SAOCOM-CS:
Flight Dynamics operational approach to a highly demanding formation

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The concept of a passive receiving small satellite flying in formation with an active satellite for bistatic Synthetic Aperture Radar (SAR) imaging has been the subject of numerous international studies. In 2013, ESA received an offer from the National Commission for Space Activities of Argentina (CONAE) to collaborate with SAOCOM mission (L-band SAR). Following this offer, ESA defined SAOCOM-CS as a passive-receive-only satellite flying in formation with the SAOCOM–1a/-1b satellite and capturing SAOCOM radar echoes reflected from Earth’s surface. The combined mission supports multiple science objectives by varying the relative in-orbit positions of SAOCOM-CS satellite with respect to SAOCOM-1a/-1b. The current paper gives an overview of the formation flying design and safety concept of SAOCOM-CS mission. Having two spacecraft in close formation, the key principle of the mission shall be safety. Other important drivers for the mission design are to keep a simple operational concept and to optimize the delta-v while enhancing the scientific return.
The mission development has been halted due to budgetary constraints after successful completion of Phase B2 in April 2017.

Key Words: Saocom-CS, Formation flying, bi-static SAR

1. Introduction

The concept of a passive receiving small satellite flying in formation with an active satellite for bistatic Synthetic Aperture Radar (SAR) imaging has been the subject of numerous international studies. In 2013, ESA received an offer from the National Commission for Space Activities of Argentina (CONAE) to collaborate with SAOCOM mission (L-band SAR). Following this offer, ESA defined SAOCOM-CS as a passive-receive-only satellite flying in formation with the SAOCOM–1a/-1b satellite and capturing SAOCOM radar echoes reflected from Earth’s surface. The combined mission supports multiple science objectives by varying the relative in-orbit positions of SAOCOM-CS satellite with respect to SAOCOM-1a/-1b. These include four specific geometries:

1. Tomographic Geometry which is defined by short baselines (Fig. 1 green box).
2. Along-Track Bistatic geometry which is defined by large along-track displacements and small across-track baselines (Fig. 1 orange box).
3. Perpendicular Bistatic geometry with is defined by both large along-track and across-track baselines (Fig.1 purple box).
4. Specular geometry in which the companion satellite views the illuminated scene from the specular direction (Fig. 1blue box).

Each of the four geometries (see Fig 1) results in unique imaging and information extraction capabilities, which relate to different application fields.

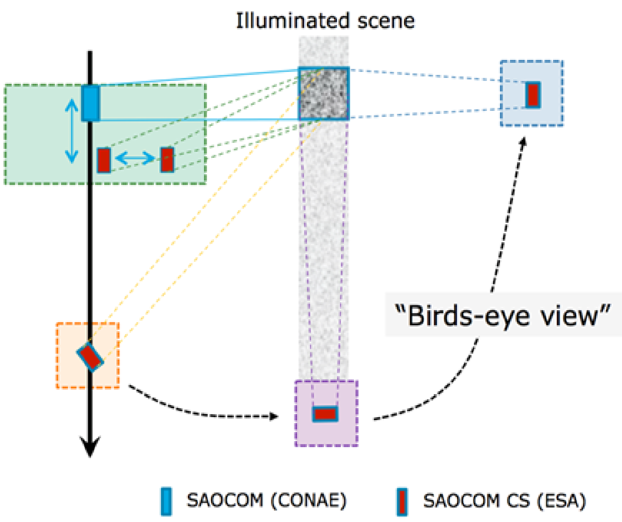

Figure 1 SAOCOM-CS different geometries

The current paper gives an overview of the formation flying design and safety concept of SAOCOM-CS mission. Having two spacecraft in close formation, the key principle of the mission shall be safety. Other important drivers for the mission design are to keep a simple operational concept and to optimize the delta-v while enhancing the scientific return.

Due to the short duration of the phase B2 still several analysis need to be performed. However for the most challenging part of the mission, that is the along-track baseline control during the tomographic phase, detailed analysis and simulations have been performed, proving the feasibility of a SAOCOM-CS formation flying concept and control safe and robust while optimizing the scientific requirements.

During the tomographic phase SAOCOM-CS will fly ahead SAOCOM with an along-track distance between 5 km to 7 km. On top of that a changing across-track drift is imposed by the science requirements. The formation needs to be inherently safe, such that if the orbit control of either spacecraft is lost, the uncontrolled evolution of the relative along-track distance should not lead to a major collision risk. Moreover none of the orbit control maintenance manoeuvres during this phase shall pose a major risk. The orbit control strategy of SAOCOM-CS consists not only of small in-plane manoeuvres to maintain the along-track distance, but also of larger semi-major axis corrections to replicate the SAOCOM drag compensation manoeuvres, coordinated collision avoidance manoeuvres and, in order to achieve the across-track drift, out-of-plane manoeuvres that are typically two orders of magnitude larger than the maintenance in-plane manoeuvres. All this while minimising the formation break-up duration. Taking into consideration that the two satellites are controlled from two different Mission Control Centres, each located on a different continent, it becomes clear that coordination of operations will play an essential role for the success of the SAOCOM-CS Mission.

The other phases of the Mission are not exempt from challenges, the transition between the different geometries of the mission, including the initial orbit acquisition, shall optimize the delta-v consumption and comply with the timeline and the stringent geometry requirements to fulfil the scientific objectives. The paper also describes the current approach to resolve them.

2. Challenges, Orbit Acquisition

2.1 Orbit Acquisition

SAOCOM-CS will fly in the same orbit as SAOCOM and Cosmo-SkyMed satellites, and with a relative position with respect to SAOCOM as explained previously.

