An innovative operations concept for close formation flight: the ESA CompSAR case study

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The CompSAR mission study took place in ESA concurrent design facility for the assessment design of a Passive SAR on a Small Companion Satellite flying in formation with Sentinel-1 with the goal of measuring costal currents using the back-scattered signal of the active instrument. The study highlighted the operational risks and challenges associated with close, lose formation flight. Three major areas of trade off were identified: Orbit Determination and Reconstitution, Data Downlink and TT&C scenario, and Formation Flight strategy. While for the first two areas the mapping of mission requirements to available technologies and infrastructures permits to identify adequate solutions, for the Formation Flight, a further level of analysis is required, detailing the choices for general navigation strategy implementation, nominal formation maintenance, and contingency handling. Although operational solutions for the nominal scenario are straightforward if not simple, the non-nominal scenarios bring about the fundamental problem of a possible collision risk in a relatively short delay. A careful choice of the mission geometry can provide risk mitigation, but, especially for the contingency scenarios, innovative operational strategies need be devised. To this end, three measures are identified as greatly beneficial to relax safety related constraints and increase the scientific return by simply enabling robust and safe formation flight: ad-hoc design of orbit formation configuration, on-board relative navigation, and increased ground visibility (and commandability).

I. Introduction

THE interest of using more spacecraft's to fulfill a mission objective is now widely recognised ([1], [2], [3]), and proved by the actual return obtained by missions of this type in operations (eg ERS-2/ENVISAT, Swarm, Cluster II) . The concept has been applied successfully to various types of mission, from navigation, to communications, to Earth (but not only) observation missions.

The ESA Concurrent Design Facility (CDF) has been used to provide an assessment design of a Passive SAR on a Small Companion Satellite, flying in formation with Sentinel-1 and receiving the back-scattering signal of the active instrument (i.e. the Sentinel-1 SAR).

Studies by CNES and ASI ([4], [5]) have already proposed to use (small) satellites flying in formation with a conventional (large) SAR and carrying a passive SAR antenna to receive the backscattered signal, adequate to perform single pass interferometry. ESA has been investigating formation flying issues and similar SAR

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applications. CompSAR, by using the concurrent design facility of ESA, was the first attempt to give a realistic assessment of the feasibility of this type of mission, covering all aspect of the mission implementation, from the technical challenges in designing the spacecraft, to the cost involved, the ground segment and more specifically (and object of this paper) the operational implications.

II. Some Principles of Formation Flight

Three different types of formation flight can be distinguished: constellation, formation, and loose formation. They can be characterised as follows:

Constellation:
- Adoption of a specific orbit relationship between the satellites
- The miss-distance between the spacecrafts (s/c) is above a specific threshold such that the impact on s/c and ground segment design is in general negligible
- Typical examples are Sentinels 1/2/3 series (EO), Iridium (Communication), GPS/Galileo (Navigation)

Formation:
- Adoption of a specific relative position (and eventually attitude) relationship by the satellites
- The miss-distance between the s/c is below a specific threshold such that the impact on s/c and ground segment cannot be disregarded since it represents one of the main design drivers
- Typical examples are TERRASAR/TANDEM-X (EO), Cluster (Space environment)

Loose-Formation:
- Adoption of a specific orbit and/or relative position relationship by the satellites
- The miss-distance between the s/c is kept above a minimum threshold such that the impact on s/c and ground segment is minimised
- From a spacecraft design perspective, the satellites are 'un-cooperative', i.e. there is no need for a metrology or data exchange system between the spacecrafts
- From a programmatic perspective, the development and operations of the various satellites does not require necessarily a strict coordination
- Typical example are Sentinel-5 Precursor and NPOESS (NOAA), SWARM (all EO)

For the last two categories, the relative instantaneous distance between the spacecraft composing the formation is at the same time the very enabler for the fulfillment of the mission goal and one of the principal risk factor, thus resulting in a major driver for mission design (orbit control), spacecraft architecture (FDIR, AOCS), and the ground segment and operations. It is evident that, when very small distances between the spacecrafts are required (close formation), the impact of this factor becomes paramount.

From the operations perspective, it is evident that the close and loose formations (i.e. uncooperative spacecraft) are the most challenging cases, both for the fact that the mission goal depends on the accuracy of the relative positions of the spacecrafts involved, and for the possibility, in case of an anomaly, of a collision threat.

III. The CompSAR Mission Study

A. Mission definition and drivers

The CompSAR mission study took place in ESA concurrent design facility in 2011, bringing together ESA experts in the different fields involved for a synergic effort at providing a preliminary assessment and design of the mission proposed, highlighting the most important challenges for its possible implementation.

The main goal of the CompSAR mission (study) is to assess the feasibility of a passive C-band SAR satellite, flying in formation with Sentinel-1, and receiving back-scattering signal from the active instrument, for estimation of coastal currents velocity;

The main design drivers identified are:
- Distance between satellites (baseline) shall be low enough to guarantee required performances

- Formation flying configuration and operational strategy shall minimise collision risks, mission cost and complexity, coping with performances requirements
- SAR antenna shall be as simple and compact as possible

Of these drivers, only the first two have a direct impact on the operations concept.

In terms of mission analysis, the main requirement comes from the scientific objectives: it prescribes boundaries on the distance between Sentinel-1 and CompSAR:
- Along-track: the distance shall be greater than 150 m and lower than 400 m
- Across-track: the maximum distance shall be less than 300 m

As a consequence the formation configuration will have to comply with these stringent requirements.

