Aeolus Orbit Control Strategy: Analysis and Final Implementation

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Abstract

The ESA satellite Aeolus was launched on August the 22nd 2018 on a Vega launcher vehicle from Europe's Space Port in Kourou. Aeolus will be the first satellite to acquire profiles of Earth's wind on a global scale, improving largely the accuracy of numerical weather prediction. The Aeolus orbit is controlled by the Flight Dynamics (FD) team at the European Space Operations Centre (ESOC) to follow a sun-synchronous, dusk-dawn reference orbit with a 7 day ground-track repeat cycle. At the very low altitude of 320 km, the atmospheric drag force is the predominant perturbation, imposing a high frequency of orbit control manoeuvres. This paper summarizes the mission analysis studies performed by the FD team before launch in order to develop a FD system suitable to cope with this demanding environment and the additional constraints imposed by the main instrument operations. The outcome of the analysis is complemented with a comparison against the Aeolus in-flight orbit control results achieved during the first months of mission.

Keywords: Aeolus, LEOP, LEO, Earth observation, orbit control, atmospheric drag force, dusk-dawn orbit

Introduction

The fifth ESA Earth Explorer satellite Aeolus was launched on August the 22nd 2018 on a Vega launcher vehicle from Europe's Space Port in Kourou. The Aeolus satellite carries just one large instrument, a Doppler wind Lidar called Aladin, that will probe the lowermost 30 km of the atmosphere to measure the winds. During its nominal mission lifetime of 3.25 years, Aeolus will be the first satellite to acquire profiles of Earth's wind on a global scale, which will improve the accuracy of numerical weather and climate prediction.

Aeolus is controlled to follow a sun-synchronous reference orbit with a mean solar Local Time of Ascending Node (LTAN) at 18:00 hours and a repeat ground-track of 7 days and 111 orbital revolutions. The distance with respect to the reference orbit is defined in terms of perpendicular ground-track deviation at the Equator crossings and deviation in LTAN. These deviations should be controlled inside control bands of ±25 km and ±10 minutes respectively. Additionally, the evolution of the mean eccentricity is to be kept below a value of 0.003.

The FD team at ESOC (in Darmstadt, Germany) is responsible for the maintenance of the Aeolus orbit during the whole mission. Flying at an altitude of 320 km, the Aeolus orbit control is challenging. At this altitude the main perturbation driving the execution of maintenance manoeuvres is the atmospheric drag force, with a twofold effect: the in-plane component of this perturbing force causes a continuous decay in semi-major axis, which requires frequent compensation; its out-of-plane component results in a continuous decrease in inclination, which causes a drift in LTAN. In addition to this demanding environment, operational constraints imposed by the instrument Aladin further increase the complexity of the Aeolus FD orbit control system. These constraints comprise not only limitations on the selection of slots to perform orbit correction manoeuvres (to avoid interfering with science data acquisition), but more importantly the execution of instrument calibrations, which imply the activation of the propulsion system with non-negligible effect on the orbit. Instrument calibrations (IC) are planned by a different team responsible for the instrument operations. This team, which is located outside the Aeolus control centre at ESOC, delivers the IC operations timeline with one week notice. The FD orbit control system had to be design to be compatible with a frequency of ICs during routine operations of at least one per week. During most part of the commissioning phase, three ICs a week were executed.

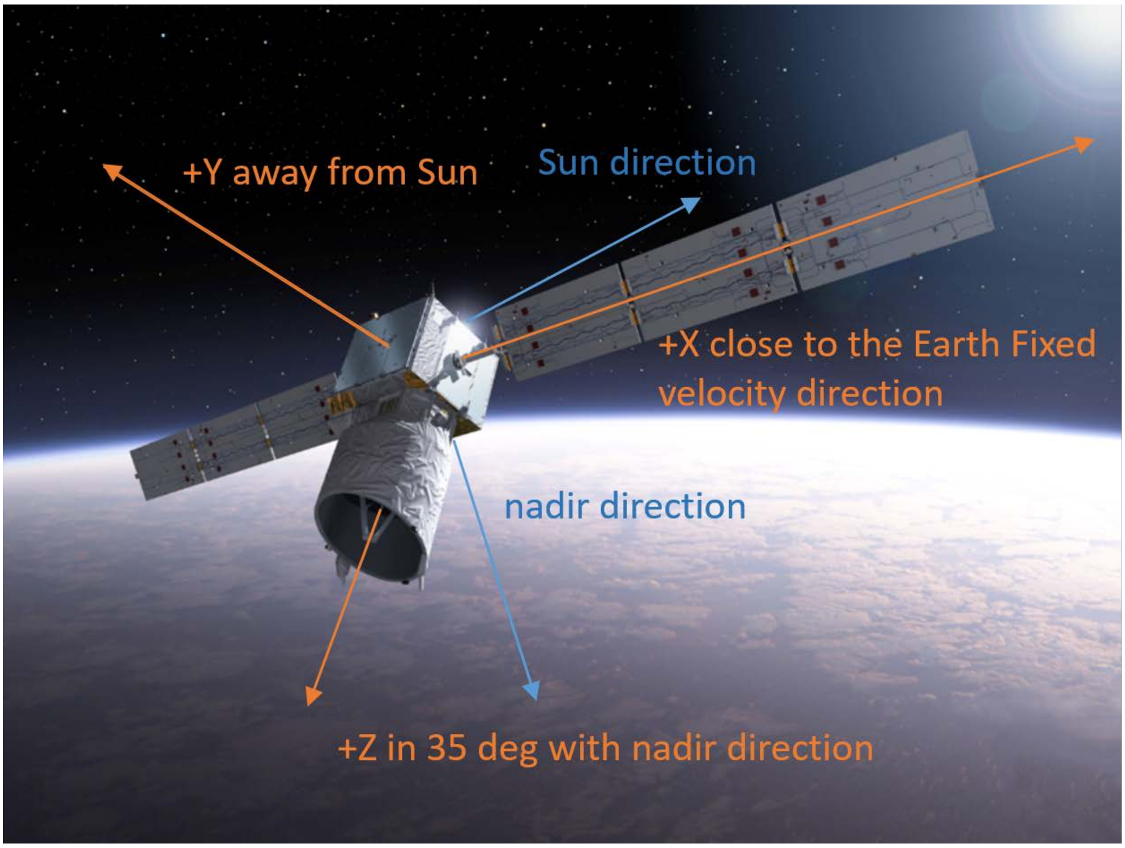

Fig. 1: Aeolus Spacecraft depicted flying in Normal Mode with a representation of the reference frame attached to the S/C body: X-axis along the solar panels direction, Z-axis along the Aladin (Lidar) line of sight and Y-axis completing a right-hand-oriented frame

The Aeolus spacecraft (S/C) is depicted in Fig. 1 in its nominal flying mode, called Normal Mode (NM). Like in many Earth observation missions, this flying mode aims at keeping the line of sight of the main instrument, in this case the Lidar, in a perpendicular direction to the trajectory followed by the sub-satellite point on the Earth surface. Aeolus is equipped with a hydrazine propulsion system, with a redundant set of four 5 N thrusters used for orbit control, all of them mounted on the -X S/C plate. When activated, this set of thrusters deliver a delta-v mostly in the direction of the S/C +X axis. The execution of orbit control manoeuvres takes place in a flying mode called Thruster Control Mode (TCM), after the execution of a suitable S/C rotation to align the +X S/C direction with either the orbital inertial velocity (for in-plane corrections) or with the orbital angular momentum (for out-of-plane corrections).

The FD team has reused the infrastructure and expertise acquired from the support to the Sentinel-1 mission, which is also controlled at ESOC and requires the execution of frequent orbit control manoeuvres (in the order of one per week). The development of a new FD orbit control system for this mission was presented at the International Symposium on Space Flight Dynamics (ISSFD) in 2012 [1]. This FD orbit control system is based on a configurable

pre-scheduled approach, where the maintenance manoeuvre execution windows and the slots during working hours for the optimization and generation of manoeuvre-related FD products (commands, station predictions, reports, etc) are configurable and can be selected to suit to the maximum extent possible the overall ground segment operational concept.
This system had to be enhanced for Aeolus in order to include as part of the pre-planned manoeuvre execution cycle the effect on the orbit of the ICs. The favourable Aeolus reference repeat cycle of 7 days led to the sensible working assumption that the ICs would be executed on fixed calendar week days, since they are executed over Earth regions with given Albedo characteristics. Those are located within a given subset of the 111 reference tracks.
One of the main advantages of this FD system is the compatibility with a high level of automation. The intervention of FD operators can be reduced to performing checks on the manoeuvre commands before sending them out of the FD system for up-linking on board the S/C. The subsequent sections will provide a summary of the activities that took place before launch to configure the FD orbit control system for Aeolus, demonstrate its feasibility and show figures on the performance of the orbit control achieved in-flight up to the moment of writing, which coincides approximately with the end of a three month mission commissioning phase.

