SENTINEL-1: OPERATIONAL APPROACH TO THE ORBIT CONTROL STRATEGY

M. A. Martin Serrano(1)**, Ian Shurmer**(2) **and Xavier Marc**(3)
(1) *SCISYS Deutschland GmbH at ESA/ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt Germany , telephone: +496151902273, E-mail: miguel.martin@scisys.de*
(2)*ESA/ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt Germany, telephone: +496151902637, E-mail: ian.shurmer@esa.int*
(3)*ESA/ESOC, Robert-Bosch-Straße 5, 64293 Darmstadt Germany, telephone: +496151902210, E-mail: xavier.marc@esa.int*

Abstract: *Sentinel-1 is an ESA two satellites system developed in the frame of the Global Monitoring for Environment and Security programme (GMES). The launch of the first Sentinel-1 satellite into a Sun-synchronous, dusk-dawn orbit with a 12-day repeat cycle is planned with a Soyouz from Kourou for winter 2013.*
The on-ground orbit control of Sentinel-1 poses a high challenge on the Flight Operations Center and in particular on the Flight Dynamics system due to the demanding orbit control requirements. The Sentinel-1 orbit shall be maintained inside a tube-shaped boundary defined around its reference orbit with a RMS-radius of 50 m. The high frequency of manoeuvres needed to achieve this orbit maintenance required the implementation of a new Flight Dynamics orbit control system based on pre-scheduled manoeuvre optimization and manoeuvre execution opportunities.
The paper presents the results of the analysis carried out by Flight Dynamics at ESOC to demonstrate the feasibility of this new orbit control strategy, including the main operational constraints which have driven the design of the system.

Keywords: *Sentinel-1, orbit control, SAR mission, Earth observation.*

1 Introduction

Sentinel-1 is designed as a two-satellite system each carrying a C-band Synthetic Aperture Radar (SAR), aimed at providing continuity of crucial data for user services initiated with the ERS and Envisat missions. The launch of the first Sentinel-1 with a Soyouz rocket from Kourou is planed for winter 2013. The main characteristics of the Sentinel-1 operational reference orbit are summarized in Table 1.

Table 1. Sentinel-1 reference orbit

Orbit type	Near polar, Sun-synchronous, frozen eccentricity
Local Time of the Ascending Node (LTAN)	18:00 hours (dusk-dawn)
Repeat cycle length	175 orbital revolutions
Repeat cycle duration	12 days

The Sentinel-1 osculating Earth Fixed orbit shall be maintained inside a tube-shaped boundary defined around the osculating Earth Fixed reference orbit with a RMS-radius of 50 m. The maximum allowed absolute deviation in Mean Solar Local Time of the Ascending Node (LTAN) is 5 minutes. This strict on-ground orbit control poses a high challenge on the Flight Operations Center and in particular on the Flight Dynamics System.

Depending on the level of solar and geomagnetic activity a maintenance manoeuvre frequency ranging from 2 to 5 manoeuvres per week will be required to keep the Sentinel-1 orbit within the predefined control dead-band. This high frequency of manoeuvres justifies the implementation of a new Flight Dynamics orbit control system that can support a manoeuvre maintenance process with the following two main characteristics:

- Cyclic pre-planned (pre-scheduled) uplink opportunities in order to load the manoeuvre execution products on-board the satellite
- Fixed number of manoeuvre execution opportunities per cycle, allowing the selection of the calendar days on which these manoeuvre opportunities occur. This provides the ability to define a deterministic orbit maintenance manoeuvre timetable

A fixed manoeuvre timetable is highly desirable in order to couple the manoeuvre maintenance activities with the working calendar as well as to take into account constraints coming from the payload mission planning. This approach also aims at reaching a high level of automation of the orbit control tasks, which is essential given the expected manoeuvre frequency.

An operational approach has been designed, aiming at maximizing the duration of the manoeuvre optimization cycles (or in other words, minimizing the number of manoeuvre optimizations and uplinks) as well as minimizing the number of manoeuvre execution opportunities per cycle.

The paper presents the most relevant results that have led to the final selection of the orbit control concept that will be applied to the Sentinel-1 mission.

2 Implementation of the new Sentinel-1 Flight Dynamics orbit control system

2.1 Need for a new orbit control approach and top level requirements

The orbit control requirements for Sentinel-1 are very demanding compared with previous ESA missions like ERS-2 or Envisat (flying at around 800 km altitude), which were controlled within a 1 km dead-band around their reference ground-track. The expected orbital maintenance manoeuvre frequency for Sentinel-1 ranges from 2 to 5 manoeuvres per week. In contrast, Envisat, with a ground-track dead-band of 1 km, needed to perform a single orbital IP maintenance manoeuvre every 3 to 8 weeks depending of the solar activity level and a total of 3 to 4 inclination corrections per year.

When performing orbit control of ERS-2, Envisat or Cryosat-2 Flight Dynamics monitor the ground-track evolution of the satellite orbits on a periodic basis and give the Flight Control Team at least 24 hours notice to perform a manoeuvre and deliver the associated manoeuvre execution products. This results in an orbital maintenance approach where the manoeuvre frequency is known approximately and where advanced warning of a manoeuvre can be only 24 hours. One advantage of such an approach is that there is the flexibility to plan orbital manoeuvres to avoid other satellite operations if necessary.

As Sentinel-1 will demand a higher manoeuvre frequency, the current Flight Dynamics operational approach becomes impractical. Flight Dynamics would be required to continuously monitor the ground-track evolution 7 days per week and probably outside of normal working hours. Flight Dynamics would also need to generate and deliver manoeuvre execution products 2 to 5 times per week, plus sufficient uplink opportunities would be required to ensure that these products could be uplinked to the satellite in advance.

In addition, if manoeuvres were only performed when absolutely necessary, the days on which manoeuvres are performed would vary from week to week making the planning of other satellite operations very difficult, i.e. given the very small ground-track maintenance dead-band of Sentinel-1, there is little or no flexibility to vary the orbital maintenance manoeuvre times without risking dead-band violations. In other words, other satellite operations need to be performed in parallel to, or around, the manoeuvre operations.