Operational Reference Orbit	
Sun-synchronous & Frozen Eccentricity	
MLST asc. Node	06:12h
Repeat Cycle	16 days / 237 orbits

The first challenge the mission encounters is already the acquisition of the formation geometry. For the Tomographic phase requirements the along-track distance shall be controlled between 5 km to 7 km, while the across-track baseline shall be able to swap a dead-band up to ±12km.

The required different along-track baselines can be easily achieved just by changing the semi-major axis which will induce an along track drift. Actually, in order to optimize the delta-v, a different semi-major axis will be targeted at launch, so an initial drift is obtained for free, and propellant is used only to stop it. However, achieving the desired across-track baseline is more challenging, the tight requirements on the along and across-track baselines determine the orbital plane difference between both satellites and leave no margin for deviations.

To derive a general case, it will be assumed that SAOCOM-CS is launched in a separate launch from the SAOCOM s/c targeted as master s/c. In this sense the injection errors and orbit acquisition strategy of both satellites are detached. This represents the most challenging scenario in terms of delta-v, as SAOCOM-CS will have to correct its initial Mean Local Solar Time (MLST) to achieve the desired geometry with respect to SAOCOM.

The first error to be corrected is the launch dispersion on the targeted orbital plane. Typical error values that can be found on launcher user manuals are in the order of 25 seconds. However the client can request the launcher authority to tighten the MLST accuracy. For both Sentinel-2B and Sentinel-3B a tighter MLST has been agreed for respectively the VEGA and ROCKOT launcher. This tightening in the accuracy allows to correct the MLST error either directly or by means of inclination bias with an affordable delta-v and in a reasonable time.

The second error to be corrected is the MLST drift induced by the inclination launch dispersion. In order to minimize the effect of this drift, SAOCOM-CS shall be ready to perform out-of-plane maneuvers early in the mission. It is expected the first manoeuvre is feasible within the first week after launch, constraining this drift to a few seconds, eventually setting the required MLST drift towards the final MLST.

Finally along-track drift needs to be stopped at the right moment. While SAOCOM-CS is drifting towards SAOCOM, it is in an orbit with a lower/higher semi-major axis, and the sun-synchronicity is lost, causing a drift on the orbital plane. One possible solution would be to bias accordingly the inclination in order to maintain the sun-synchronicity, but in order to save delta-v a different solution is proposed.

In first order approximation, it can be demonstrated that the MLST drift depends only on the drifted angle in argument of latitude. To give an example, if both satellites are separated initially 120 degrees in argument of latitude, and SAOCOM-CS drifts to the position of the master SAOCOM, the final MLST is independent on how the approach is done. It doesn't depend on the number, size and time of the performed maneuvers, only of the drifted argument of latitude angle. Therefore we have determined the relation between the initial angle between both satellites and the drifted MLST. For SAOCOM-CS it is in the order of 40 second per 360 degrees drifted argument of latitude.

On the order hand, the initial position between both satellites is only determined by the launch day and it repeats every 16 days, i.e. the repeat cycle.

Performing this analysis that takes into account the target semi-major axis bias, its accuracy and all the operation constrains, a robust orbit acquisition plan can be defined for each launch day, so the total drifted angle in true latitude is known a priory. Then biasing the targeted MLST accordingly and depending on the launch day, the final desired MLST is achieved. This has been successfully implemented for the Sentinel-2B launch, arriving at the final orbit position with an MLST error of 1 second in just a few weeks from launch.

Many of the above orbit acquisition concepts have been conceived for the entry into the A-train constellation (see Ref. (1)), but needs to be implemented with a much tighter requirements

It has been said previously that there are no margins on the deviation of the initial difference on the orbital planes, as the along-track and across-track baselines are controlled very tight. However certain margin can be attained when considering the temporal dimension. The across-track baseline is not constant but drifting from -12km to +12 km and back. There is certain freedom in the initial position (-12km, 0km and +12km) and in the initial drift direction (both directions in case starting at zero baseline), resulting in four possible initial scenarios. That is, after launch and knowing all the launcher dispersions, four slightly different MLST can be targeted depending which one is the most beneficial scenario.

After considering all the injection errors, the possibility to select a MLST depending on the launch day and the small freedom on the final MLST selection, it can be concluded that the desired geometry between both satellites can be achieved minimizing the impact on the delta-v budget.

2.2 Tomographic Phase, obtaining the across-track drift

In the tomographic phase two different kind of forest are targeted, boreal forest, covering a latitude range from 50 deg to 70 deg north, and tropical forest, covering a latitue range from 25deg south to 25 deg north.

The same location will be scanned every 16 days with a different across track baseline between Saocom and Saocom-CS. All the observation are done in the descending part of the orbit and specific requirements to the across track baselines are made according to the canopy height. Requirements are set regarding the spacing between two acquisitions, the minimum baseline and the maximum baseline, as outlined in figure 2. The spacing can’t be too large so as to capture the behaviour of the function. The smallest baseline acquisition can’t be too large, and the largest baseline can’t be too small, so that the beginning and end of the function are not missed.

The final requirements on these three characteristics are shown in table 1. These requirements are different for different swaths because of their difference in incidence angle. They differ in the different phases because of the different latitudes of interest and because the average canopy height.

Finally there is a temporal restriction, the boreal forest shall be sampled from May to October, when the trees have leaves and the chance of snow is minimum.

