Flex Tandem with Senintel-3: Control Concept

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Abstract

The FLuorescence EXplorer (FLEX) is an Earth observation mission developed by ESA, whose main objective is to perform quantitative measurements of the solar induced vegetation fluorescence with the goal of monitoring the vegetation photosynthetic activity. FLEX will orbit in tandem with one of the Copernicus Sentinel-3 satellites. The swath of the FLEX instrument (FLORIS) needs to be contained within the swath of the OLCI camera 4 on board of Senitnel-3 and that the time difference between the observations of each of the instruments shall be within 6 to 15 seconds, keeping the selected distance as stable as possible. Scheduled for launch in 2023, FLEX mission is currently in phase B2. This paper illustrates the requirements for the tandem, the analysed tandem concepts and the current status of the tandem control strategy design.

Keywords: Flex, Senintel-3, Tandem, Formation Flying, Safety.

Introduction

The FLEX mission concept foresees a small satellite flying in convoy with Sentinel-3. The combination of FLORIS and Sentinel-3's OLCI camera 4 and SLSTR instruments allows for an integrated package of measurements providing all the necessary auxiliary information to retrieve the fluorescence signal. Sentinel-3 instruments will provide information related to the atmospheric state and land-surface characterization needed for fluorescence retrieval covering the visible spectrum with OLCI and dual-angle visible / infrared and thermal infrared with SLSTR.
The FLEX satellite will fly in the same orbit as Sentinel-3, which is a near-polar, Sun-synchronous frozen orbit with a repeat cycle of 27 days and 385 orbits at 814.5 km altitude. FLEX will be preceding Sentinel-3 within 6 to 15 seconds, with the aim to keep the distance between both satellites as close and constant as possible.
FLEX observations shall be nadir looking with the field of view symmetrical with respect to the orbital plane and they shall mimic as much as possible the observation geometries of the Sentinel-3 OLCI camera closest to nadir (camera 4) to simplify the image co-registration [1].

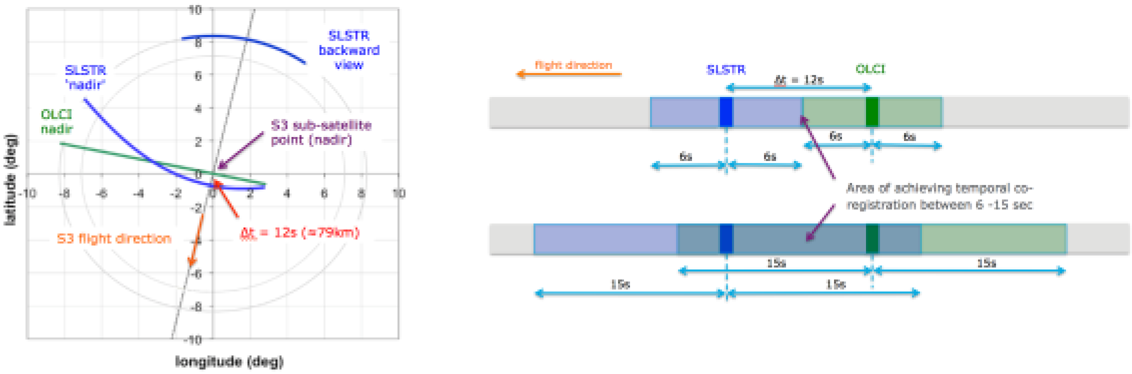

Fig. 1: Sentinel-3 schematics with possible FLEX time co-registration

Sentinel-3 is already operational and under no condition shall the operations of FLEX impose or require an action on Sentinel-3 operations, meaning the absolute orbit definition and maintenance is defined by Sentinel-3. Relative manoeuvres, if any, are to be performed by FLEX.

Passive safety shall be considered by default, meaning that in case of contingency of one or both satellites, they will naturally drift apart. Active safety shall only be considered when no other passive safety option is available, meaning that in these occasions, one satellite needs to actively react. In this cases a sufficient reaction time needs to be guaranteed. The suggested reaction time is based on typical space debris values of 7 days (goal) / 3days (requirement). In the scenarios when both satellites enter in safe mode shall be passively safe.