Sentinel-1 SAR Instrument operations can be performed in parallel with orbital maintenance operations, though will avoid them if possible. Optical Communications Payload operations, however, are not allowed in parallel with thruster firings due to the risk of optical head contamination and hence will have to be planned around the orbital maintenance operations. Therefore, a deterministic orbit maintenance manoeuvre timetable is very desirable.

Hence there is the need for a new Flight Dynamics operational approach driven by the following top level requirements:

- The Flight Dynamics system shall design, implement and support a cyclic (e.g. weekly) pre-planned (pre-scheduled) orbit maintenance process that allows the generation of all manoeuvre products in advance, for a configurable time period, based on a set of initial orbital and environmental assumptions, i.e. there will then be no correction/re-planning between the cyclic planning opportunities.
- The number of manoeuvre planning/optimisation and product generation cycles shall be minimized i.e. the duration of the planning cycle should be maximized. This way, the number of uplink opportunities required in order to load the manoeuvres execution products on-board the satellite is minimised.
- Nominal manoeuvre planning/optimisation shall be performed during normal working hours and shall not be required at weekends.
- It shall be possible to select the number of manoeuvre execution opportunities per week, and the calendar days on which these opportunities occur, as inputs to each manoeuvre planning cycle, i.e. this provides the ability to define a fixed (deterministic) orbit maintenance manoeuvre timetable.

2.2 Sentinel-1 orbit control requirements

As for other Earth observation missions the orbit control for Sentinel-1 is based on following a reference orbit within a maximum allowed deviation. However, the definition of the distance of the Sentinel-1 orbit with respect to its reference orbit is different from the classical definition applied to other ESA Earth observation missions in the following sense:

Previous ESA missions approach: The distance with respect to the reference orbit is computed in terms of perpendicular distance to the reference ground-track and difference in LTAN. Variations in altitude between different repeat cycles are controlled through the performance of eccentricity control. The reference ground-track is defined as the projection of the reference orbit on an Earth surface model.

Sentinel-1 approach: The distance with respect to the reference orbit is measured directly in perpendicular distance with respect to the Earth Fixed reference orbit. Additionally, the maximum allowed deviation with respect to the reference orbit is defined as the root of the mean squares of the distance (at a given true latitude) for a whole repeat cycle and not based on punctual deviations (at a given true latitude). The distance should be maintained at all true latitudes.

In order to implement a more practicable definition of distance from an operational perspective, the Sentinel-1 orbit control requirements have been reformulated. Thanks to mission analysis studies it has been concluded that the Sentinel-1 orbit control requirement can be translated to an equivalent absolute (no RMS definition) ground-track dead-band control at the Equator crossings and at the point of maximum latitude in the orbit. The width of the control dead-band around the reference ground-track is 60 m.

Sentinel-1 is equipped with a state-of-the-art mono-propellant propulsion system. The orbit control is achieved by implementing two types of manoeuvre: In-Plane (IP) manoeuvres to control the ground-track deviation at the Equator crossings and the evolution of the eccentricity vector and Out-Of-Plane (OOP) manoeuvres to control the ground-track deviation at maximum latitude as well as the LTAN and its drift.

The computation of the required OOP manoeuvres is deterministic and their frequency is determined by the third body perturbation and the solid tides perturbation. The computation of IP manoeuvres is affected by the well known problem of the orbit prediction accuracy for LEO satellites. IP manoeuvres aim mainly at compensating the permanent decay in semi-major axis due to the atmospheric drag. The optimization of IP manoeuvres relies on the orbit predictions available on the day the optimization takes place. These predictions are affected by the rather unreliable forecast of the air drag force encountered during the prediction period due to the poor predictability of solar and geomagnetic activity.

2.3 Main features of the new Sentinel-1 orbit control software

In order to support the new operational concept described before, a new Sentinel-1 orbit control software has been implemented with the following main features:

- A sequence of fixed IP and OOP manoeuvre opportunities times is provided as input. In particular it allows the user to specify the calendar days on which the manoeuvre opportunities are to occur. The software will iterate to find the optimal manoeuvre execution time closest to the given input times. The optimal manoeuvre location depends on the target and constraints associated to each type of manoeuvre (ascending or descending node for OOP manoeuvres and the correct argument of latitude to achieve the eccentricity control for IP manoeuvres).

- Constraints on the maximum and minimum elapsed times between manoeuvres can be provided as inputs to the optimization in order to meet platform constraints.
- The eccentricity control is achieved through the execution of double burn IP manoeuvres i.e. two IP burns performed at opposite arguments of latitude.
- The ground-track deviation at maximum latitude is controlled to avoid violations of the control dead-band at the orbit pole between two consecutive OOP manoeuvre opportunities. In particular when no OOP manoeuvre is needed to achieve the orbit control at the maximum latitude, the manoeuvre opportunity will be skipped.
- It minimizes the ground-track deviation at the Equator crossings with respect to the reference ground-track, while making use of a maximum allowed deviation or dead-band. The software determines which IP manoeuvre opportunities should be skipped based on an analytical estimation of the duration of the control cycles depending on the input solar and geomagnetic profile and the width of the control dead-band at the Equator.
- If at the start of the optimization the ground-track deviation at the Equator crossings is out of the control dead-band a recovery mode is triggered. The first IP control manoeuvre will aim at returning to the dead-band by the time the subsequent IP control is scheduled.
- The effect of the OOP manoeuvres is taken into account when optimizing IP manoeuvres. Simultaneous optimization of OOP and IP manoeuvres in the same run is possible.
- It ensures a high level of automation. The software guarantees robust convergence of the optimization algorithm for different scenarios (different levels of solar activity, fixed-size manoeuvres, recovery in case the control drops out of the dead-band, etc).

