nominally 16km) than the operational one where Metop-A is operated; therefore an important relative drift in in-orbit position (nominally of 16.8deg/day) is observed. Metop-B will then get naturally, sooner or later, depending on the initial angular separation from the targets (depending on the launch date) and on the real orbital drift (depending on the launcher performance, which may cause error in the injection up to +/-8km), into its target location; at this point it is sufficient to perform an orbital maneuver to bring its altitude to the operational value and the drift is stopped. The target orbit is acquired.

Unfortunately it is not possible to execute the drift-stop maneuver at any point in time, due to operational constraints deriving from the platform and the instrument SIOV activities:

1) Instrument decontamination starts 7 days after end of the LEOP phase (so-called hand-over) and lasts 3 weeks; no contamination is acceptable in the last 2 weeks of the decontamination and the longer is that period, the better; therefore the drift-stop maneuver shall be executed as soon as possible and in any case not later than 14 days after hand-over.
2) Some time is needed by EUMETSAT on one side to perform initial operations on the platform (fine adjustment of the attitude bias of the platform to align it properly to the operational piloting frame), on another to properly initialize the flight dynamics and mission planning processes; two days are required to acquire perfect knowledge of the satellite orbit using data from the EUMETSAT ground stations (necessary for preparing the maneuver) and two days are needed between ingestion of the maneuver in the mission planning and its execution (as 37 hours of operations in advance are planned). Considering 1 day for the preparation of the maneuver itself, then the drift-stop maneuver shall be executed not earlier than 5 days after hand-over.

ESOC shall therefore ensure during LEOP, by executing, if necessary, a maneuver to adjust the orbital drift, that the satellite reaches at least one of the two targets within the time window described here above (so called SIOV maneuvering window). Moreover, the following optimization criteria are imposed:

1) Fuel consumption shall be minimized.
2) Time to target shall be minimized; to be pursued only if not causing any fuel penalty.
3) Radio-frequency interference with Metop-A shall be avoided; to be pursued only if not causing any fuel or time to target penalty; interferences are observed when Metop-B goes during the drift over the Metop-A orbital position (explained more in detail in paragraph 3.3).

Based on the computation of the time needed by the satellite to naturally get to target (two times for two targets) it is possible to identify 4 different scenarios, depending on launch date and injection error. These scenarios are depicted in Fig. 1 for a nominal injection case; numerical values presented here below are computed for this case too:

A) Metop-B gets to target (for at least one of the two targets) within SIOV maneuvering window; no need of performing any drift adjustment maneuver during LEOP; Metop-B from -69.8deg to 93.9deg with respect to Metop-A position at time when ESOC maneuver is foreseen (2.5 days after injection); interferences observed for initial negative separation.
B) Metop-B gets to target too early (for both targets); ESOC shall perform a maneuver to slow down the drift to get to target, T1 or T2, 5 days after hand over (no fuel penalty and time to target minimized); Metop-B from 93.9deg to 173.8deg (location of first target, T1) with respect to Metop-A position at time when ESOC maneuver is foreseen.
C) Metop-B gets to target too late (for both targets); ESOC shall perform a maneuver either to accelerate the drift to get to the first target, T1, 14 days after hand-over (with minimal fuel penalty) or to reverse the drift to get to the second target, T2, 14 days after hand-over (with minimal fuel penalty), whatever is fuel optimal; in case both options present the same fuel penalty, the reverse drift one shall be preferred (as ensuring no interference); for nominal injection, Metop-B from -69.8deg to -173.8deg (location of second target, T2) with respect to Metop-A position at time when ESOC maneuver is foreseen.
D) Metop-B gets to one target too late and to the other too early; that happens when Metop-B is between the two targets at time when ESOC maneuver is foreseen; that case can be handled either as the B or the C (reverse drift) case.

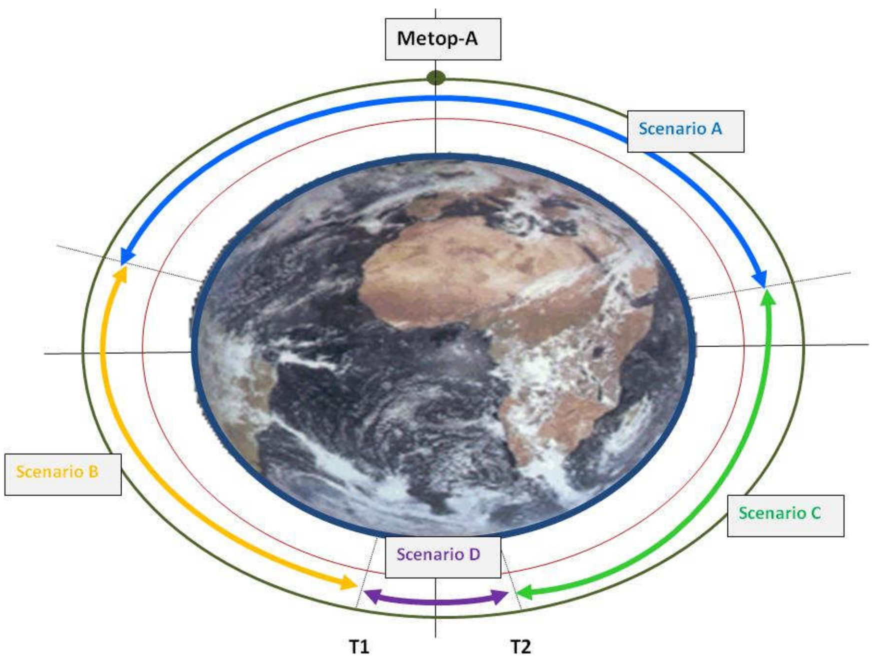

Figure 1. Metop-B target acquisition scenarios

More details on that subject can be found in an ESOC paper presented to this same conference (Ref. [1])

3. Overview of pre-launch analyses

3.1. Characterization of the maneuver execution error

In those cases when the Metop-B satellite is injected very close to its target in-orbit positions, the maneuver required during LEOP is very large, as the drift to be implemented is extremely small, not to get too early on target. It is clear that even a little error in such a large maneuver is sufficient to create a relatively very large error in the achieved drift and then in the time required to get to target.

