SENTINEL-1: LINK BETWEEN ORBIT CONTROL AND INTERFEROMETRIC SAR BASELINES PERFORMANCE

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Abstract: *Sentinel-1A was launched in April 2014 carrying a 12 m-long advanced synthetic aperture radar (SAR). The 'radar interferometry' (InSAR) remote sensing technique combines two or more radar images over the same area to detect changes occurring between acquisitions Interferometry allows for the monitoring of even slight ground movement – down to a few millimetres – across wide areas. The performance of the radar interferometry depends strongly on the geometry between the positions of the satellite when the combined acquisitions were taken, namely baselines. For the Sentinel-1A mission small baselines are preferred, therefore a tight orbit control has been implemented. The orbit control requirements have been defined as an orbital tube, and then translated into classical ground-track control requirements. The achieved orbital tube during almost one year of mission is evaluated, and it will be shown how the resulting InSAR baselines are not linked only to the orbital tube maintenance. Firstly because the resulting tube has an ellipsoidal shape but also because the selected repeat cycle and the frequency of the manoeuvres play a role when comparing orbits that are one repeat cycle apart.*

Keywords: *InSAR baselines, Orbital tube, Sentinel-1.*

1. Introduction

Sentinel-1A was launched in April 2014 in order to provide radar vision for Europe's Copernicus programme. Sentinel-1A carries a 12 m-long advanced synthetic aperture radar (SAR), working at C-band. The advantage of radar as a remote sensing tool is that it can image Earth’s surface through rain and cloud, and regardless of whether it is day or night.

Radar data can also be used for monitoring land deformation. The 'radar interferometry' (InSAR) remote sensing technique combines two or more radar images over the same area to detect changes occurring between acquisitions. Interferometry allows for the monitoring of even slight ground movement – down to a few millimetres – across wide areas. As well as being a valuable resource for urban planners, this kind of information is essential for monitoring shifts from earthquakes, landslides and volcanic uplift.

The performance of the radar interferometry depends strongly on the geometry between the positions of the satellite when the combined acquisitions were taken, namely baselines. The baselines are decomposed into the line of sight of the radar, i.e., parallel baseline, the perpendicular to the line of sight, i.e., perpendicular baseline, and into the direction of the satellite velocity, i.e., along-track baseline. Each component is important for different applications.

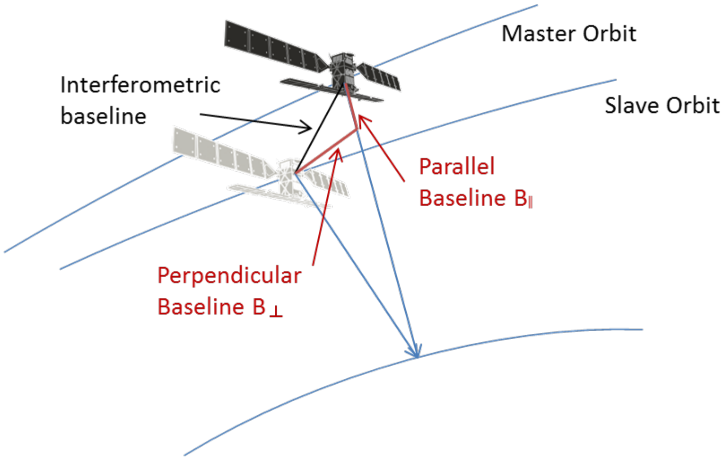

Figure 1 Geometry of a satellite interferometric SAR system

For the Sentinel-1A mission small baselines are preferred, therefore the following orbit requirement was defined:

"The reference orbit shall be maintained within an Earth-fixed orbital tube of a diameter of 100 meter-rms, at every orbital point, over any repeat cycle, during the nominal mode operation time."

But the orbital tube is just an artefact, i.e., a comparison with an ideal reference orbit, whereas the real performance is given by the resulting interferometric baselines. That is to say, the relative geometry between the actual positions of the satellite over the same area. Furthermore, an statistical orbital tube concept is very difficult to implement operationally, so it had to be translated into a classical ground track control.

From the implemented ground-track control, the resulting orbital tube statistics during almost one year have been calculated, and then they are compared with the InSAR baseline statistics.