3 Analysis of a feasible configuration for the Sentinel-1 orbit control

The configuration of the new orbit control software for the Sentinel-1 case required the conduction of an analysis to achieve a feasible and optimal configuration in line with the requirements described in section 2.1. Two parameters were subject to analysis:

- The frequency of orbit control manoeuvre optimizations and uplinks.
- The frequency of orbit control manoeuvre execution opportunities (IP and OOP) per cycle.

After the manoeuvre optimization for a cycle is performed and the manoeuvre parameters are uplinked to the spacecraft no further modifications to that manoeuvre sequence is possible.

3.1 Approach to the analysis

The computation of the required OOP manoeuvres to control the ground-track deviation at maximum latitude is deterministic. The manoeuvre frequency is determined by the perturbations due to the Sun, Moon and solid tides. Due to the effect of the Moon, this frequency has to be higher than 1 manoeuvre per week (see Figure 1)

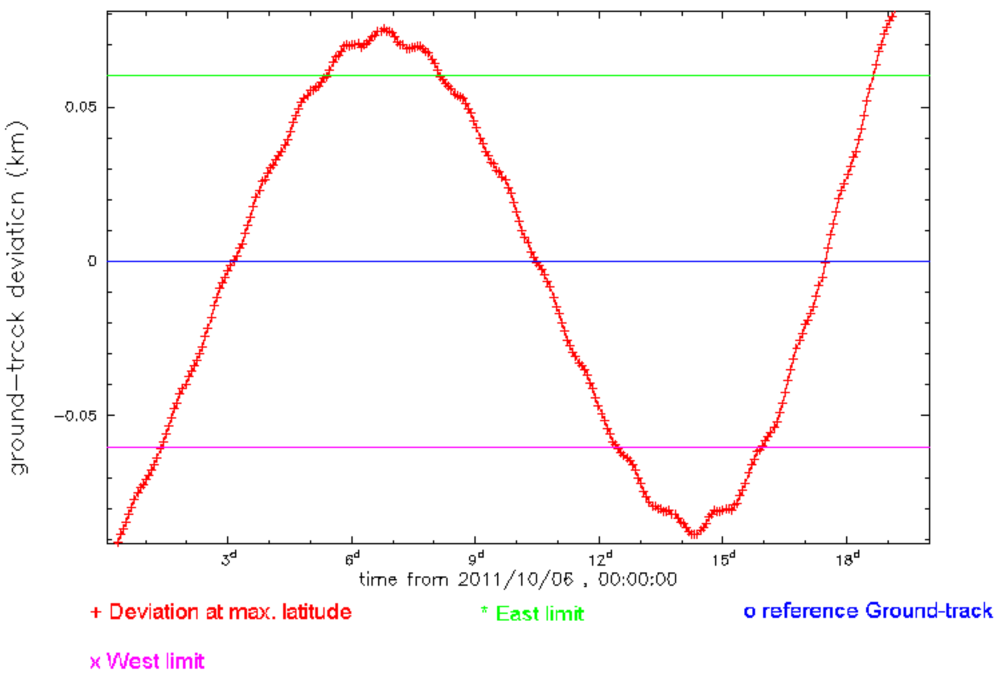

Figure 1 Ground-track deviation at maximum latitude. Effect of the Moon

The computation of IP manoeuvres is affected by the problem of predicting the drag force, connected to the poor predictability of solar and geomagnetic activity.

A fundamental parameter to compute the air drag force is the atmospheric density. The model used by the Sentinel-1 orbit control software is the NRLMSISE-00. The parameters affecting the air drag in NRLMSISE-00 are the F10.7 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. The predictions made at ESOC cover 27 days in the future (see [2]).

For the purpose of the analysis, it was assumed that the thrusters are calibrated and that thruster calibration errors are negligible. Similarly, it is assumed that the orbit determination errors at the start of each planning cycle are negligible as a continuous estimate of the satellite's orbit based upon the GPSR orbit data dumped each orbit from the on-board mass memory will be maintained.

The selected approach to demonstrate the feasibility of the orbit control strategy involves reproducing the conditions of unpredictability of the solar and geomagnetic indexes in a simulation as described in the steps below:

- Step1. Optimize the Sentinel-1 orbit control manoeuvre sequence for cycle 1 using a profile for the solar and geomagnetic activity. At this step this solar activity profile represents the predictions available on the day the manoeuvre optimization takes place.

- Step2. Propagate the Sentinel-1 orbit over the optimized manoeuvre sequence in cycle 1 up to the next manoeuvre optimization cyle using a different solar and geomagnetic activity profile. The profile at this step represents the real activity registered during propagated period (cycle 1).
- Step3. Check the ground-track deviation in cycle 1 resulting from the propagation carried out in Step2 and optimize the Sentinel-1 orbit control manoeuvre sequence for cycle 2.

This manoeuvre optimization exercise is repeated for different scenarios representing different levels of solar and geomagnetic activity. The extended lifetime of Sentinel-1 is 12 years, which means that in principle the mission will be operated throughout a complete solar cycle. Consequently, the operational orbit control strategy has to be able to cope with different levels of solar and geomagnetic activity, in particular with those representing the maximum and minimum levels within the solar cycle.

The simulation approach described above involves carrying out orbital propagations with "predicted" and "real" solar activity profiles. It is a key aspect for the analysis to use profiles that represent realistic atmospheric environments in terms of reference values and expected maximum error in the predictions. At the same time they should be representative of the boundary cases amongst the expected behaviour, so that the results of the analysis really size the problem.

Three sets of solar activity profiles have been used in this analysis. Each set represents a period of low, medium and high solar activity respectively. The reference values for the F10.7 and the Ap indexes have been taken from [1] and are shown in Table 2.