Taking into consideration the mission requirements and constrains stated above a tandem flight formation and its control needs to be defined. During phase B1 two different strategies to evaluate the trade-off between orbit control stability and safety versus operational simplicity have been analysed:

- Coordinated control box. It requires the minimum coordination between mission control centres, but the distance requirements are marginally met
- Master-Slave control. Here two cases have been also differentiated,
    - Perfect mimicking of the manoeuvres performed by Sentinel-3. It improves the control of the along-track distance in most of the scenarios
    - Perform tandem maintenance manoeuvres in between the Sentinel-3 mimicked manoeuvres. This strategy is the current baseline, providing a tighter control. It is designed to be adaptive to the environment conditions, varying the number and size of intermediate manoeuvres accordingly. The result may well be that under certain conditions no intermediate manoeuvres are needed, comprising therefore previous strategy of only mimicking Sentinel-3 manoeuvres.

Coordinated Control Box

The concept of control box is well known thanks to the A-train [2]. This control has also being implemented in two ESA missions, first in Sentinel-5P and Suomi-NPP loose formation flying and more recently on Sentinel-3 A/B tandem phase.

Only a minimum coordination between satellites is needed in order to synchronize the out of planes manoeuvres, which are not very frequent and easily predicted. The in-plane manoeuvres remain uncoordinated as each satellite keeps its reference ground-track within a certain dead-band.

Because the out of plane manoeuvres are synchronized, The Mean Local Solar Time evolution is exactly the same for both satellites. Therefore the along-track difference between them due to this effect constant during the mission. Only the along-track variation caused by the deviation with respect to the reference ground-track shall be considered.

Sentinel-3 maintains a ±1km dead-band control, therefore, in order to comply with the along-track difference requirements, Flex shall keep a dead-band of ±0.5km. In this way the ideal time co-registration would be between 8.6 and 15 seconds, having still 2.6 seconds of margin to account for the possible deviations in the of the out of plane manoeuvres performance and coordination

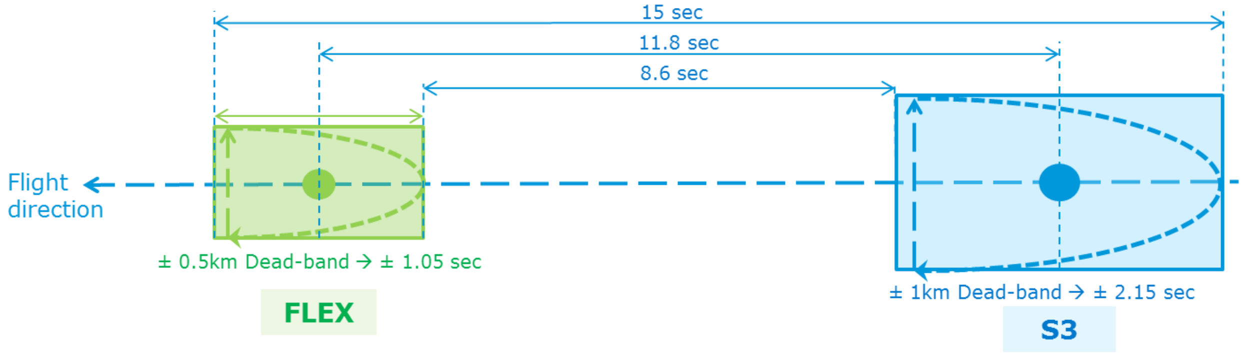

Fig. 2: Flex – Sentinel-3 control box schematics

The tandem formation control is reduced to a classic reference ground-track maintenance, in which the out of plane manoeuvres are dictated by Sentinel-3 schedule. With the current assumptions FLEX is expected to have a mass of 450 kg, and a cross sectional area of 4.5m^2. To be conservative it a drag coefficient of 3.0 is assumed. With this satellite characteristics, even during periods of high solar activity the manoeuvre frequency is not higher than once a week.

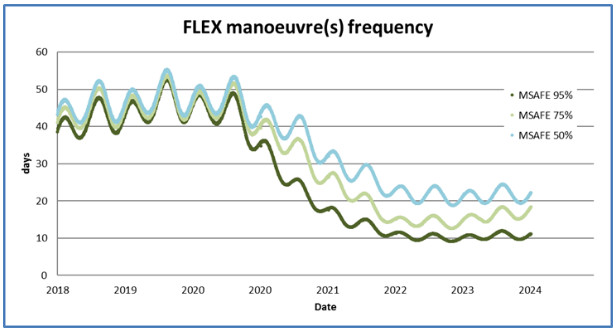

Fig. 3: Flex control box: manoeuvre frequency

In the safety aspects of this control, only two cases when a failure leads to close encounter situation. If Sentinel-3 loses control and it is not able to keep its ground-track, and in case of an over-performance of a FLEX in-plane manoeuvre. This last case has not been analysed yet because of the uncertainties in the propulsion system definition. A proper study will be done during phase B2.