The first result is that shape of the orbit tube is an ellipsoid, so it makes more sense to define an RMS requirement for each axis of the orbital tube. In this case the RMS distance will depend on the chosen axis, if radial and across-track or parallel and perpendicular baseline axis. The latest ones should be the chosen ones, because of the geometry of the problem and the difference applications of the perpendicular and the parallel baselines.

Other interesting result is the non-intuitive correlation between the baselines when the actual orbit is compared to the reference orbit and when the actual orbit is compared to the actual orbit one repeat cycle apart, that is the actual position of the satellite over the same area 12 days later.

Beyond the geometrical reasons, the manoeuvre frequency, moon periodical perturbations and the selected repeat cycle of the SAR mission will play an important role when comparing the orbital tube with the resulting InSAR baselines.

2. Orbital Tube Requirement Implementation

The main requirement of Sentinel-1 mission related to orbit control was expressed as:

“The reference orbit shall be maintained within an Earth-fixed orbital tube of a diameter of 100 meter-rms, at every orbital point, over any repeat cycle, during the nominal mode operation time.”

This is an statistical requirement given in terms of RMS, very difficult to implement operationally, therefore it was needed a redefinition into a classical ground-track control definition.

“The satellite shall be maintained to a reference ground track such that it does not exceed the following boundaries at the equator and at the northernmost point:
- 60 meters to the East of the reference ground track
- 60 meters to the West of the reference ground track.”

Note that this definition only constraints the dead-band at equator and the northernmost points, for the rest of the latitudes it is unconstrained, expecting the worst case at 45 degrees.

This is a very tight requirement, beyond the inclination’s oscillation due to the Moon perturbation. Its fulfilment implies a great number of out-of-plane manoeuvres in order to control the dead-band at the northernmost latitudes. For this reason it was decided to relax the ground-track control to a 120 meters dead-band at equator and northern most latitudes until routine operations were reached. Although this status of the mission was reached long ago, to date the dead-band requirement is still relaxed.

In order to have an overview of the achieved orbital tube the actual orbits have been compared to the reference orbit for the period 17th October 2014 to 1st August 2015. To have a meaningful comparison for a SAR mission, a position in the reference orbit is selected, then the zero-doppler target for that position is calculated, and finally the position of the actual orbit at which the same target is seeing also with zero-doppler is computed. The difference between these two positions is decomposed in along-track, radial and across track component. The absolute distances are averaged over one day and presented in Fig. 2.

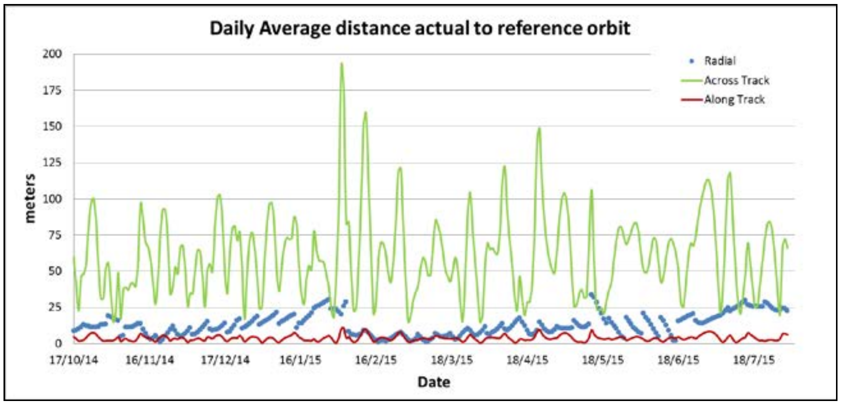

Figure 2 Daily averaged distance between actual and reference orbit

The across-track together with the radial component define the orbital tube, that is represented in the left side of Fig. 3. As expected the along-track component is much larger than the radial one, resulting in an ellipsoidal shape rather than in a circular tube. It needs to be noted that for a InSAR mission the important axis are the parallel and perpendicular baselines directions. The relation between both reference systems is a conversion to the zero doppler reference frame and then rotation in roll according to the roll steering law definition of the satellite. Sentinel-1 attitude is defined in the zero-doppler reference frame with a roll steering law resulting in a roll close to 30 degrees. The orbital tube defined in the parallel and perpendicular baseline axes is showed in the right side of Fig 3.