Configuration of the pre-planned orbit control system for Aeolus and feasibility demonstration before launch

The values of the Aeolus S/C features relevant to our orbit control analysis are listed in Table 1 in two columns: once as they were assumed for the analysis and then the actual values at the time the orbit control manoeuvre started, two years after the conduction of the analysis. The S/C mass propellant used in the analysis was accounting for a much worse orbit injection by the launcher vehicle than the actual one.

Table 1: Aeolus S/C parameters relevant to the orbit control analysis

S/C parameters	At the time of the analysis	At start of orbit control phase
Dry mass	1140 kg	1079 kg
Propellant mass	220 kg	262 kg
Equivalent drag area	6,163 m^2	6,163 m^2
Cd	2.2	1.5
SRP area	24,25 m^2	24.25 m^2
SRP coefficient	1.5	1.3

The ICs imply two S/C rotations which are apart in time approximately by 35 minutes. Each of these rotations bring the Aladin line of sight from its operational orientation to a direction close to the S/C nadir direction and back to its nominal measurements orientation in NM respectively (see Fig. 1). At the end of every rotation, the Reaction Wheels (RW) must return to a pre-configured speed value, at which time thruster actuation takes place to maintain the acquired orientation. This thruster actuation depends on the status of the wheels at the start of the IC, which in turn depends on the S/C orbital location at that moment. The FD orbit control system has to be able to account for the effect of this thruster actuation on the orbit.
Before launch, an average effect delta-v of 0.140 m/s in the flight direction was derived from the Aeolus manufacturer documentation as a conservative expected IC effect on the orbit. Maximum and minimum expected delta-v values were also derived from documentation and its difference used as expected uncertainty. This difference was 0.02 m/s and consequently the expected error in predicting the delta-v imparted on the orbit by ICs was conservatively

modelled as a Gaussian distribution with a standard deviation value of 0.02 m/s. In terms of predictability of the execution times of the ICs, it was assumed that they would be executed on fixed calendar week days, given the 7 day repeat cycle of the Aeolus reference orbit.

Control of semi-major axis and ground-track at the Equator crossings

The first parameter that had to be configured in the new FD orbit control system for Aeolus was the expected manoeuvre frequency, in order to determine the typical length of the orbit control optimization cycles (in integer multiples of one week) and the number of manoeuvre slots that should be allocated in every control cycle (integer number of manoeuvres slots per week). The frequency of in-plane manoeuvres to compensate the decay in semi-major axis depends on the atmospheric density, which depends largely on the level of solar and geomagnetic activity. The in-plane manoeuvre frequency also depends on the selected control-band size for the ground-track deviation at the Equator crossings, in the Aeolus case ±25 km.

Operationally, the optimization of in-plane manoeuvres is affected by the problem of predicting the S/C trajectory for LEO satellites. The optimization process relies on the ESOC FD orbit predictions available on the day the optimization takes place. The main sources of prediction errors in the case of Aeolus are:

- The very unreliable prediction of the air drag force encountered during the prediction period due to the poor predictability of solar and geomagnetic activity.
- Manoeuvre performance errors.
- The presence of ICs during the orbit predicted period.
- Errors in the initial state vector used in the propagation, which comes from the latest operational orbit determination

The last contribution to the error in the FD orbit predictions listed above could be neglected in the analysis. The GPS navigation solution available in the S/C telemetry is used to perform daily orbit determination on-ground, which allows to determine the S/C semi-major axis with a sub-metre accuracy. This error is clearly negligible in the presence of the larger sources of prediction errors mentioned above, primarily the uncertainty on the atmospheric drag force.
Expected manoeuvre performance errors were set to 1% (based on previous experience) and the errors on predicting the effect of the ICs on the orbit was ignored in a first approach to the problem. This parameter was taken into account on a second step of the analysis based on realistic long term simulations, which is described later on in this section.

The main source of uncertainty considered initially was therefore the poor predictability of the drag force. A fundamental parameter to compute the air drag force is the atmospheric density. The main inputs to the NRLMSISE-00 density model are the indexes F10.72 and Ap. These parameters are estimated on a daily basis taking as input the observed indexes released in the USAF/NOAA Report of Solar-Geophysical Activity, available in the NOAA ftp site [4]. The predictions made at ESOC FD cover 27 days in the future. The approach described in [1] was applied to reproduce the maximum expected orbit prediction errors at the moment of optimizing an in-plane orbit maintenance manoeuvre; afterwards by comparing several orbit propagations the consequent impact on the prediction of evolution of the ground-track deviation with respect to reference at the Equator crossings was obtained. The same analysis was repeated for two different levels of solar activity: low and medium levels according to the European Cooperation for Space Standarization (ECSS) recommendations [2], included in Table 2.

Table 2. ECSS recommended values for modelling the solar activity

	Low	Medium	High
F10.7	65	140	250
Ap	0	15	25

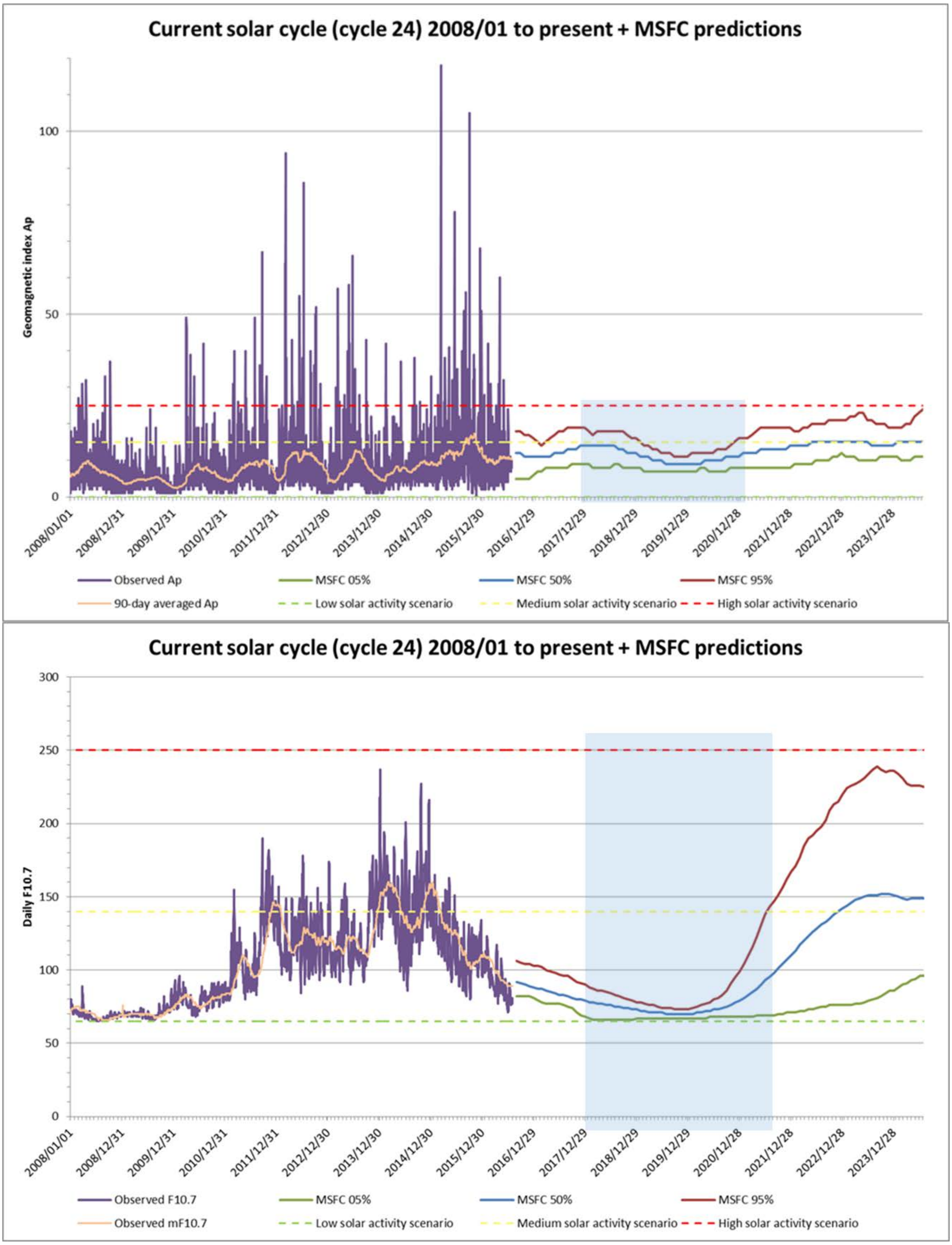

Fig. 2: Evolution of the solar and geomagnetic indexes for the current solar cycle and the predictions by the MSFC from January 2017. Expected Aeolus Mission duration (3.25 years) marked by the blue region

These recommended values for modelling low and medium solar activity regimes were indeed good boundary cases when looking at the long term predictions of the solar activity issued monthly by the Marshall Space Flight Centre (MSFC) [3] at the 5 and 95% confidence bounds for the expected Aeolus mission lifetime. In Fig. 2 a comparison between the MSFC predictions used at the time of the analysis and the ECSS recommended values is shown, marking the ECSS values for low and medium solar and geomagnetic activity with green and yellow lines respectively; the expected Aeolus mission lifetime is depicted by the blue shadowed region.