Fig. 4 shows the worst along-track shift in seconds after 3(blue) and 7(green) days if no in-plane manoeuvre is performed. In case Sentinel-3 is not able to perform a manoeuvre and assuming it is rotated to its maximum cross section area, it is guaranteed it won't enter FLEX control box in less than 3 days. The 7 days goal cannot be assured for the periods of high solar activity, but it shall be noted that in such scenario FLEX control cycle is also in this order, so by not performing any in-plane manoeuvre too, it will be drifting apart on the other side of the control box.

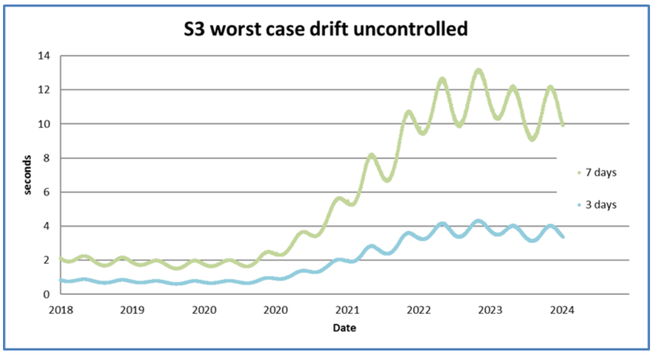

Fig. 4: Sentinel-3 along-track shift in 3 (blue) and 7 (green) days

The preliminary analysis have proven that a coordinated control box control is safe and feasible. It complies with the along-track distance requirements, but this compliance is marginal and as stated before if the along-track distance is maintained more constant it will result in an improvement on the science return. Therefore a master-slave control, although requiring a higher coordination, is also analysed.

Master Slave Control

The improvement of a pure Master-Slave formation is being analysed. This strategy requires more coordination between the control centres and an advanced control, but provides a more stable distance and safer formation flying. Currently the focus is on the in-plane manoeuvres strategy, where different kind of manoeuvres have been identified:

- Mirror Manoeuvres: if the masters moves, the slave follows.
- Formation maintenance manoeuvres: Due to different ballistic coefficients additional manoeuvres to keep the formation are needed.
- Parasitic in-plane component of the out of plane manoeuvres needs to be replicated and or corrected.
- Collision Avoidance Manoeuvres may need to be mirrored too.

The major driver of the achievable control are the mirror manoeuvres. When Sentinel-3 performs an in-plane manoeuvre it can’t be followed immediately by FLEX. Before confirmation and calibration of the Sentinel-3 manoeuvre is needed to replicate the manoeuvre. This delay between manoeuvres together with the altitude difference during this time creates a relative shift that will be the limit for the along-track control stability.

To have an initial understanding on the dynamics, a parametric study just mimicking Sentinel-3 manoeuvres was done, that is, focusing only in the mirror manoeuvres without any intermediate formation maintenance manoeuvre.

Parametric study of the tandem formation only mimicking Sentinel-3 manoeuvres

At this early stage of the mission there are many variables that are not known beforehand, therefore a straight parametric analysis was required to have a better understanding on the dynamic of the tandem and the influence of each variable on it. This analysis proposes a manoeuvring strategy based on a perfect mimicking of the orbital manoeuvres performed by Sentinel-3, it is detailed in [3].

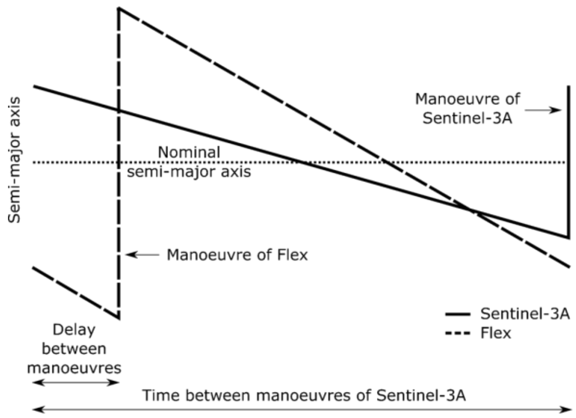

Fig. 5: General manoeuvre strategy

The three analysed variables that play a role in the along-track control are:

- The time delay between Sentinel-3 and FLEX manoeuvres. For safety reasons Senitnel-3 shall perform first the in-plane manoeuvre. If FLEX would perform an in-plane manoeuvre while Sentinel-3 has not performed or underperformed its own, a higher drift than desirable of FLEX towards Sentinel-3 would be induced.
- The ratio between the ballistic coefficients of both satellites. This will affect to the difference in the along-track drift rate between them.
- The solar activity will result in a different drift during the time between manoeuvres.