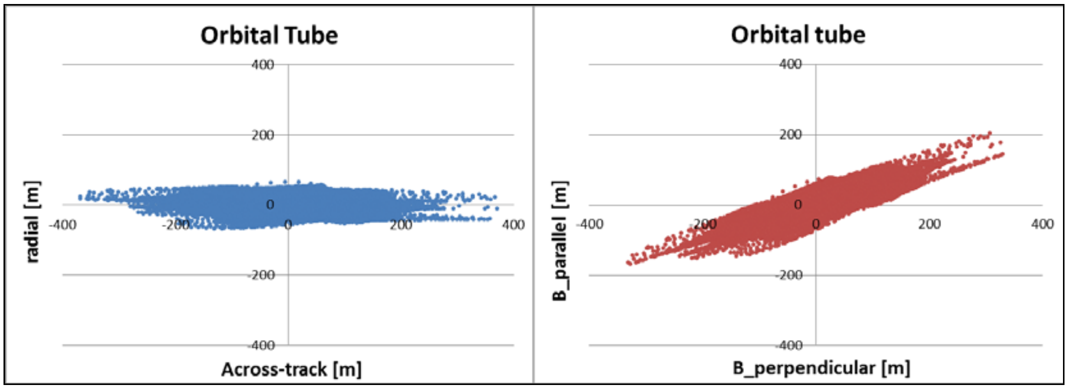

Figure 3 Orbital Tube

The resulting RMS of the absolute distance to the reference orbit is independent of the chosen axis. For the analysed period a +/- 120 meters dead-band control at the equator and northernmost point of the orbit has resulted in an orbital tube of 77 meters RMS radius. However when the distances are decomposed into axis, the results are very different depending on the chosen axis. Table 1 summarises these results:

Table 1 RMS distance to reference orbit

Axis	RMS
Bs parallel	37.62 m
Bs perpendicular	67.11 m
Across-track	75.05 m
Radial	16.93 m

3. Baselines between actual acquisitions

In the previous section the actual orbit have been compared with respect to the reference one. But the reference orbit is an artefact, the performance of the InSAR is given by the baselines between two real acquisitions. Sentinel-1 has a repeat cycle of 12 days and 175 orbits. Here the same analysis will be repeated but comparing to actual orbits that are 12 days apart.

Figure 4 shows the daily average between the distances of two orbits that are 12 days apart. Obviously the distance between two actual orbits is not the linear sum of its respective distances to the reference orbit, but it could be expected that when calculating the distances between real orbits, the results would be significantly higher than when comparing them to the reference orbit, Fig. 2.

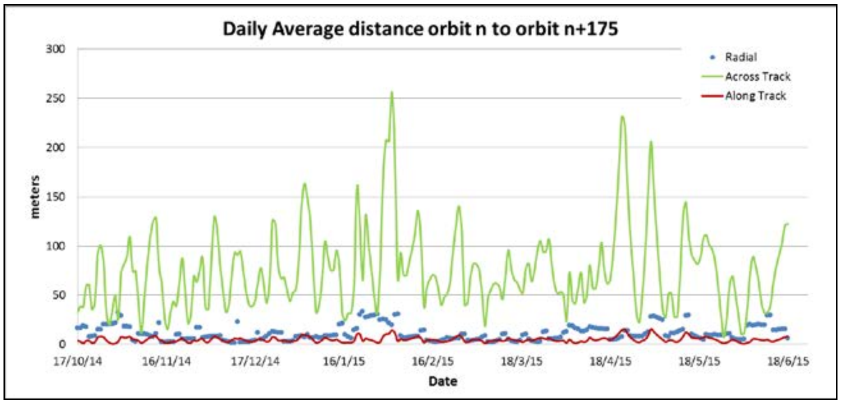

Figure 4 Daily averaged distance between actual orbits

The discrepancy to the expected difference is more clear when the distances are represented as "orbital tube". It is not really an orbital tube, as not reference is used, but it can be compared to the results of the orbital tube shown in Fig. 3. There the maximum across-track distance to the reference orbit was in the order of nearly 400 meters on each side, therefore, it could be expected that the maximum distance between two actual orbit would reach values close to 800 meters, i.e. the case of comparing one orbit on one extreme of the orbital tube with one orbit on the other extreme. The left side of Fig. 5 shows the radial vs the across track distance between two actual orbits is represented, the maximum across-track distance between actual orbits is in the in the order of only 435 meters. Right side of Fig. 5 represent the same distances but in the parallel and perpendicular baseline axis.