Furthermore, there is a list of requirements following the non-cooperative nature of the Sentinel-1/CompSAR formation concept:
- It is desirable to minimise the impact of CompSAR presence on Sentinel-1 operations: in the optimistic case, Sentinel-1 will not have to perform any manoeuvre related to CompSAR, e.g. formation keeping or escape manoeuvres.
- It is not planned to have a direct communication or measurement link between Sentinel-1 and CompSAR: every exchange of information will have to go through the ground (e.g. application of a manoeuvre or GPS measurements).
- There is no on-board autonomy in terms of manoeuvre application.

B. The CompSAR Orbit

The orbit of CompSAR is roughly that of Sentinel-1:
- Altitude: 693 km
- Inclination: Sun-synchronous
- Local time of the ascending node: 18:00 hours (dawn-dusk)

Given that, with the identified characteristics of the CompSAR spacecraft, the ballistic coefficient of Sentinel-1 is roughly 0.6 times that of CompSAR (196 kg/m2), in order to achieve a configuration where both satellite naturally drift apart from each other, CompSAR will be located behind Sentinel-1. This is illustrated in figure 1, showing the evolution of the relative motion between CompSAR and Sentinel-1 (Sentinel-1 is the origin of the frame).

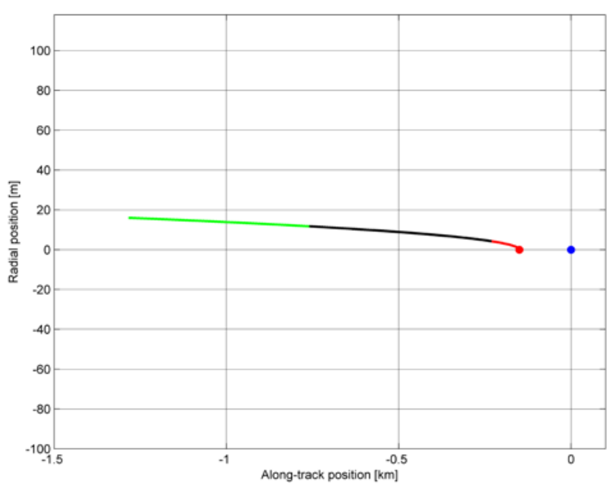

Figure 1: Illustration of the natural drift between CompSAR and Sentinel-1

The natural evolution shows a drift away from the initial intersatellite distance of 150 m. This drift depends on the solar activity, e.g. after one day with a strong solar activity, the intersatellite distance has reached 1.3 km.

IV. Formation Geometry

With respect to formation geometry, of the possible designs (baseline, pendulum, in-plane ellipse and helix), only the baseline and the helix were kept for evaluation.

For the baseline configuration, the orbital parameters of CompSAR are all equal to that of Sentinel-1, except for the argument of latitude $u = \omega + v$. Assuming a as Sentinel-1 semi major axis, the distance between both satellites is $a\Delta u$.

With this configuration there is no motion in any of the three directions of the local orbital frame radial-alongtrack-crosstrack (under Keplerian motion assumption).

The helix configuration is defined with help of eccentricity (e) and inclination (i) vectors deviations. The angle between $\Delta\bar{e}$ and $\Delta\bar{i}$ is a free parameter.

The eccentricity vector deviation will generate an elliptic in-plane motion. The inclination vector deviation will generate an across-track pulsation (with $a\|\Delta\bar{i}\|$ amplitude).

The in-plane and out-of-plane projections (fig. 2) for the case where the eccentricity and inclination vectors are parallel show that, in case of along-track drift, the separation is guaranteed by the out-of-plane separation.

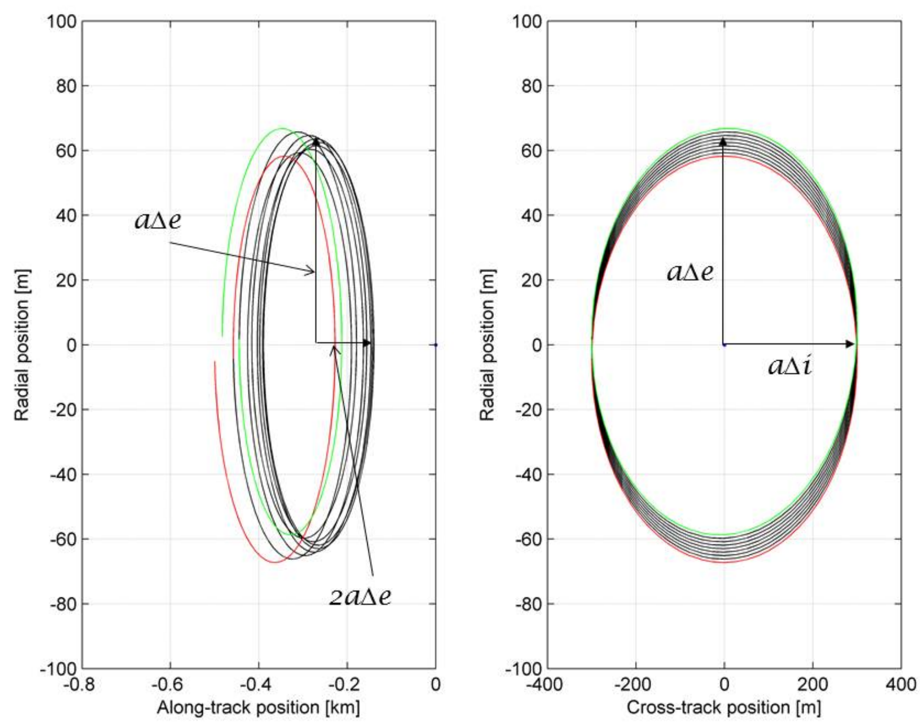

Figure 2. Helix configuration with parallel eccentricity and inclination vectors deviations: in-plane projection (left) and out-of-plane projection (right). Relative motion over a cycle for the perturbed motion

Because of the difference in the ballistic coefficients, regular formation keeping manoeuvres will be necessary on CompSAR. During a cycle between two manoeuvres, due to orbital perturbations, the ellipse will librate around a central location.