Fig. 6 illustrates the along-track distance variation for a medium solar activity level under different ballistic coefficient ratios and different times required for FLEX to mimic a Sentinel-3 manoeuvre. A perfect control is considered, so these cases illustrate a perfect manoeuvre performance and solar activity prediction. The first conclusion that can be observed is an improvement for the cases when the ratio between that ballistic coefficients is higher than 0.65. It also shows the importance to minimize the time delay to mimic Sentinel-3 manoeuvres, that with the current information it is not expected to be longer than 3 days.

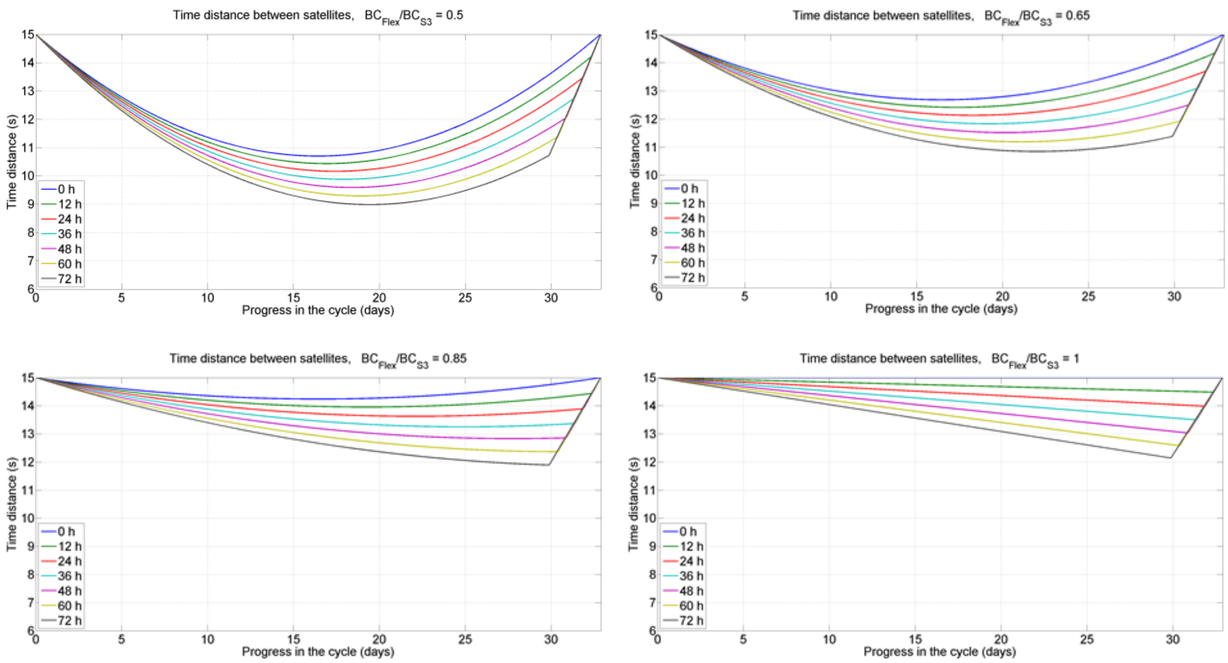

Fig. 6: Effect of time delay between manoeuvres for difference ballistic coefficients ratio

The solar activity variation will result in higher manoeuvres needed, therefore increasing the drift rate during the time passed between the manoeuvre of Senintel-3 and FLEX, that is a major driver in the achievable control. Fig. 6 shows the maximum along-track distance for different solar activity values.