This situation could have been observed, for instance, for a launch on the 21st of September. For that date the separation in in-orbit position between the Metop-B satellite at injection and the two targets is respectively of ~63deg and ~75.5deg. Assuming a very large underperformance (8km below the injection orbit, so 24km below the operational one, causing ~25.2deg/day of drift in orbital position), the separation at the time when ESOC performs the drift adjustment maneuver (2.5 days after injection) is ~0deg for the first target and of only ~12.5deg for the second one; the first target cannot be anymore reached in the desired time window and the second one has to be selected. A maneuver of ~11.5m/s is needed to reduce the drift to the value of ~2.3deg/day needed for getting into the second target not earlier than 5 days after hand-over. Note that around 91% of the drift is cancelled out and that the residual drift is then quite small.

An error of ~5% on that maneuver, value provided by the spacecraft manufactured as expected one for the first maneuver, correspond to an error of ~50% on the acquired drift: that causes an enormous error in the time to target: the satellites gets in target ~5.5 days later in case of overperformance and ~2 days earlier (only three days after hand-over) in case of underperformance. If a later time to target is selected, to mitigate the effect of an underperformance, then the penalty in case of under and over-performance gets even larger; targeting for instance 9 days after hand over, then the delay to target in case of 5% underperformance gets to ~4.5 days; that is still acceptable as we get in target ~4.5 days after hand-over, violating only marginally the 5 days constraint; however, an overperformance of 5% causes a delay of more than three months in the time to target, operationally unacceptable; this case is presented in Fig. 2.

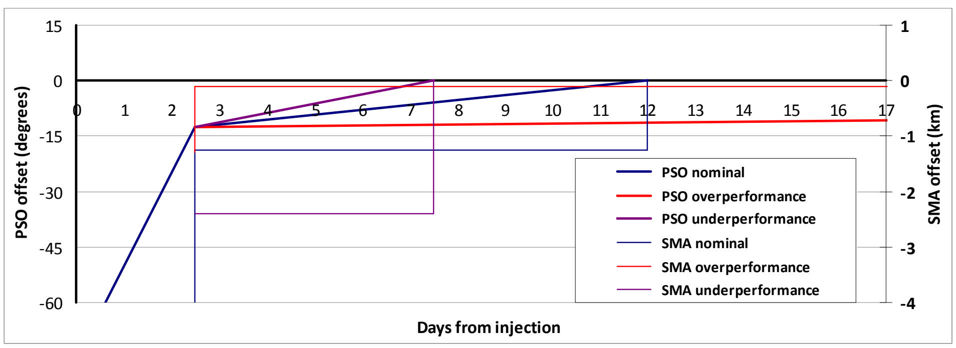

Figure 2. Target acquisition plot: evolution before propulsion characterization

Detailed analyses were performed to better characterize the expected performance of the platform in case of maneuver execution. A model of the propulsive system was created in Matlab, taking into account:

- Force generated by each thruster in the satellite frame as function of the tank pressure (function of the fuel on-board) and of the thruster alignment (taken from satellite database).
- Torque generated by each thruster in the satellite frame as function of the force generated (bullet above), of the thruster location and alignment (taken from satellite database) and of the location of the centre of mass (reference value considered).
- Expected off-modulation of the selected main propulsion thrusters (always two thrusters are commanded at the same time for propulsion, each one generating at the same time a torque in yaw) to maintain torque equilibrium in yaw.
- Expected activation of the pitch and roll attitude control thrusters to maintain torque equilibrium in pitch and roll.

In order to compute reliable values of the expected performances it is necessary to apply representative errors to the elements with higher uncertainty, the COM location and the thruster alignments; the errors in the thruster locations and were considered to be of lower importance and therefore not modeled. A normal distribution of the errors was then generated with these characteristics:

- 0.005 meters (1 sigma) in for the COM location around the reference position.
- 0.1deg (1 sigma) for the alignment of each thruster around the reference alignment.

A Montecarlo analysis was then performed for maneuvers in the velocity direction (those on which we are interested); for each run the difference between the resulting force and the reference propulsion force, generated by the activation of only the propulsion thrusters and assuming no error in any parameter, was computed. That difference, divided by the reference force, provides a direct measurement of the error caused by the activation of the attitude control thrusters; the resulting distribution is shown in Fig. 3.

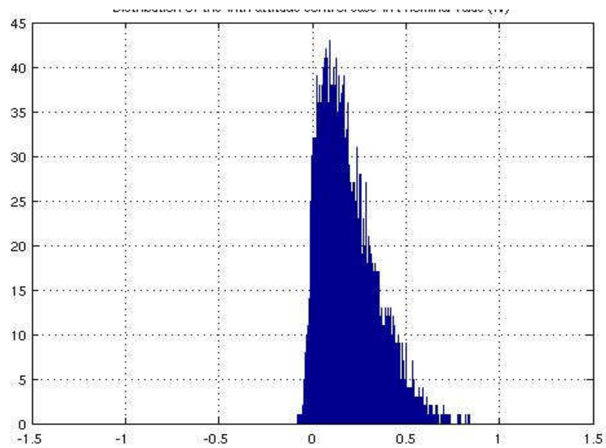

Figure 3. Distribution of propulsion force error

It is interesting to notice that the resulting distribution is no more a normal one. That is linked to how the attitude control thrusters in pitch are mounted; both positive and negative control thrusters are nearly perfectly aligned with the anti-velocity direction, causing therefore a systematic underperformance in case of maneuver in the velocity direction (positive direction in the satellite frame correspond to anti-velocity); the rate of activation of these thrusters depend on the pitch torque generated by the propulsion thrusters. It can be concluded that the probability of having an underperformance when performing an orbital raise maneuver is much larger than the one of having an overperformance. Being the reference force of around -18.3N, the distribution is then contained between ~4.5% underperformance (in line with the value provided by the satellite manufactured) and ~0.4% overperformance (one order of magnitude lower); if a 2% underperformance is assumed a-priori that is equivalent to an execution error of only ~2.5%.

That makes possible to consider strategies reducing the altitude offset with respect to the target orbit to a very small value with much reduced risk of having the satellite stranded with an insufficient residual drift in case of overperformance. Coming back to the reference case above, a 0.5% overperformance causes a delay to target of only of ~1 days if 9 days after hand-over is considered as time to target, absolutely acceptable operationally, as we get on target well earlier than 14 days after hand-over, as in Fig. 4.

