DInSAR Performance Investigations with the TOPS mode

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Abstract

The TOPS (Terrain Observation by Progressive Scans) mode is characterized by the steering of the antenna from aft to the fore within a burst. This acquisition geometry introduces a large azimuth-dependent Doppler variation, resulting in very stringent coregistration requirements in order to retrieve accurate interferometric products. The methodology in order to process interferometric data stacks requires additional effort to avoid that such phase errors impinge the retrieved information. In this context, this paper presents an analysis to evaluate TOPS performance for subsidence monitoring by means of DInSAR techniques, namely PS and SBAS. In particular, two interleaved time series acquired by the TerraSAR-X (TSX) sensor in TOPS and Stripmap modes, respectively, are used to evaluate and compare the results. Interferometric processing aspects related to the TOPS mode are also expounded, namely the coregistration requirements and the burst mis-synchronization.

1 Introduction

The Sentinel-1 mission will use as main mode of operations over land, the Interferometric Wide Swath (IW) mode, which has a swath coverage of 250 km achieved through the multi-swath TOPS mode. Contrary to ScanSAR, TOPS allows a wide coverage with an azimuth-invariant SNR and distributed target ambiguity ratio (DTAR), avoiding scalloping. This is achieved by steering the antenna from aft to the fore, so that every point on the ground is viewed with the entire antenna pattern. The steering of the antenna results in a large azimuth-dependent Doppler centroid variation, which can be several times larger than the pulse repetition frequency (PRF). To cope with this fact additional processing effort is required. Especially for interferometry, if not properly considered, the Doppler variation generates phase artifacts that bias the final result. Therefore, stringent requirements have to be fulfilled in order to avoid such phase errors [4]. In this context it is important to assess the DInSAR performance for subsidence monitoring over large areas with data acquired in the TOPS mode. This paper presents time series analyses performed with permanent scatterers (PS) [1], as well as with the small baseline (SBAS) [2] techniques to monitor the subsidence over Mexico City, with data acquired by the German TerraSAR-X sensor. In particular, interleaved TOPS and Stripmap time series spanning roughly two years are analyzed to evaluate the TOPS performance in comparison with Stripmap. Such evaluation is based on the quantitative comparison of the retrieved mean deformation velocity and DEM error.

The paper is organized as follows. Following a description of the test site data set and a brief analysis of the main interferometric processing issues and their implication for the TerraSAR-X sensor case, the paper focuses on the time series analysis and the subsidence estimation.

1.1 Overview of Mexico City data set

The test site is characterized by strong subsidence due to ground water extraction [3] and consists mainly of an urban scenario. Interleaved TOPS and a Stripmap time series have been being acquired by the TSX satellite since 2009 in a descending orbit configuration. Therefore, such a constellation is very suitable for a performance analysis of the TOPS mode in terms of the exploitation of time series for subsidence estimation. The TOPS data stack consists of 27 images acquired between the 20th of September, 2009, and the 4th of January, 2012, while the Stripmap data set is composed of 36 images covering approximately the same time period (from October, 2009 until January, 2012). The repeat-pass interval is therefore 22-days for each time series. **Figure 1** shows the baseline distribution for the TOPS and Stripmap data sets.

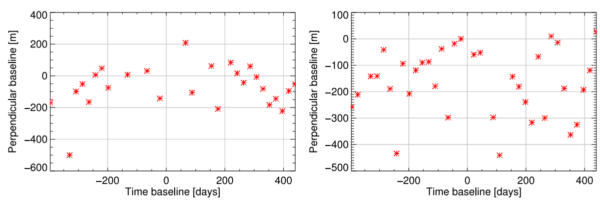

Figure 1: Baseline distribution of the data sets over Mexico City. (Left) TOPS with 27 images and (right) Stirpmap with 36 images.