Table 2 ECSS recommended reference F10.7 and Ap indexes

	Long term			Short term
	Low	**Medium**	**High**	**High**
F10.7	65	140	250	300
Ap	0	15	45	240

Typical short time variations (1 week) of the F10.7 index can be derived by computing the difference in absolute value between the daily and the average F10.7 (i.e. m10.7) in the archived data over the last solar cycle. This provides a good figure of the expected spread of the value of this index over several days. The same approach has been taken to derive typical variations for the Ap index over several days. The derived figures for the short term variations of the F10.7 and the Ap are gathered in Table 3

Table 3 Derived short term spread error of F10.7 and Ap indexes

	Derived values of indexes variation		
	Low	**Medium**	**High**
F10.7	10	20	50
Ap	5	8	10

The figures in Table 3 are taken as prediction error in the Ap and F10.7 since these short term variations are the main unknowns driving the prediction errors. These figures are considered extreme. Prediction errors are expected to be larger only under certain conditions, namely when there is a severe solar storm, which can occur at any point of the solar cycle. A special profile based on archived solar data during a storm has been generated and included in the analysis (see last entry in Table 4).

For each reference level of solar activity (low, medium and high) three constant activity profiles are generated. The three profiles assume constant values of all indexes in the past. One of them, which will be called nominal in what follows, contains also constant values for the predicted part. The other two, called + and – in what follows, will represent a higher and lower evolution of the solar activity with respect to the nominal predictions. A description of the profiles is included in Table 4.

Table 4 Solar and geomagnetic profiles used in the analysis

Scenario	Daily F10.7	Mean F10.7	Daily Ap
low (-)	55	65 decreasing 0.1 units per day	0
low (nominal)	65	65 constant	0
low (+)	75	65 increasing 0.1 units per day	5
medium (-)	120	140 decreasing 0.2 units per day	7
medium (nominal)	140	140 constant	15
medium (+)	160	140 increasing 0.2 units per day	23
high (-)	200	250 decreasing 0.5 units per day	15
high (nominal)	250	250 constant	25
high (+)	300	250 increasing 0.5 units per day	35, 100 during the first day[1]

The approach to the simulation can be summarized now as follows: for every reference atmospheric environment (low, medium, high solar activity regime or a storm) the following steps are performed:

- Step 1. Perform an orbit maintenance manoeuvre sequence optimization for cycle 1 using any of the three profiles available (nominal, + or -) as predicted solar activity for that cycle.
- Step 2. Propagate the optimized manoeuvre sequence over cycle 1 using a profile adjacent to the one used in step1 as “real” or observed solar activity evolution for cycle 1. Comparisons between a high (+) and a low (-) profiles are considered to be too pessimistic and were not be part of the analysis. The maximum expected error in the solar predictions is this way limited to the values presented in Table 3.

[1] This puts on top of the constant offset a geomagnetic storm during the first day.

- Step 3. Perform an orbit maintenance manoeuvre sequence optimization for cycle 2. This optimization will correct the effect of the differences in ground-track deviation during cycle 1 due to the differences between the predicted and real solar activity.

3.2 Results of the analysis

The conclusions after analysing different manoeuvre optimization/uplink frequencies and number of manoeuvre opportunities per cycle are summarized in Table 5.

Table 5 Analysed scenarios

	2 manoeuvre opportunities per week	**4 manoeuvre opportunities per week**
1 optimization per week	Not feasible	**Selected scenario**
2 optimizations per week	Not feasible	Feasible

The selected scenario uses the minimum number of manoeuvre opportunities per week as well as manoeuvre optimization cycles: 1 per week. The manoeuvre opportunities will be placed on Thursday, Friday, Monday and Tuesday, being the optimization performed on Wednesday. This pattern is selected to have all orbit control operations within working hours.

The solar activity profiles described in the previous subsection represent worst case differences between predicted and observed solar activity. Based on these profiles we perform simulations which are intended to stress our orbit control configuration. So violations of the control dead-band are expected and allow us to evaluate the robustness of the control.

Section 3.2.1 discusses simulation results of the medium solar activity case with the selected scenario. Section 3.2.2 provides results for the high solar activity case, including a severe solar event. Results corresponding to the low level of solar activity case are not included since the control constraints are easily satisfied.

In section 4 results of a nominal orbit control simulation based on operational predictions of the solar activity are presented. These results confirm the validity of the selected scenario.

3.2.1 Results of the medium solar activity case

Figure 2 shows the evolution of the ground-track deviation after the optimization in week (cycle) 1. This optimization was performed using the medium-nominal solar activity profile. It can be noticed that the IP manoeuvre opportunities 2, 3, and 4 are skipped. As mentioned in section 2.3, the orbit control software estimates the duration of an IP control cycle based on the input solar activity and decides to skip these IP manoeuvre opportunities accordingly.