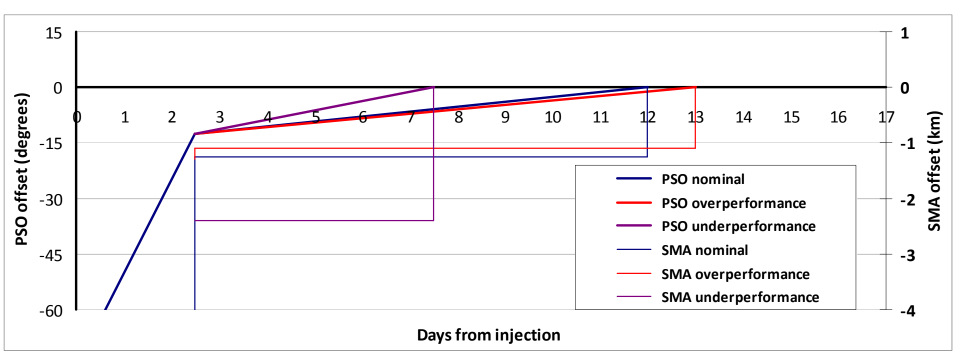

Figure 4. Target acquisition plot: evolution after propulsion characterization

Further optimization could be performed, if desired, to cancel out the marginal violation still observed in case of underperformance, thanks to the margins now available in case of the overperformance.

3.2. Acquisition of frozen eccentricity in case of large underperformance

In those cases when the Metop-B satellite is injected quite far away from its target in-orbit positions, no maneuver is required during LEOP, as the natural drift is sufficient to get on target within the desired time window. The entire correction in semi-major axis required to acquire the operational altitude when on target is therefore executed during SIOV. However, even if the propulsive system would be capable to fully correct the altitude (the platform can execute double-burn in-plane maneuvers providing a Delta-V of ~6.4m/s per burn), that is not necessarily true for the eccentricity.

This situation could have been observed, for instance, for a launch on the 19th of September. Assuming a very large underperformance (8km below the injection orbit, so 24km below the operational one) coupled with a relatively large error in eccentricity (up to 0.0011), then the orbit presents a relative perigee ~32km and a relative apogee ~16km below the nominal altitude (Clohessy-Wiltshire notation is used here, described in Ref. [5]). Two maneuvers respectively of ~8.4m/s and ~4.2m/s would be required to correct at the same time the altitude and the eccentricity. The size of the first maneuver is however outside the capabilities of the platform. Please note that the presented case is not to be considered statistically irrelevant (both errors close to their expected maximum), as a strong cross-coupling can be present between the two errors, for instance when the under-performance is caused by an incorrect execution of the circularization burns performed by the Fregat module of the launcher.

Two options can be foreseen:

1) Wait for the satellite to get to the target-ground track (in the case under analysis ~11 days after injection), and then perform a double-burn maneuver (~6.3m/s per burn) to bring the altitude to the nominal value, and stopping therefore the orbital drift (drift-stop maneuver); the eccentricity is left unaffected (relative perigee ~8km below and relative apogee ~8km above the nominal altitude). On the following day perform another double-burn maneuver (~2.1m/s per burn) but with burns in opposite directions, in order not to modify the altitude and to bring the eccentricity to the nominal value; this maneuver is also used to compensate for execution errors in the first maneuver (touch-up maneuver); this strategy, called drift-stop is depicted in Fig. 5.
2) Few hours before the satellite crosses the target ground-track perform a double-burn maneuver; one maneuver (of ~6.4m/s) corrects as much as possible the relative perigee of the orbit (so ~24km out of the initial ~32km) and the other one (of ~4.2m/s) corrects fully the relative apogee. A residual drift is created by the remaining difference in altitude (~4km), which brings the satellite in target after several hours: being the residual altitude offset, and then the induced orbital drift, much smaller (~1/6 of the initial value), a much larger time (six times more) is needed. When the target is reached, a single burn maneuver (of ~2.0m/s) is executed to stop the drift and, at the same time, acquire frozen eccentricity by fully correcting the relative perigee; this strategy, called dog leg, is depicted in Fig. 6; a case with 2 days time between the two maneuvers is considered (drift stop 8 hours before nominal crossing of the target ground-track).

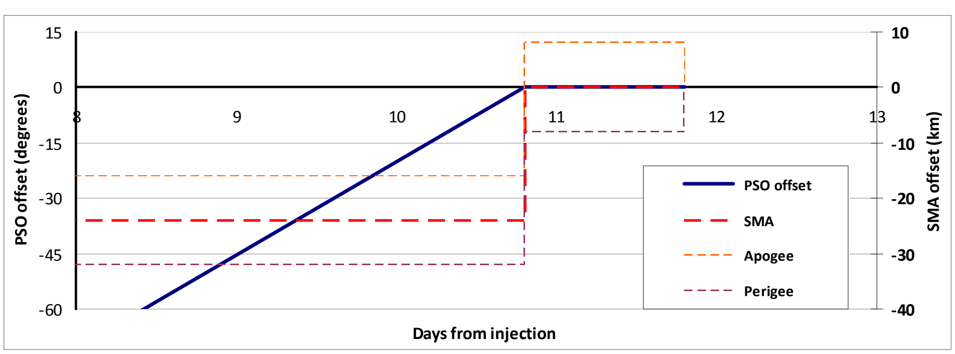

Figure 5. Drift-stop strategy

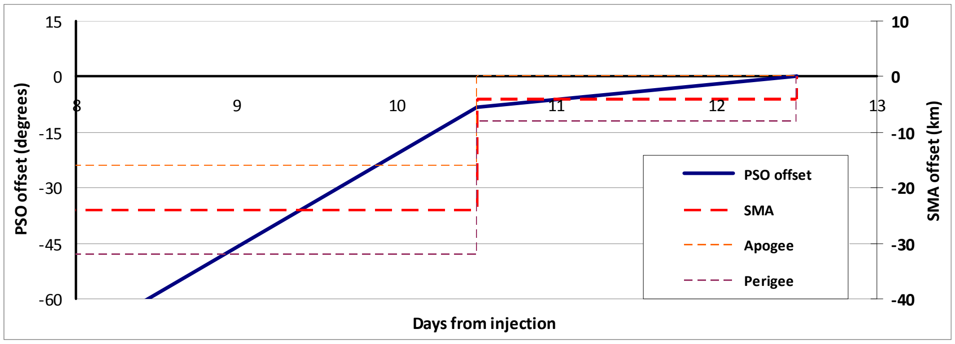

Figure 6. Dog-leg strategy

The drift-stop strategy presents a clear fuel penalty with respect to the dog-leg one (~4.2m/s in the case taken into account). Furthermore, other operational consideration may also help in selecting the better strategy for cases not so clear (lower or no fuel penalty):

