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INCREASE OF SENTINEL-1A ORBITAL TUBE: IMPACT ON INTERFEROMETRY

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List of references

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1. INTRODUCTION

Sentinel-1 is a constellation of two C-band SARs flying on the same orbital plane, 180deg apart. Each spacecraft is designed for a nominal lifetime of 7.5 years. Sentinel-1A was launched in April 2014, followed by Sentinel-1B two years later. The first units will be gradually replaced by two new ones (the C and D units) providing continuity of measurements for the 2020's decade and beyond. Currently, Sentinel-1 mission is by far the largest provider of open SAR data and has become the backbone of most operational applications relying on SAR.

Following the premature failure of Sentinel-1B, in December 2021, the mission relies exclusively on Sentinel-1A, which became a critical resource to guarantee the Copernicus SAR imaging capacity and to safeguard the continuity of measurements. Since then, the priority has been to replenish the constellation, as soon as possible. However, due to issues related to the availability of launchers, S1C had to be postponed and the launch is currently planned for Q4-2024, for a start of routine operations in Q1/2-2025. At that moment, Sentinel-1A will have reached 11 years in space, far beyond its designed lifetime.

1.1. Sentinel-1 Orbit Control

The Sentinel-1 orbit control is a fundamental component of the mission that has required specific implementation **[S1_ORBITCONTROL]**. Its purpose is to limit the orbital baseline inbetween repeat cycles to optimise the SAR signal for detection of ground movement based on SAR Interferometry (InSAR). For Sentinel-1, the following requirement has been derived at the beginning of the mission to steer the system design:

The reference orbit shall be maintained within an Earth-fixed orbital tube of a diameter of 100 *m* (RMS) at every orbital point, over any repeat cycle, during the nominal mode operation time

This requirement has been relaxed to a diameter of 200 m (RMS), based on the InSAR results during the S1A commissioning. Furthermore, it has been translated into more classical representation for flight operations, being a dead-band around a reference ground-track of +/- 120m. The mission analysis performed, allow to define as strategy based on the dead-band controlled at Equator crossing and Maximum latitudes thank to a Combination of: ESA UNCLASSIFIED – For ESA Official Use Only Page 5/14



- In-Plane Orbit Control Manoeuvres (OCM) to control the ground-track deviation at the Equator crossings.
- Out-of-Plane OCMs to control the ground-track deviation at northern and southern most latitude.

The performance of the current orbit control is illustrated in the **Figure 1** for the year 2022 and partially 2023.



Figure 1: Evolution of the S-1A ground track during; blue at equator, grey at maximum latitude. Red lines are showing the current +/- 120m dead band on which the orbit is controlled in.

The interferometric baselines are monitored by the SAR Mission Performance Cluster (MPC) and reported in the cyclic and annual performance reports (e.g., [S1_ANUALREPORT22]). The limits of the achieved baselines (w.r.t a reference cycle in 2015) are shown in Figure 2, for the year of 2023. As can be seen, all baseline components are very well controlled and distributed around 0 m. Moreover, the perpendicular baseline is well below 500 m, i.e., less than 10% of the critical baseline of 5km for the Interferometric Wide Swath mode (IW), first sub-swath.





Figure 2: S-1A parallel (top), normal (mid) and along-track (bottom) interferometric baseline components during 2023, computed for the given cycle with respect to a fixed reference cycle. Warm colors are used for the maximum value and cold colors for the minimum value of each orbit. The colors represent the track number.

In February 2024, following a thruster anomaly the decision was taken to discontinue the outof-plane maneuvers in order to secure spacecraft safety. In-plane maneuvers will continue as usual, as they do not rely on the affected thruster. The lack of out-of-plane maneuvers translates into a larger ground track deviation proportionate to latitude. The higher the latitude (north or south) the larger the ground track deviation, and, hence, the orbital baseline. At the equator, the current performances are preserved.

In order to characterize the impact on InSAR applications, the expected ground track deviation and corresponding interferometric baselines have been simulated. The predicted results are shown in Section 2. The preliminary conclusion, supported by InSAR experts, is that the perpendicular baseline, a key InSAR performance indicator, will remain within acceptable limits. Burst synchronization at data-take start is not expected to be impacted, and degradation within data-take and as well as reduction of spectral overlap due to crossing orbits are expected to be limited [INSAR TUBE].



Session 2 presents the prediction of ground-track evolution and interferometric baseline for the next years, considering no further out-of-plane maneuvers.

The ground track deviation and related InSAR baseline evolution will continue to be carefully monitored, as well as the burst synchronization. A new issue of this document will report results from the observations in the following months. Any significant deviation with respect to the expected behavior shown in Section 2, might require revisiting the orbit control strategy without out-of-plane maneuvers.



2. ORBIT AND BASELINE EVOLUTION WITHOUT INCLINATION CONTROL

In order to assess the discontinuation of the inclination control, a long-term simulation has been conducted using, as initial condition, the spacecraft position after the last Orbital Control Manoeuvre (OCM) performed on 21st of February 2024 and propagating five years in the future. The propagation incorporates an Earth gravity model (EGM96) and accounts for the gravitational influences of the Sun and Moon as third-body perturbations. Atmospheric drag, solar radiation pressure and daily variations were intentionally omitted as considered as of minor relevance. The 5 years simulation allows to assess the orbit evolution much beyond the S1C/D launch.