The outcome of this initial analysis based on single propagations is summarized in Table 3. The corresponding plots showing the evolution of the ground-track deviation for the different propagations are shown in Fig. 3 only for the low solar activity scenario. A safety margin on the west side of the control-band has been applied. The selection of this margin is such that in case the solar activity during the predicted period turns out to be lower than predicted no violation of the west side of the control-band occurs.

Table 3: Summary of in-plane orbit control analysis based on propagations accounting for expected predictions errors due to solar activity and manoeuvre performance errors.

Typical behaviour of	Low Solar Activity	Medium Solar Activity
Nominal Control cycle duration	2 weeks	< 1 week (6 days)
Shortest Control cycle duration	< 2weeks (10 days)	< 1 week (5 days)
Orbit control Delta-v	1.240 m/s	2.780 m/s
IC Delta-v	0.140 m/s	0.140 m/s
West control-band margin	9.0 km	8.0 km
Control-band violation	None	East side after 5 days

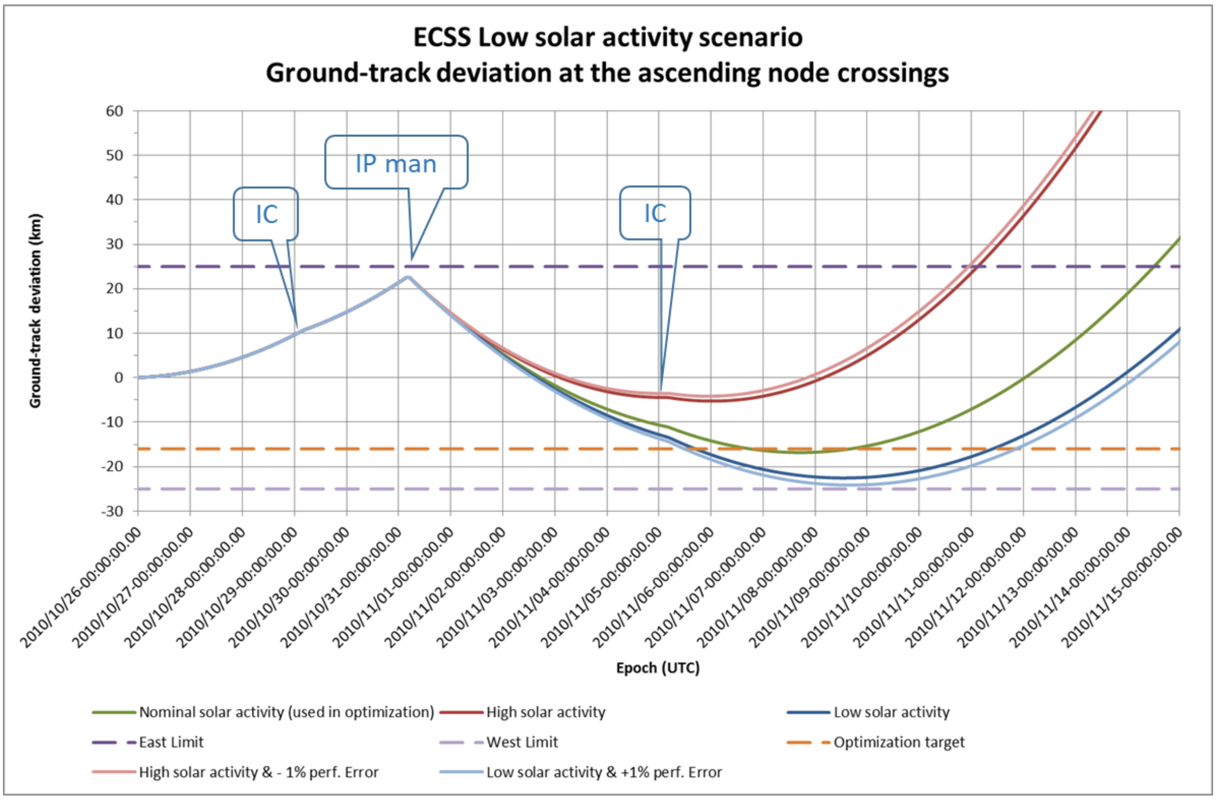

Fig. 3: In-plane manoeuvre optimization in the low solar activity scenario with applied uncertainty to the solar activity predictions and the in-plane manoeuvre performance

The evolution of the ground-track deviation as predicted on the manoeuvre optimization day is represented by the green line. Blue and red lines show the evolution of the ground-track deviation in case the solar activity is respectively lower or higher than predicted. It can be observed that the ±1% manoeuvre performance error (light blue and red lines) does not affect significantly the evolution of the ground-track deviation at the Equator.

The main conclusion is that the manoeuvre frequency will be one manoeuvre every 1 to 2 weeks depending on the intensity of the solar and geomagnetic activity levels. For the medium solar activity level even 1 manoeuvre per week might not be sufficient and a second manoeuvre slot will be required. Based on these preliminary results the FD orbit control software (S/W) was fully configured for the Aeolus case and the feasibility of the orbit control under that configuration was tested by running long term simulations. The orbit control simulator approach can be summarized in the following steps:

- Step 1: The simulator optimizes the in-plane maintenance manoeuvre(s), taking into account all the configured manoeuvre slots for one optimization control cycle, in this case only one slot per week. Manoeuvre slots are skipped if no orbit correction is required. The optimization is performed by the orbit control S/W covering one optimization cycle, this is, one week. The solar activity is predicted making use of the archived solar and geomagnetic indexes prior to the optimization day. This solar activity prediction is performed with the same S/W that is used in routine operations. The optimization takes into account the effect of any ICs which are planned inside the optimization cycle.

- Step 2: The manoeuvre(s) optimized in step 1 and the ICs are propagated up until the start of the next week. This propagation is performed using the archived solar and geomagnetic indexes, and not the predictions generated in step 1. Additionally, manoeuvre performance errors and the expected errors in predicting the IC delta-v are applied to the propagation.

- Step 3: An initial state vector at the start of the next manoeuvre optimization cycle (next week) is retrieved from the final propagation performed in step 2 and the optimization described in step 1 is performed again for the subsequent weeks.

The possibility to compare the solar activity predictions generated by the ESOC FD operational S/W against the real observed and archived solar and geomagnetic activity indexes justifies the selection of the simulation epoch in the past, between 2009/01 and 2012/03. Looking at the solar activity predictions in Fig. 2, these 3.25 years are representative of the low to medium ECSS levels of solar activity, which were the ones assumed for the feasibility analysis. The period 2009/01 to 2011/03 corresponds to the ECSS low solar activity and the period from 2011/04 to 2012/03 corresponds to the ECSS medium solar activity.

The first orbit control simulation was run configuring only one manoeuvre slot per week. The 3.25 years of ground-track deviation at the Equator crossings for that simulation are shown in Fig. 4.The simulation has been intentionally started with the ground-track deviation outside the control band. The S/W identifies the violation and performs a recovery manoeuvre, which aims at reaching the centre of the control band at the time of the next manoeuvre opportunity one week later. Although a safety margin of 8 km at the west side of the control band was identified in the pre-simulation analysis, the margin was set to 3 km in this simulation. This has been changed in view of the results of a first round of simulations. There it was observed that violations on the west side of the control band have a less significant impact on the overall orbit control. Violations on that side of the control band are typically short and require no intervention to resume the orbit control inside the control band after a couple of days.