- As the touch-up is meant to re-align the real satellite post-maneuver evolution with the one foreseen before the maneuver execution itself, there is normally no need of re-planning of the post maneuver activities to account for the drift-stop execution error. That is however true only if the drift-stop execution error is not so big that the maximum allowed time-difference between foreseen and real post-maneuver evolution is reached before the execution of the touch-up itself. Assuming a 2.5% error (2% underperformance taken as a-priori value, as described in paragraph 3.1), ~10 seconds of error are accumulated before the execution of the touch-up one day later. That is operationally unacceptably high (normally only few seconds are tolerated); the drift-stop strategy is acceptable only in case a small drift-stop maneuver is needed or calibrated thrusters are used.
- The need of using for the touch-up a non calibrated thruster to correct for eccentricity may seriously affect the accuracy of the acquisition, obliging therefore the operator to perform a further ground-track maintenance maneuver shortly after the touch-up. SIOV constraints requires a period of around 4 to 5 weeks without maneuver after acquisition, which would be difficult to ensure; the drift-stop strategy is acceptable only if the size of the touch-up is small (no need to correct for eccentricity).
- Due to the normally large size of the second maneuver executed in a dog-leg strategy re-planning before execution of the second maneuver is normally required (assuming that only one maneuver at a time can be handled by the mission planning system, which is the case for Metop); that forces to increase the time between the two maneuvers (2 days considered in the case presented above); acquisition of target orbit is achieved slightly later than with the drift-stop strategy. Dog-leg strategy is acceptable only if postponement of final orbit acquisition is acceptable.
- The dog-leg strategy ensures a certain robustness against execution error of the first maneuver, which translates into a slightly earlier or later arrival on the target ground-track and then on the execution time of the second maneuver. Moreover, the second maneuver is always executed with calibrated thrusters, ensuring good accuracy of execution and of the resulting acquisition. Nevertheless the drift-stop strategy presents normally better accuracy in the final acquisition as the touch-up is normally smaller than the second maneuver of the dog-leg.

Selection of the strategy to be implemented operationally is therefore a not so simple trade-off exercise, strongly depending on the orbital conditions at injection and on what was executed in LEOP.

3.3. Radio-frequency interferences management

As the two Metop satellites are identical, radio-frequency (RF) interferences can be observed whenever the two satellites are too close as observed from a ground station (GS); that happens for instance when Metop-B is injected in an orbital position behind Metop-A and a forward drift strategy is selected (see scenario A and C in paragraph 2); Metop-B has to overtake therefore Metop-A, getting therefore so close to it that the two satellites are seen from ground at the same azimuth and elevation. These interferences may jeopardize the capability of safely operating both satellites at the same time.

Several interference cases can be identified during LEOP:

1) The TM of both satellites is received at the same time in a LEOP GS; that happens whenever Metop-A as seen from a LEOP GS has an angular separation lower than 3.0deg from Metop-B; Metop-B TM is jammed by Metop-A TM and LEOP operator, ESOC in this case, is blind. This case is considered of high criticality as endangering the operations of the satellite in LEOP.
2) The TM of both satellites is received at the same time in a EUMETSAT GS; this case is symmetrical to the one above and EUMETSAT is blind. This case is considered of low criticality, as TM for the Metop-A satellite can be safely collected from the stream multiplexed in the X-band downlink, containing the instrument data.
3) The telecommand carrier sent to Metop-A from a EUMETSAT GS is received also by Metop-B; that happens whenever Metop-B as seen from a EUMETSAT GS has an angular separation lower than 3.2deg from Metop-A. This case is considered of high criticality if Metop-B is in visibility of a LEOP GS; any carrier sent to Metop-B from the LEOP GS would be unlocked by the carrier from the EUMETSAT GS and any on-going commanding would be interrupted, endangering the operations of the satellite in LEOP. Being the EUMETSAT prime GS located in Svalbard and two of the LEOP GS being in Alaska and in Kiruna, that is nearly always the case.
4) The telecommand carrier sent to Metop-B from a LEOP GS is received also by Metop-A; this case is symmetrical to the one above and EUMETSAT commanding may be affected. This case is considered of low criticality, as Metop-A disposes of around 36 hours of on-board autonomy.
5) The ranging tone sent back by Metop-A to a EUMETSAT station performing ranging is also received by a LEOP station while performing ranging on Metop-B; that happens whenever Metop-A as seen from the LEOP GS has an angular separation lower than 22deg from Metop-B. The reason why interference in ranging can be observed with such a large angle is that range measurements are much more sensitive to external perturbation than TM or telecommands: a small parasitic signal can be easily filtered out by the TM receiver in the station or by the on-board transponder as is done with the noise (signal close to noise), but may still cause a large error in the timing measurement of the ranging tone (signal added to noise). Again, due to the large overlap in visibility between the LEOP GS and the prime EUMETSAT GS, concurrent ranging is the most current case. This case is considered of high criticality as ranging data are of paramount importance during a LEOP.
6) The ranging tone sent back by Metop-B to a LEOP GS performing ranging is also received by a EUMETSAT GS while performing ranging on Metop-A; this case is symmetrical to the one above and EUMETSAT ranging may be affected; This case is considered of low criticality, as Metop-B disposes of GPS data for orbit determination.

It is clear that, in order to implement adequate operational countermeasures it is necessary to have an as clear as possible picture of the possible interferences in the future. For this reason a dedicated tool was developed within the Flight Dynamics system. That tool takes as input the operational orbit of the two Metop satellites and computes, for all the GS identified, the following:

A) <u>Interference events</u>, defined as the time intervals during which the estimated angular separation (as seen from the considered GS) is below a given threshold (which could be station dependent);

S-band (a single event is sufficient to cover both TM and tele-command interference, being the two thresholds very similar) and ranging interference events are considered during LEOP.

B) Interference period, defined as the interval between the start of the first interference event and the end of the last one.

C) Clean visibility events, defined as the intervals within the interference period where a spacecraft is seen from a GS without interference with the other satellite. These events are computed for selected GS (nominally the EUMETSAT ones) and for a given satellite (nominally Metop-A).