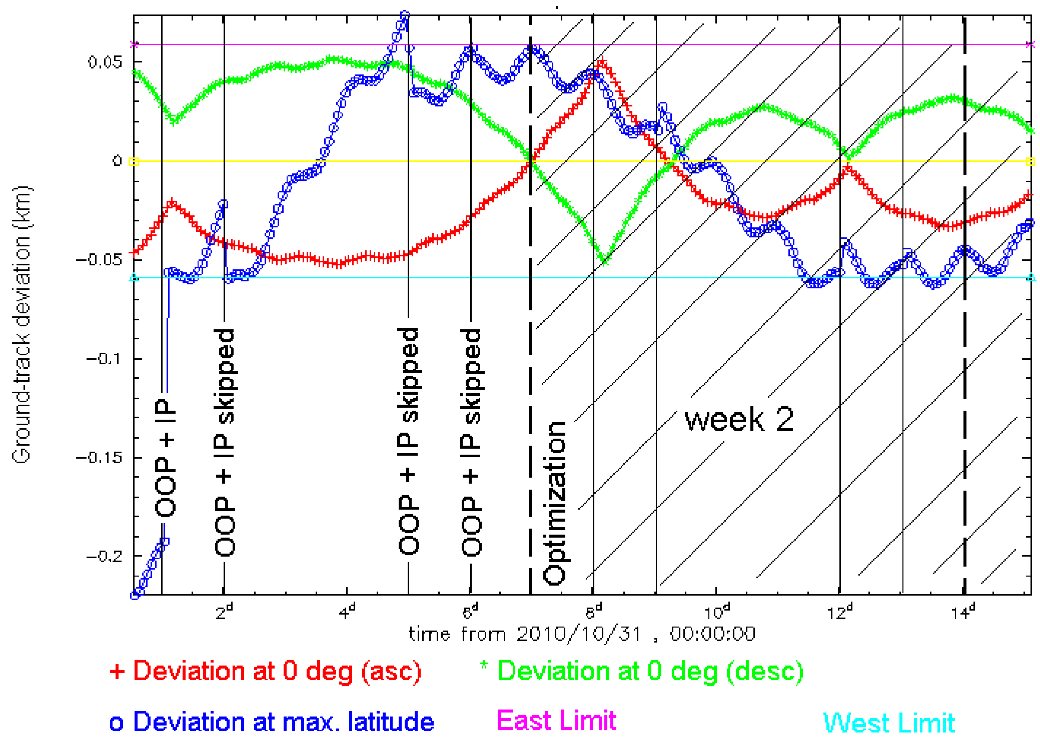

Figure 2 Step 1: evolution of the ground-track deviation after manoeuvre optimization on week (cycle) 1. Medium solar activity

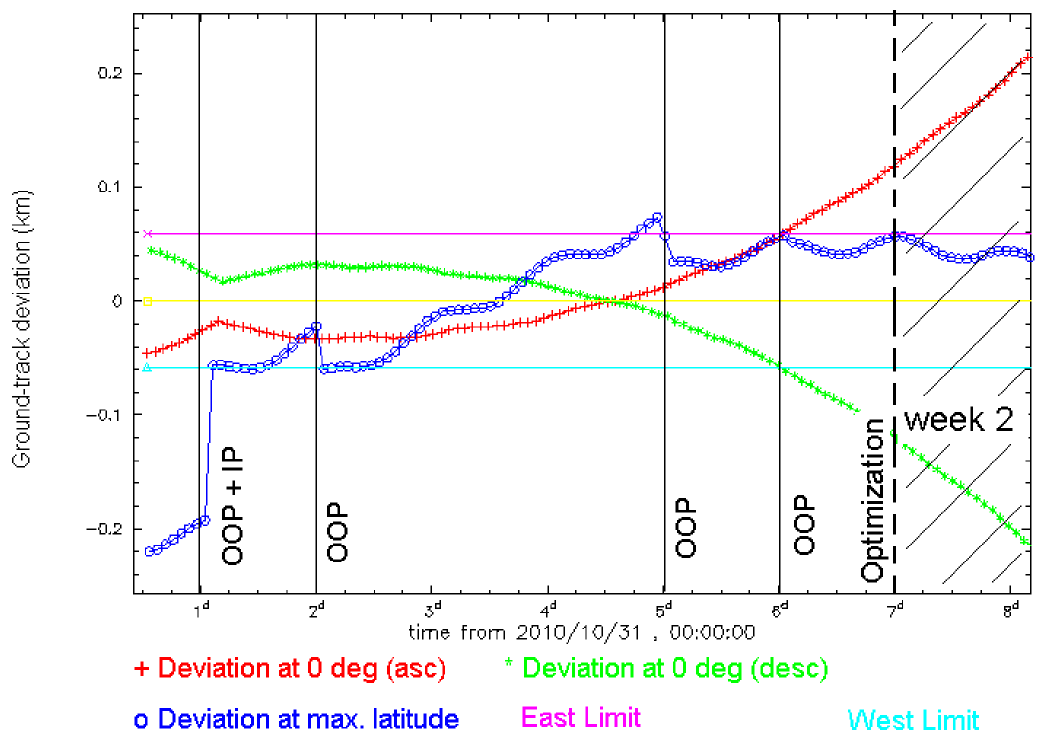

Figure 3 Step 2: real ground-track evolution during week (cycle) 1. Medium solar activity

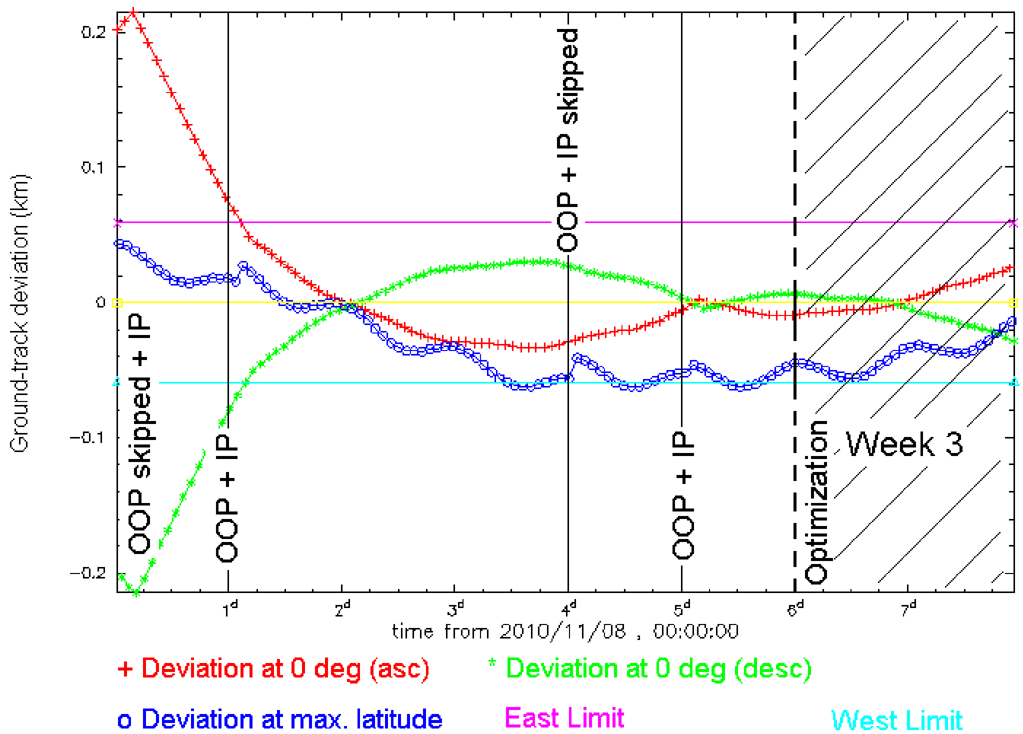

Figure 4 Step 3: recovery after manoeuvre optimization on week (cycle) 2. Medium solar activity