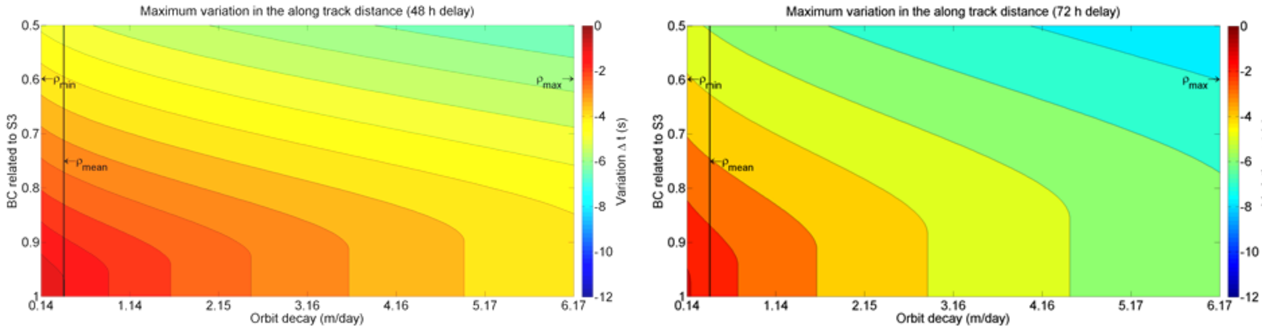

Fig. 7: Maximum along-track distance depending on solar activity.

The main conclusion of the parametric study was that it is needed to reduce the along-track shift during the interval between manoeuvres. This can be done by reducing the time interval but the minimum value will be determined by operational constrains on the time needed for the required activities since Sentinel-3 performs to the moment FLEX can perform its own manoeuvre. The other way to reduce the shift is to reduce the altitude difference between both satellites during this time interval.

Master-Slave control with formation maintenance manoeuvres

Reducing the along-track shift during the time interval between manoeuvres and therefore tightening the formation control, while maintaining a safe constellation has been the key objective in this final proposed strategy. This is done by means of one or more intermediate manoeuvres, which we will refer as formation manoeuvres. The optimum solution would be to perform just before Sentinel-3 manoeuvre half of the required altitude raising and the other half just after it. However this approach is not considered safe, as in case Sentinel-3 couldn't perform its own manoeuvre, FLEX would be drifting towards at a high rate. The challenge would be then to optimize the time and size of FLEX formation manoeuvre so the shift is reduced while keeping a safe scenario in case Sentinel-3 manoeuvre cancellation.

The sequence of a control cycle can be summarized as follows

- T0: Time at which S3 IP manoeuvre takes place.
- T1: Time at which the mimic FLEX manoeuvre takes place.
- T2: Time at which the FLEX formation manoeuvre of the cycle takes place.
- T3 = T0: Time at which the S3 IP manoeuvre of the next cycle is assumed to take place.

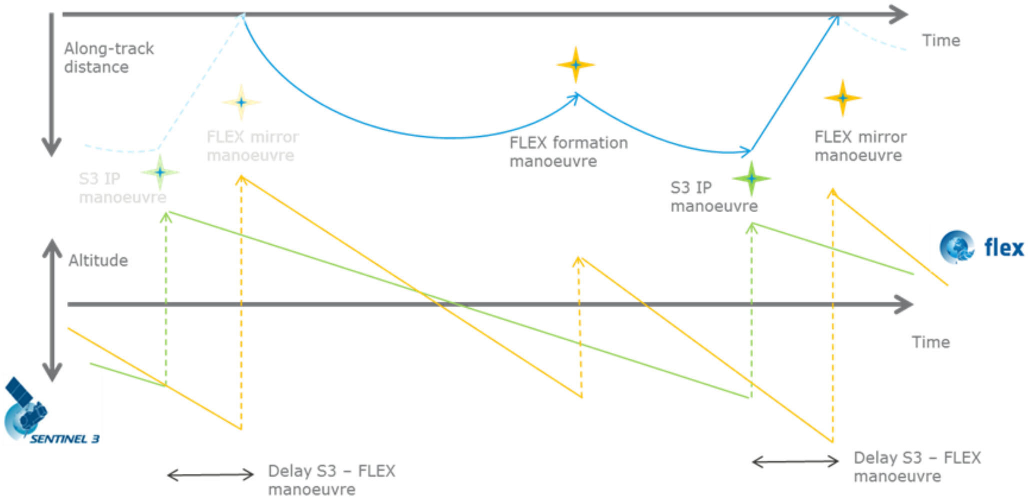

Fig. 8: Schematics of a control cycle

At T1, the situation of Sentinel-3 is known and its evolution is propagated. A guess of when its next manoeuvre will be performed is done, together with the position and altitude of at this moment. Based on that T2 is calculated, together with the desired along-track of FLEX at this moment. Then the mimic manoeuvre performed by FLEX at T1 shall target the calculated along track separation at T2.