It needs to be noted the difference between across track distance and baseline. This difference is based on the Earth rotation and is therefore also dependent on latitude. The baseline of the acqiusition at a certain latitude is based on three components: the difference in MLST, the difference in inclination (MLST drift) and the yaw difference from inertial

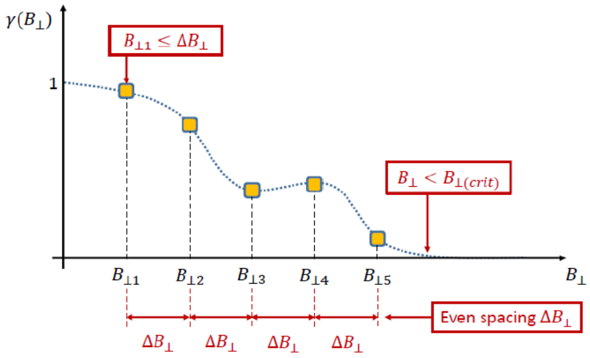

Figure 2 Restrictions set on across track baselines, based on the sampling theorem, from M. Azcueta, S. Tebaldini, Politecnico di Milano.

	Boreal	Tropical			
	DP1 & DP2	DP1	DP2	QP1	QP2
Spacing	< 600	< 680	< 820	< 530	< 600
Min Baseline	< 1,200	< 680	< 820	< 530	< 600
Max Baseline	> 3,200	> 5,500	> 6,700	> 4,300	> 4,900

Table. 1. Tomographic Phase: Across track baselines requirements

velocity to Earth Fixed velocity.

It was found in Ref. 2 that to fullfill all the requirements several out of plane manouvres to initiate and control the desired across-track drift were necessary. Furthermore, the size of the these manouvres was orders of magnitude bigger than the in-plane ones needed to control the along-track distance. This posed a risk for both satellites, as any small in-plane parasitic component of the out-of-plane manouvre may intiate an along-track dirft towards SAOCOM. In order to mitigate any potential risk the formation will be broken before the out-of-plane manouvres, SAOCOM-CS will increase the distance with respect to SAOCOM, perform the manouvre and will recover the formation. During this period science is interrupted, and therefore the amount of out-of-plane manouvres shall be minimized.

Several trade-offs were done in order to derive a control that simplify operations while maximize science resturn without compromising the safety of the mission. All the trade-off considered six months of acquistions over tropical areas followed by six months over boreal ones.

Because of the explained relationship of across track baselines with latitude and drift rate, the transition at zero baseline needs to be from boreal towards tropical in order to

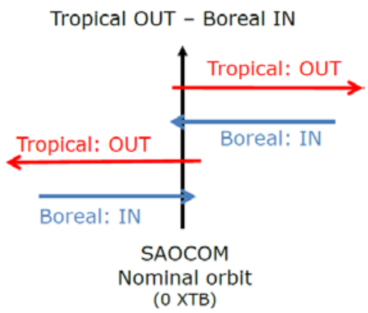

Figure 3 Drift direction optimised for observation area

have an overlap on the small baselines, as depicted in Fig. 3. If the other option is considered, a gap would be created and small baselines would be missed.

The requirements specify different drift rates for tropical and boreal phases. If the drift is to be adjusted between boreal and tropical phases, an out of plane manoeuvre would need to be performed in a moment of zero across track distance. This would imply a possible break in the formation and a loss of small baseline acquisitions. This is therefore to be ignored, and the same drift is suggested for both phases.

This way, out-of-plane manoeuvres are solely performed in the transition from tropical to boreal scans, when across track baselines are the largest.

The proposed scenario (see Fig. 4) consists of four phases of 11 cycles each. Tropical areas are scanned from small baselines to larger ones and boreal forests from larger baselines to smaller ones. The MLST drift rate is the same for tropical and boreal phases.

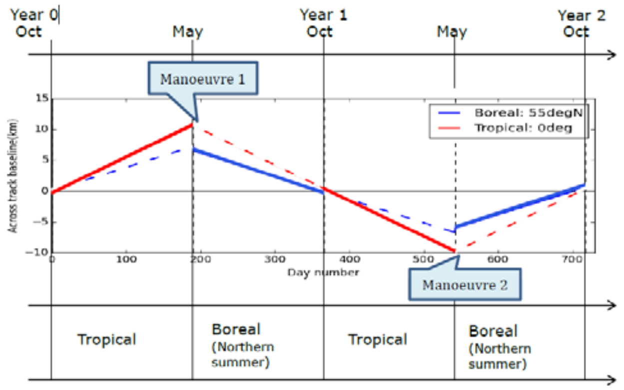

Figure 4 Two years of Tomographic Phase

Two out of plane manoeuvres shall be performed. These are in the transition from tropical to boreal scans. These manoeuvres imply a delta v of 1.01m/s per manoeuvre. Because each cycle has 16 days, this means the whole scenario requires 704 days. To complete the timeline in two years, this leaves 26 days for the two manoeuvres to be done at the extremes.

The boreal requirements were prioritised over tropical requirements and are therefore fulfilled. The requirements for tropical are not perfectly met, resulting in a higher spacing than ideal. The original plan for 2 years Tomographic phase required large out-of-plane manoeuvres every 6 months, of about the double size, plus out-of-plane manoeuvres increasing the drift rate during each 6 months measurement phase. The optimised plan requires therefore 4x less delta-v to implement the tomographic phase, having these smaller out-of-plane manoeuvres when the across track is maximum and allowing 26 days to recover the along track phasing.

3. Orbit Control concept, Tomographic Phase

A detailed orbit control concept has been analysed in Ref. 3. This orbit control concept has been devised for the demanding tomographic phase, using the following assumpions:

3.1. SAOCOM assumptions

It is assumed that SAOCOM orbit will be controlled around a reference ground-track by means of the execution of two types of manoeuvres:

- In-plane manoeuvres: to control the perpendicular ground-track deviation with respect to the reference at the equator crossings and the evolution of the eccentricity vector. The manoeuvres are assumed to be performed with single burns selecting the argument of latitude that achieves a change in eccentricity vector in the direction of the frozen eccentricity.
- Out-of-plane manoeuvres: to control the perpendicular ground-track deviation with respect to the reference at high latitudes and the evolution of the MSLT. The manoeuvres are assumed to be performed at the ascending node crossing.