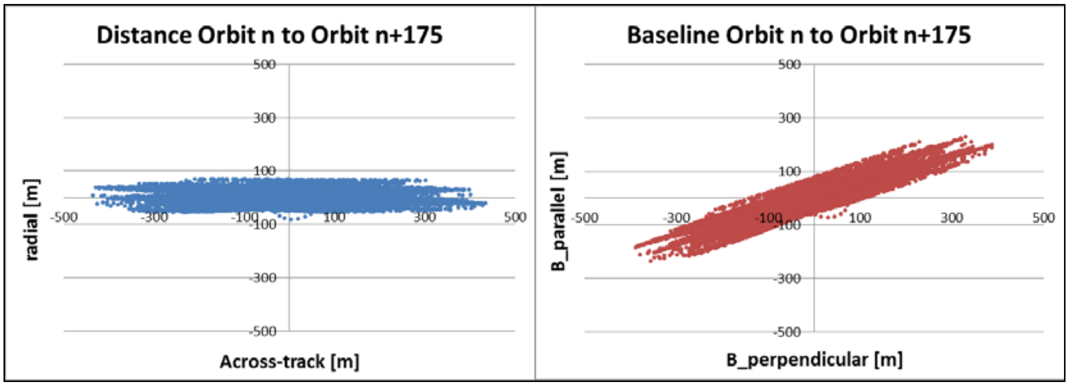

Figure 5 Baselines between actual orbits

As expected the statistical distribution of the distances varies also when comparing to the reference orbit that when comparing two real orbits. The absolute RMS distance in the case of comparing orbits that are 12 days apart is 97.6 meters, the RMS of the distances decomposed into the different axis are given in Table 2.

Table 2 RMS distance to real orbits

Axis	RMS
Bs parallel	49.41 m
Bs perpendicular	84.18 m
Across-track	96.31 m
Radial	15.88 m

It can be concluded that for the Sentinel 1 mission and with the current orbit maintenance, i.e. 120 meters dead-band at equator and northernmost latitudes, the baselines between acquisitions separated 12 days can be represented within an “orbital tube” that is less than 100 meters RMS diameter. This conclusion resembles the initial requirement if orbit is replaced by real InSAR baselines.

4. Influence of the orbital elements control

As explained, it is not straight forward to derive the resulting InSAR baselines from the orbital tube control. The requirement to control the dead-band at northernmost latitudes and at equator drives the inclination and semi-major axis manoeuvres. In this section it will be explained that not only the size of the dead-band influence on the resulting InSAR baselines. Same dead-band sizes would result in smaller InSAR baselines if manoeuvres, perturbations and repeat cycle of were synchronized. Also the role of the eccentricity control will be explained.

4.1 Inclination Control

The dead-band at the northernmost latitudes is driven by the inclination control, i.e. the inclination of the actual orbit with respect to the reference one. Figure 6 shows the resulting inclination control for Sentinel-1, the annual perturbation of the Sun is corrected, remaining only the Moon perturbation perfectly centred around the reference inclination.

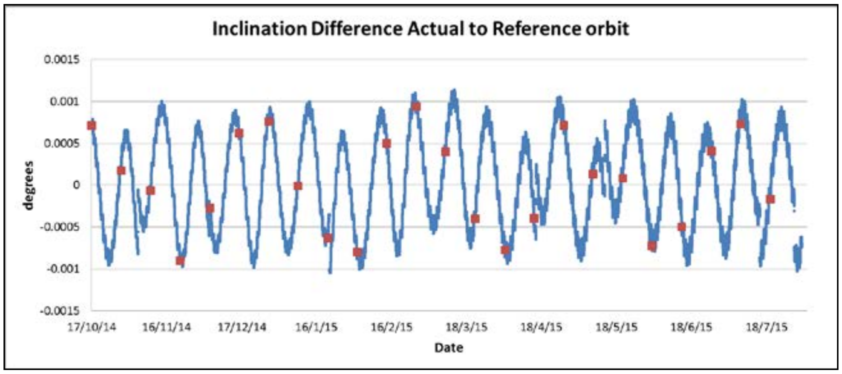

Figure 6 Inclination Difference w.r.t Reference Orbit

The red marks in Fig. 6 indicate the beginning of each repeat cycle. The inclination difference between orbits that are 12 days apart is illustrated in Fig 7. The de-synchronization between the moon oscillation and the repeat cycle causes that in some occasions the out of plane manoeuvres performed in order to fulfil the orbit requirements are in detriment of the InSAR baselines. A more relaxed dead-band at the northernmost latitudes would have result in the same if not tighter InSAR baselines.