At T2 the formation manoeuvre shall rise FLEX altitude as much as possible respecting the constraint that in case S3 doesn't perform any manoeuvre at T3 still the minimum distance between both satellites won't be reached in less than 3 (goal 7) days.

The next step has been to test the proposed tandem control concept in a realistic environment, concerning solar activity, optimization and propagation software. For this purpose an orbit control simulator (OCSIM) has been implemented. It simulates both, the Sentinel-3 and the FLEX orbit control, meaning that the FLEX orbit control is run on top of a "life" Sentinel-3 simulation.

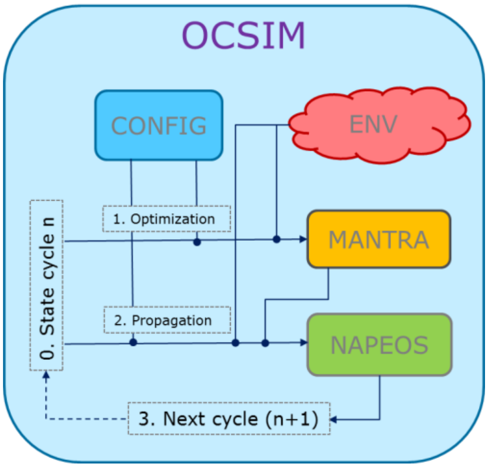

Fig. 9: Schematics of the OCSIM

OCSIM simulations require the definition of the following elements:

- Orbit Control Law: For the moment, the time execution of FLEX formation manoeuvre (T2) is defined as a fraction of the cycle. Further evolution on the algorithm to select this time will be done in next phases of the mission. Selected along-track targets for each one of the manoeuvres, in order to reduce along-track distance progressively.

- Spacecraft data: It is assumed fixed spacecraft characteristics (mass, frontal area). The relative ballistic coefficient modelled is achieved by means of the FLEX aerodynamic coefficient: Cd

- Solar activity: Predicted vs real solar activity in optimization different than in propagation. Historical data is used.

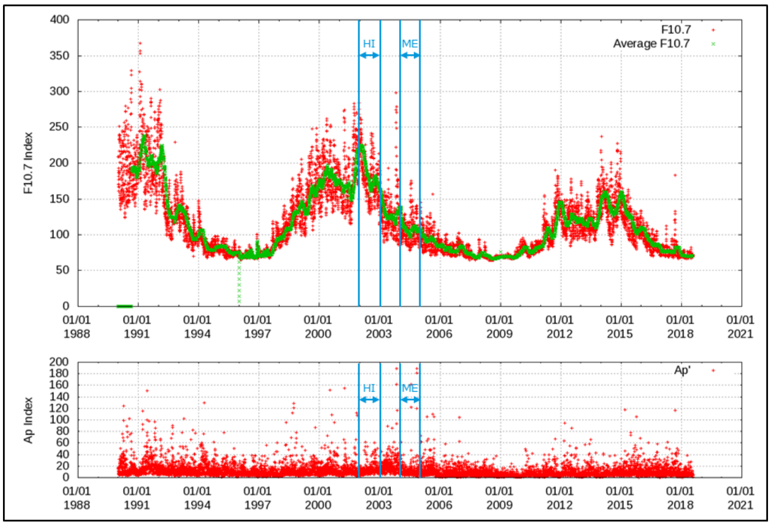

Fig. 10: Solar activity

No manoeuvre misperformance and no OOP manoeuvre de-pointing is currently considered in by the OCSIM. This implies, IP manoeuvres perform as expected and OOP manoeuvres do not introduce in IP component. This effects will be included in following versions of the simulator.

Several simulations have been performed for high and medium solar activity ranges, here three of them will be shown as a sample. The worst considered scenario assumes a 3 days delay between Senitnel-3 manoeuvre and FLEX mimicking one, a ballistic coefficients ratio of 0.5 and it is run under high solar activity conditions. The outcome of that simulation s shown in Fig. 11. The first exclusions of the dead-band are an artefact of the simulator, as the initial conditions are not optimized. For the rest it is shown that the along-track shift it well kept within the boundaries, actually most of the simulation it is controlled in a 4-5 seconds range.

