

Interferometry with TOPS: coregistration and azimuth shifts

Francesco De Zan, German Aerospace Center (DLR), Oberpfaffenhofen, Germany
email:francesco.dezan@dlr.de, tel. +49 (0) 8153 28 2150, fax +49 (0) 8153 28 1135
Pau Prats-Iraola, German Aerospace Center (DLR), Oberpfaffenhofen, Germany
Rolf Scheiber, German Aerospace Center (DLR), Oberpfaffenhofen, Germany
Alessio Rucci, TRE-TeleRilevamento Europa, Milan, Italy

Abstract

Recently concerns have emerged regarding interferometry with TOPS, since it has been stated that a highly accurate azimuth alignment is needed to avoid phase bias in the interferometric phase. However, one should distinguish between effects due to limited geometric accuracy related to the static scene (e.g., orbit or DEM), and geophysical signals (actual azimuth displacements), which might give rise to legitimate phase jumps at the border between subsequent bursts. This paper addresses this topic and suggests an alternative methodology to process and interpret TOPS interferograms of non-stationary scenarios.

1 Introduction

The TOPS mode was introduced to equalize the image quality of ScanSAR acquisitions in the azimuth direction [1]. Interferometry with this new mode seems at first sight to present more challenges than interferometry with the regular stripmap mode. Similar as with the ScanSAR mode, the difficulties derive from the (relatively) large Dopplers involved, which produce a significant coupling between the range and azimuth signals.

A SAR sensor measures very accurately the distance between sensor and target during the formation of the synthetic aperture. The variation of this distance is exploited to achieve resolution in the along-track direction, i.e., azimuth. However, the non-orthogonal acquisition geometry in the presence of a squint angle results in the appearance of phase ramps (both in range and azimuth) in the impulse response function (IRF). The IRF in zero-Doppler geometry without unnecessary terms is given by [3, 4]

$$\begin{aligned} s(t; r_0) = & s_r(\tau - \tau_0) \cdot s_a(t - t_0 - k \cdot (\tau - \tau_0)) \\ & \cdot \exp \left[-j \frac{4\pi}{\lambda} \cdot r_0 \right] \\ & \cdot \exp [j \cdot 2\pi \cdot f_0 \cdot (\cos \beta - 1) \cdot (\tau - \tau_0)] \\ & \cdot \exp [j \cdot 2\pi \cdot f_{dc} \cdot (t - t_0)], \end{aligned} \quad (1)$$

where τ is the range time, t is the azimuth time, τ_0 and t_0 are the target positions in seconds at closest approach in range and azimuth, respectively, r_0 is the closest approach distance (proportional to τ_0), s_r is the compressed range envelope, s_a is the compressed azimuth envelope, k accounts for the skew of the sidelobes in the range direction in a zero-Doppler focusing geometry (see [3, 4]), f_{dc} is the Doppler centroid, λ is the wavelength, f_0 is the center frequency, and β is the squint angle of the acquisition geometry.

The phase ramps given by the last two exponential terms in (1) can be directly interpreted as a consequence of a

modulated spectrum due to the squinted acquisition geometry. But they can be also interpreted as a consequence of the unknown sub-pixel target position within the resolution cell. Indeed, the phase ramps cross zero at the maximum of the IRF, as noted in (1). This means that if, by chance, the sampling occurs at the maximum of the IRF, the phase of the signal will be just given by the first exponential term, i.e., the well-known $4\pi r_0/\lambda$. In a most generic case, however, the sampling will not occur at the maximum, and additional phase contributions due to the phase ramps occur. And although one could be tempted to consider these values as “biases”, they are indeed a legitimate measurement of the slant-range distance to the scatterer phase center. Therefore, the phases ramps appear in order to “correct” the phase measurement, which was forced to be at zero-Doppler during the focusing step, and hence provide the *real* distance for the given acquisition geometry. It is interesting to note that, as shown in [4], the phase ramp in range vanishes when selecting a conical focusing geometry. The phase ramp in azimuth, however, remains, due to the lack of orthogonality between range and azimuth in the acquisition geometry.