It is obvious that the in-plane elliptic motion is not advantageous to satisfy the scientific requirements in terms of distance. With the baseline configuration the along-track separation remains constant. Thus, from a scientific point of view, the baseline configuration is preferred to the helix configuration.

However the selection shall take also into consideration the robustness of a configuration with respect to the collision risk. As illustrated above (fig. 1), in case the safe mode occurs on Sentinel-1, its ballistic coefficient will decreases, thus increasing even more the difference with CompSAR: both spacecraft will drift apart even faster than in nominal operations. But the opposite will happen in case of safe mode occurring on CompSAR.

In this scenario of CompSAR entering safe mode, in case of the baseline configuration, the collision risk (ie the satellite miss-distance) reaches a critical threshold after one day (or even critically less in case of high solar activity, 7.5 hours). Every time CompSAR will enter a safe mode, a collision avoidance (escape) manoeuvre will be needed on Sentinel-1. Operationally this approach is not robust and thus not acceptable.

Simulations of the same case, with the helix configuration, demonstrate that there is always an out-of-plane separation, whose minimum is the radial amplitude. This separation decreases the collision risk in case of safe mode on CompSAR (see also section VIII-C below).

This justifies the selection of the helix configuration is kept although slightly less optimize with respect the scientific objectives.

V. CompSAR Operations Characterisation

A. Operations Requirements

The high level requirements for the CompSAR mission operations can easily be derived from the mission statement to satisfy the prime mission goal, and from the technical constraints dictated by the corresponding mission context.

The top level operations requirements can be summarised as follows:

1. The CompSAR GS shall ensure very precise off-line Orbit reconstitution in support of data processing
    - Precision Orbit Determination (POD) with performances in the order of cms
    - Goal: inter-satellite position determination with an accuracy of mms
2. The impact of CompSAR mission on Sentinel-1 Operations shall be minimised
    - In nominal flight situation, in terms of ground operations execution
    - In anomalous/contingency scenarios, in terms both of in-flight induced risk and of on-ground contingency handling complexity
3. The Ground Segment architecture shall ensure the complete downlink of the scientific data, expected to average (baseline) 385 GB/orbit

C. Operations Design Drivers

Given the requirements above, and the missions architecture presented above, the most important design driver is to ensure operability and safety in all flight conditions.

The safety aspect, in light of the close formation flight with Sentinal 1, translates into the reduction and proper mitigation of the induced (collision) risk in case of non-nominal situations.

The required minimisation of potential collision risk between CompSAR and Sentinal 1, translates into the optimisation of the interactions between Sentinel-1 and CompSAR Ground Segments.

Further design drivers are identified in the optimisation of the ground segment development and routine cost, which translates into the reuse of existing infrastructure and the minimisation of the need for ground operator intervention during CompSAR routine phase.

VI. Operations Assumptions and Trade-Offs

Some basic assumptions had to be made in the study:

- CompSAR spacecraft design is consistent with standard ESA EO missions Operations Interface Requirement Document (e.g. ECSS PUS compliant, adequate TM/TC buffers, autonomy/FDIR as per Sentinels)
- Sentinel 1 spacecraft is un-cooperative, i.e. there is no on-board autonomy in support of formation flight. All coordination for the flight formation must be done by either using Sentinel-1 as a passive target (in-flight measurement), or via the ground segment.
- The CompSAR operator is not necessarily the same as Sentinel-1

Based on these assumptions, three major areas of trade offs are identified:

- Orbit Determination and Reconstitution
- Data Downlink and TT&C scenario
- Formation Flight strategy

While for the first two areas the analysis of the available technologies and infrastructures permit to identify the more adequate solutions, for the Formation Flight, a further level of analysis is required, detailing the choices for general navigation strategy implementation, nominal formation maintenance, and contingency handling. The paragraphs below present the results of the analysis for these trade-offs.

A. Orbit Determination & Reconstitution

Orbit determination and reconstitution is of paramount importance for the CompSAR mission. In this area, the choice is driven by the availability and accuracy of the different systems implemented, and applicable given the spacecraft architecture (AOCS sensors).

The Sentinel-1 Ground Segment features a POD function that allows achieving accuracy in the order of cm. A specific requirement for the mission ground segment states that:

"The S1 PDGS shall be able to generate precise POD orbit data with accuracy better than 5 cm on all 3 axes for off-line processing"

It is safe to assume that, for CompSAR, the same level of accuracy can be reached based on use of the same or similar POD service.

In relation to inter-satellite position determination, an accuracy in the order of millimeters is requested as a goal in support of data processing.

To this end, known close formation missions have been analysed to verify the achieved inter-satellite position determination accuracy. In particular, a relevant mission from the orbit design point of view can be found in the TANDEM-X and TERRASAR formation operated by DLR-GSOC.

It shall be noted that, for TANDEM-X and TERRASAR the POD service achieves accuracies of 5-10 cm (3D, RMS) by processing the data from the on-board GPS receivers (IGOR dual freq./Mosaic GNSS)

Within the same missions, for the satellite relative positioning accuracy, ad-hoc studies ([6], [7]) claim that relative orbit accuracies of 1-2 mm (3D, RMS) can be achieved based on two GPS based independent solutions. These exhibit a representative agreement at the 3-4 mm level including systematic biases of 1-2 mm and a standard deviation of 0.5-1.5 mm in the individual axis. It must be noted that these measurement are complemented by laser ranging measurement via a laser reflector on-board TANDEM-X.