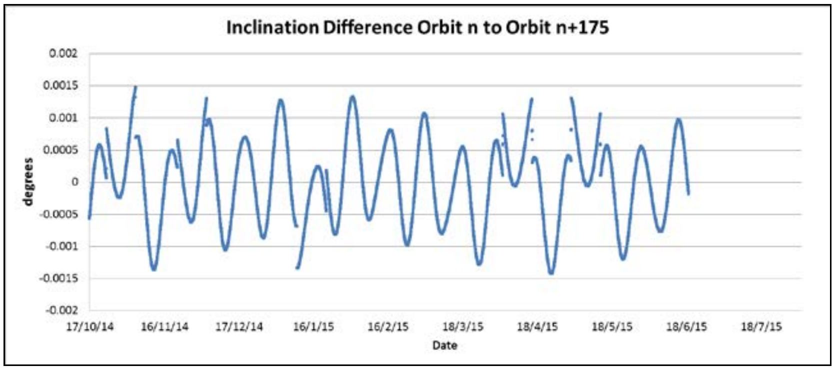

Figure 7 Inclination Difference btwn InSAR pair positions

The ideal case in order to obtain very small baselines with a low operational cost would be to define a repeat cycle of 14 days, that is synchronized with the Moon perturbation. For Sentinel-1 mission the full coverage of the Earth in the shorter possible time was a priority, that is why 12 days were chosen, as it is the lower repeat cycle allowing complete coverage with the SAR swath. For other mission in which target an small baselines and have no temporal constraints a 14 days repeat cycle is recommended.

4.2 Semi-Major Control

A similar analysis to the dead-band at the northernmost latitudes can be done for the dead-band at equator, that is driven by the semi-major axis control manoeuvres. Figure 8 shows the achieved dead-band at equator, the “peaks” of the plot represent a semi-major axis raising manoeuvre. I order to ease operations, nominal manoeuvres are only allowed at a certain slots fixed on a weekly basis. Currently, due to the low solar activity, only one slot per week, on Wednesdays, is used. Collision avoidance manoeuvres may alternate this weekly pattern.

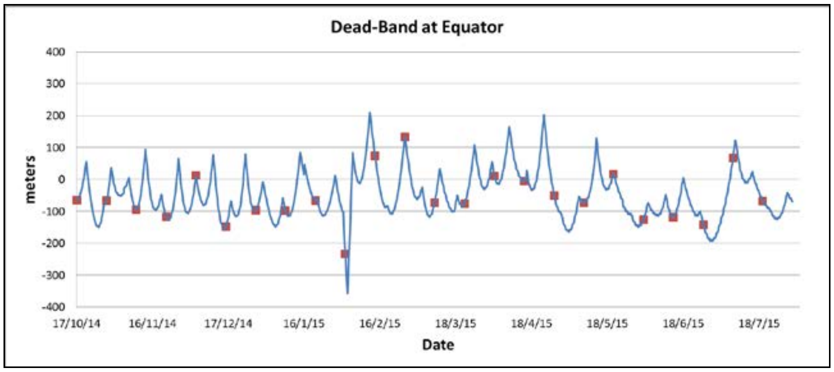

Figure 8 Dead-band at Equator

The red marks in Fig. 8 indicate the beginning of each repeat cycle. It can be appreciated there is no synchronization between the repeat cycle and the manoeuvres. When the distance between the longitudes of ascending nodes of orbits that are 12 days apart are calculated, Fig. 9, the resulting values are much higher than if manoeuvres were synchronized with the repeat cycle, even with a larger dead-band control was allowed.