The following operational rules can therefore be derived:

- Whenever an S-band interference event on a LEOP GS is identified, Metop-A S-band transponder must be muted, to mitigate the risk from interference case (1); moreover it is recommended to not to perform commanding on Metop-A, to avoid the problems deriving from interference case (4).
- Whenever an S-band interference event on a EUMETSAT GS is identified, on-ground operation requiring telecommand carrier to be sent to Metop-A must be suspended, to mitigate the risk from interference case (3); moreover it is recommended to mute Metop-A S-band transponder, to avoid the problems deriving from interference case (2).
- Whenever a ranging interference event on a LEOP GS is identified, ranging on Metop-A must be suspended, to mitigate the risk from interference case (5).
- Whenever a ranging interference event on a EUMETSAT GS is identified, it is recommended to suspend ranging on Metop-A, to avoid the problems deriving from interference case (6).

It can be noted that, if the recommended actions are handled as mandatory, then the actions to be taken are identical, regardless of the GS on which the interference event is detected. Furthermore, it is also recommended to minimize the number of mute and un-mute operations on the S-band transponder. In terms of operations therefore the following procedures were implemented:

- Metop-A transponder is muted before the start of the S-band interference period and un-muted (via time-tagged telecommand sent before muting the transponder) after its end.
- Metop-A on-ground operations requiring telecommand carrier to be sent to Metop-A are suspended before the start of the S-band interference period and resumed after its end; commanding is automatically suspended in the same time interval.
- Metop-A ranging operation are suspended before the start of the ranging interference period and resumed after its end.
- Clean visibility events of sufficient duration can be used for resuming S-band operations within the S-band interference period in case of need; note that interference events are normally at the beginning and at the end of a pass, as the angular separation as seen from a ground station at these points in time is much smaller than at maximum elevation, for a given in-orbit separation between the two satellites.

In order to ensure the operational feasibility of that strategy, it is necessary to evaluate the expected duration of the interferences periods for the nominal injection case (16km below the operational orbit) and for degraded cases within the expected launcher performances (+/-8km error). As a real risk of interference was observed for a launch on the 18th of September, detailed computation of the duration of these interferences was performed and the results are shown in Tab. 1 (values in *italics* represent cases where the interference lasts up to the end of the LEOP; that time is considered as end time).

As expected the duration increases the smaller is the separation in altitude from the operational orbit (so in case of an overperformance of the launcher); however, even the maximum duration for the S-band interference period is well below the satellite autonomy of 36 hours.

Table 1. Duration of interferences for different injection errors

Injection altitude error (km) and equivalent sigma	Duration of S-band interferences (hours)	Duration of ranging interferences (hours)
-8.0 (-3sigma)	3.58	26.01
-5.3(-2sigma)	5.23	27.37
-2.7(-1sigma)	5.32	33.82
0.0	6.43	39.75
+2.7(+1sigma)	8.57	47.06
+5.3(+2sigma)	8.74	*50.60*
+8.0(+3sigma)	*13.06*	*45.35*

As we have seen, the countermeasures in place are strongly based on the capability to mute the Metop-A S-band transponder during the interference period. However, if the Metop-A satellite enters safe-mode, then the backup on-board computer switches autonomously the S-band transponder on and it is no longer possible to switch it off. The only way to avoid S-Band interference in this scenario is then to request ESOC to mute Metop-B transponder. Moreover, whenever Metop-A enters safe-mode it is mandatory to perform commanding and ranging as soon as possible to maximize the probability of saving the mission (or minimize the risk of loosing it). ESOC should then suspend commanding and ranging operations on Metop-B. A special agreement was prepared in this direction and dedicated procedures were developed by ESOC to be able to react as expected.

The problem above described is however particularly severe if S-band interferences are observed on the first 12 hours of the LEOP, while critical operations are carried out for Metop-B; in this case to ask ESOC to suspend what they are doing may mean the loss of the Metop-B satellite; just imagine what would happen if operations have to be suspended before it has been possible to fully deploy the solar array. The initial launch date was selected in such a manner to ensure that no S-band interferences are observed the first 12 hours of LEOP as well as for the following 3 days (possible further launch attempts). For the 18th of September S-band interferences start after 22 hours in the worst case, that is considered still acceptable. Risk of interferences within the first 12 hours is observed on the 13th of September, whereas on the 8th of September interferences start already at injection; those dates and the three before were therefore considered as forbidden for launch.

If we can try to minimize, or even cancel, the risk of having interferences during LEOP on 4 consecutive dates (even if it was not the case at the end, as interferences on LEOP were observed on the second day of the campaign), it is impossible to avoid that during the SIOV. This situation was expected for a launch on the 19th and 20th of September. The main differences between interference management during LEOP and SIOV is that during SIOV both satellite are operated by EUMETSAT using the same GS network and that another RF band is to be considered, the X-band, used for instrument data download (no X-band is on during LEOP of a satellite) X-band interference events are also computed by the Flight Dynamics tool above described, taking as angular separation threshold 0.5deg. It is therefore necessary not only to mute the S-band transponder on one of the two satellites during S-band interferences, but also to mute the X-band transponder on the other satellite during X-band interferences (if both transponders are muted on the same satellite then we have no more visibility on its TM at all). The baseline considered was to maintain X-band on Metop-A, not to affect the operational mission and S-band and ranging on Metop-B.

4. Metop-B operational orbit acquisition operations

4.1. Selection of acquisition strategy and LEOP maneuver

As explained in paragraph 2, the selection of the acquisition strategy for Metop-B depends on the launcher performance and on the launch-date. The orbital separation between the injection in-orbit position and the two possible targets was, for a launch on the 17th of September, respectively of ~123deg and ~135.5deg. The launcher provided ~3km of overperformance (injection ~13km below nominal altitude), therefore causing a drift of ~13.5deg/day. The two targets were reached respectively ~6 days and ~7 days after hand-over, perfectly in line with requirements. Moreover the inclination was so close to the selected one that no inclination correction was necessary.

Two options were evaluated during LEOP:

1) Do not perform any maneuver and leave the satellite drift naturally and then stop the drift once on target (first target selected to have operations completed as soon as possible) using a dog-leg strategy, being the thrusters not calibrated (as explained in paragraph 3.2)
2) Perform a small IP maneuver to calibrate the thrusters, but not modifying in a significant manner the time required to get to target, and then stop the drift once on target using a drift-stop strategy (as explained in paragraph 3.2).

The goal was to select on one side the strategy permitting to complete the acquisition of the operational orbit as early as possible (to start as early as possible SIOV activities on final orbit), on another to minimize the error in ground-track during the following 5 weeks of SIOV (to maximize the reliability of the collected data). At the same time it was considered as operationally beneficial to synchronize the execution of the maneuver with the routine update of the satellite telecommand, executed daily at ~13:00 UTC, not to have to modify the routine operational schedule.