The Stripmap time series overlaps with the third subswath of the TOPS acquisition. Therefore, only this sub-

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swath has been analyzed in this study, while the scene size of the presented results is $20\ \mathrm{km} \times 10\ \mathrm{km}$ in azimuth and range, respectively. It is important to remark that, for the sake of a fairer comparison, the Stripmap resolution has been filtered to match the TOPS one, both in the range (from $150\ \mathrm{MHz}$ to $100\ \mathrm{MHz}$) and azimuth (from $3.3\ \mathrm{m}$ to $18.5\ \mathrm{m}$) dimensions.

2 Interferometric processing issues

This section is dedicated to describe the impact of a residual azimuth coregistration error and the burst mis-synchronization on the interferometric TOPS phase.

2.1 Coregistration

The existence of a Doppler centroid in the signal introduces an azimuth phase ramp in the impulse response of the target. In the presence of a constant azimuth coregistration error a bias will be present in the interferometric phase given by [4]

$$\Phi_{bias}(t) = 2\,\pi \cdot f_{\mathrm{dc}}(t) \cdot \Delta t \tag{1}$$

where $f_{\mathrm{dc}}(t)$ is the Doppler centroid, which in the TOPS case is azimuth variant and dependent on the azimuth time t, and Δt is the coregistration error. Since in TOPS the Doppler centroid varies linearly with azimuth, equation (1) will result in an azimuth phase ramp in the presence of a constant azimuth coregistration error and, consequently in phase jumps between bursts. Taking as example the parameters for Sentinel-1, where a Doppler variation of 5.5 kHz within a burst is present, a coregistration error of 0.1 pixels introduces an azimuth phase ramp of 1.74 π radians within the burst. Therefore, an overall azimuth coregistration accuracy better than 0.001 of the pixel spacing is required for this configuration in order to achieve an error smaller than $3°$. In order to achieve such good coregistration performance it is necessary to follow a proper processing strategy to compensate for the limited orbit accuracy. For Sentinel-1, it is expected to have an orbit accuracy between 5 cm - 15 cm, similar as with TerraSAR-X. Therefore, an error in the along-track position of 5cm corresponds to an azimuth coregistration error of 0.004 pixels, so that it is still necessary to estimate a small residual azimuth coregistration error, which shall be almost constant for the relatively large acquisitions. In order to estimate this residual error the enhanced spectral diversity (ESD) technique introduced in [4] and based on the spectral diversity technique (SD) proposed in [5], has been successfully applied. The basic idea is to exploit the pixels at the overlap region between two consecutive bursts, since they are observed under two different squint angles, whose spectral separation is much larger than the one that can be achieved within the azimuth processed bandwidth. This large spectral separation improves the accuracy of the misregistration estimation allowing one to fulfill the requirements. Therefore, the proposed methodology to perform the image coregistration is to first compute the coregistration offsets using a purely geometrical approach (orbit and DEM), and afterwards apply ESD in order to estimate the residual azimuth coregistration error.

2.2 Burst mis-synchronization

A further aspect related to the burst-mode operation in the TOPS mode is the burst synchronization. Each acquisition of an interferometric pair needs to start on the same along-track orbit position in order to observe the targets under the same squint angle during the sweep of the antenna and, in this way, avoid azimuth spectral decorrelation. The TerraSAR-X SAR instrument has an on-board time correction in order to perform this adjustment, so that the error is kept below 50 m (about 7 ms) [6].
Using typical values for the TerraSAR-X sensor, the spectral shift is about 27 Hz assuming a 50 m along-track positioning error, hence resulting in about a 6% azimuth spectral decorrelation. If the azimuth spectra are not filtered, the spectral decorrelation will introduce a phase bias for point targets and phase noise for distributed scatterers. In the present case, however, the data have not been filtered due to the small mis-synchronization error, an assumption that has a negligible impact in the final results for the present case.

3 PS analysis

The permanent scatterers (PS) technique [1] is an established approach for subsidence monitoring.