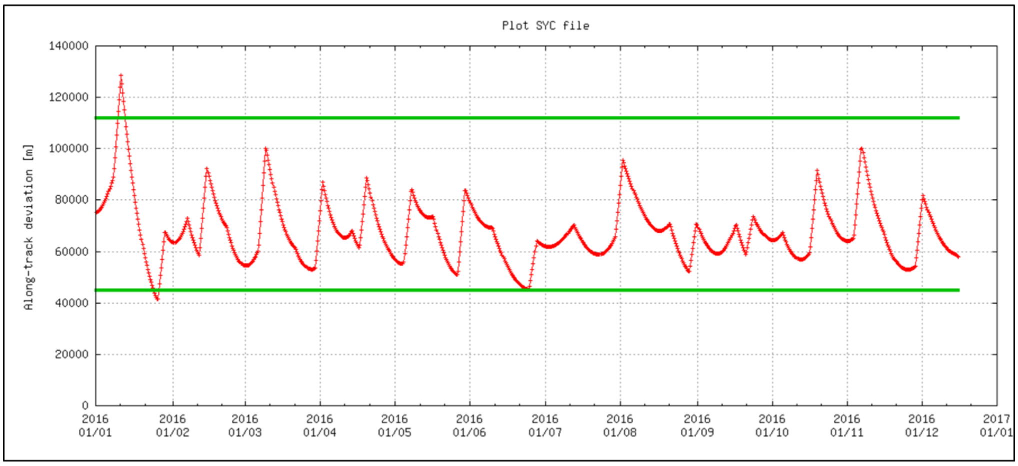

Fig. 11: Simulation 1: 3 days delay, 0.5 ratio, high solar activity

The second simulation shows the effect of reducing the time delay between the manoeuvres of both satellites. The same hypothesis were assumed, but the time delay was set to 2 days. In general, as expected, the achieved control is better, within a bit more than 3 seconds. Again the two first exclusions of the dead-band are an artefact. The exclusion towards the end of the simulation is due to the execution of an out of plane manoeuvre too close to the needed in-plane. When an out of plane manoeuvre is performed by Sentinel-3, FLEX mimics it after a certain time delay, later a slot is reserved to correct the parasitic in-plane component of the out of plane manoeuvres, therefore FLEX is prevented to perform formation manoeuvres for a certain interval. In this simulation this rule created a no realistic situation.

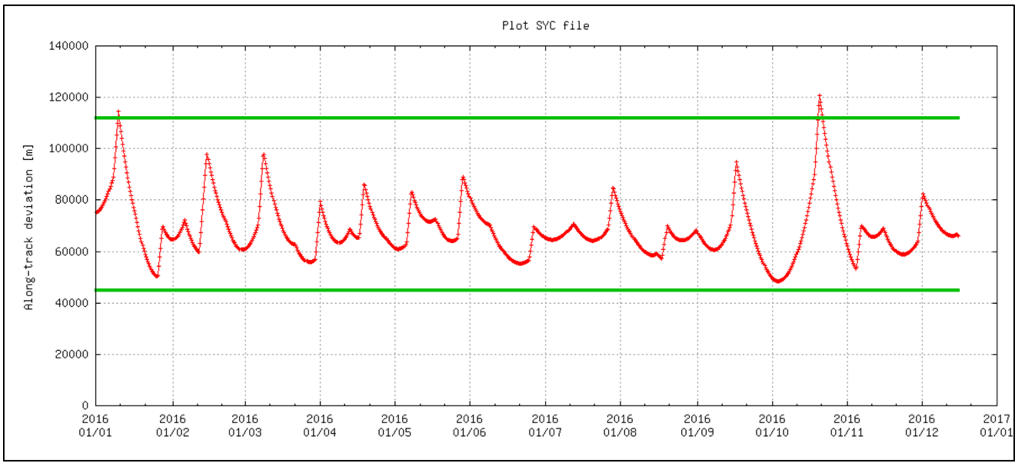

Fig. 12: Simulation 2: 2 days delay, 0.5 ratio, high solar activity

Finally a more favourable scenario is run by the simulator. The time delay is set to 2 days, the ballistic ratio to 0.7 and a medium solar activity is considered. The results are illustrated by Fig. 13. The achieved along-track control is within 3 seconds, even at the beginning of the mission where the initial conditions are not optimised. The most remarkable outcome of this simulation is that during some control cycles the formation manoeuvre is skipped. This demonstrates the adaptability of the control, optimizing not only the along-track distance stability but also the operational simplicity. It can also be observed that is some cycles the maximum shift in the along-track distance is not given by the delay between Sentinel-3 and FLEX manoeuvre, but by the relative drift during the cycle. Currently the formation manoeuvres aim to reduce the altitude difference at the moment of Sentinel-3 manoeuvre, but introducing formation manoeuvres to keep the maximum shift due to the different drift rates within a certain boundaries it tough to improve the control.