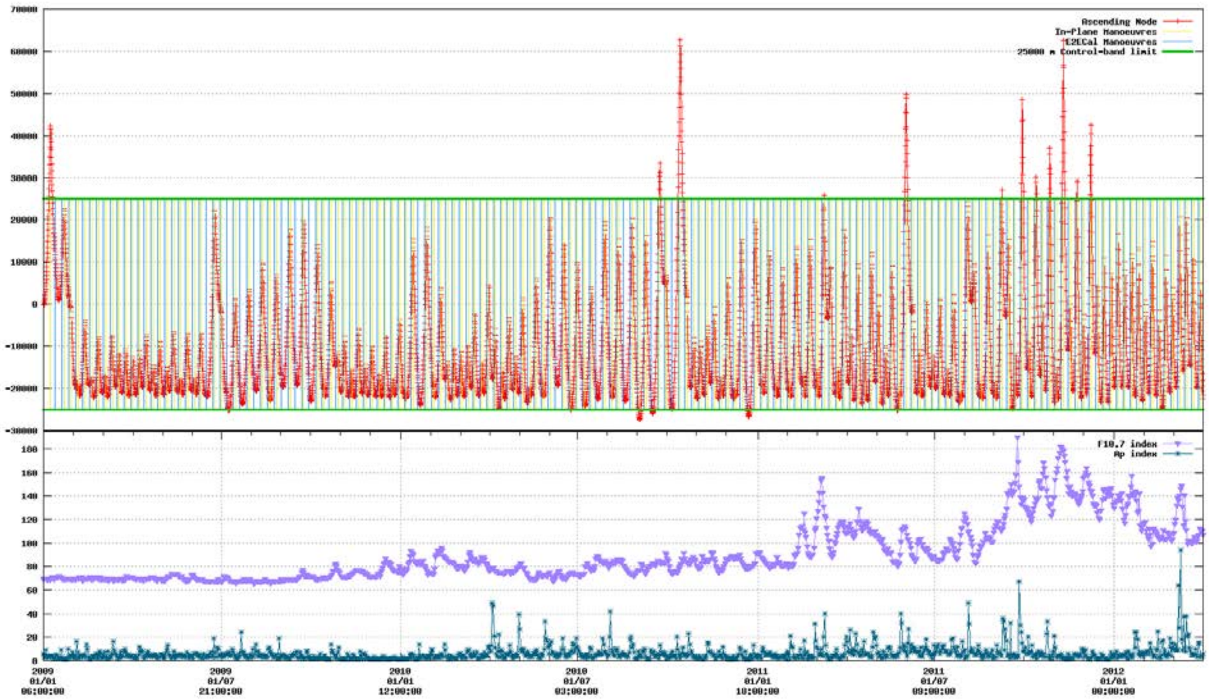

Fig. 4: Ground-track deviation and solar activity for simulation based on one manoeuvre slot per week

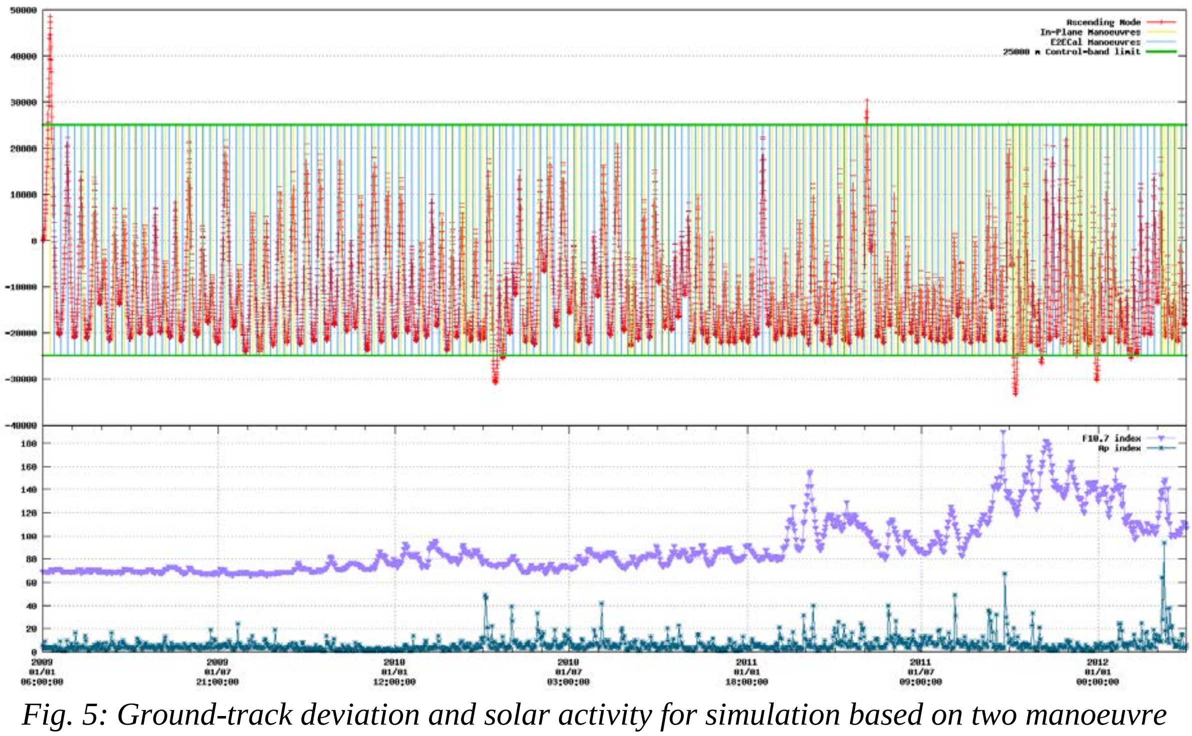

Fig. 5: Ground-track deviation and solar activity for simulation based on two manoeuvre slots per week

The orbit control is achieved without a significant number of violations of the control band during the period of low solar and geomagnetic activity (evolution of F10.7 and Ap also depicted in Fig. 4). These violations increase as the levels of solar activity raise. The reason for these violations is not related to the lack of accuracy in predicting the solar activity but rather to the imposed manoeuvre pattern of one fixed slot per week and a fixed control-band width. A possible way to improve the orbit control in these cases is to add a second manoeuvre slot per week. This has been done in a second simulation, with results shown in Fig. 5. The FD orbit control S/W decides based on the predictions of the ground-track deviation which manoeuvre slots should be used to perform orbit corrections; one or the two slots might be skipped if no maintenance manoeuvres are required.

The overall conclusion extracted from the simulations using the FD orbit control S/W was that the Aeolus ground-track control was achievable under the assumptions of weekly executions of the S/W configured to allow one or two fixed orbit control executions windows, depending on the levels of solar and geomagnetic activity. The result accounted as well for manoeuvre performance errors and 15% uncertainty in predicting the effect of ICs on the orbit.

Eccentricity Control

The requirement on the evolution of the eccentricity vector for Aeolus is not particularly strict, namely the mean eccentricity should be kept below 0.003 at all phases of the mission. In view of the expected size of orbit maintenance manoeuvres to control the ground-track deviation shown in Table 3, changes in eccentricity ranging from 0.00017 to 0.00065 can be achieved with the a single maintenance manoeuvre. The relation between the change in eccentricity and the size of a tangential change in S/C velocity is given by Eqn 1, where the Aeolus reference velocity is V = 7.717 km/s, and α_0 is the argument of latitude where the manoeuvre takes place.

$$\left(\Delta e_x, \Delta e_y\right) = 2\frac{\Delta v}{V}\left(\cos(\alpha_0)\,,\sin(\alpha_0)\right) \qquad (1)$$

Aiming at minimizing the complexity of the FD orbit control system, the assumption that the orbit control manoeuvre slots would cover at least a complete orbit revolution was made. This assumption was supported by an analysis on the expected number of complete orbital revolutions from the 111 orbits in the repeat cycle, which do not cross any of the regions of high importance for mission data generation. This assumption, together with the attainable eccentricity changes with the orbit control manoeuvres performed on a weekly or biweekly basis mentioned above, leads to a very simply eccentricity control strategy, where all maintenance manoeuvre are executed either at the ascending or the descending Equator crossings.

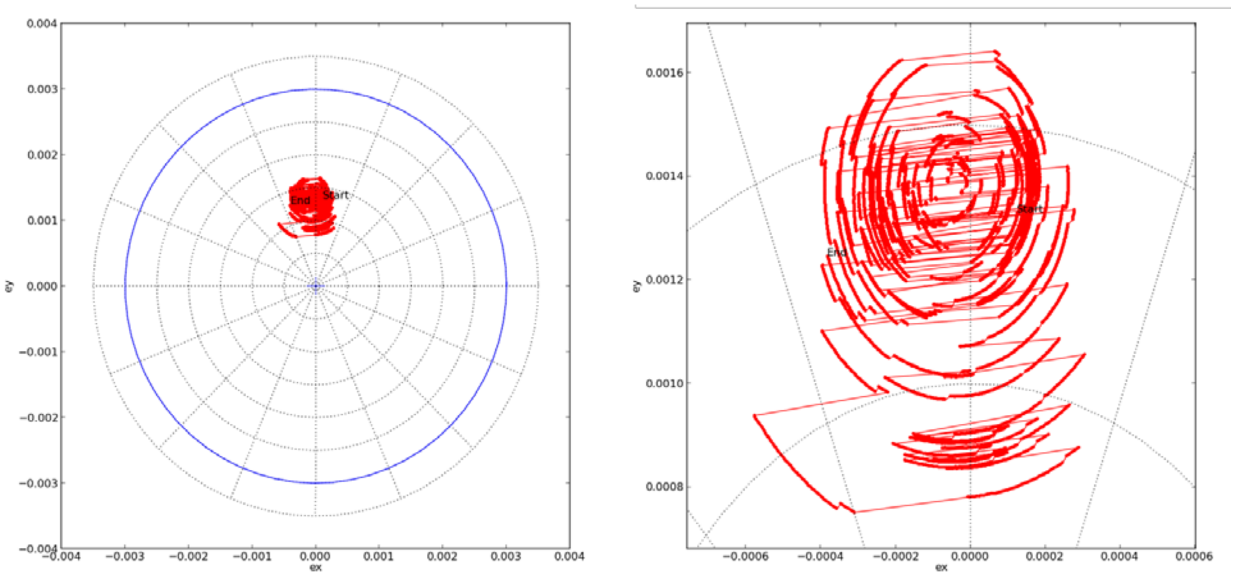

Fig. 6: Evolution of the mean eccentricity during a 3.25 years orbit control simulation. Orbit control manoeuvres executed close to Equator crossings. In blue the required control region. Detailed evolution on the left side

The evolution of the mean eccentricity vector in a 3.25 year orbit control simulation applying this eccentricity control is shown in Fig. 6. This gave evidence that the requirement on eccentricity control was easily achievable.