The resulting variation of the ground track at maximum latitude is provided in **Figure 3**, which **represents a worst-case scenario** for the orbit control. It can be observed that the ground track follows a yearly pattern further modulated by a long-term drift, with worst deviation during summer and a smaller deviation during winter. However, the ground track deviation, thanks to the in-plane control, remains limited and marginally exceeds twice the current dead-band. At lower latitude, the deviation would remain within the current dead-band. Furthermore, the cyclic pattern ensures that the ground-track in between repeat cycles or at 1 year interval remains in the same ballpark.





Figure 3: Evolution of the S-1A ground track without orbit inclination control for the next five years at maximum latitude

An increased orbital tube has an impact in interferometric applications [INSAR_TUBE]. In order to assess the impact, the InSAR baseline has been computed at different latitudes. The perpendicular baseline is the key InSAR performance indicator considered here, as it directly relates to the ground track deviation and translates into a direct reduction of the interferometric coherence and increase of height of ambiguity.

The baseline is computed with respect to a fixed reference orbit chosen to be the 22nd of February 2024 and its perpendicular and parallel components are depicted in **Figure 4**. The solid lines correspond to an assumed ground-track deviation of 0 m at ANX crossing, whereas the shadow areas give the spread when considering ground track-deviation between -120/120 m at ANX.





Figure 4: (Top) Perpendicular and (bottom) parallel baseline evolution as function of argument of latitude.

As expected, the baselines show a similar variation to the ground track deviation at maximum latitude, presenting a seasonal variation and long-term drift. The worst-case scenario indicates perpendicular baselines reaching around 560 m at $(\pm)75^{\circ}$ latitude. The lower the latitude, the smaller the spread of the baseline along time. At the equator the baseline follows the current pattern, i.e., no degradation is expected.

For stack-based InSAR (Persistent Scatterer or Distributed Scatterers) techniques (e.g. deployed in EGMS), the degradation does not translate into a significant loss on target density or accuracy, as the technique is robust to a wider baseline excursion as demonstrated with previous missions like Envisat. The long-term drift introduces correlation between temporal and perpendicular baselines, which might need to be considered when selecting arcs. Moreover,



depending on the algorithm used, adaptations might be required due to the increased sensitivity to topography related to larger baselines (e.g., limiting the allowed baselines), and good topography models could be used as input to the chains to support the processing. As positive consideration, the perpendicular baseline diversity and increased topography sensitivity might improve target height estimation and location, in the long run.

For classical differential InSAR based on single or few interferograms, the coherence degradation would be limited to around 10% worst case, i.e. at maximum latitude and over the next five years. This loss can be mostly compensated by employing spectral filtering techniques at the cost of slightly degraded spatial resolution. Note that this corresponds to a coherence loss for flat terrain. For areas of steep topography, the loss will be larger, and might be compensated with slope-adaptive range spectral filtering at a cost of a larger degradation of resolution (up to the limits of the critical baseline) and requiring good knowledge of the terrain.

Several application fields rely in single or few short temporal baseline interferograms at 12-, 24- or 36-days difference. The related perpendicular baseline distribution is depicted in **Figure 5** at different latitude bands and different time lag. The magnitude of perpendicular baseline does not exceed 300m (for 36 days lag), which is limited and comparable to the current situation with a perpendicular baseline within $\pm 100m$. For 12-days interferograms, the magnitude of the perpendicular baseline is still smaller than $\pm 165m$, even at higher latitudes.

The distribution of the height of ambiguity (HoA) for short temporal baseline interferograms (12-, 24- or 36-days lag) can be seen in **Figure 6**. The simulation considers Interferometric Wide Swath mode sub-swath 1 (IW1), i.e., should represent a worst-case scenario. For 12-days interferograms, the worst-case scenario indicates a height of ambiguity around 82 m at 75° latitude. For 36-days interferograms, the worst-case scenario indicates a HoA of around 34 m at 75° latitude, and more occurrences below 100m are observed also at lower latitudes. Due to increase of height of ambiguity, and depending on the application/imaged scene, improved topography information might be required to support phase unwrapping.





Figure 5: Histogram of perpendicular baseline at 12, 24 and 36 days interval for different argument of latitude 30, 60 and 75°.



Figure 6: Histogram of height of ambiguity (HoA) at 12, 24 and 36 days interval for different argument of latitude 30, 60 and 75°. The plots consider an incidence angle of around 30° and slant range of around 800.5 km, corresponding to an example of IW1 near range. The histogram focuses on HoA's smaller than 500 m only.

In the case of interferometry between different units (i.e., upon S1C launch), the degradation on the short-temporal baseline interferograms will be more critical, as at worst-case, perpendicular baselines up to 700 m at higher latitudes could be expected.

It should be noted that for both short and long temporal baseline cases, the estimated perpendicular baseline remains a small portion of the critical one, which is of 5km for IW1. It is also noted that although IW mode is the main mode used for interferometry, it is possible to perform interferometry with Extra Wide Swath mode (EW) for which the critical baseline is 1.2km, comparable to the Envisat case. The EW case has been excluded from this assessment as it has never been promoted by ESA.



As a final consideration, large baselines might result in increased differential FM-rate-related effects in InSAR applications with S-1 TOPS acquisitions, especially for areas with large topography variations [TOPS_DOPPLER]. Hence, if necessary, the use of post-processing methods such as the Extended Time Annotation Data (ETAD) FM-rate correction [ETAD] or post-focusing algorithms [TOPS_DOPPLER] might be considered to minimize effects in the InSAR phase and co-registration.