The evolution of the ground-track deviation during week (cycle) 1 leads to a violation of the control dead-band of 150 m approximately (Figure 3). This propagation was performed using the medium (+) solar activity profile. The violation triggers a recovery action during the manoeuvre optimization in week (cycle) 2 as shown in Figure 4. The duration of the excursion out of the control dead-band is three days approximately.

3.2.2 Results of the high solar activity case (plus solar storm)

Figure 5 shows the optimization of the manoeuvre sequence in week (cycle) 1. At this level of solar activity (the profile used is high (+)) all four manoeuvre opportunities per week are used and yet there are marginal violations of the control dead-band.

The real ground-track evolution (profile high-nominal used) differs largely from the predicted evolution and a violation of 1 km occurs. The high predictions for the air density at the time of the manoeuvre optimization lead to a westwards drift at the ascending node (Figure 6).

The optimization in week (cycle) 2 starts with a recovery, being the total time outside the control dead-band close to seven days (Figure 7).

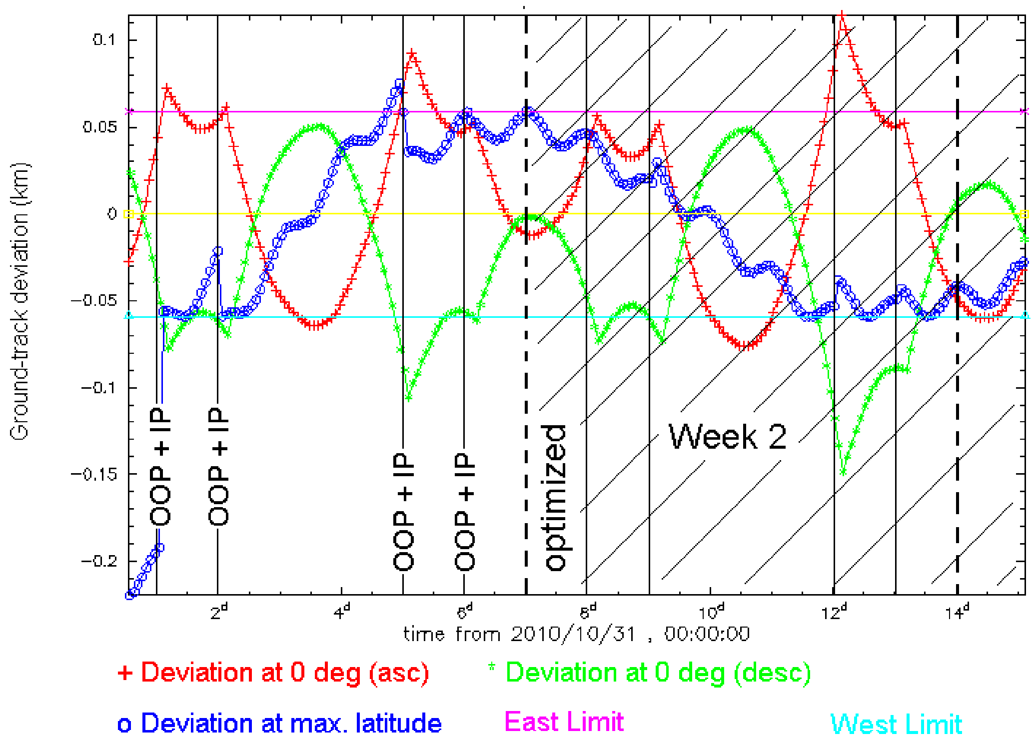

Figure 5 Step 1: evolution of the ground-track deviation after manoeuvre optimization on week (cycle) 1. High solar activity (+ storm)