It can thus be concluded that inter-satellite position accuracies in the order of millimeters can achieved by specific off-line navigation data processing.

B. Data Downlink and TT&C

For the downlink of the scientific data via X-band, as well as TT&C contacts, in addition to the classical option of S and X band ground station passes, the formation flight offers the opportunity of coordinating the X-band passes with the leading Sentinel-1 spacecraft.

In the CompSAR mission scenario, a mechanism to downlink the measurement data of CompSAR in 'coordination' with Sentinel-1 has indeed been chosen. As a matter of fact, due to the proximity of the two satellites (global miss distance inferior to 1.5 km), the ground visibility is the same, thus same X-band passes over the same stations are possible.

This is also ideal for the scientific return, as with the data downlinked over the same X-band station it can be processed and distributed in Near Real Time.

In addition to this, use of the same X-band station potentially reduces complexity and cost

This scenario is actually possible with the use of new Cortex Receiver at the X-band ground station, with polarisations separation that avoids signal interference.

In this solution, the average of 385 GB/orbit of data generation does not pose any problem for the download (it is less than the Sentinel 1 data downlink requirement).

For the TT&C Handling, assuming as baseline an S-band TT&C system, two daily TT&C passes are considered adequate to cover routine phase as per Sentinels.

In conclusions, the use of the same X-band station and simultaneous data downlink is possible by small updates of the ground stations receivers, and a traditional S-band TT&C system with 2 daily passes in routine phase is considered adequate.

C. Formation Flight

While for orbit determination and data downlink the technical solution is rather straightforward, a more detailed trade-off is necessary to determine the solution for formation flight control.

As an important element for the following discussion, it must be noted here that although the impact on Sentinel-1 mission is to be minimised, an interface with the Sentinel-1 Ground Segment is needed, at least to cope in a coordinated way with possible contingency situations.

1. Navigation

The first architectural decision regards the possibility to have on-board autonomous or ground based navigation, and is summarised in table 1 below.

Table 1.Formation Flight: trade-off for navigation architecture

Option	Pros	Cons	Decision point / comments
On-board Autonomous	Short Reaction time Limited impact on CompSAR work-time	Not demonstrated On-board complexity Higher initial cost	Necessary risk mitigation translates into need for ground based back-up, thus offsetting benefits
Ground based	Proven orbit maintenance algorithms Simple AOCS/CPS Simple FDIR	Longer reaction time Impact on Sentinel-1 Operations Workload on FOS	Risk due to reaction time mitigated by the specific orbit design Hi-freq. planning necessary in any case to maintain formation

As apparent from the table, the solution chosen for CompSAR is to implement a ground based navigation system. As a matter of facts this solution minimises the impact both on the Sentinel-1 mission (both operations and flight segment), and on the complexity in the design of CompSAR. This conclusion is primarily due to the un-cooperative nature of Sentinel-1.

The impact on routine nominal operations of both Sentinel-1 and CompSAR is considered not significant with respect to introducing on-board autonomy given the level of maturity of the necessary technologies to implement the latter solution.

2. Formation Maintenance

Once established that navigation will be driven from ground, it is clear that a minimum level of interchange of information at planning level with the Sentinel-1 FOCC must be put in place. The knowledge of the Sentinel-1 orbit is necessary for the mission geometry to respect the (tight) requirements in terms of overall inter-satellite miss distance.

This implicitly requires that the orbital manoeuvres plan be known to the CompSAR FOS (FDS) to establish CompSAR own manoeuvre planning. With respect to this, a possible option is to manoeuvre independently from Sentinel-1 to maintain the formation (a-synchronous formation maintenance). An alternative strategy is to establish a synchronised manoeuvre plan, following the same plan of Sentinel-1, and adjusting (independently) for possible needed orbital corrections (synchronous manoeuvring).

The table below summarises the trade off for this decision.

Table 2. Formation Flight: trade-off for formation maintenance

Option	Pros	Cons	Decision point / comments
Asynchronous Manoeuvring	No impact on S1 ops Fully independent planning cycle	High risk of exiting along-track distance dead-band Risk of reducing Minimum Miss Distance (MMD) below collision threshold	Risk too high for scientific return
Synchronous manoeuvring	Better control of along track distance dead- band Reduced risk of Minimum Miss Distance (MMD) evolution	Impact on S1 Ops (minimal) S1 dependent planning cycle (Limited) risk of along-track dead-band violation after OCM	Impact tolerable (minimisation strategy) Hi-freq. planning necessary in any case to maintain formation

The analysis and simulations carried out show that the risk of breaching the limitation imposed for the scientific return on the inter-satellite distance are not acceptable for the asynchronous manoeuvring option. The solution retained is thus to have synchronous manoeuvring with Sentinel-1.

3. Formation Contingency Handling

An important trade off to be carried out regards the operational handling of possible contingencies. The options possible for contingency handling can be reduced, similarly to the nominal navigation execution, to on-board (autonomous) or ground based (FOS driven) handling. This latter is made available by the results obtained by the Mission Analysis study, and the careful choice of the helix orbit parameters presented above.

As reported in the table 3 below, summarising the trade off for this decision, the solution envisaged is to have ground based contingency handling.