Inclination and LTAN control

Deviations of the orbital inclination with respect to the reference value have an impact on the ground-track deviation with respect to the reference ground-track at the maximum latitude of the orbit and also affect the sun-synchronism by introducing a drift in LTAN. Since there are no ground-track control requirements outside the Equator crossings, inclination corrections would only be needed to ensure that the LTAN is maintained inside the required interval [17:50 – 18:10] h. The two major perturbations acting on the inclination of the orbital plane are the third body perturbation (Sun and Moon) and the out-of-plane component of the atmospheric drag force.

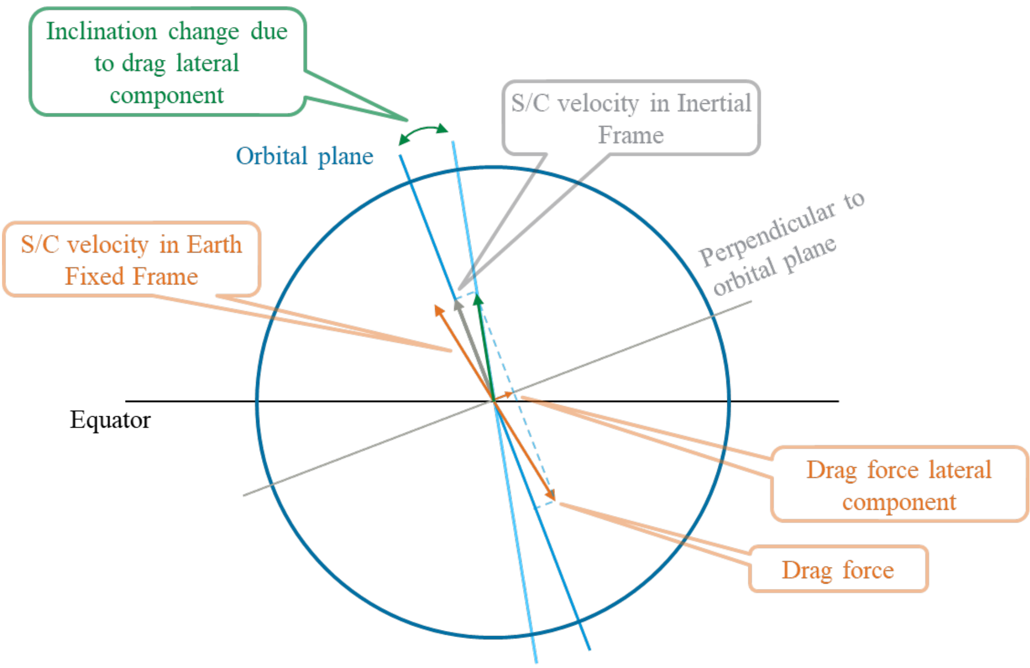

Fig. 7: Effect of drag lateral component on inclination. Diagram represents the ascending node crossing

Being Aeolus in a dusk-dawn orbit, the effect introduced by the third body perturbation does not cause any significant secular change in orbital inclination. A 3.25 year propagation has been performed, taking an initial state vector based on the Aeolus ESOC FD reference orbit and not taking into account the air drag perturbation, keeping this way the semi-major axis un-perturbed during the propagation. The LTAN reaches a maximum deviation of approximately 20 seconds at the end of the 3.25 year mission. Clearly this perturbation does not play any role on the inclination control selected approach.

At 320 km altitude, the effect of the lateral component of the drag force (depicted in Fig. 7) causes a non-negligible change in inclination and consequently a drift in LTAN, which ought to be controlled. The effect of this perturbation has been assessed making use of the results of a 3.25 year orbit control simulation presented in one of the previous subsections. The atmospheric density in that simulation corresponded to the observed levels of solar and geomagnetic activity during the period of time January 2009 to March 2012 (see Fig. 2). Those levels of solar activity were in line with the expectations for the Aeolus mission at the time of the analysis and they proved to be a good assumption also after launch. The evolution of the differences in True Of Date (TOD) inclination and LTAN with respect to the reference values during this simulation are shown in Fig. 8. A total decrease in inclination in the order of 50 mdeg is observed. The induced drift in LTAN exceeds the 10 minutes control margin before the end of the mission lifetime of 3.25 years.

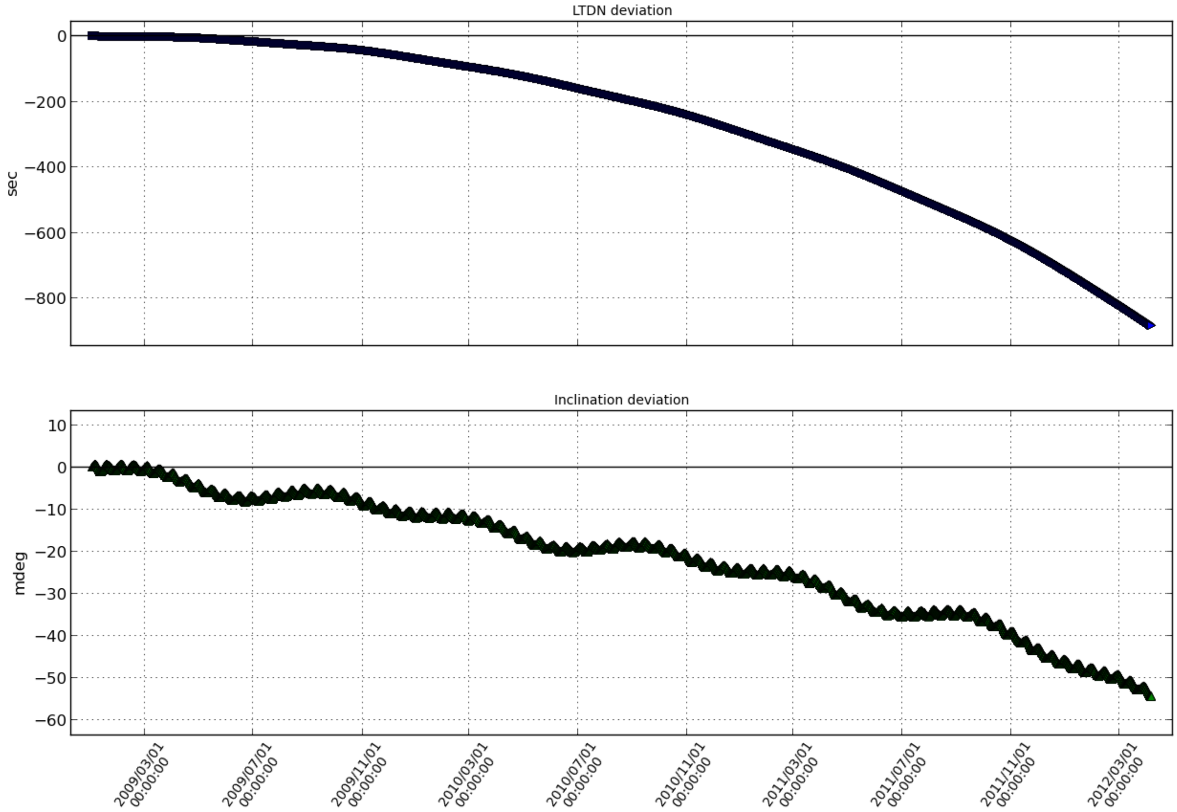

Fig. 8: Evolution of the TOD inclination and LTDN deviations with respect to the reference values for a 3.25 year orbit control simulation

The effect of the lateral drag component on the inclination is not easily predictable, due to the large uncertainty on the expected evolution of the solar and geomagnetic activities, together with the uncertainty about the drag coefficient, which is characterized once in flight. Additionally, the low atmosphere wind model available at ESOC FD has not been extensively used in operations. In view of these limitations, the suggested approach to the inclination control was, under nominal injection conditions, to perform the first inclination correction only one year after launch. The intention behind this approach is to monitor the evolution of the LTAN deviation during the first year of mission and only then, after calibration and adjustment of the prediction models, perform the first inclination correction. This approach is depicted in Fig. 9 for a particular simulation case. In this case, a change in inclination of 15 mdeg (corresponding approximately to a 2 m/s out-of-plane manoeuvre) performed after the first year of mission would be enough to keep the LTAN within the required control band for the whole mission lifetime.