As explained in paragraph 3.2, if a dog-leg strategy is selected, it is necessary to foresee 2 days of time between the execution of the first and the second maneuver to allow synchronizing the mission planning between the two maneuvers; at the same time it is necessary to ensure that the second maneuver is not too big to avoid violation of the operational dead-band (5km wide) during the SIOV. Assuming a 1% error on that maneuver (calibrated thrusters would used), that implies a second maneuver not larger than the 1/8 of the entire required Delta-V (~6.8m/s); the first maneuver would have then to be executed ~6 hours before the nominal crossing time of the target ground-track and the second maneuver ~42 hours afterwards.

If a drift-stop strategy is implemented then the touch-up is required ~24 hours after the drift-stop (time needed to calibrate the drift-stop and re-plan the touch-up); that means that it is acceptable to have the nominal crossing time of the target postponed by up to ~18 hours (as consequence of a LEOP calibration maneuver) before getting a time penalty in comparison with the dog-leg strategy. A reasonable calibration maneuver of ~0.5m/s on LEOP (long enough to observe activation of the attitude control thrusters during the propulsion phase) would imply getting in target only ~13 hours later.

Furthermore, the size of the required touch-up would be of few centimeters per second (~6cm/s, assuming 1% error in the execution of the ~6.3m/s drift-stop maneuver with calibrated thrusters), while the size of the second maneuver in a dog-leg case would be much larger (~0.9m/s, 1/8 of the entire correction, taking into account also 5% underperformance in the execution of the first maneuver). The accuracy in acquisition of the target ground-track that can be expected by the touch-up is clearly larger.

Finally, foreseen crossing time in case no LEOP maneuver was performed was in the middle of the night, and then the maneuvers, in case of dog-leg strategy, would have resulted in the late evening. A small adjustment would have permitted to set the crossing time at around the time foreseen for the routine telecommand execution. In order to account for possible underperformance of the ESOC maneuver (no a priori calibration was used by ESOC), then the selected time for crossing the target ground-track was accordingly modified from ~13 to ~14 hours after the original crossing time without maneuver in LEOP.

The following maneuver was then implemented by ESOC (single burn, as no need of correcting the eccentricity during LEOP was identified):

- 1st burn: 2012/09/20-06:53:00.000; 0.539m/s

4.2. Detailed calibration of LEOP maneuver

Dynamic calibration of the LEOP maneuver performed by ESOC, based on direct comparison of the foreseen Delta-V with the one estimated through orbit determination, provided a quite high underperformance of ~5.5%. That value is larger than what expected from the analysis presented in paragraph 3.1, which makes it questionable for direct usage for the SIOV maneuvers. Moreover, the maneuver executed by ESOC during LEOP was remarkably shorter than those required in SIOV (~0.5m/s executed during LEOP versus around ~2 and ~4m/s required in SIOV). Therefore the impact of non linear parasitic thrusts is much more important.

The following four Delta-V values were computed for the LEOP maneuver:

1) Delta-V corresponding to the maneuver telecommand generated by ESOC (taking into account only the thrust provided by the propulsion thrusters); as reference pressure the value measured in telemetry shortly before execution of the maneuver was considered.
2) Delta-V corresponding to the integration of the force generated by the pulses provided by the satellite during the pure propulsion phase (including both propulsion and attitude control thrusters); same reference pressure as above was used.
3) Delta-V corresponding to the integration of the force generated by the pulses provided by the satellite during the entire thrusting phase (including both propulsion and post maneuver stabilization phase); same reference pressure as above was used.
4) Delta-V estimated through orbit determination.

In Fig. 7 the pure propulsion phase (8 pulses at 8 hertz from the propulsion thrusters) and the stabilization phases (individual pulses afterwards) can be clearly distinguished.

The following parameters were then derived:

A) Ratio between Delta-V (2) and Delta-V (1); efficiency of the propulsive system due to activation of attitude thrusters during the propulsion phase.
B) Ratio between Delta-V (4) and Delta-V (3); efficiency of the propulsive system due to efficiency of the individual thrusters.
C) Difference between Delta-V (3) and Delta-V (2); non-linear parasitic Delta-V caused by stabilization.

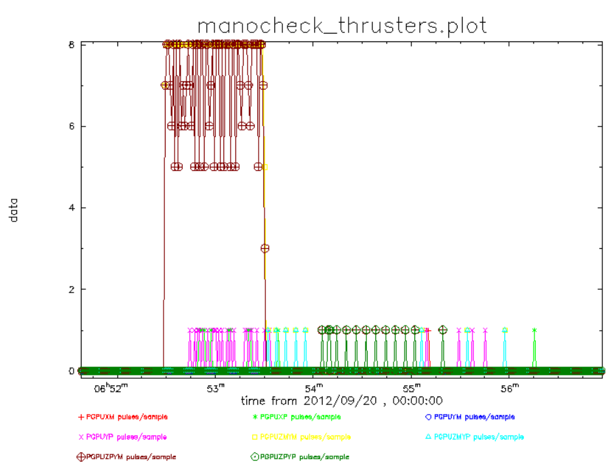

Figure 7. Pulses (per second) executed during LEOP maneuver

The following was then observed:

- Delta-V (1) differs from the target Delta-V selected by ESOC, being ~1.5% smaller; that is due to an large decrease of the pressure between ESOC reading, at entry in wheel attitude controlled mode, after earth pointing acquisition (18.8 bars) and at maneuver execution time (18.5 bars).

- Efficiency (A) is ~99%; that means that ~1% of underperformance is caused by the activation of attitude thrusters during the propulsion phase, in line with expectations from paragraph 3.1 and much lower than for Metop-A (better alignment of the propulsion thruster with the satellite centre of mass).
- Efficiency (B) is ~97.5%; the real force generated by the individual thrusters causes an underperformance of ~2.5%, much larger than what is observed for Metop-A (around 0.5%); it is unclear if that underperformance is linked with a lower mass flow being ejected or by a lower ISP than expected. This question can be answered only when a large enough fuel mass is spent, by cross-comparison between mass estimation based on pulse-count and on pressure-volume-temperature method; if less mass flow is really taking place than expected the two estimation should diverge in an important manner.
- Difference (C) is ~-3mm/s, very similar to what observed for Metop-A; that contributor is therefore responsible for an underperformance of the LEOP maneuver of ~0.5%.