A ground-track control band at the Equator and maximum latitude of ± 1.0 km has been assumed, in order to derive the expected SAOCOM orbit maintenance manoeuvres frequency and sizes.

The assumed SAOCOM S/C parameters and Reference Orbit features are summarized in the table 2.

Spacecraft Parameters	
S/C Mass	3000 kg
Equivalent drag area	6.0 m^2
Cd	2.2
SRP area	6.0 m^2
SRP coefficient	1.5

Table. 2. SAOCOM Spacecraft parameters

3.2 SAOCOM-CS assumptions

Spacecraft Parameters

In the analysis three different sets of values for the S/C mass, drag area and Cd coefficient have been assumed for SAOCOM-CS, see table 3. Every set leads to a different relative ballistic coefficient between the two satellites. The relative ballistic coefficient is defined as

$$Relative\ B^* = \frac{B^*_{SAOCOM-CS}}{B^*_{SAOCOM}}$$

$$B^* = \frac{\text{Mass}}{\text{Cd} * \text{Area}}$$

Relative B*	0.3	0.5	0.7
S/C Mass (kg)	350	377	450
Equivalent drag area (m^2)	1.8	1.4	1.3
Cd	2.8	2.2	2.0
SRP area (m^2)	1.8		
SRP coefficient	1.5		

Table. 3. Saocom-CS Spacecraft parameter sets

Control target

The orbit control target is to maintain the along-track separation with respect to SAOCOM between 5.0 and 7.0 km at all SAOCOM-CS orbit locations. The along-track distance is computed on the SAOCOM's inertial orbit local reference frame. A positive along-track component of the distance means ahead of SAOCOM's position (in the flight direction). Because the SAOCOM-CS ballistic coefficient is lower than the SAOCOM one, the effect of the atmospheric drag on SAOCOM-CS leads to a faster semi-major axis decay, which increases the along-track separation with respect to SAOCOM.

The execution of nominal maintenance manoeuvres on SAOCOM aims mostly at increasing the semi-major axis to compensate the decay introduced by the atmospheric drag. A SAOCOM semi-major axis increase leads to an orbital period increase and consequently an increase of the SAOCOM-CS along-track separation with respect to SAOCOM.

The SAOCOM-CS orbit control is achieved by executing in-plane manoeuvres to control the along-track separation with respect to SAOCOM and to control the evolution of the relative eccentricity vector between the two S/C. It is assumed that no relative navigation data is available as input to the orbit control functionality.

Propulsion system

The SAOCOM-CS propulsion system is composed of four 1-N thrusters. The following worst case expected thruster performance is assumed: Performance error is to be modelled as a Gaussian distribution with the following 3–sigma levels:

- 5% in delta-v magnitude
- 1.0 deg in delta-v direction

However, manoeuvre performance errors ranging from nominal to ±20% in magnitude and 1.5 deg in pointing have been considered in order to investigate the limits of the Orbit Control concept for different control-band sizes

Initial orbit determination errors

The SAOCOM-CS orbit control S/W propagates initial state vectors of SAOCOM and SAOCOM-CS. Any error in these initial state vectors will be propagated over the optimization/uplink cycle causing a deviation of the expected along-track distance between the two S/C. It is therefore important to quantify this error and decide whether it should be included or neglected in the overall analysis.

During Routine operations the initial SAOCOM and SAOCOM-CS state vectors will be taken from the orbits determined by ESOC FD. These orbit determinations will be based on the GPS data of both S/C received at ESOC FD. The accuracy of the orbit determination performed by ESOC FD has been assessed. The assessment consisted in comparing the archived orbit determination performed by the ESOC FD Team against the archived orbit determination performed by the Precise Orbit Determination (POD) Team for three different ESA Earth bounded missions: Sentinel-1A, Sentinel-2A and Cryosat-2.

The Cryosat-2 orbit determination performed by the FD team is based on radiometric data (ranging and Doppler measurements from a high latitude ground station). The comparison has been however included in this report since at the time of writing it is not known whether SAOCOM-CS will be carrying an S-band transponder or not. Should that be the case the SAOCOM-CS orbit determination could be performed based on radiometric data during periods of GPS outage.

The comparison has been performed in one day segments, ignoring segments in both archived orbits that were flagged as invalid (due to outage of GPS data, issues with the orbit determination process, etc). Therefore the results can be directly interpreted as the along-track prediction error per day to be expected in the ESOC FD predictions due to the initial state vector determination error.

Mission	Period	Along-track difference		
		RMS	1- σ	3-σ
Sentinel 1A	Jan-15 Jun-16	1.6 m	1.5 m	6.1 m
Sentinel 2A	Dec-15 Jun-16	1.4 m	1.5 m	5.9 m
Cryosat 2	Jun-10 May-16	6.2 m	6.0 m	24.2 m

Table. 4. ESA POD archived orbit vs. ESOC FD archived orbit determination. Comparison summary

As it can be seen in Table 4, the expected growing along-track error due to the error in the determined initial semi-major axis for these three missions is less than 25 m per day at 3-sigma level. Results are slightly worse for the Cryosat-2 comparison due to the fact that FD determines the Cryosat-2 orbit using radiometric data instead of GPS measurements.

In view of these results, it was concluded that the contribution of the orbit determination errors to the overall orbit prediction error analysis can be considered negligible.

3.3 Approach to the analysis

The purpose of the analysis is to propose a feasible FD orbit control strategy for SAOCOM-CS based on the assumption presented. The expected high maintenance manoeuvre frequency justifies the adaptation of the Sentinel-1 Orbit Control S/W into a SAOCOM-CS Orbit Control S/W prototype.