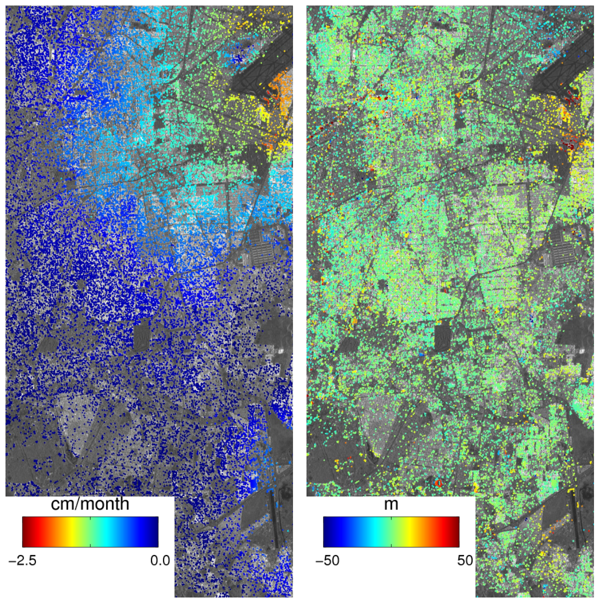

Figure 2: TOPS data set. Estimated (left) mean deformation velocity and (right) DEM error over Mexico City with PS. The top right part of the test site is affected by motion while the rest is mainly stationary.

This section shows the PS results over Mexico City, with the main objective of evaluating the TOPS performance by comparing it with the filtered Stripmap results. The result of the estimation process for the TOPS mode is depicted in **Figure 2**. The selected amplitude dispersion index corresponds to 0.2. The subsidence can be clearly observed, especially at the top right corner where the international airport of Mexico City is located [3]. As expected, most PS are concentrated in the urban area of the site. Concerning the filtered Stripmap data, the results corresponding to the selected part of the TOPS test site are depicted in **Figure 3**. The estimations for the mean deformation and the DEM error are consistent with those obtained with TOPS.

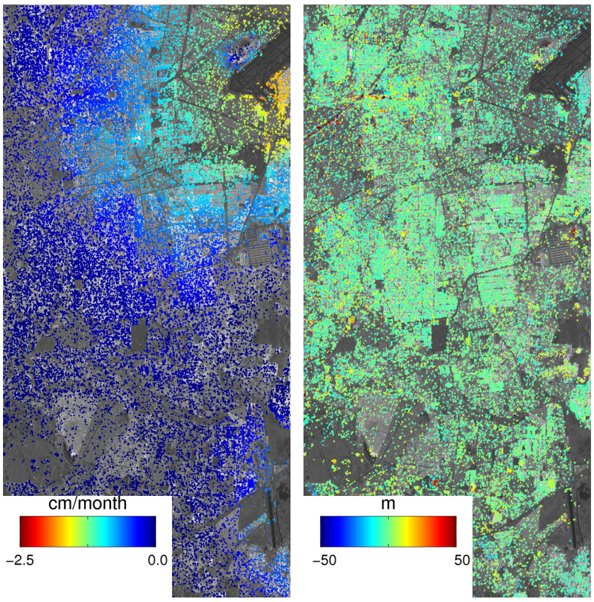

Figure 3: Stripmap data set. Estimated (left) mean deformation velocity and (right) DEM error over Mexico City with PS.

In order to further evaluate the results, the estimated entities are compared for the TOPS-Stripmap common points. **Figure 4** shows the two-dimensional histogram for the mean deformation velocity. Figure 4(left) shows a good agreement between the two estimates, since the points lie on the slope one line.

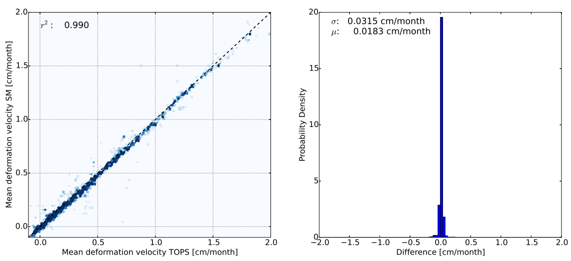

Figure 4: (Left) Two dimensional histogram of the estimated mean deformation velocity for TOPS and Stripmap with PS. (Right) Histogram of the difference between the two estimations.