Table 3. Formation Flight: trade-off for contingency handling

Option	Pros	Cons	Decision point / comments
On board Autonomy	Short reaction time Limited Impact on CompSAR Ops work-time	Not demonstrated On-board complexity	(High) Risk mitigation and technology maturity level impose ground based back-up May not be required thanks to helix orbit design fine-tuning
Ground Based	Proven orbit maintenance algorithms Simple AOCS/CPS	Longer reaction time Interface with S1 FOS	Risk due to reaction time is mitigated by helix orbit design Communication with S1 CC are necessary in any case

It must be stressed that this choice is considered feasible by the careful Helix orbit design, which avoids any collision risk for the vast majority of the potential failure scenarios. Thus ground intervention is required only for very specific scenarios which occurrence is deemed extremely unlikely. In these cases (where risk of collision could not be avoided by the specific orbit design), the time between contingency occurrence and reaching of the inter-satellite distance considered unsafe is long enough to permit the ground to react.

More details on the baseline operations approach to cope with the identified worst-case contingency scenarios will be given in the following sections.

VII. Baseline Operations Design

Thanks to the chosen strategy of re-using both the concept and the infrastructure made available by Sentinel-1, the Ground Segment architecture and Operations Concept for CompSAR are well established. More challenging, and specific to CompSAR, is the operational approach envisaged for formation flight maintenance and contingency handling. The following paragraphs explain the baseline retained for these elements.

A. Ground Segment Architecture

The chosen strategy for data downlink and TT&C contacts permits to design the CompSAR ground segment baseline following the very same approach as the Sentinels missions, with the breakdown of the Ground Segment into two main elements, namely the Flight Operations Segment (FOS) responsible for s/c monitoring and control, and the Payload Data Ground Segment (PDGS) responsible for measurement data reception, processing, distribution and archiving.

B. Operations Concept

Similarly to the GS, the CompSAR Operations concept baseline follows the same approach as the Sentinels, with spacecraft controllers shifts covering normal working hours 7 days a week, and on-site support available during normal working hours.

For the recorded HKTM downlink, the strategy is to use both the X-band (parallel use of GS with S1) and S-band (twice per day during nominal passes) links.

The Mission Planning cycle foresees a nominal daily generation of a 96 hours plan including the PDGS payload schedule, uplinked at the end of each working days (Mon-Fri)

C. Formation Maintenance Manoeuvring

As already introduced, the orbit manoeuvre plan of CompSAR mirrors the weekly manoeuvres plan, with daily evaluation of estimated orbit evolution with respect to the reference orbit (ground track deadband), envisaged for Sentinel-1.

The CompSAR orbit manoeuvre plan will be generated synchronously wrt the Sentinel-1 manoeuvre plan. To achieve the necessary coordination, the following Orbit maintenance approach is envisaged for CompSAR:

1. The Sentinel-1 CC communicates the manoeuvre plan to the CompSAR CC at least 24 hrs before the first manoeuvre execution

2. CompSAR CC computes a 'shadow' manoeuvre plan scheduling each manoeuvre to execute at approximately the same time of the corresponding S-1 manoeuvre

3. CompSAR CC also loads on-board an "escape manoeuvre" (designed to maintain a safe miss distance in the unlikely event of Sentinel-1 manoeuvre abort). Execution of this "escape manoeuvre" requires enabling by ground command

4. Within 24 hrs of each manoeuvre completion both S-1 CC and CompSAR CC determine the new orbit and the associated manoeuvre calibration

D. Impact of manoeuvre mis-calibrations

Normally a small (few %) difference between the planned and calibrated delta V is observed for each manoeuvre. For typical in-plane manoeuvers this error would have an impact on the nominal along-track formation baseline. This baseline is nominally controlled between 150 and 400 meters via the helix orbit configuration. A manoeuvre mis-calibration error would therefore affect this baseline which would evolve by few meters per orbit.

In this case, ad-hoc Operational Recovery measures shall be built into the operation planning strategy for CompSAR. To this end, any mis-calibration (under or over performance) affecting significantly the formation flight configuration will be corrected by CompSAR CC (and not Sentinel-1 to avoid disrupting this mission) by slightly adapting the next manoeuvre size (i.e. burn duration).

It must be noted that the potential impact on the data products of an inter-satellite distance smaller than the nominal thresholds, might be decreased by appropriate selection of the latitude at which the minimum and maximum along-track distance occurs with respect to the target latitude for observation (e.g. by placing these 2 points at the equator).

VIII. (Formation) Contingency Handling

An important exercise for the design of the operation of CompSAR is to baseline the policy for contingency handling. The mission analysis results permit to identify 4 scenarios in which a different application of ΔV to one only of the two satellites flying in formation (i.e. CompSAR and Sentinel-1) might cause important variations of the nominal inter-satellite (miss) distance.

The proposed operational baseline for these scenarios is reported in the following sub-sections.

A. Scenario 1: manoeuvre NOT executed by CompSAR

The first scenario sees a manoeuvre executed nominally by Sentinel-1, but not executed by CompSAR.

This scenario is, depending on the manoeuvre size, the most critical, as the two satellites start drifting towards each other. The minimum miss distance reached as well as the time to reach this distance is a function of the manoeuvre size.

A baseline minimum miss distance of 60 m is here assumed to be the starting distance at manoeuvre time.

In this case, the CompSAR CC will immediately inform the Sentinel-1 CC and:

EITHER:

- If needed → CompSAR CC will update the next manoeuvre burn to account for the baseline evolution between the satellites

OR:

- Sentinel-1 CC will perform a collision avoidance manoeuvre

It shall be noted that, based on previous experience on similar missions, this scenario is considered extremely unlikely (e.g. an autonomous manoeuvre abort has never occurred in ENVISAT)

The results of simulations, depicted in fig. 3 and fig. 4, have shown that the worst case of a 20 mm/s manoeuvre on Sentinel-1 (largest possible ΔV foreseen), the minimum miss distance is reached after less than one revolution and is ~20 m.