2 Interferometric Phase

The two phase ramps can impose severe requirements in the coregistration of interferometric image pairs [3, 4]. For the case under consideration, the range phase ramp can be neglected, since the squint angles in the TOPS mode are below 1° . The phase ramp in azimuth, however, will introduce a phase bias in the presence of an azimuth coregistration error, which is given by

$$\Delta\phi = 2\pi \cdot f_{dc} \cdot \Delta t \quad (2)$$

where f_{dc} is the mean Doppler frequency of the target (Doppler centroid) and Δt is the slow-time displacement. It has to be remarked that f_{dc} is a quantity that varies periodically in azimuth being linked to the position within

a burst. At the burst center the mean Doppler frequency is zero, but it is negative at the beginning of the burst and positive at the end. As it was already noted in the past, a constant Δt error will produce a series of phase ramps (in azimuth) in the interferograms.

In [2] it was estimated that to keep the phase below a few degrees it is necessary to guarantee a very high azimuth coregistration accuracy, in the order of 1 cm for TerraSAR-X (similarly for Sentinel-1), which corresponds to about 0.001 azimuth resolution cells. It was shown that exploiting the burst overlaps it is possible to reach an adequate accuracy by averaging large areas; however, concerns remained about local azimuth shifts, when it is not possible to average large areas to improve the estimates. A spatially adaptive filter has been suggested in order to accommodate the azimuth-variant requirements [5], which are specially stringent at burst edges. An alternative approach is given in the next section.

3 TOPS Interferometry and line-of-sight Measurements

In this contribution it is argued that local geophysical shifts are not introducing any special requirement in TOPS interferometry, while it is important to be careful with the interpretation of the interferometric phase.

The interferometric phase measured by SAR is the variation of the line-of-sight distance between two acquisitions. For targets which are not at zero Doppler, the line of sight (LOS) is not orthogonal to azimuth: a coupling arises between the two SAR coordinates. Interferometric phase shifts appear even for pure azimuth displacements. This is a possible way to read Eq. (2) and is also the interpretation of azimuth delta-k given by [6]. In this optic, one should remember that with TOPS the line of sight varies with azimuth, with abrupt jumps passing from one burst to the next.

Figure 1 shows an example of the resulting azimuth phase ramp within a burst in the presence of a constant azimuth coregistration error. The figure shows one subswath with 13 bursts of a TerraSAR-X (TSX) TOPS acquisition over Mexico City. The azimuth coregistration error is 0.05 azimuth samples, resulting in phase jumps at burst edges of about 145° , which in this case would turn into a DEM discontinuity of 45 m between bursts, or similarly to a jump of 6 mm in the differential InSAR case. The enhanced spectral diversity (ESD) approach proposed in [2] was used to estimate the residual azimuth coregistration error.

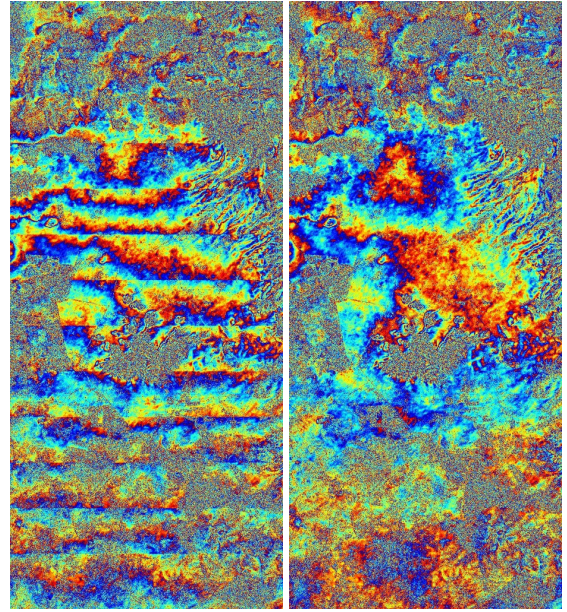


Figure 1: TSX TOPS flattened phase over one subswath. (Left) With a coregistration error of 0.05 samples. The phase jumps at burst edges are about 145° , which in this case would turn into a DEM discontinuity of 45 m between bursts, or similarly to a jump of 6 mm in the differential InSAR case. (Right) After estimating the error using ESD and correcting the shift, where the jumps are no longer visible. Range is horizontal and azimuth is vertical.