The minor discrepancies can be attributed to the difference in the number of acquisitions between the Stripmap (36 images) and the TOPS data stacks (27 images) impacting the quality of the estimations. The resulting accuracy in the estimation of the mean deformation rate corresponds to $2.6\ \mathrm{mm/yr}$. It is obtained, for the two independent measurements, by dividing by $\sqrt{2}$ the yearly deviation, noting that the total time span of the time series is roughly two years.

Considering now the DEM error, it is possible to observe from **Figure 5** that the results for both Stripmap and TOPS are consistent. The resulting accuracy in the estimation of the DEM error is about $2.8\ \mathrm{m}$.

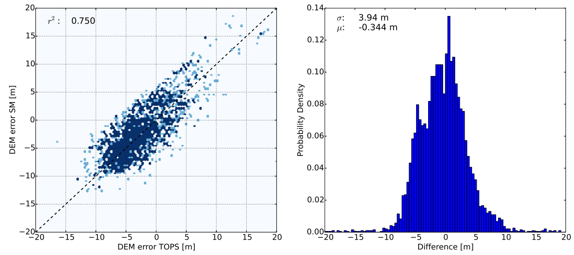

Figure 5: (Left) Two dimensional histogram of the estimated DEM error for TOPS and SM. (Right) Histogram of the difference between the two estimations.

4 SBAS analysis

In this section DInSAR results generated using the SBAS technique [2], following [7] guidelines, are shown. In particular, coherent pixels (CP), which present a certain averaged coherence within the stack, are considered and linked by means of the Delanuay triangulation.

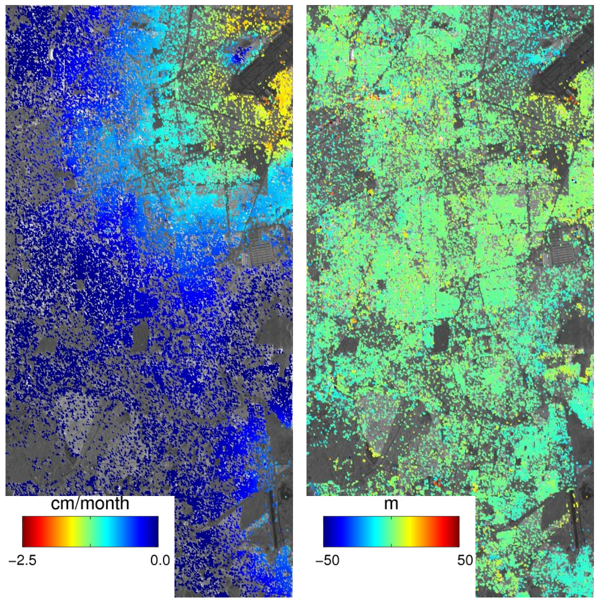

Figure 6: TOPS data set. Estimated (left) mean deformation velocity and (right) DEM error over Mexico City by means of the SBAS technique.

The stack of images has been generated by fixing a maximum perpendicular and temporal baselines of $300\ \mathrm{m}$ and 120 days, respectively. The temporal separation has been restricted to that amount because of the large subsidence rate in some city areas, and in this way range spectral decorrelation is avoided. As a result of the imposed temporal and spatial baselines, the TOPS and Stripmap stacks are composed of 89 and 137 interferograms, respectively. **Figures 6** and **7** show the deformation and DEM error estimation with SBAS for TOPS and Stripmap, respectively. As it can be observed, the two estimations are similar.