This value increases to a minimum separation of ~30 m reached after 1-2 hours when the manoeuvre size is 15 mm/s.

It is here reminded that a typical routine in-plane manoeuvre for Sentinel-1 is 10 mm/s, and that 30 m is assumed to be the collision critical distance.

Given the potential risk associated with this scenario, therefore, and imagining that CompSAR might not be able to perform any manoeuvre, it is considered necessary to prepare a collision avoidance escape manoeuvre on Sentinel-1.

For operations planning and execution the situation above translates into the need for very fast reaction time, with the following actions taking place in less than 1 hour:

- CompSAR CC awareness of manoeuvre non-execution, via corresponding TM response (ground station pass or inter-satellite TM link)
- Transmission to Sentinel-1 CC
- Uplink/execution of the escape manoeuvre on Sentinel-1

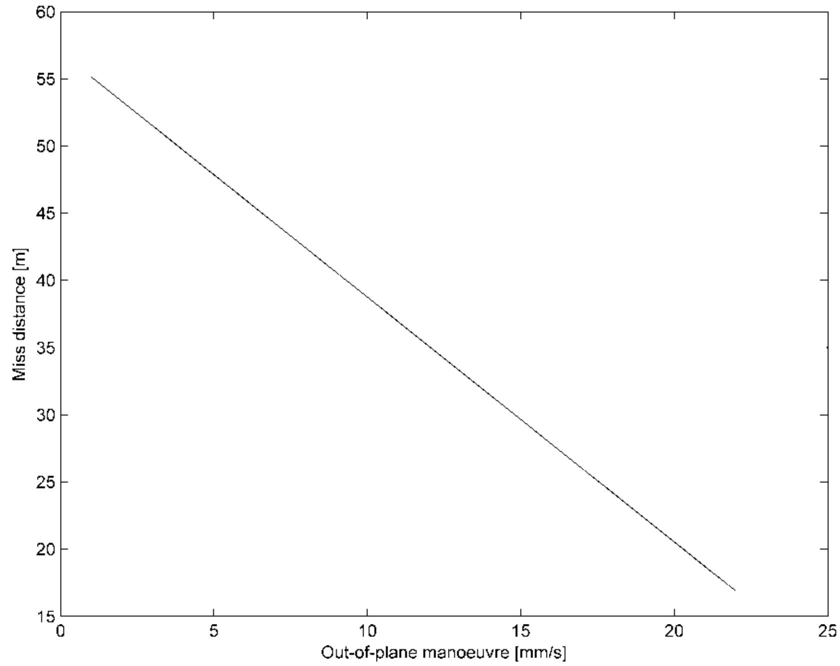

Figure 3. Evolution of the miss distance as a function of the in-plane manoeuvre size

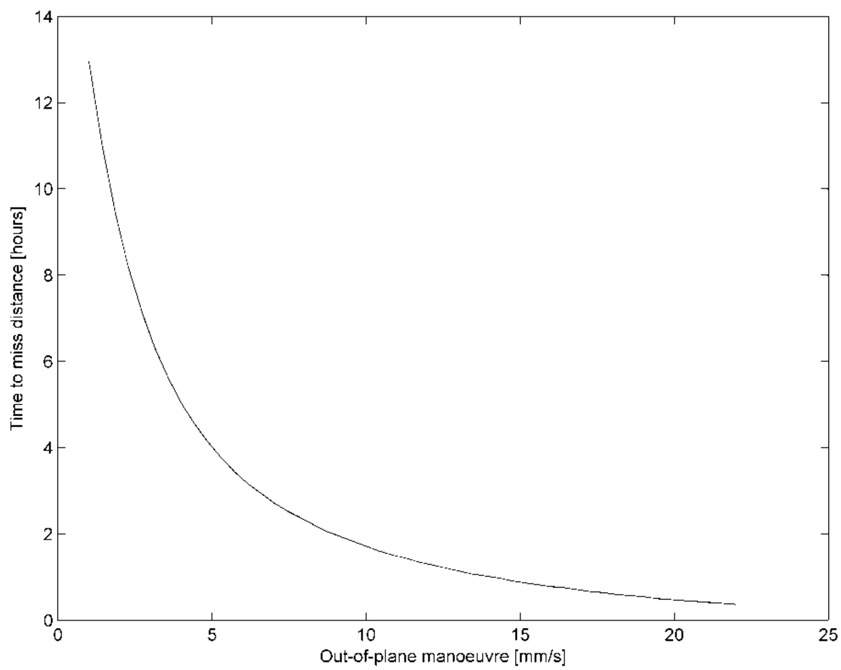

Figure 4. Time to reach the miss distance as a function of the in-plane manoeuvre size

It must be here recalled that this contingency case corresponds to an extremely unfavorable initial conditions, and is considered very unlikely.

B. Scenario 2: manoeuvre is NOT executed by Sentinel-1

In the event that CompSAR executes the orbit manoeuvre and Sentinel-1 does not (opposite case as the one encountered in scenario 1 above), the two satellites starts drifting apart. This is illustrated in figure 5.