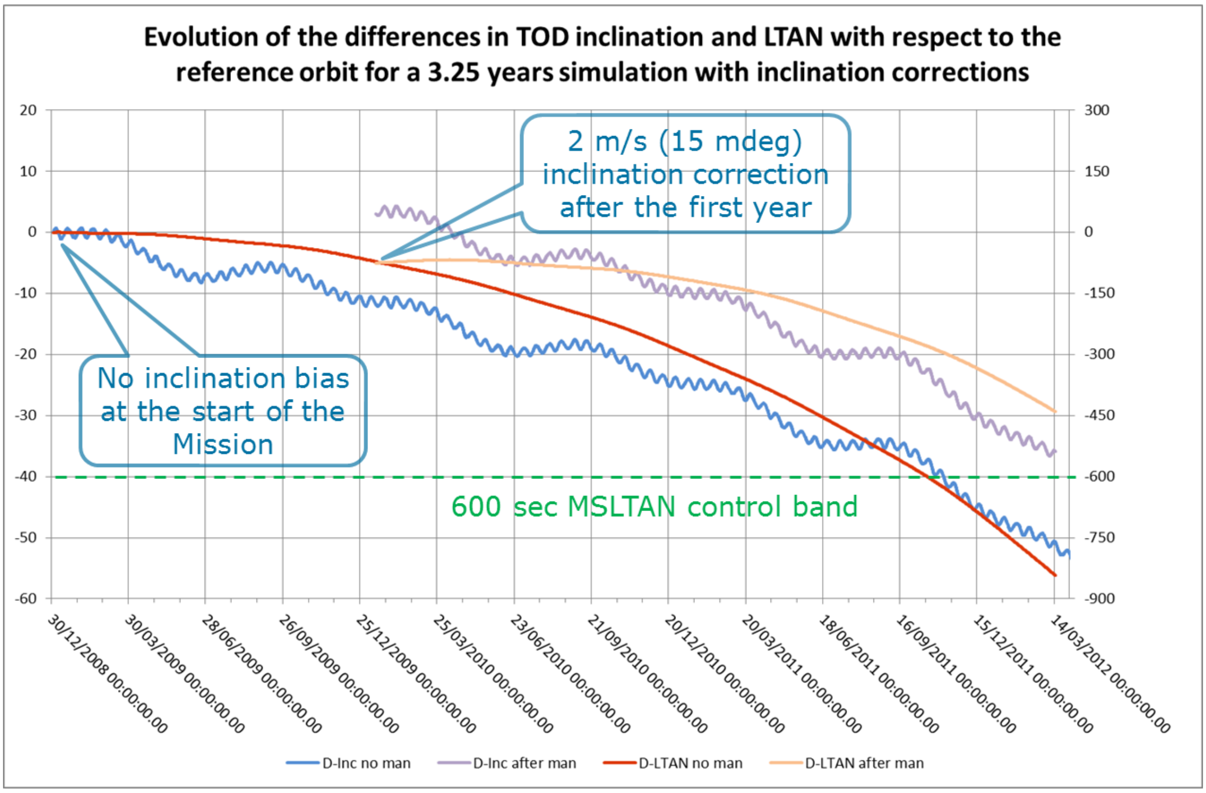

Fig. 9: Evolution of the TOD inclination and LTAN deviations with respect to the reference values for a 3.25 year orbit control simulation including a 2m/s out-of-plane manoeuvre 1 year after the start of the Mission

In-flight first results on the achieved orbit control (2018/10/23 – 2018/12/15)

From end of LEOP to the acquisition of the reference ground-track

Aeolus was successfully launched on the 2018/08/22-21:20:09.478 UTC. The injection achieved by Vega and its upper module was very close to nominal, with a semi-major axis error smaller than 1 km and an inclination error of -7 mdeg. The nominal injection state vector requested to the launcher was biased with respect to the reference, so the offsets in semi-major axis and inclination at injection with respect to the reference orbit were +2.7 km and +1 mdeg respectively.

During LEOP the S/C attitude control involved the use of the propulsion system during all flying modes different from NM. The accumulated thruster actuation during LEOP, together with the effect of a 0.5 m/s in-flight direction test manoeuvre executed towards the end of the first day of LEOP, resulted in an overall altitude offset with respect to the Aeolus reference altitude of +5.6 km at the conclusion of LEOP operations. Fig. 10 shows the evolution of the Aeolus altitude towards its reference altitude in the weeks that followed the end of LEOP. The altitude increments after LEOP are the effect of the ICs on the orbit, which were executed with a frequency of three per week from mid-September onwards (with some exceptions).

A second test manoeuvre was unsuccessfully executed during LEOP, some hours after the execution of the first test manoeuvre. The scope of this second manoeuvre was to test the behaviour of the S/C when performing a orbit control manoeuvre delivering the delta-v against the flight direction. This manoeuvre sequence requires a S/C rotation close to 180 deg, in order to align the S/C +X axis with the direction opposite to the S/C inertial velocity, while keeping the Sun incidence angle on the solar panels close enough to 90 deg (see Fig. 1). During the execution of this manoeuvre the blinding of a star tracker by the Earth led to an unforeseen sequence of autonomous on-board events, which eventually caused the S/C to fall back to safe mode. Although the cause of the problem has in the meantime been corrected, no further attempts to perform an orbit control manoeuvre against the flight direction have been made. Consequently, the FD orbit control S/W has been consistently updated in order to supress the possibility to include manoeuvre against the flight direction in the optimization cycles.

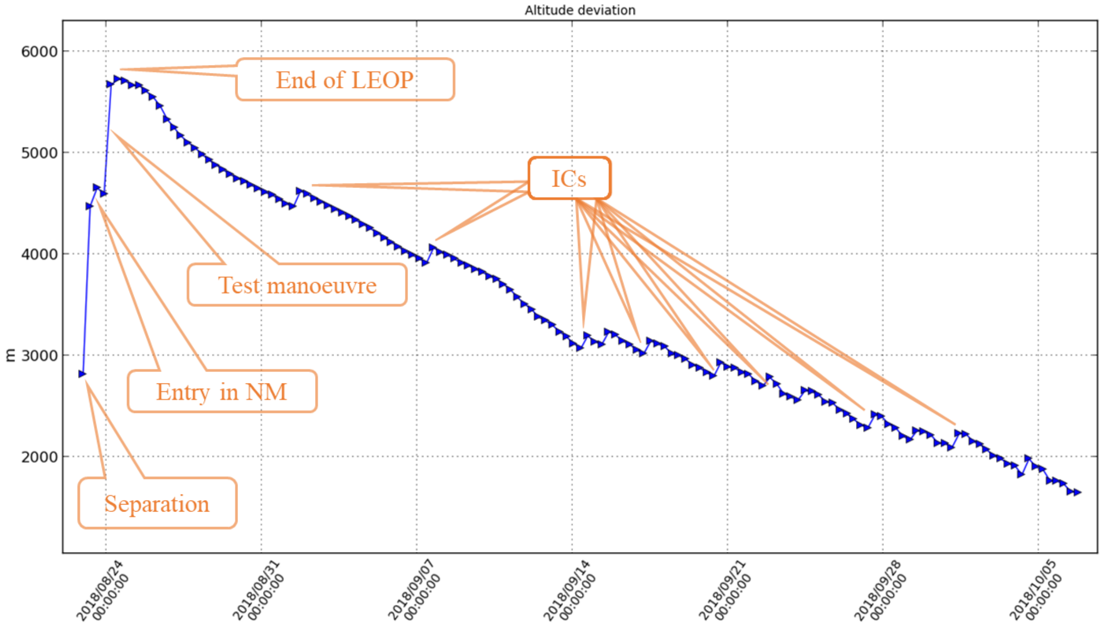

Fig. 10: Evolution of the altitude difference with respect to the Aeolus reference orbit from launch to the acquisition of the reference ground-track

The estimated Aeolus drag coefficients as part of the daily orbit determination are shown in Fig. 11 since the start of the orbit control phase. Because only daily values of the solar and geomagnetic indexes are input to the atmospheric density model, a total of 4 drag coefficients per day are estimated in order to model variations in the atmospheric air density with period shorter than 24 hours.