The real calibration scale factor to be used is then the product of efficiency (A) and efficiency (B), therefore around 96.5% corresponding to an underperformance of 3.5%.
The 1.5% underperformance linked to the different pressure reading can be nullified by refreshing the pressure used for the telecommand generation shortly before up-link on-board.
The -3mm/s of non linear Delta-V caused by the stabilization shall be directly removed from the target Delta-V before telecommand generation.

4.3. Selection of ground-track target for the drift-stop maneuver

The goal of the SIOV maneuver is to stop the satellite when inside the operational 5km dead-band around its reference ground-track (generated by shifting Metop-A one by 14/29 of one orbit, as explained in Ref. [2]), and to ensure that it remains inside up to the end of the SIOV (so at least five weeks); as target crossing of the reference ground-track at the end of the SIOV is then selected.

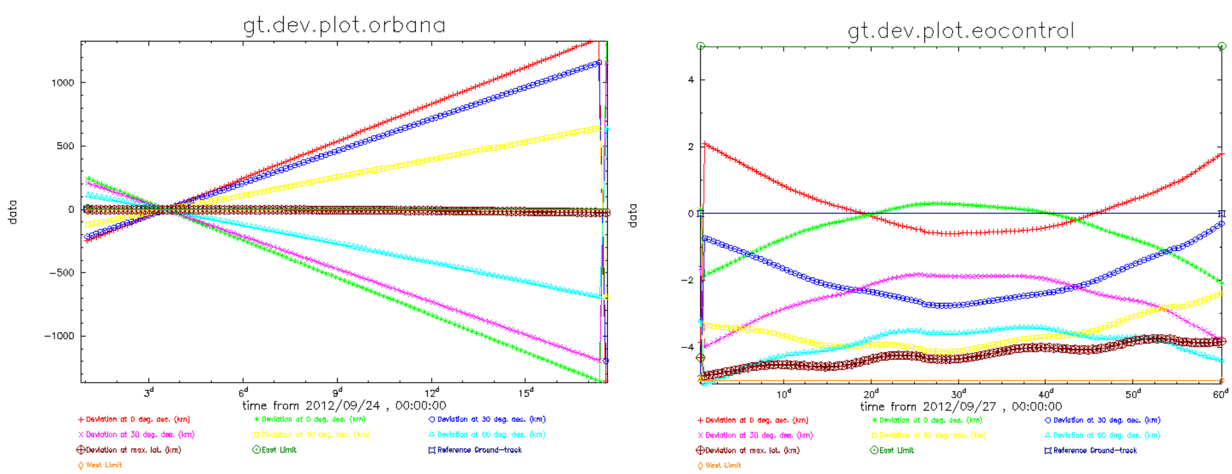

Figure 8. Ground-track evolution without (left) and with (right) drift-stop maneuver

Figure 8 shows the evolution of the ground-track with and without drift stop maneuver; an enormous drift of around 100km per day is observed, caused by the very large offset in semi-major axis with respect to the operational one (~12km lower). The drift-stop maneuver reduces that drift to around 0.1km per day; the evolution remains very close to the reference ground-track (red and green curves represent the deviation at equatorial crossing) for the entire SIOV, being the deviation very small at the end of the SIOV. That maximizes the probability of not exiting the dead-band during the entire SIOV.

The probability above is however quite small, as already an error of 1% on the drift-stop maneuver causes a residual drift of 1km per day, leading to exit of the dead-band within less than one week. Therefore a touch-up maneuver had been foreseen on the following day, to cancel out the effect of the drift-stop execution error; the target for the touch-up must be identical to the one selected for drift-stop, to ensure that the ground-track evolution remains as close as possible to the expected one and minimizing then the impact on the planned post-maneuver activities (the Metop mission planning system has a tolerance of 5 seconds; if that limit is exceeded re-planning is needed).

4.4. Selection of eccentricity target for the drift-stop maneuver

During Metop-A operations a secular drift of the eccentricity vector away from the frozen eccentricity value has been observed; that is due to the not negligible radial parasitic Delta-V (~5% of the commanded value) provided by the platform when an inclination correction is implemented.

That is coupled with the fact that inclination maneuvers are executed yearly; therefore between two inclination maneuver an integer number of librations of the eccentricity vector around the frozen value is observed (3, being the libration period of 4 months), making the effect cumulative (see also Ref. [3]). All that can be clearly observed in Fig. 9 (initial evolution close to center).

It is foreseen for Metop-B to execute inclination maneuvers close to the autumn equinox, to maximize their efficiency, the first one being planned in 2013, one year after the launch; also for Metop-B it can be expected that the eccentricity will diverge in a similar manner, being the observed radial parasitic thrust very similar to the one of Metop-A.

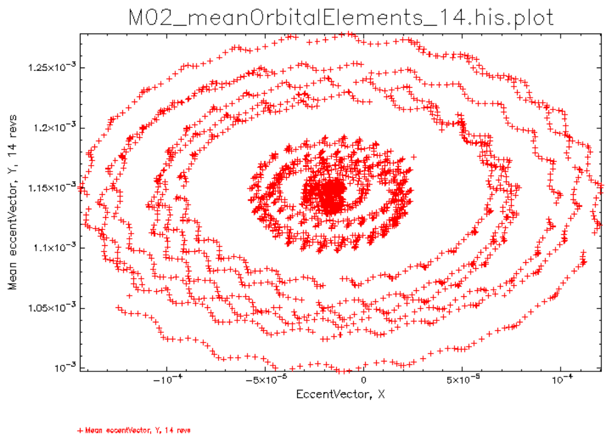

Figure 9. Historical evolution of Metop-A eccentricity

Initial eccentricity for Metop-B was then selected considering an expected drift of the eccentricity vector in the first three years of mission by [0.000088, 0.000120], assuming the same yearly deviation as observed for Metop-A; as target eccentricity vector [-0.000218, 0.001030] was selected, being the frozen eccentricity vector [-0.000013, 0.001150].

4.5. Execution of the drift-stop maneuver

In order to achieve the two targets described in paragraphs 4.3 and 4.4 the following two burns maneuver was planned:

- 1st burn: 2012/09/27-13:10:18.482; 4.045m/s
- 2nd burn: 2012/09/27-14:01:00.159; 2.198m/s

This timeline was perfectly in line with standard routine commanding activities, as routine telecommand sets are generated with execution time at first ascending-node after 13:00; therefore no need of modifying the routine operational timeline was identified.
The actual telecommand was computed on the same morning of the maneuver, based on the expected evolution of pressure; the tank heaters were switched-on autonomously the day before the maneuver, causing a remarkable pressure increase of 0.36 bars in less than 24 hours.