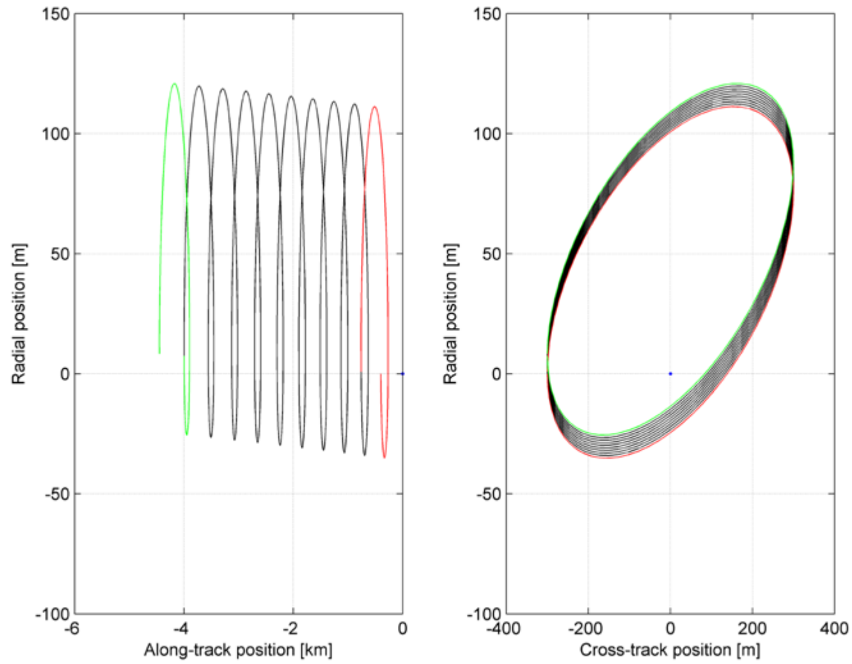

Figure 5: Evolution of the relative motion if the manoeuvre is not executed by Sentinel-1

However, the Sentinel-1 CC will immediately inform the CompSAR CC and:

- The CompSAR CC will send a command to enable the execution of the 'escape manoeuvre' (pre-loaded on-board) to maintain the miss-distance greater than the established minimum
- After proper Orbit Determination a formation re-acquisition manoeuvre will be planned and executed

C. Scenario 3: CompSAR switches to SAFE MODE:

In this third scenario, Sentinel-1 continues nominal operations, while CompSAR switches to safe mode. It is here assumed that safe mode makes the satellite passive with respect to orbit control (free evolution of the orbit subject to perturbations).

The ballistic coefficient of CompSAR decreases in case of a safe mode, and becomes smaller than that of Sentinel-1. The consequence is a drift of CompSAR towards Sentinel-1 as seen in figure 6. However, the formation helix orbit design ensures that the minimum radial distance (e.g. 30 meters) is not reached thanks to the cross-track separation (see above)

For operations purposes, the CompSAR CC will in any case immediately inform the Sentinel-1 CC in order to update the next planned manoeuvres to maintain the inter-satellites separation and avoid falling into the scenario 1 (critical) case, or increase it to account for the required recovery time on CompSAR if needed.

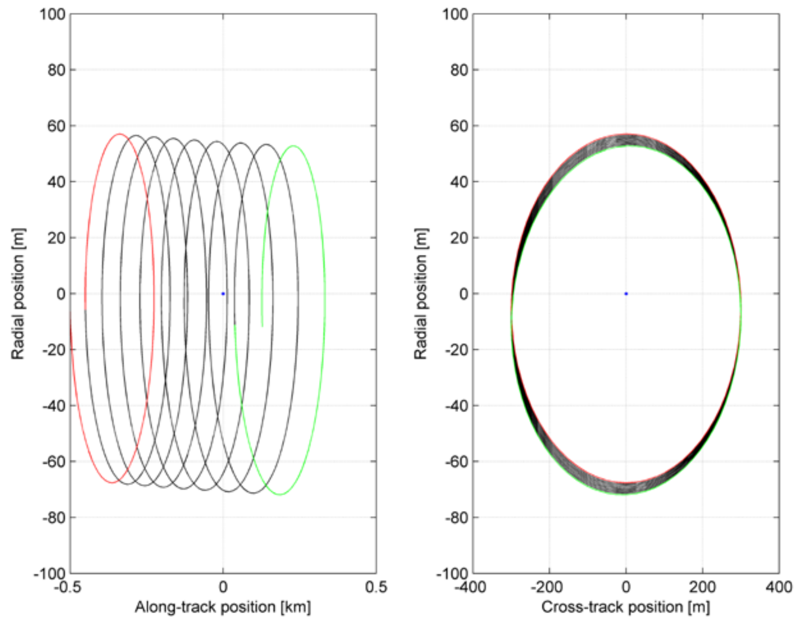

Figure 6 Evolution of the relative motion in case CompSAR enters safe mode

D. Scenario 4: Sentinel-1 switches to SAFE MODE:

Finally, we analyse the case that Sentinel-1 goes into safe mode (i.e. turns into a passive satellite, same assumption above).

The safe mode of Sentinel-1 implies a decrease of its ballistic coefficient. Thus the difference with CompSAR increases in this case. The two spacecraft therefore drift apart even faster than in nominal operations as illustrate in figure 7.