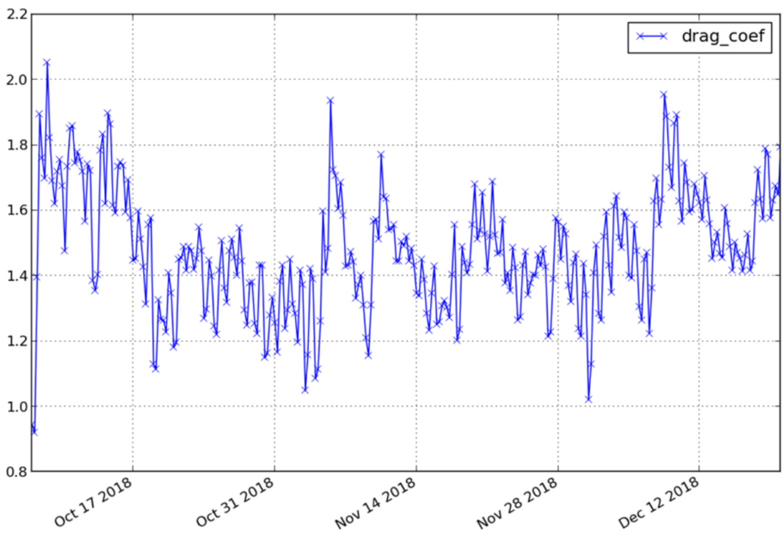

Fig. 11: Aeolus estimated drag coefficient from 2018/10/07 to 2018/12/18

In view of these results, an averaged drag coefficient value of 1.5 has been configured in the FD orbit control S/W, instead of the value 2.2 used during the analysis and feasibility tests (see Table 1).

A total number of 34 ICs have been performed between the 2018/09/01 and the 2018/12/20 with an averaged delta-v imparted in the along-track direction by a single IC of 0.110 m/s and a standard deviation of 0.006 m/s. Taking into account the good match with the expected effect during the feasibility analysis (0.14 m/s) and the very moderate variability of the observed effect (the analysis had assumed a Gaussian error with 0.02 m/s standard deviation), there was no need to modify either the configuration of the orbit control S/W or the operational concept.

Start of the active orbit control after the acquisition of the reference ground-track

On the 2018/10/07 Aeolus entered the 25 km control band around its reference ground-track. No acquisition manoeuvre was required, since the reference orbit was selected in such a way that the acquisition of its projection on the Earth surface would be achieved by the natural semi-major axis decay induced by the drag force. At that point in time the total hydrazine mass available to support the orbit control for the remainder of the mission was 262 kg. The expression of the acceleration due to the atmospheric drag force is recalled in Eq.2, where ρ is the atmospheric density, C_D is the S/C drag coefficient, *A* is the S/C equivalent frontal area, *m* is the S/C mass and *V* is the S/C velocity with respect to the co-rotating atmosphere.

$$a_D = -\frac{1}{2}\rho\left(\frac{C_D A}{m}\right)V^2 \qquad (2)$$

Comparing the assumptions on the S/C mass and drag coefficient during the analysis phase (1360 kg and 2.2 respectively) with the actual ones at the time of commencing the orbit control manoeuvres (1341 kg and 1.5), at equal conditions of atmospheric density the drag acceleration experience by Aeolus is being 30% smaller than expected. The assumed configuration of one semi-major axis correction every two weeks (corresponding to the low solar activity scenarios described in Table 3) is therefore valid with the possibility to apply larger safety margins to the west side of the 25 km control band at the Equator ascending crossings.

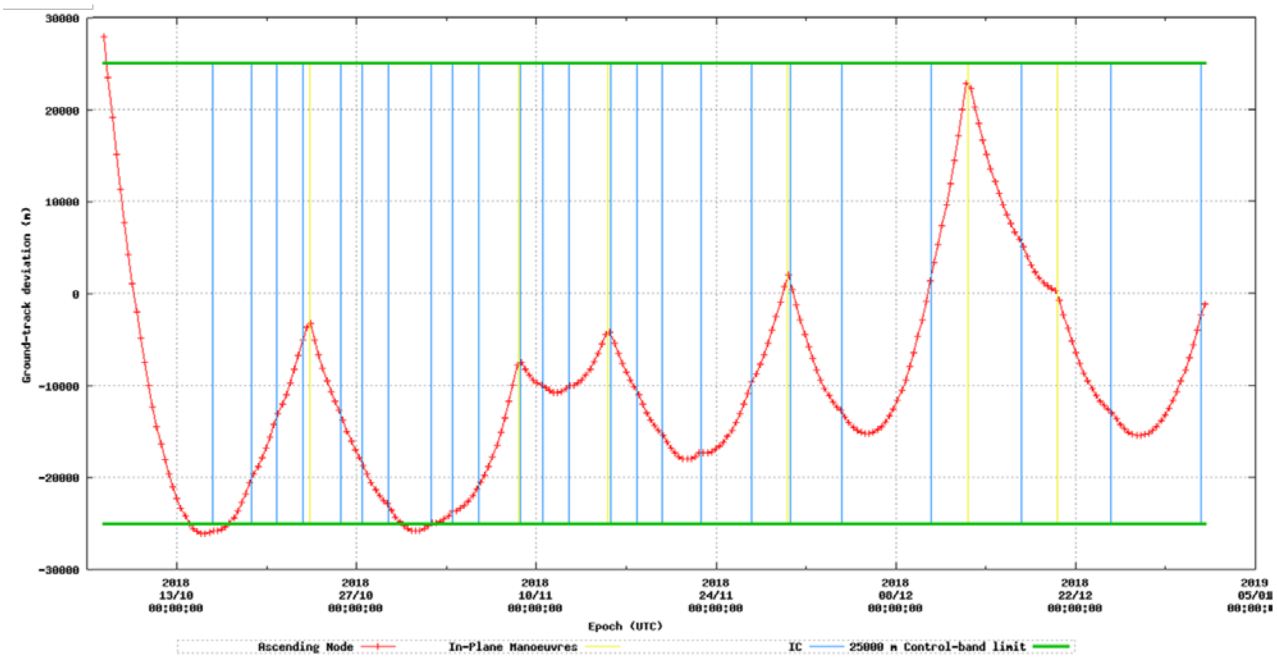

Fig. 12: Achieved ground-track deviation at ascending Equator crossings

The control of the Aeolus ground-track has been successfully achieved up until the time of writing with a minor violation on the west side of the control band after the first orbit maintenance manoeuvre (Fig. 12). Following that violation and as precaution measure, the safety margin applied on the west side of the control band has been increased to 12 km (instead of the 9 km mentioned in Table 3). This additional margin does no impact negatively the overall orbit control performance, since there is no requirement on the FD orbit control system to minimize the frequency of orbit maintenance manoeuvres throughout the mission.

The execution of every Aeolus orbit maintenance manoeuvre is followed by the so-called calibration process by the FD system. As part this process, orbit determinations are run at fixed time intervals, making use of all available GPS position data extracted from the S/C telemetry. This process finishes 24 hours after the manoeuvre execution; at that time the estimated delta-v vector determined as part of the orbit determination is not further modified.
Additionally, as part of the manoeuvre calibration FD activities, the thruster actuation telemetry is retrieved and processed. Part of the outcome of this task is the derivation of a delta-v profile corresponding to the thruster actuation during the complete manoeuvre sequence, including the actuation triggered by the attitude control during the sequence.