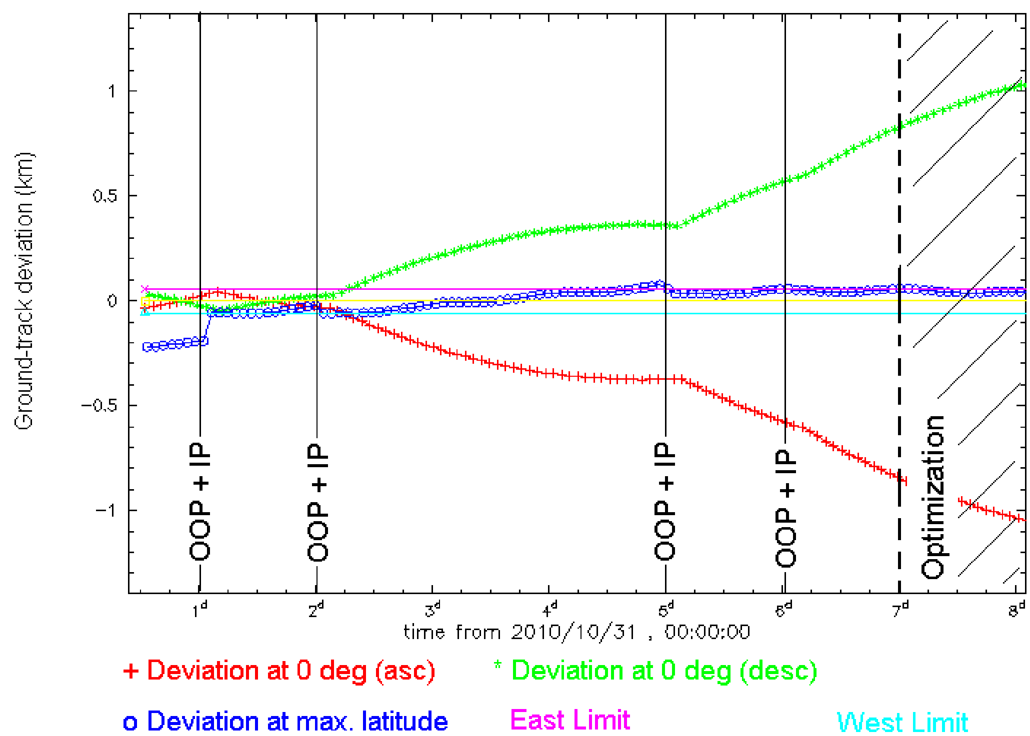

Figure 6 Step 2: real ground-track evolution in week (cycle) 1. High solar activity (+ storm)

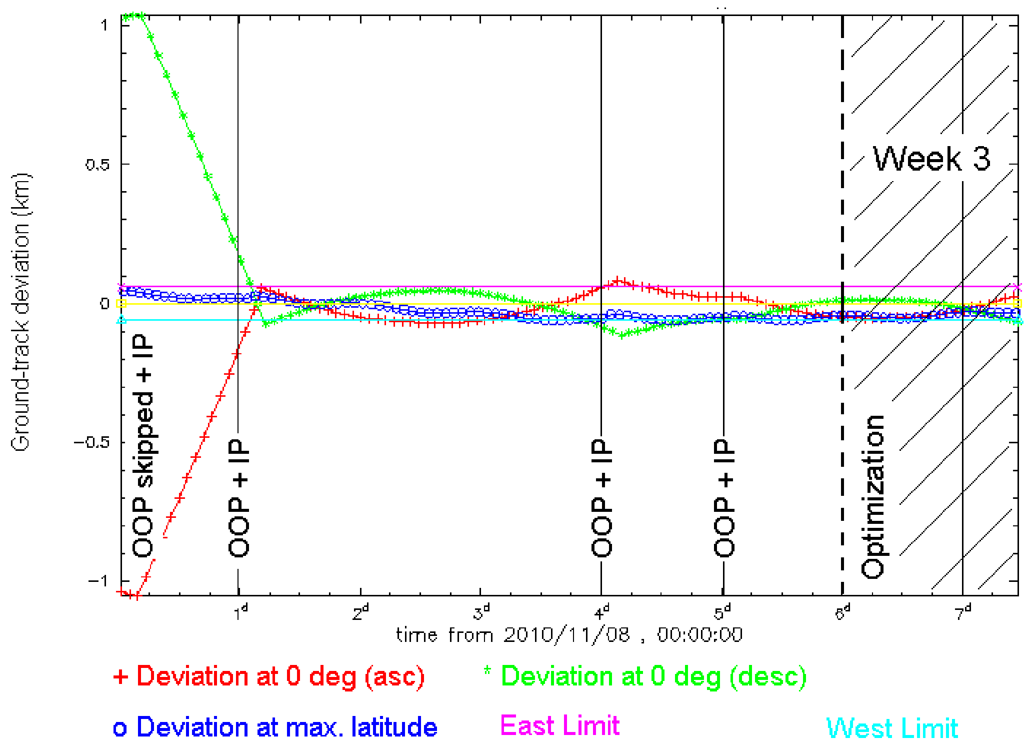

Figure 7 Step 3: recovery after manoeuvre optimization on week (cycle) 2. High solar activity (+storm)

4 Four month orbit control simulation

The main conclusion of the previous section is the feasibility of the orbit control assuming one manoeuvre optimization/uplink per week and four manoeuvre execution opportunities per week. The solar and geomagnetic profiles used as boundary cases to reach this conclusion can be considered somewhat pessimistic in the sense that there will be a significant number of weeks in the year when the predictions of the solar activity will be affected by smaller errors than the ones assumed in the analysis.

In order to have a short-time-scale picture of what the orbit control of Sentinel-1 will look like with the proposed scenario an orbit control simulation has been carried out weekly from November 2011 to April 2012 using the operational solar predictions available at Flight Dynamics ESOC. The levels of solar and geomagnetic activity at the end of 2011 beginning of 2012 fall in the medium solar activity scenario analysed in section 3.2.1. The results of this simulation confirm the conclusions extracted in that section.