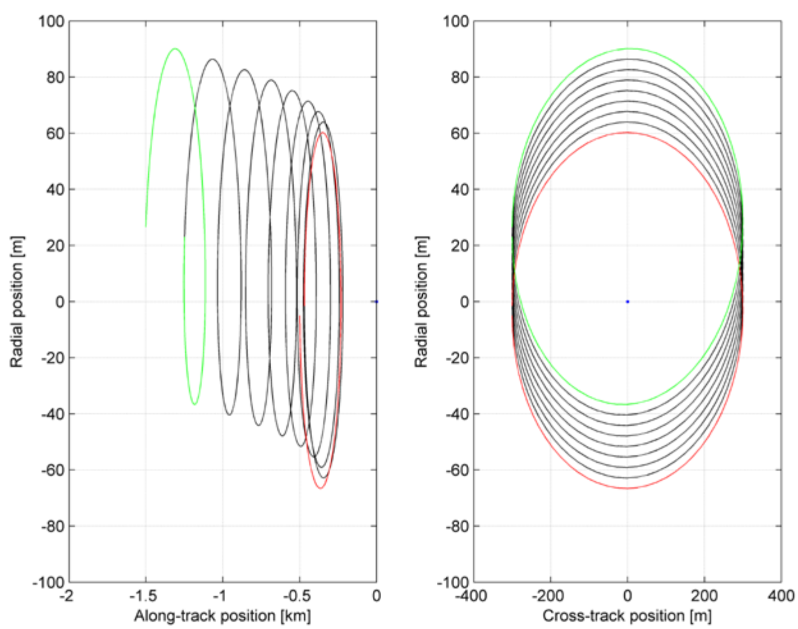

Figure 7: Evolution of the relative motion in case Sentinel-1 enters safe mode

Thus, the formation helix orbit design ensures that in such scenario the predefined minimum miss distance (e.g. 30 m) is never reached between the 2 satellites (in the absence of a manoeuvre for CompSAR).

The Sentinel-1 CC will in any case immediately inform the CompSAR CC to take due measures with respect to the planned orbit manoeuvres.

IX. Conclusions and Recommendations

The CompSAR study has confirmed the potential benefits (in terms of scientific performances) of close formation flight and, at the same time, the operational risks associated with this type of missions.

To this respect, two technologies would be greatly beneficial to relax even further safety related constraints and increase the scientific return by simply enabling robust and safe formation flight:

- On-board relative navigation, and
- Increased ground visibility (and commandability).

For what regards relative navigation, the concept largely coincides with the adoption of cooperative satellites design, with various degrees of on-board complexity. The use of relatively complex navigation devices on board the spacecraft composing the formation has evident advantages, but important impact on the cost and avionics complexity. Without considering this type of active formation flight devices (eg the PRISMA system used for the Tango-Mango and the Terrasar/TandemX missions), it is here highlighted how the simple exchange of basic navigation information between the satellites in the formation (e.g. a ranging transponder) would permit a real-time autonomous estimation of the relative distance, thus enabling both autonomous navigation and first level contingency counteraction. The On-board relative navigation concept fatally implies that the spacecraft composing the formations are designed together, at least for the cooperative system. Although the missions of this type flown so far all have been designed since inception for the formation mission, and this can be considered a primary design driver, the design impact of the formation cooperation system might be largely reduced. As a matter of fact, it is be noted that cooperation can take the form of simple passive target for radar/laser ranging from one satellite to the other. Limited adaptation of existing technology is considered necessary to offer this limited cooperation system, with the cost impact depending on the system complexity.

With respect to the increase of ground visibility, this would permit to achieve the needed fast reaction time for handling contingency scenarios. As a matter of fact (as described above) in case of non-nominal variation of the orbit of one of the satellites (due to e.g. aborted manoeuvre), it is necessary to have both visibility of the event and commandability of the satellites for recovery actions. The best scenario in this case would be to have a narrow-band TT&C link available on a 24/7 basis (Ground, LEO or GEO data relay systems) for satellites positive feedback service ("watchdog" signal) & ad-hoc (contingency) commanding. The use of (existing) ground based telecommunication systems have several critical issues to overcome, namely the frequency coordination, geographical dispersion of the service operators, and cell hand-over time. Conversely, the use of space based systems for the implementation of this "beacon LEO TTC" service has been proved (Dial-a-Sat, Rubin technology demonstration program). A wide range of service can be achieved via the adaptation to the specific use of simple existing receivers/transmitters technology to interface with existing space based communication infrastructures (comsat constellations), and with a limited cost impact.

It is noted that neither of these two technologies requires development of new systems, and can simply be implemented by using off the shelf products. In the case of the inter-satellites TT&C narrow-band link, the service could be offered by flying the necessary unit (wide-range antenna and transponder) on LEO or GEO platforms (e.g. the EDRS satellites), or using space based communication infrastructures already available commercially (e.g. Orbcomm, Iridium, Globalstar, Inmarsat BGAN).

Appendix A

Acronym List

AOCS	Attitude and Orbit Control System
CC	Control Centre
CDF	Concurrent Design Facility
ECSS	European Cooperation for Space Standardisation
eg	exempli gratia
EO	Earth Observation
ERS-2	European Remote-sensing Satellite-2
FDIR	Failure Detection Isolation and Recovery
FDS	Flight Dynamics System
FOCC	Flight Operation Control Centre
FOS	Flight Operation Segment
GB	Giga-Byte
GEO	Geosynchronous Earth Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground Station / Ground Segment
LEO	Low Earth Orbit
MMD	Minimum Miss Distance
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
OCM	Orbit Correction Manoeuvre
PDGS	Payload Data Ground Segment
POD	Precise Orbit Determination
PUS	Packet Utilisation Standard
SAR	Synthetic Aperture Radar
S1	Sentinel-1
S1-CC	Sentinel-1 Control Centre
TC	Telecommand
TM	Telemetry
TT&C	Telemetry Tracking and Control

Appendix B
Glossary

Ascending node	The point at which an orbit crosses a reference plane (such as a planet's equatorial plane or the ecliptic plane) going north.
Geosynchronous	A direct, circular, low inclination orbit about the Earth having a period of 23 hours 56 minutes 4 seconds.

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