The analysis aims at finding suitable values for:

- The number of manoeuvre optimization/uplink cycles per week. Between two manoeuvre optimization/uplink cycles no update to the maintenance manoeuvres is performed, neither in size nor in execution time
- The number of orbit control manoeuvres per week, which are executed on fixed days at a configurable time window
- The definition of a criterion to trigger an SAOCOM-CS evasion manoeuvre or CAM

The selection of these orbit control parameters is driven not only by the feasibility of the orbit control strategy but also by the complexity of the FD Orbit Control System (in term of operations automation and interfaces) which should be minimized.

The number of orbit control manoeuvres required per week to achieve the orbit control is mainly driven by the along-track control band width and the level of solar and geomagnetic activity, whereas the required number of manoeuvre optimization/uplink cycles per week is driven by the expected ESOC FD orbit prediction errors for SAOCOM and SAOCOM-CS. Additionally the execution of maintenance manoeuvres by SAOCOM has to be followed by the execution of a SAOCOM-CS maintenance manoeuvre, so that the along-track distance does not drift apart.

The analysis has been performed in two steps:

- Step-1: analysis of the ESOC FD orbit predictions accuracy and typical SAOCOM-CS control cycle duration in absence of SAOCOM maintenance manoeuvres.
- Step-2: high fidelity, long-term numerical simulations employing the SAOCOM-CS Orbit Control S/W prototype configured based on the results obtained in Step-1.

Step-1 is a first contact with the orbit control most relevant aspects in order to understand the various factors which contribute to the FD orbit predictions inaccuracy: to get a first estimation of the frequency and size of the SAOCOM-CS maintenance manoeuvres and to get information about the expected relative along-track drift rates under different solar activity regimes and expected manoeuvre performance errors. These rates are used to decide on a CAM triggering criterion. Step-2 incorporates the execution of SAOCOM maintenance manoeuvres and demonstrates the validity of the selected orbit control setup derived in Step-1 by means of long term numerical simulations based on the SAOCOM-CS Orbit Control S/W prototype. The orbit control setup is stretched in order to derive limit figures for the propulsion system performance.

3.4. Step 1: Single propagation propagation

The optimization of SAOCOM-CS manoeuvres is affected by the problem of predicting the orbit for LEO satellites. The two main contributors to the orbit prediction errors that are going to be addressed in the analysis are the prediction of the atmospheric drag force that is going to be encountered by the two S/C's and the SAOCOM-CS manoeuvre performance errors.

As already mentioned before, SAOCOM-CS maintenance manoeuvres aim mainly at compensating the effect of the drag force. The manoeuvre optimization relies on the orbit predictions available on the day the optimization takes place. These predictions are impacted by the unreliable prediction of the atmospheric drag force encountered during the prediction period due to the poor predictability of solar and geomagnetic activity.

A fundamental parameter to compute the drag force is the atmospheric density. The model used by ESOC FD 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.

The selected first approach to investigate the required manoeuvre execution and manoeuvre optimization frequency for SAOCOM-CS is simply to reproduce the conditions of unpredictability of the solar and geomagnetic indexes.

This manoeuvre optimization exercise is repeated for different scenarios representing different levels of solar and geomagnetic activity that SAOCOM-CS might encounter throughout its mission lifetime. The analysis is also repeated for the three different assumed relative ballistic coefficients mentioned in table 3,

The way the analysis is conducted can be now summarized more in detail. For every reference atmospheric environment (meaning low, medium, high solar activity regime) the following steps are carried out:

Step1: Run an orbit maintenance manoeuvre optimization using the nominal profile as predicted solar activity for that optimization cycle

Step2: Propagate the optimized manoeuvre using the other two profiles (+) and (-). The maximum expected error in the solar predictions is this way limited to the values presented in Table 5.

Step3: Check the differences in the evolution of the along-track inter-satellite distance between the propagations in step1 and step2. Derive relevant information like maximum and minimum duration of the control cycles, typical maintenance manoeuvre size, etc.

Scenario	Daily F10.7	Mean F10.7	Daily Ap
Low (-)	55	65 - 0.1 / day	0
Low	65	65, constant	0
Low (+)	75	65 + 0.1 / day	5
Medium (-)	120	140 – 0.2/day	7
Medium	140	140, constant	15
Medium (+)	160	140 + 0.2/day	23
High (-)	200	250 – 0.5/day	15
High	250	250, constant	25
High (+)	300	250 + 0.5/day	35, 100 (1st day)

Table. 5. Description of the Solar and Geomagnetic profiles used to performed single propagations

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3.5 Results

The initial state vector of SAOCOM-CS has been adjusted at the beginning of every scenario, depending on the relative ballistic coefficient and the level of solar activity in order to reach the upper limit of the along-track control band at the time of the manoeuvre execution when assuming the nominal solar activity profile.

As already mentioned, in this step of the analysis the SAOCOM orbit maintenance manoeuvres are not taken into account, therefore the selected initial along-track drift rates (or initial semi-major axis difference between SAOCOM and SAOCOM-CS) represent only those cases where no SAOCOM maintenance manoeuvre has taken place. When that is the case the initial along-track drift rate can become much larger and it will be subject of study in the second step of the analysis (see Section 3.7).

A 24 hour period between manoeuvre optimization and manoeuvre execution is assumed. In particular the elapsed time between manoeuvre optimization and execution impacts the prediction of the along-track distance at the time of the manoeuvre execution.

Even though the relevant information to the design of the SAOCOM-CS orbit control functionality is contained in the low and medium solar activity scenarios, the high solar activity scenario results are also included for the sake of completeness.