3.1 Shift caused by geophysical signals

Interferometric phase jumps observed at the burst edges might be legitimate geophysical signals and, in this case, they should not be considered as artifacts. A similar situation is encountered for ScanSAR, albeit since the Dopplers involved are typically smaller, the phase effects are more limited (a factor three smaller than with TOPS in the case of TSX). In order to better understand this perspective, eq. (2) can be rewritten as

$$\begin{aligned}\Delta\phi &= 2\pi \cdot f_{dc} \cdot \Delta t = \left\{ f_{dc} = \frac{2v}{\lambda} \sin \beta \right\} \\ &= \frac{4\pi}{\lambda} \cdot \Delta x \cdot \sin \beta,\end{aligned}\quad (3)$$

where v is the sensor velocity, β is the squint angle and $\Delta x = v \cdot \Delta t$. Eq. (3) is nothing but the azimuth shift projected in the line-of-sight direction. The total interferometric phase related to scene motion is therefore given by

$$\phi_{\text{motion}} = \frac{4\pi}{\lambda} \cdot \hat{e}_{\text{LOS}} \bullet \vec{g}, \quad (4)$$

where \hat{e}_{LOS} is the LOS vector, which in the TOPS case varies in the azimuth dimension due to the steering of the antenna pointing within the burst, \vec{g} is the motion vector between the two acquisitions, and \bullet represents the dot product.

Figure 2 shows a portion of a 11-day TSX TOPS flattened interferogram over the Lambert glacier, Antarctica.

Three bursts are shown, which are about 9 km long in the azimuth dimension. Only the top-right rocky area is stable, while the rest of the scene corresponds to the glacier. While the rocky area shows no phase jumps, one can clearly see them over the glacier. In order to properly interpret the results of Figure 2 it is necessary to know the LOS vector for every pixel, information that can be derived from the acquisition geometry.

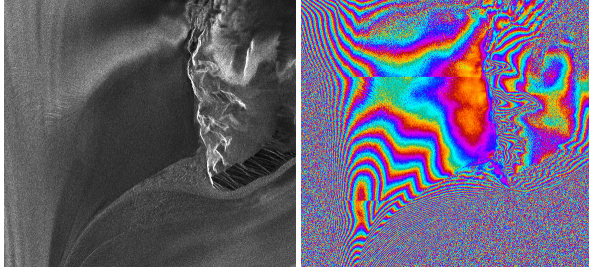


Figure 2: 11-day TSX TOPS interferogram over the Lambert glacier, Antarctica. (Left) Reflectivity image and (right) flattened interferogram. The images show three consecutive bursts (9 km per burst in azimuth), where the top-right part is a stable rocky area showing no phase jumps at burst edges. The glacier, on the other hand, shows clear jumps at burst edges. The jumps are legitimate and correspond to the projection of the motion in the LOS direction, being the latter azimuth-dependent. At burst edges the LOS vectors have opposite azimuth directions, and therefore the jumps can be clearly seen. Range is horizontal and azimuth is vertical.

3.2 Shifts caused by timing errors

If the shifts are not caused by geophysical signals of interest but by the errors in the geometry, e.g., orbital timing errors or DEM inaccuracies, they should be corrected. In this case phase ramps will appear systematically in all bursts, as shown in Figure 1, and the methodology proposed in [2] can be adopted, considering that only a constant or very-slowly-varying shift is to be estimated. One could try to select stable areas or simply repeat the estimates for several bursts and range positions and discard the outliers before averaging. It is important to remark that any geophysical signal behaving in an almost constant manner within the observed scene, e.g., earth tides, cannot be separated from geometric errors when using the proposed methodology.

For the cases where only subsidence is present, e.g., in an urban scenario, the scenario can be considered stable in terms of azimuth shifts, and hence not critical, since no azimuth shifts will be present. The good performance of TOPS time series processing and analysis in urban scenarios has been shown in [7, 8].

3.3 Shifts caused by the ionosphere

The effects of the ionosphere deserve special attention. In fact the ionospheric phase screen can produce local

azimuth delays in the images, which do not correspond to phase changes as predicted by Eq. 2 for the large Doppler variation between one burst and the next in an overlap area. This can happen because the azimuth phase ramps caused by the ionosphere can be limited in azimuth, whereas a rigid shift generates an infinite phase ramp in Doppler domain. Under certain conditions (geographical location, geomagnetic activity) C-band local azimuth shifts can amount to several centimeters (lower frequencies are affected more seriously). Low-resolution modes, like TOPS, are believed to be more affected by azimuth shifts, because of the reduced Doppler bandwidth.