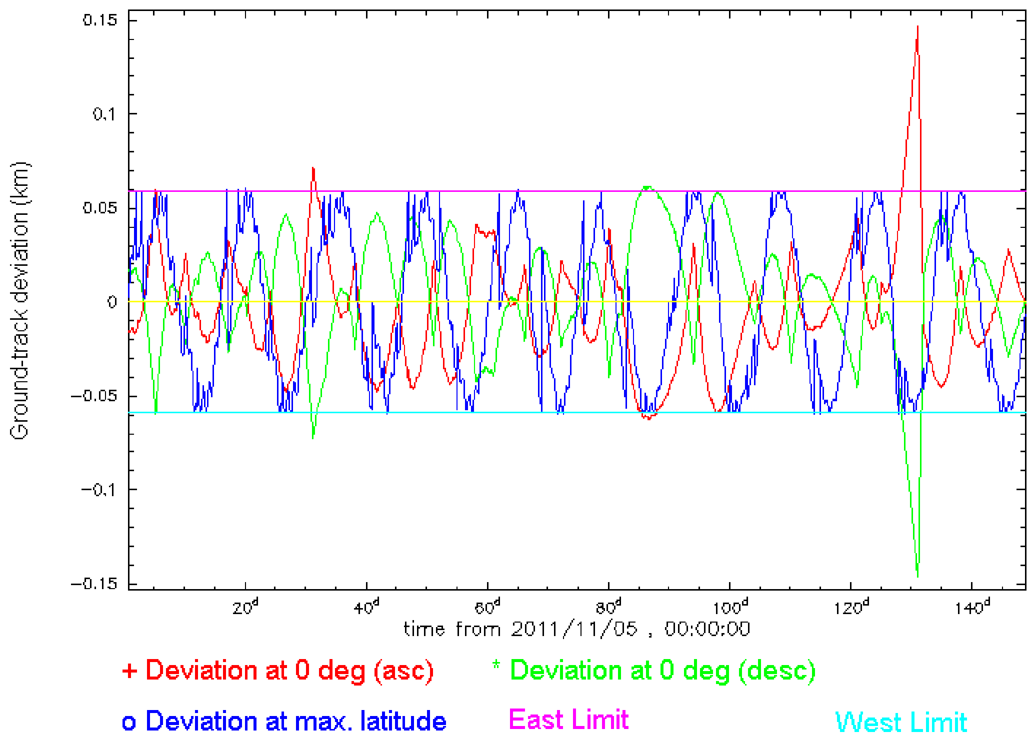

Figure 8 Results of the nominal orbit control simulation. Ground-track deviation

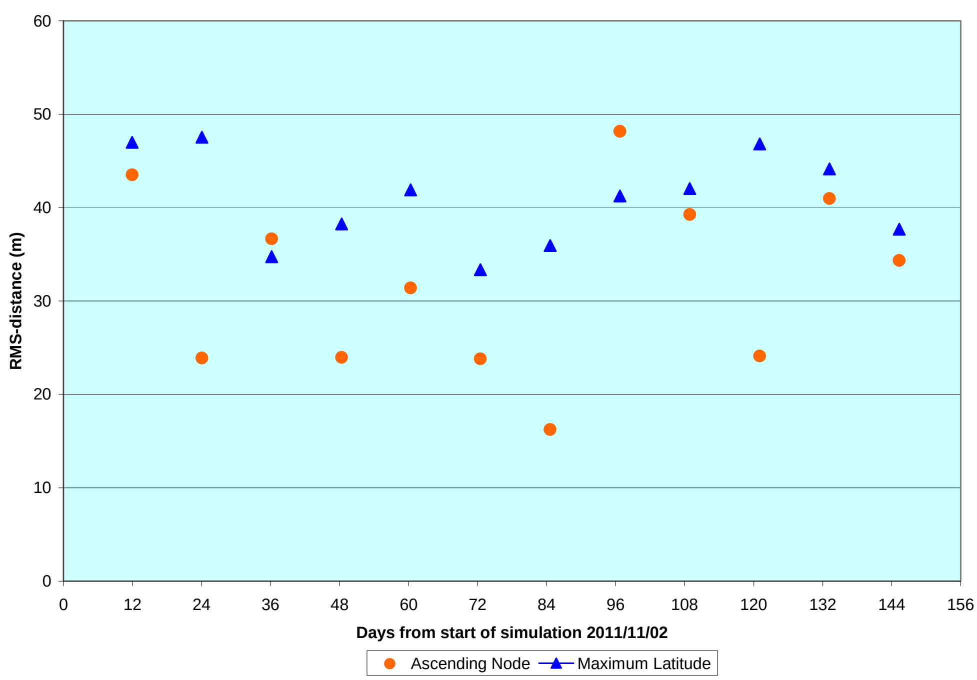

Figure 9 RMS distance with respect to the Earth Fixed reference orbit

The evolution of the ground-track deviation during the whole simulation is shown in Figure 8. Throughout a simulation period of 21 weeks only one significant violation of the dead-band occurred due to a major solar event on week 10/11 of 2012. The maximum ground-track deviation at the ascending node crossings during that violation reached 150 m, which is in line with the results presented for a medium solar activity environment. The recovery is successfully completed at the next manoeuvre optimization opportunity in week 11/12 with a total excursion time out of the control dead-band of 3.1 days.

The evolution of the absolute and RMS distance (averaged over 175 orbits) with respect to the Earth Fixed reference orbit is kept in a 50 m dead-band at the Equator crossings and at the maximum latitude as show in Figure 9.

5 Conclusions

The paper has presented the results of a study performed in order to demonstrate the feasibility of a pre-planning orbit control approach and has provided an assessment of how this approach can be applied to the particular orbit control requirements of the Sentinel-1 mission.

The main features of the orbit control software developed to support this new operational approach have been summarized in terms of top level requirements and relevant features of the implementation.

The main objective of the analysis was to provide an assessment of what can realistically be achieved operationally. The differences between the solar and geomagnetic profiles used for the manoeuvre optimisation (i.e. the “predicted” profiles) and the ones representing reality (i.e. “actual” profiles) while realistic, aim at setting boundary cases for the study. In that sense worse situations than the ones presented in sections 3.2.1 and specially 3.2.2 are unlikely, i.e. to be expected with a very low frequency under medium and high solar activity conditions respectively. In particular the following has been concluded:

- In the low and medium solar activity cases, a weekly planning and uplink cycle together with 4 manoeuvre execution opportunities per week, is sufficient to meet the Sentinel-1 ground-track dead-band requirement, even in the presence of worst case short term variations in solar activity, with occasional limited dead-band violation shorter than 3 days.
- The results of the analysis for the high solar activity environment (geomagnetic storm) show that the manoeuvre optimization and uplink frequency will have to be reviewed and increased during any mission lifetime phases when the uncertainty in the drag prediction is too high for a sustained period. An alternative solution would be to relax the control dead-band. In any case, as Envisat and ERS in orbit experience has shown that these storm conditions occur very rarely, they are not considered a driver for the choice of the baseline manoeuvre optimisation and uplink frequency.
- Fewer than 4 manoeuvre execution opportunities per week is generally considered insufficient to maintain the Sentinel-1 ground-track dead-band
- The “pre-planning” approach can provide a deterministic orbit maintenance scenario that can then be made available to other ground segment elements, as planning inputs.

6 References

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