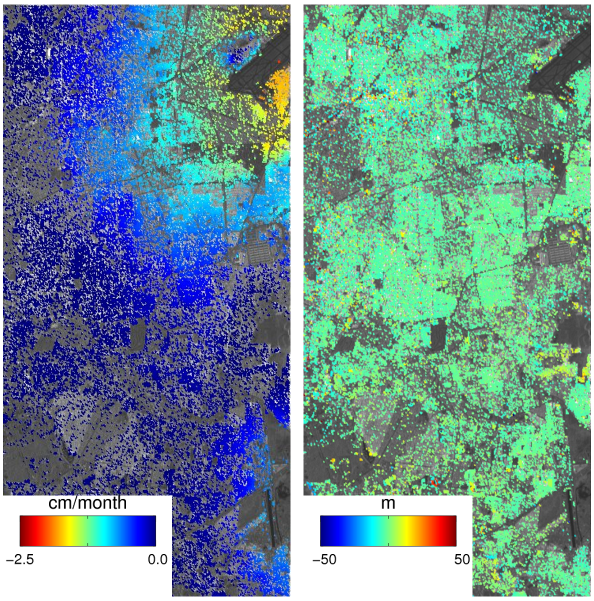

Figure 7: Stripmap data set. Estimated (left) mean deformation velocity and (right) DEM error over Mexico City by means of the SBAS technique.

As discussed in Section 3, a more accurate comparison of the estimations can be quantitatively achieved by evaluating for each common CP, the difference in the estimates for TOPS and Stripmap. **Figures 8** and **9** summarize those results.

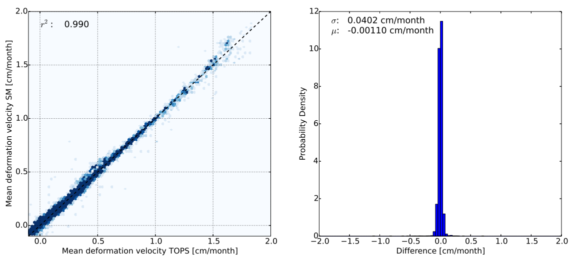

Figure 8: (Left) Two dimensional histogram of the estimated mean deformation velocity for TOPS and Stripmap by means of the CP technique. (Right) Histogram of the difference between the two estimations.

It can be observed that also for this case the estimations carried out with different data are consistent with each other. The final accuracy in the estimation of the mean deformation rate and the DEM error is $3.4\ \mathrm{mm/yr}$ and $2.22\ \mathrm{m}$, respectively, being consistent with the results obtained with PS shown in the previous section.

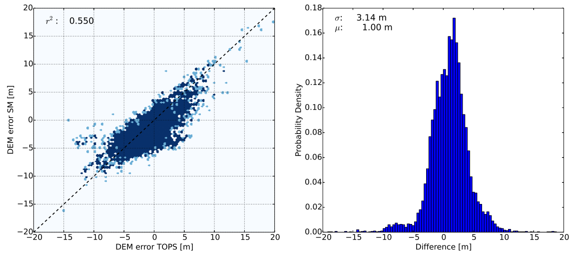

Figure 9: (Left) Two dimensional histogram of the estimated DEM error for TOPS and SM by means of the CP technique. (Right) Histogram of the difference between the two estimations.

5 Conclusions

In this paper the DInSAR performance of the TOPS mode has been investigated and compared with Stripmap by exploiting both the PS and SBAS techniques. Independently on the DInSAR processing philosophy used and on the acquisition mode, the results have shown to be consistent with each other. It is possible to conclude that, once the TOPS requirements in terms of interferometric coregistration are fulfilled, the achievable performance of TOPS time series analysis for subsidence monitoring basically corresponds to that of Stripmap. In this sense, no artifacts in the estimations have been observed for the area under study. As a final remark, the performance of TOPS DInSAR in the presence of shifts in the azimuth direction is currently being investigated. Note that in this case the residual azimuth shift cannot be assumed to be constant for the whole scene, hence preventing the use of ESD, since such measurement is only locally available on the overlap region. Current investigation results for non-stationary scenarios experiencing azimuth displacements can be found in [8] and [9].

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