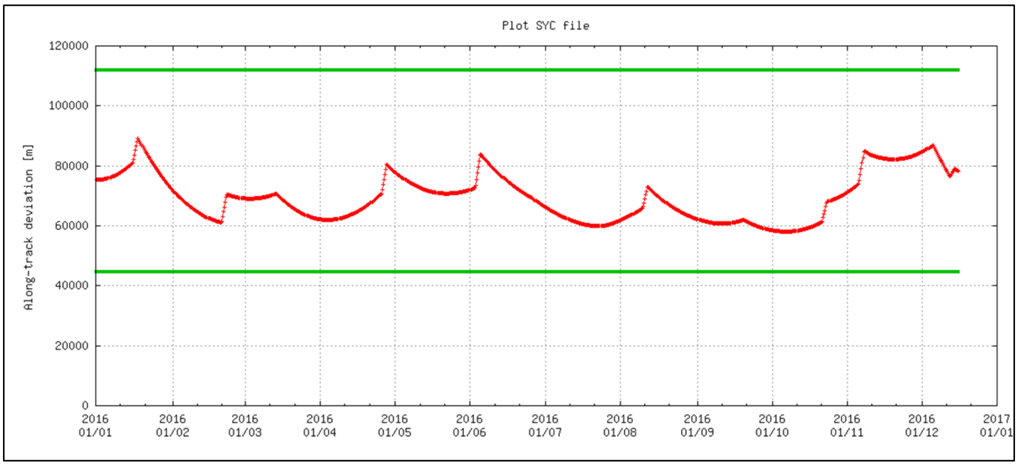

Fig. 13: Simulation 3: 2 days delay, 0.7 ratio, medium solar activity

Next Steps

After the promising results of the performed simulations, the next step is to optimize the selection of T2 for the execution of FLEX formation manoeuvre. Studding the benefit of additional formation manoeuvres will be also part of this progress.

The simulator shall enhanced to consider manoeuvre mis-performances and de-pointing. Special attention will be paid to the effect of the parasitic in plane component of out of plane manoeuvres, and its correction.

On top of Senintel-3 simulated data, it is also foreseeing to run simulations during the time it has been flown with historical Sentinel-3 control.

Finally the tandem control shall be proven safe under any failure. Scenarios with Sentinel-3 and FLEX long safe modes will be analysed and simulated. Also collision avoidance manoeuvres situations will be addressed.

Conclusions

Scheduled for launch in 2023, FLEX mission is currently in phase B2. At this stage of the mission there are still many uncertainties, therefore the proposed orbit control shall be able to work under a wide range of scenarios.

When defining the orbit control strategy safety have been the highest priority, while keeping FLEX operations as simple as possible. In addition, the proposed concept avoids any disturbance on the Sentinel-3 nominal orbit control.

The most simple and straightforward approach coordinated control box strategy, similar to the A-train concept. It has been demonstrated that it is a feasible and safe solution; however, the distance between both satellites, although within the requirements, varies more than what it would be optimal for its scientific goals, that is the reason why a more challenging master-slave was analysed.

Reducing this along-track shift while maintaining a safe constellation has been the key objective in the final proposed strategy. The analysis has shown the improvement when introducing formation FLEX manoeuvres, especially for the cases in which the ratio between the ballistic coefficients is low, reducing significantly the variation in the along-track distance to values of 3 to 5 seconds.

The analysis are still in an early phase, but the preliminary results are promising and the roadmap for the following steps to optimize the tandem control are clear.

References

1. FLEX Earth Explorer 8 Mission Requirements Document, MRD. EOP-SM/2221/MDr-md, 2.0

2. Angelita C. Kelly, Warren F. Case. “Implementation lessons learn from the A-train”

3. David Arnas, Pedro Jose Jurado Lozano, Itziar Barat, Berthyl Duesmann, Ralf Bock4. “FLEX: A parametric study of its tandem formation with Senitnel-3”. IGARSS-20018, Valencia, Spain.