3.5.1 Low Solar Activity Scenario

The plot shown in Figure 5 includes simultaneously the results for the three relative ballistic coefficients. The evolution of the along-track distance between the two S/C as predicted on the day of the manoeuvre optimization is represented with green lines (different line type for every relative ballistic coefficient). Blue and red lines show the evolution of the along-track separation between the two S/C in case the solar activity is respectively lower or higher than predicted.

The increasing along-track distance variation within orbital revolution (that can be perceived in these plots as the increase in apparent thickness of the lines representing the evolution of the along-track distance) is due to the change in eccentricity vector imparted by the SAOCOM-CS simulated manoeuvre. The relevant information extracted from the single propagation analysis has been summarized in Table 6.

Relative B*	0.3	0.5	0.7
Delta-v (mm/s)	2.7	1.8	1.3
Nominal control cycle duration (days)	14	24	40
Shorter cycle duration (days)	10	18	24
Longer cycle duration (days)	18	28	48
Lower control band limit violation after (days)	6	9	15
Minimum along track distance (km)	4.6	4.7	4.7

Table. 6. Single propagation analysis results in the low solar activity scenario

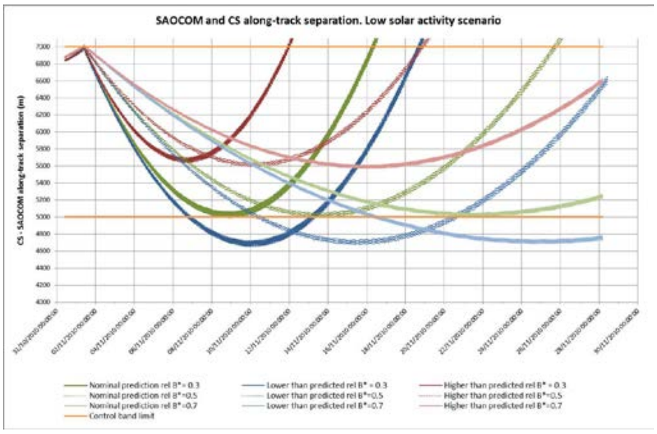

Figure 5. Along-track separation evolution at low level of solar activity after propagation of a single manoeuvre.

3.5.2 Medium Solar Activity Scenario

Figure 6 includes again simultaneously the results for the three relative ballistic coefficients.

As in the low solar activity case, the executed manoeuvre introduces a change in the SAOCOM-CS eccentricity vector. Before the manoeuvre execution the eccentricity vector difference between the two S/C is negligible. After the manoeuvre the variation of along-track distance within an orbit, due to the difference in eccentricity between the two S/C is noticeable (amplitude of the wobbling which is superimposed to the parabolic behaviour of the along-track distance between the two S/C). This effect already indicates the need to perform a control on the evolution of the eccentricity difference as part of the SAOCOM-CS orbit control.

The relevant information extracted from the single propagation analysis has been summarized in Table 7.

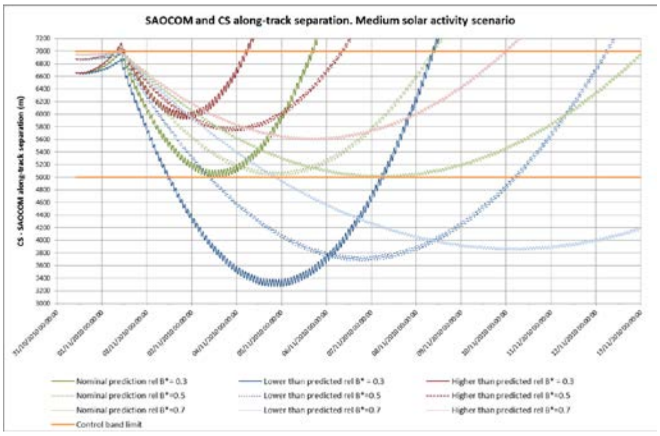

Figure 6. Along-track separation evolution at medium level of solar activity after propagation of a single manoeuvre.

Relative B*	0.3	0.5	0.7
Delta-v (mm/s)	9.9	5.4	3.0
Nominal control cycle duration (days)	4.0	7.0	11.5
Shorter cycle duration (days)	2.5	5.0	8.5
Longer cycle duration (days)	7.0	10.5	17.0
Lower control band limit violation (days)	1.0	2.0	3.5
Minimum along track distance (km)	3.3	3.7	3.9

Table. 7. Single propagation analysis results in the medium solar activity scenario

3.5.3 High Solar Activity Scenario

The results for this scenario have been included in the analysis for the sake of completion. The SAOCOM-CS Mission will most likely not encounter these high levels of solar activity for the intended Mission lifetime.

The main conclusion form this scenario is that if short along-track separation was required during periods of high solar activity like the ones used in this analysis, manoeuvre optimization/uplink and execution would be required every day, and even in that case it is not likely that the formation can be controlled in the assumed [5.0, 7.0] km control-band in a stable fashion. A control-band increase would be recommendable if that measure is compatible with the Mission science return. Table 8 includes again simultaneously the results for the three relative ballistic coefficients.

Relative B’	0.3	0.5	0.7
Delta-v (mm/s)	32.8	16.8	8.8
Nominal controlcycle duration (days)	1.5	3.0	4.5
Shorter cycle duration (days)	0.0	1.5	3.0
Longer cycle duration (days)	3.0	4.5	7.0
Lower control band limit (days)	<0.5	0.5	1.0
Minimum along track distance (km)	1.9	3.0	3.5

Table. 8. Single propagation analysis results in the high solar activity scenario

3.6 Medium Solar activity with Manoeuvre Performance Errors Scenario

Manoeuvre performance errors of 5%, 10%, 15% and 20% have been applied for the Medium solar activity scenario and taking into account only the worst case for the relative ballistic coefficient of 0.3.