4 Methodology

In light of the aforementioned aspects, the recommended methodology is to first perform a coregistration based on the geometry (orbit and external DEM) as proposed in [9]. This approach is very accurate in relative terms even with low quality DEMs, and especially considering the small orbital tube like in the TerraSAR-X or Sentinel-1 missions. Then, the residual azimuth coregistration error occurring due to geometric errors can be estimated as proposed in [2] by exploiting the overlap between bursts and using only stable areas. The rest of areas subject to motion might present phase jumps between bursts if azimuth shifts are present. However, the LOS vector for every pixel shall be used in order to know the direction of the motion and properly interpret the measurements.

In scenarios where large shifts are expected to occur, one could additionally estimate adaptively the shifts, e.g., using conventional cross-correlation techniques. This would improve in the first term the interferometric coherence. However, for a proper interpretation of the interferometric phase, the phase due to the azimuth shift should be reinstated in the signal using (2). Afterwards, the pixel-dependent LOS vector shall be used as commented before.

Alternatively, the conventional approach would be to decouple the range and azimuth signals by first estimating the azimuth shifts and then interpreting the phase as the one in zero-Doppler geometry, i.e., assuming a non-squinted acquisition geometry. This can be done in the TOPS mode by using adaptive windows as suggested in [5], where the requirement in the coregistration estimate needs to be carefully considered, since it increases, the closer to burst edges.

4.1 Phase ambiguities between bursts

In scenarios with large along-track deformation, the interferometric phase difference could have a change of more than π between successive bursts. In this case the simplest methodology seems to be coregistering the local azimuth shifts to eliminate phase discontinuities. After phase unwrapping, the phase which was removed by coregistration could be re-inserted in the interferograms, to avoid losing phase accuracy because of the limited performance of cross-correlation.

A second possibility is to unwrap independently each burst and solve for the absolute phase in a second step, for example using radargrammetry on large areas.

5 Conclusions

Azimuth displacements can introduce large phase variations in TOPS interferometry. However, one should be careful in distinguishing the source of the displacements: those coming from limited geometric accuracy should be corrected as far as possible using the data, noting that they are approximately constant errors affecting whole scenes. Those coming from actual azimuth displacements will contribute to the interferometric phase, so that one should use the line-of-sight vector for each pixel, as depicted in (4), in order to properly interpret the measurement.

The decoupling of the azimuth and range contributions in the interferometric phase through the independent estimation of the azimuth offsets is also a possibility, but one needs to consider the strong requirements at burst edges, so that a clear trade-off is present in this case between the required accuracy and the spatial resolution of the estimates [5].

References

- [1] F. De Zan and A. Monti Guarnieri, *TOPSAR: Terrain observation by progressive scans*, IEEE Trans. Geosci. Remote Sens., vol. 44, no. 9, 2006
- [2] P. Prats-Iraola, R. Scheiber, L. Marotti, S. Wollstadt, and A. Reigber, *TOPS Interferometry With TerraSAR-X*, IEEE Transactions on Geosci. Remote Sens., vol. 50, no. 8, 2012
- [3] M. Bara, R. Scheiber, A. Broquetas, A. Moreira, *Interferometric SAR signal analysis in the presence of squint*, IEEE Transactions on Geosci. Remote Sens., vol. 38, no. 5, 2000
- [4] G. Fornaro, E. Sansosti, R. Lanari, M. Tesauero, *Role of processing geometry in SAR raw data focusing*, IEEE Transactions Aerospace and Elec. Systems, vol. 38, no. 2, 2002
- [5] R. Scheiber, M. Jäger, F. De Zan, P. Prats, D. Geudtner, *Analysis of speckle tracking and interferometric coregistration for non-stationary scenarios with TOPS SAR data*, Living Planet Symposium, Edinburgh, UK, Sep. 2013
- [6] N. Bechor and H. A. Zebker, *Measuring two-dimensional movements using a single InSAR pair*, Geophysical research letters vol. 33, no. 16, 2006
- [7] L. Marotti, P. Prats, R. Scheiber, S. Wollstadt, A. Reigber, *Differential SAR Interferometry with TerraSAR-X TOPS Data: Mexico City Subsidence Results*, Proc. EUSAR, Nuremberg, Germany, Apr. 2012
- [8] M. Nannini, P. Prats, F. De Zan, D. Geudtner, *Investigations of the DINSAR Performance in the TOPS Mode Using Experimental TerraSAR-X Data*, Living Planet Symposium, Edinburgh, UK, Sep. 2013
- [9] E. Sansosti, P. Berardino, M. Manunta, F. Serafino, G. Fornaro, *Geometrical SAR image registration*, IEEE Trans. Geosci. Remote Sensing, vol. 44, no. 10, Oct. 2006