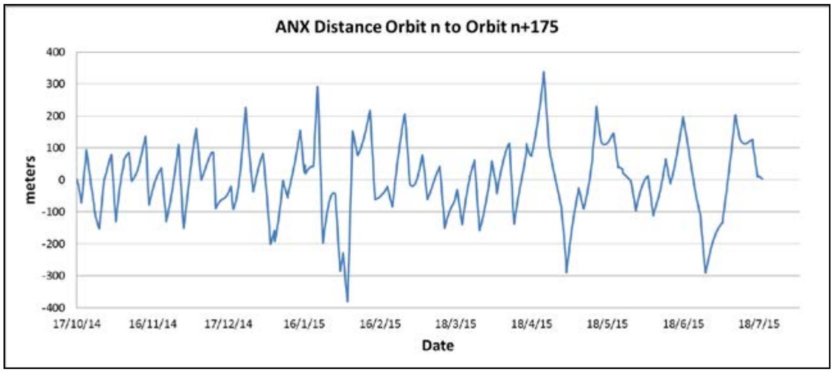

Figure 9 Distance between longitudes of ascending nodes

The baselines could be reduced at lower latitudes by synchronizing the semi-major axis raising manoeuvres with the repeat cycle of the mission, being the frequency of the manoeuvres a submultiple of the repeat cycle. However this option may not be so optimal depending on the operational cost and the number of collision avoidance manoeuvres breaking the synchronization.

Considering the desired weekly slots for manoeuvring and the Moon's perturbation the ideal repeat cycle for an InSAR mission to obtain small baselines at all latitudes would be 14 days.

4.3 Eccentricity Control

The radial distance effect on the resulting baselines is much lower than the across-track distance, however it has an impact on the relative velocities of the satellite while acquiring data over the same area. This is of major importance for the burst synchronization for long data takes. Sentinel-1 can synchronize better than 2 milliseconds (std dev) the beginning of the data take of one acquisition with respect to another, but a different velocity of the satellite over both acquisitions will cause a drift in this synchronization. The difference in velocity is proportional to the radial difference, therefore the radial component of the orbital tube needs to be small enough to maintain the de-synchronization within the limits during the data takes acquisition time

As shown in Fig 5, the radial distance between two consecutive acquisitions varies in a range of 50 meters, but only part of this variation is due to the semi-major axis control, shown in Fig. 10, the rest is consequence of the eccentricity control.

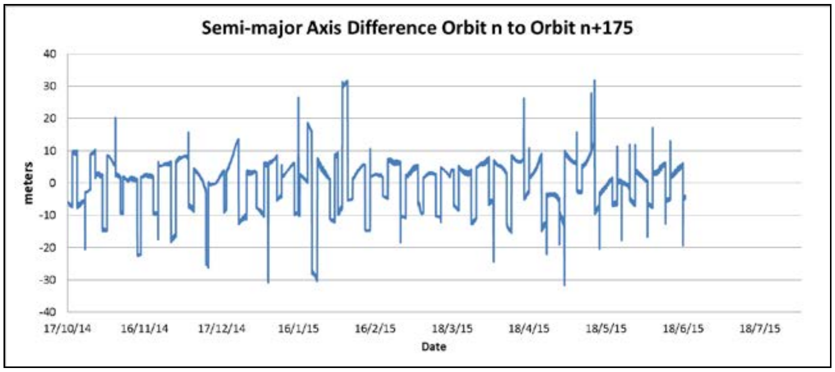

Figure 10 Semi-major axis difference

The semi-major axis variation is mainly driven by the requirement to keep a 120 meters dead-band at the equator, however no requirement is given for the eccentricity control.

Despite the lack of requirement, Sentinel-1 mission has kept eccentricity vector very close to the frozen one, allowing long data takes, of 25 minutes, with a total de-synchronization, i.e. initial plus drift, of less than 5 milliseconds. Figure. 11 illustrates the difference in the eccentricity vector components between two acquisitions.

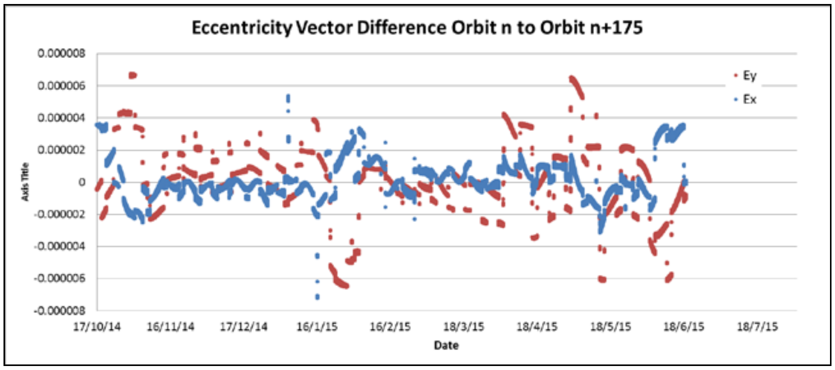

Figure 11 Eccentricity Vector Difference

5. Latitude dependence

There is one aspect that has not been taken into account yet, the geographical distribution with respect to the latitude. All the statistics have been averaged in time or given globally for the whole analysed period, but the initial requirement ask for fulfilment at each latitude. In this section an overview of the latitude dependence is presented

Figure 12 shows the baselines with respect to the reference orbit as function of true latitude. Despite a few points that go to higher values around the equator, the distribution is quite uniform over the orbit.