The manoeuvre performance errors have been applied in a way that their impact on the along-track prediction error does not compensate but increment the error due to the solar activity prediction errors. In other words, positive manoeuvre performance errors have been applied only to the case where the real solar activity turned out to be lower than predicted on the day of the manoeuvre optimization. In such scenario SAOCOM-CS drifts closer and faster towards SAOCOM than predicted not only because the optimized manoeuvre was too large for the actual drag force encountered by the two S/C but also because the executed manoeuvre was larger than originally commanded. Similarly, negative manoeuvre performance errors have been applied only to the case where the real solar activity turned out to be higher than predicted on the day of the manoeuvre optimization. In this case SAOCOM-CS drifts more slowly towards SAOCOM and does not reach a position as close to SAOCOM as predicted. This scenario has been used to derive a first suggestion for the minimum safety along-track distance that should trigger the execution of a CAM on SAOCOM-CS. The decision whether to perform a CAM or not should in principle not depend only on the two S/C relative along-track separation, but also on the along-track drift rate at the time the decision is taken. It is however operationally desirable to have a clear and unambiguous trigger a CAM procedure.

In the scenario the strongest along-track drift rate of SAOCOM-CS towards SAOCOM is represented. This corresponds to the case where a 9.9 mm/s manoeuvre has been optimized to maintain the constellation and that control manoeuvre over-performs by 20%. In this case the total semi-major axis change achieved is

$$9.9 * 1.2 \frac{mm}{s} * 1.857 * \frac{\frac{m}{mm}}{s} = 22.1m$$

Which translates to a change in SAOCOM-CS orbital period of

$$22.1\, m * 1.249\ 10^{-3} \frac{s}{m} = 0.028\, s$$

Taking 7.544 km/s as reference velocity this change in orbital period can be translated into an along-track drift rate of

$$0.028\, s * 7.544 \frac{km}{s} = 0.208 \frac{km}{revolution}$$

At this drift rate the along-track distance between the two S/C changes 3 km approximately in 24 hours. Considering 24 hours a sufficiently large time span to implement and execute a CAM and taking the along-track drift rate of 0.2 km/orbit as an upper bound of the possible drift rates that will be encountered during medium solar activity phases, 3 km is a good candidate to place the CAM threshold. Moreover, looking back in Table 6 and Table 7 one can see that the minimum along-track separation between SAOCOM-CS and SAOCOM never reaches 3 km in neither the low nor the medium solar activity scenarios.

3.7. Step 2: Long term numerical simulations

The adaptation of the Sentinel-1 Orbit Control S/W described in the previous sections has been used in the second step of the analysis. An Orbit Control Simulator, which invokes the Orbit Control S/W, has been configured with the results listed in the conclusions of step 1 of the analysis:

- Two manoeuvre slots per week
- Two manoeuvre optimization/uplink cycles per week
- Safety along-track distance to trigger CAM execution set to 3 km

Different simulations were performed. The execution of these simulations led to the fix of several simulator issues and the following relevant findings.

- Confirmation that a manoeuvre optimization/uplink frequency of once per week is valid to achieve the orbit control during low levels of solar activity but needs to be augmented to two per week as the solar activity becomes more unsettled.
- The execution of SAOCOM in-plane maintenance manoeuvres introduces a strong along-track drift in the formation, which depending on the size of the manoeuvre can result on drift rates between 2.0 and 10.0 km per day.
- For periods of medium solar activity the orbit control can be achieved by either:
  - o executing SAOCOM-CS orbit control manoeuvres shortly after the execution of every SAOCOM manoeuvre. This implies the execution of additional manoeuvres with respect to the manoeuvre frequency stated in the first bullet
  - o or by taking into consideration a relaxation of the along-track control band to [5.0 – 10.0] km

3.8. SAOCOM-CS Mirror Manoeuvres Analysis

The results presented in the previous section regarding the evolution of the along-track distance after the execution of a SAOCOM maintenance manoeuvre did motivate the execution of further orbit control simulations, applying the suggestions to achieve the orbit control mentioned there, namely:

- Execution of SAOCOM-CS orbit control manoeuvres shortly after the execution of every SAOCOM manoeuvre.
- Relaxation of the along-track control band to [5.0 – 10.0] km

The drivers for the selection of the mirror manoeuvre approach are constellations safety constraints and operational complexity.

3.8.1 Ideal Mirror Manoeuvre Implementation Approach

The main assumptions to these simulations are summarized in the list below:

- Fixed SAOCOM manoeuvre execution window assumed
- Number of manoeuvre optimization cycles / week: 2
  - o A manoeuvre optimization cycle always scheduled one day before the execution of a SAOCOM maintenance manoeuvre
- Number of manoeuvre slots / week: 3
  - o A manoeuvre execution slot is planned 3 hours after the execution of the SAOCOM maintenance manoeuvre
- Mirror manoeuvre approach: full replication of the SAOCOM manoeuvre size three hours after the planned execution of the SAOCOM manoeuvre.
- Level of solar activity corresponding to the medium scenario.

A total of four simulations were run assuming different relative ballistic coefficients and manoeuvre performance errors. The results confirm the correct implementation of the mirror manoeuvre replication function on the simulator. Additionally it goes in the direction of confirming the recommendations to achieve the orbit control mentioned in section 3.6 (during periods of medium solar activity).

Figure 7 shows simulation results for an assumed manoeuvre performance error 1.7% in magnitude and 0.5 deg in pointing at 1 sigma level. The orbit control is achieved for a control band of [5.0 – 7.0] km with marginal violations for a relative ballistic coefficient of 0.5. For a relative ballistic coefficient of 0.3 larger and more frequent violations occur during periods of unsettled solar activity.