Table 4: Orbit control manoeuvres performance

Dv in m/s	Norm			Radial (zenith)			Along-track			Cross-track			P (%)
Time in UTC	**Pred**	**Det**	**TM**	**Pred**	**Det**	**TM**	**Pred**	**Det**	**TM**	**Pred**	**Det**	**TM**	
2018/10/23-07:38:29.29	0.6549	0.6901	0.6881	0.0000	-0.0014	0.0145	0.6549	0.6898	0.6877	0.0000	-0.0219	-0.0185	0.2890
Overall	**0.6549**	**0.6901**	**0.6881**	**0.0000**	**-0.0014**	**0.0145**	**0.6549**	**0.6898**	**0.6877**	**0.0000**	**-0.0219**	**-0.0185**	**0.289**
2018/11/08-14:05:09.09	0.0107	0.0106	0.0114	0.0000	-0.0014	0.0005	0.0107	0.0105	0.0113	0.0000	0.0005	-0.0009	
2018/11/08-14:07:53.53	0.4837	0.4855	0.4803	0.0000	-0.0021	0.0104	0.4837	0.4851	0.4801	0.0000	-0.0177	-0.0125	1.0730
2018/11/08-14:09:02.02	0.0259	0.0258	0.0296	0.0000	0.0023	0.0020	0.0259	0.0257	0.0294	0.0000	-0.0009	-0.0029	
Overall	**0.5203**	**0.5216**	**0.5212**	**0.0000**	**-0.0012**	**0.0129**	**0.5203**	**0.5213**	**0.5207**	**0.0000**	**-0.0181**	**-0.0163**	**0.0874**
2018/11/15-14:05:02.02	0.0107	0.0110	0.0116	0.0000	0.0030	0.0004	0.0107	0.0105	0.0116	0.0000	0.0011	-0.0009	
2018/11/15-14:07:46.46	0.3831	0.3885	0.3785	0.0000	0.0016	0.0078	0.3831	0.3882	0.3783	0.0000	-0.0142	-0.0102	2.6341
2018/11/15-14:08:46.46	0.0259	0.0279	0.0313	0.0000	-0.0045	0.0021	0.0259	0.0275	0.0311	0.0000	-0.0018	-0.0031	
Overall	**0.4197**	**0.4265**	**0.4213**	**0.0000**	**0.0001**	**0.0103**	**0.4197**	**0.4262**	**0.4210**	**0.0000**	**-0.0149**	**-0.0142**	**1.2187**
2018/11/29-13:19:30.30	0.0107	0.0109	0.0206	0.0000	0.0017	0.0007	0.0107	0.0107	0.0206	0.0000	-0.0007	-0.0005	
2018/11/29-13:22:13.13	0.6158	0.6304	0.6143	0.0000	0.0136	0.0136	0.6158	0.6297	0.6139	0.0000	-0.0243	-0.0159	2.6273
2018/11/29-13:24:07.07	0.0259	0.0272	0.0313	0.0000	-0.0035	0.0023	0.0259	0.0270	0.0311	0.0000	0.0014	-0.0034	
Overall	**0.6524**	**0.6679**	**0.6661**	**0.0000**	**0.0118**	**0.0167**	**0.6524**	**0.6674**	**0.6656**	**0.0000**	**-0.0236**	**-0.0198**	**0.2795**
2018/12/13-14:04:03.03	0.0107	0.0103	0.0118	0.0000	-0.0024	-0.0010	0.0107	0.0099	0.0118	0.0000	0.0014	0.0005	
2018/12/13-14:06:47.47	1.0215	1.0146	1.0200	0.0000	0.0110	-0.0289	1.0215	1.0140	1.0194	0.0000	-0.0309	0.0216	-0.5304
2018/12/13-14:09:23.23	0.0259	0.0273	0.0301	0.0000	0.0072	-0.0030	0.0259	0.0260	0.0298	0.0000	-0.0041	0.0021	
Overall	**1.0581**	**1.0506**	**1.0618**	**0.0000**	**0.0158**	**-0.0329**	**1.0581**	**1.0499**	**1.0610**	**0.0000**	**-0.0336**	**0.0242**	**-1.057**

Table 4 summarizes the outcome of these two tasks for the five maintenance manoeuvres performed up to the time of writing. The delta-v vectors and norms from three different sources are listed in the table, namely:

- The value predicted by the FD orbit determination and control team ("Pred")
- The estimated values in the orbit determination ("Det")
- The derived values using the thruster actuation extracted from the S/C telemetry and the FD models of the propulsion system ("TM")

The reference frame used to provide the calibration results is the local orbital frame, with radial pointing in zenith direction. Manoeuvre performance errors are reported in the last column. The three entries for every orbit control manoeuvre (with exception of the first one) represent the delta-v imparted on the orbit by the attitude control performed before and after the manoeuvre burn (first and third entries) and the delta-v imparted by the main burn (second entry).

The observed performance errors have not triggered any update on the FD system yet, since the values are relatively close to nominal performance. The delta-v profile for the attitude control thrusting used to predict the effect of the manoeuvre in the orbit might be changed as more manoeuvre calibration processes are performed. It has not have any noticeable impact on the accuracy of the FD orbit predictions so far.

An out-of-plane delta-v negative component (cross-track component) has been observed in all executed maintenance manoeuvres. This component has been estimated in good agreement in both FD calibration activities: orbit determination and processing of the thruster actuation telemetry. This out-of-plane delta-v component goes in the direction opposite to the S/C angular momentum. Consequently it causes a change of inclination which is positive (inclination increase) when the manoeuvre was performed close to the descending node crossing and negative (inclination decrease) when the manoeuvre was performed close to the ascending node crossing. This effect is observable in the inclination evolution plot shown , based on the Aeolus reconstructed operational orbit.

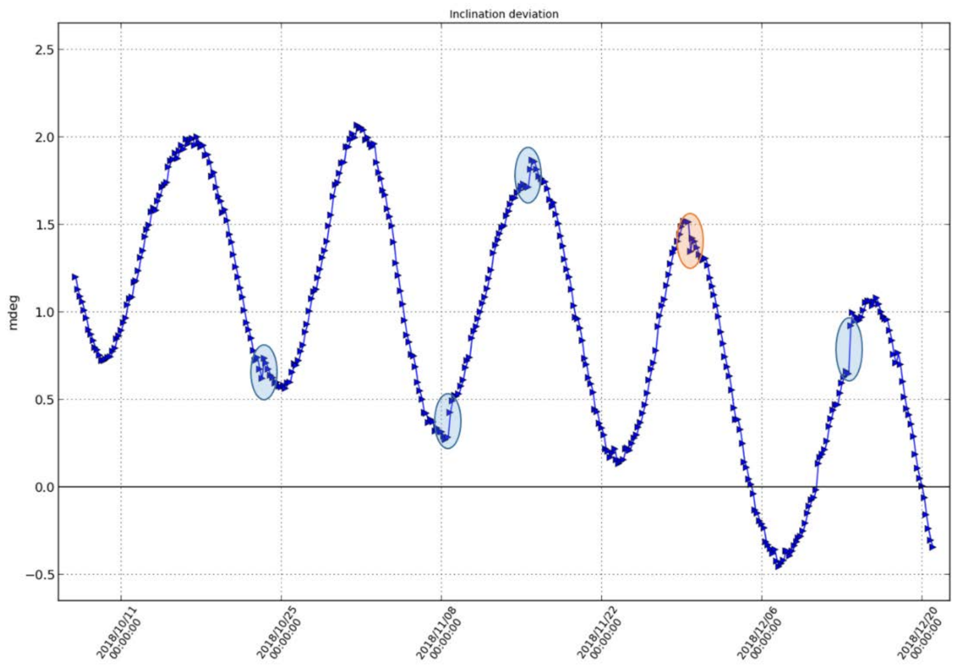

Figure 13: Evolution of the difference in inclination of Aeolus orbit with respect to its reference orbit. Effect of the out-of-plane component of the already executed maintenance manoeuvres. In blue manoeuvres executed at the descending node in blue and at the ascending node in orange

Since the orbital inclination is continuously decreasing due to the effect of the lateral component of the atmospheric drag force, the eccentricity control strategy analyzed before launch, which consists in performing all orbit maintenance manoeuvres either at the ascending or the descending node crossings, has been changed. In view of this parasitic out-of-plane component the execution of manoeuvres close to the ascending node crossings are now avoided. In order to avoid the orbit eccentricity to grow above the required value of 0.003, maintenance manoeuvres will be executed at three points in the orbit: at the descending node crossings and at the points of maximum and minimum latitude in the orbit.

Conclusions

The Aeolus FD orbit control system has been introduced, describing the main features of the Aeolus mission as well as the main drivers to the orbit control implementation approach. The selected approach is based on the re-use of the Sentinel-1 system due to the large set of commonalities between the orbit control of the two ESA-controlled missions. This system was developed at ESOC FD and presented during the 23d ISSFD in Pasadena 2012 [1]. The main enhancement required to support the Aeolus mission was to include the orbital changes caused by the instrument calibrations in the optimization cycle.

The methodology adopted to tailor, configure and test the FD orbit control S/W during the launch preparation phase has been provided. This methodology encompasses a first set of results on the expected manoeuvre frequency and size based on single propagations. A second step involves the utilization of the orbit control simulator developed by ESOC FD, which is configured based on the results of the first steps of the analysis. The high fidelity numerical simulations of the Aeolus orbit control obtained in this second step provided good proof of the feasibility of the orbit control concept using a pre-schedule approach with one optimization per week and one manoeuvre maintenance slot per week. The eccentricity control does not pose a significant challenge, since the requirement on the eccentricity evolution is not strict. The control of the orbital inclination is driven by the constraint on the maximum deviation in LTAN of ±10 min. The main perturbation on the inclination is the out-of-plane component of the atmospheric drag force, which causes a continuous decrease in inclination. The effect of this perturbation acting over a 3.25 years mission lifetime has been quantified to be in the order of tens of mdeg and the LTAN drift induced by this inclination offset could cause a violation of the 10 minutes difference control region. An inclination control strategy has been suggested, based on performing a single inclination correction one year after launch, after completing the calibration and adjustment of the parameters of the atmospheric models used to predict the evolution of the LTAN in the long term.

A brief summary of the orbit control operations conducted from the Aeolus launch until the time of writing is included in the last section of the paper. The assumptions made during the preparation phase have been contrasted with the actual values observed in operations, covering the S/C mass, drag coefficient, frequency of instrument calibrations and behaviour of the propulsion system.

Figures on the performance of the propulsion system show nominal behaviour; an out-of-plane effect has been determined after the execution of five orbit control manoeuvres. A change in the FD orbit control S/W has been introduced in order to make use of this out-of-plane component to correct the inclination, by placing the orbit maintenance manoeuvres mostly at the descending node crossing, where the effect causes an increase in inclination.

References

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