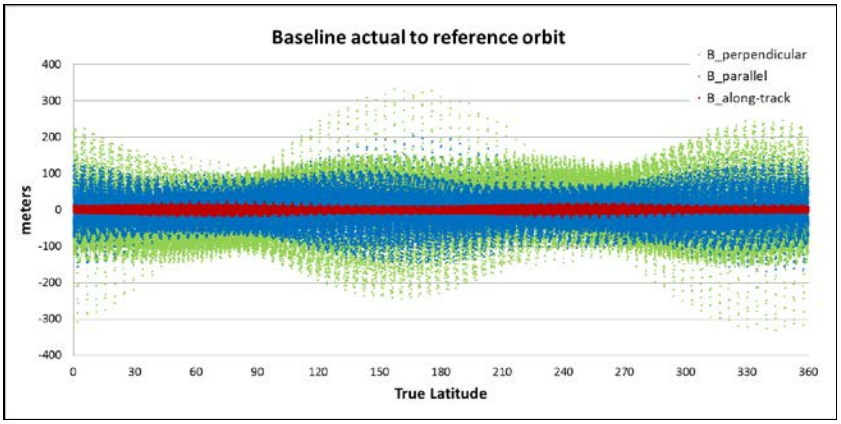

Figure 12 Baselines to the reference orbit

When the same analysis is done between real orbits, shown in Fig. 13, the dependence on latitude becomes more significant, being the absolute baselines lower around a true latitude of 75 degrees and 255 degrees, and higher around a true latitude of 155 degrees and 335 degrees.

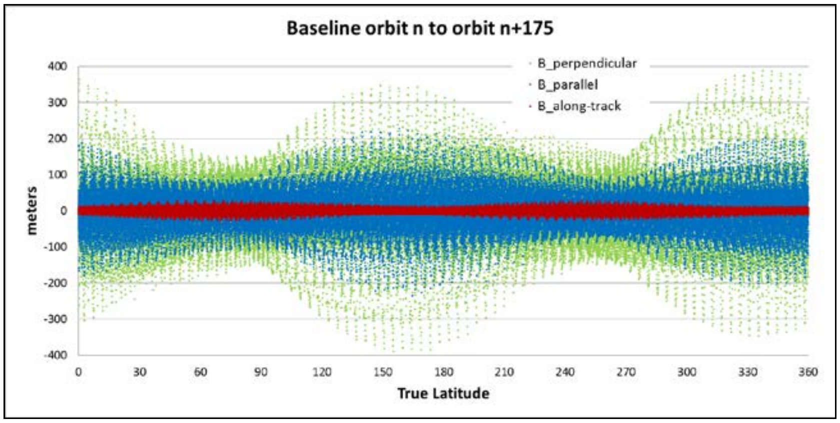

Figure 13 Baselines between real orbits

Nevertheless the results on geographical distribution are very prelaminar and further analysis are needed. There are some missions, as SAOCOM-CS, where only a latitude band is targeted. Therefore it is important to define the an strategy that optimizes the InSAR baselines for this latitude band.

6. Conclusions

The different significance of each baseline component, if parallel or perpendicular suggest to define the orbital tube requirement with an ellipsoid shape. Also the geometry of the resulting orbital tube for Sentinel-1 mission supports that definition.

The resulting InSAR baselines do not depend only of the size of the defined orbital tube, but the synchronization (or lack of) between manoeuvres, perturbations and repeat cycle plays a major role, meaning that the same orbital tube would result in different InSAR baselines depending of repeat cycle and the semi-major manoeuvres frequency. A repeat cycle of 14 days with semi-major axis manoeuvres every 7 or 14 days is suggested for missions targeting small baselines and that have no temporal constrains.

Special attention needs to be paid to the role of the eccentricity vector in the burst synchronization shift over long data takes.

Further investigations on the geographical distribution need to be performed, as the InSAR requirements shall be met for each latitude. Also to improve other missions were only a latitude range is targeted.

7. References

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