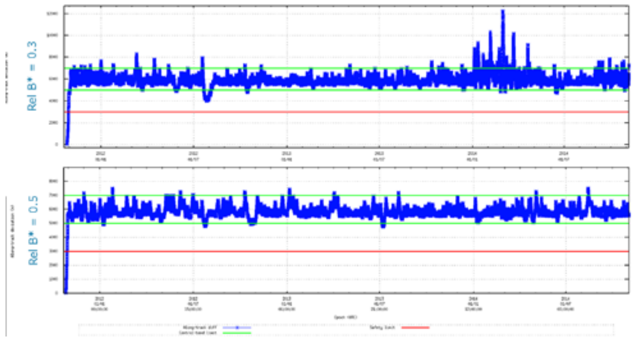

Figure 7. Mirror manoeuvre long orbit control simulation results for two different relative ballistic coefficients: 0.3 (top) and 0.5 (down). Manoeuvre performance error 1.7% in magnitude and 0.5 deg in pointing at 1 sigma level.

Figure 8. Mirror manoeuvre long orbit control simulation results for two different relative ballistic coefficients: 0.3 (top) and 0.5 (down). Manoeuvre performance error 5% in magnitude and 1.5 deg in pointing at 1 sigma level.

Figure 8 shows simulation results for an assumed manoeuvre performance error 5.0% in magnitude and 1.5 deg in pointing at 1 sigma level. The orbit control for a control band of [5.0 – 7.0] km is achieved only for a relative ballistic coefficient of 0.5 with marginal violations. For a relative ballistic coefficient of 0.3 the control is achieved for an augmented control band [5.0 – 10.0] km.

3.9 Manoeuvre simulations applying constellation safety and operational margins

The mirror manoeuvre approach described in the previous chapter relies on the implementation of SAOCOM-CS mirror manoeuvres without allocating a realistic time margin to assess the SAOCOM manoeuvre performance error, optimize and uplink the corresponding SAOCOM-CS mirror manoeuvre.

In another round of simulations the replication of the SAOCOM manoeuvre size was replaced by a manoeuvre optimization based on the evolution of the SAOCOM trajectory after a manoeuvre calibration process. This is possible only if enough time is allocated for FD to perform an SAOCOM orbit determination and a SAOCOM-CS mirror manoeuvre optimization. In particular this implies the following operational steps:

1. SAOCOM manoeuvre execution must be followed by a SAOCOM ground contact for reception of GPS TM and preparation of the GPS data interface file.
2. SAOCOM GPS data is forwarded to ESOC-FD.
3. FD processes the GPS data and performs a SAOCOM orbit determination for manoeuvre calibration.
4. FD optimizes the SAOCOM-CS mirror manoeuvre based on the SAOCOM calibrated manoeuvre and prepares and sends a manoeuvre request.
5. A manoeuvre command is generated and uplinked to SAOCOM-CS at the next S/C contact opportunity. A backup unlink opportunity is required.

12 hours is considered the minimum time to conduct this sequence of operations. Simulations show that then an along-track control band of [5.0 – 7.0] km is not feasible.

Simulations have been run or a augmented control band of [5.0 – 10.0] km showing good results.

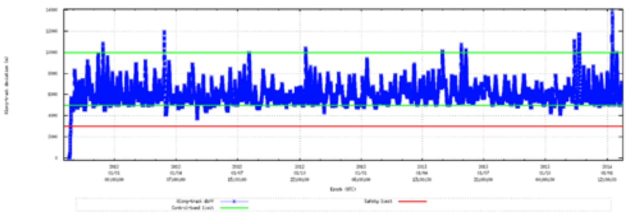

Figure 9. Mirror manoeuvres simulation results. Mirror manoeuvres performed 7 to 12 hours after SAOCOM manoeuvres. Performance error 3.3% in magnitude and 1.0 deg in pointing at 1σ. Rel.B* = 0.3. medium solar activity.

4. Conclusion

An orbit acquisition plan has been designed allowing the acquisition of the required orbital plane when arriving at the along track distance to support the tomographic phase.

The tomographic phase has been optimised, while reducing the required delta-v, and enhancing the scientific results.

In this study, the current assumed SAOCOM-CS Mission launch date at the end of 2019 implies that the short along-track distance orbit control phases will most probably occur during low to medium levels of solar and geomagnetic activity. Consequently the results of the scenarios low and medium solar activity are the ones driving the selection of the Orbit Control parameters:

1. During low levels of solar activity one maintenance manoeuvre per week is enough to keep the along-track distance within the [5.0 – 7.0] km control band. For medium levels of solar activity at least two maintenance manoeuvres per week are required.
2. The number of manoeuvre optimization/uplink cycles depends on the uncertainties in the FD orbit predictions for both SAOCOM and SAOCOM-CS. Looking at the medium solar activity scenario it is noted that predicting the solar activity for a week can lead to along-track errors of up to 1.5 km. These errors become even larger when introducing manoeuvre performance errors. During periods of low solar activity one manoeuvre optimization/uplink cycle per week shall be enough, but this frequency will have to be augmented as the solar activity rises.
3. Based on the largest observed drift rate in the medium solar activity scenario and assuming 24 hours as a reasonable response time to implement and execute a CAM on SAOCOM-CS, the safety threshold to trigger the execution of a CAM on SAOCOM-CS has been set to 3 km. Here CAM refers to a special SAOCOM-CS orbit control manoeuvre to increase the along-track separation between the two S/C if a given along-track threshold is reached.
4. Mirror manoeuvres shall be performed by Saocom-CS within 8 - 12 hours, based on calibrated manoueevres condicted by Saocom.

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