The first maneuver presented a marginal overperformance of ~0.4%, caused by a much lower than expected activation of the attitude control pulses during the propulsion phase (efficiency (A) in paragraph 4.2), probably due to the displacement of COM caused by solar array rotation; this phenomenon is not observed on Metop-A, where the misalignment of the propulsion thruster is much larger and thus the solar array impact is negligible in comparison. Nearly perfect execution was observed for the second maneuver (~0.1% underperformance); the response of the attitude system was perfectly as expected.
The large thrusting underperformance observed for the LEOP maneuver (efficiency (B) in paragraph 4.2) was confirmed and estimated to be ~3% (even a bit higher); the same for the stabilization Delta-V, estimated to be 1mm/s (a bit lower than for the LEOP maneuver).

Even if the overall performance was excellent (total error of ~0.3%) that was not sufficient to avoid violation of the dead-band during SIOV (exit after 3 weeks), as shown in Fig. 10 (left); a small touch-up maneuver was then needed. Eccentricity target is acquired nearly perfectly, as can be seen in Fig. 10 (right); 4 month of libration (one cycle is shown).

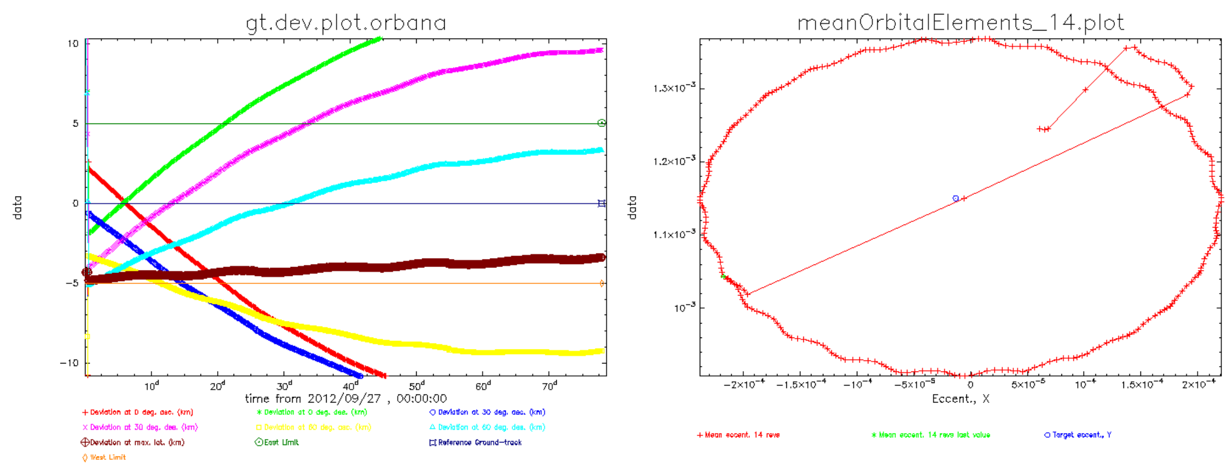

Figure 10. Ground-track and eccentricity evolution after execution of the drift-stop maneuver

4.6. Preparation and execution of the touch-up maneuver and target orbit acquisition

To compensate for the execution error of the drift-stop maneuver the following maneuver was planned:

- 1st burn: 2012/09/28-13:04:46.534; -0.015m/s

That is the first maneuver against the velocity direction performed by Metop-B, therefore no calibration values are available; generation of a-priori calibration was performed as follow:

- Efficiency (A) was computed from the number of attitude control pulses expected from the maneuver execution (procedure similar to what presented in paragraph 3.1); no pulse was expected, so 100% was used.
- Efficiency (B) was computed from the data of the drift-stop maneuver (procedure similar to what presented in paragraph 4.2); the value 97% was used.
- Difference (C) was also computed from the data of the drift-stop maneuver (procedure similar to what presented in paragraph 4.2); the value -1mm/s was used.

Also that maneuver performed very close to the expectation; 5% of overperformance (error less than 1mm/s) was observed, mainly linked to a stabilization Delta-V higher than expected, probably caused by excitation of the solar array flexible modes induced by the small thrust.

Nevertheless, the observed post-maneuver evolution of the ground-track is more than satisfactory, as shown in Fig. 11; the satellite remains inside the dead-band for ~10 weeks.

It was therefore possible to start SIOV operations on a perfect target orbit only 8 days after hand-over to EUMETSAT of the satellite after LEOP.

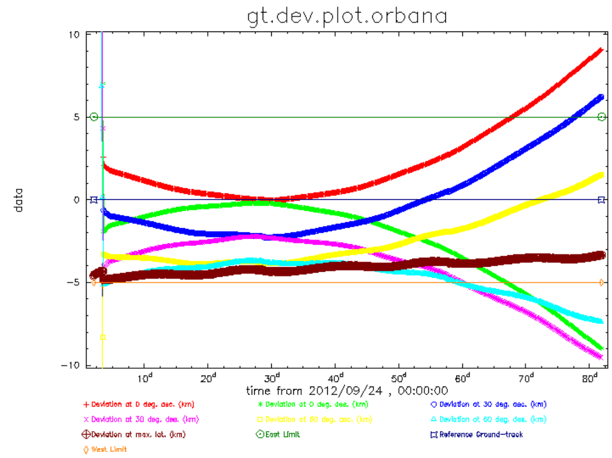

Figure 11. Ground-track evolution after execution of the touch-up maneuver

5. Conclusion and lessons learned

The main lessons learnt from the analysis performed to prepare the orbit acquisition of Metop-B and from the operations themselves can be so summarized:

- A-priori calibration computation based on Montecarlo analysis seems to provide more than excellent results; however that does not take into account intrinsic underperformance of the propulsion system, which appears to be much larger than expected.
- An alternative strategy for acquisition of the operational orbit was developed to cope with large injection error; this strategy is also applicable in other situations, when for instance not calibrated thrusters have to be used. Guidelines were defined to decide which strategy shall be preferred depending on the operational conditions.
- A new SW module and dedicated procedures were developed for interference management; even if not used for Metop-B, they are now ready for Metop-C and can also be used for other missions with similar problems, as, for instance, Sentinel-3.

6. Acknowledgment

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A special mention is given to David Lazaro and Antimo Damiano, of the Flight Dynamics team in EUMETSAT, who performed the orbit acquisition operations during SIOV, described in that paper.

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