TIME-SERIES ANALYSIS OF SENTINEL-1 INTERFEROMETRIC WIDE SWATH DATA: TECHNIQUES AND CHALLENGES

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ABSTRACT

Sentinel-1 IWS interferometric time-series analysis (SBAS and PSI) is discussed and results over Mexico City, a mega-city subject to very substantial ground deformation, are presented. In the early steps the processing needs to be adapted to the organization of the data in sub-swaths and burst, and for the SLC co-registration an extremely accurate co-registration is required for interferometry, because of the strong along-track Doppler centroid variation. Furthermore, a deramping of the co-registered SLC for an along-track phase ramp present in each burst is applied. After that interferometric time-series techniques (SBAS, PSI) can be applied in the same way as for stripmap mode data.

Index Terms— Sentinel-1 IWS, TOPS, interferometric time-series analysis, SBAS, PSI, Mexico City, subsidence.

1. INTRODUCTION

In 2014 the Sentinel-1A satellite was launched as part of the EU/ESA Copernicus Program. One of the novelties of the Sentinel-1 SAR (S1) mission is that the satellite is mainly operated in the so-called TOPS mode [1]. TOPS stands for Terrain Observation with Progressive Scans in azimuth, but the word is also the reverse of SPOT and actually the beam scanning done is the opposite of the scanning done in spotlight mode. One of the strengths of ScanSAR modes is that wide areas can be covered. In the Interferometric Wide-Swath (IWS) mode of S1 the width of the strips is about 250km. S1 is operated at C-band with an orbit repeat cycle of 12 days. In combination between S1A and S1B this results in a repeat interval of only 6 days. The orbital tube is very narrow (of the order of 100m) and the TOPS mode bursts are almost perfectly synchronized. As a result S1 IWS data are well suited for interferometric SAR (InSAR).

In the interferometric processing of S1 IWS data an extremely precise co-registration in the azimuth direction is required because of the strong Doppler centroid variation within each burst which results in a large Doppler centroid difference at the interface between subsequent bursts [2]. Even a very tiny azimuth co-registration error of 0.01 pixel leads to significant phase jumps between adjacent bursts in the resulting interferogram. Spectral diversity techniques [3] permit refining the co-registration to the required level considering in the burst overlap area the difference between the interferometric phases of the two overlapping bursts.

Once the SLC data stack is co-registered at the required accuracy a time-series analysis can be conducted using Persistent Scatterer Analysis (PSI).

In the following Sections we first describe the S1 IWS co-registration and PSI procedures used. All the processing discussed was done using GAMMA Software (http://www.gamma-rs.ch/software). After this we present and discuss results over Mexico City, as well as our experience gained and challenges encountered with S1 interferometric time-series analysis.

2. S1 IWS CO-REGISTRATION

The processing strategy used for the co-registration of a pair of S1 TOPS SLC is very important because interferometry with S1 TOPS data requires an extremely precise co-registration of the SLC pairs. In the azimuth direction an accuracy of a few thousandths of a pixel is absolutely required, otherwise phase jumps between subsequent bursts are observed.

To meet the required very high co-registration accuracy we calculate a transformation lookup table that also considers effects of the terrain topography. Furthermore, we iteratively refine this transformation using first a matching procedure and then a spectral diversity method. The refinement determined is only a constant offset in slant range and in azimuth - the same correction is applicable for all bursts and all sub-swaths.

Using matching techniques this is done to an accuracy of the order of 0.01 pixel. Often this step would not really be necessary as the orbit and DEM based transformation is already at this accuracy, when using the S1 precision state vectors available from ESA some days after the acquisition of the data (see https://qc.sentinel1.eo.esa.int/aux_poeorb/). Nevertheless, for quality control and robustness we typically keep determining this matching offset in our processing.

Then the spectral diversity method that considers the interferometric phase of the burst overlap regions is applied. Each available burst overlap region within the data set is considered. The small double difference interferograms for the overlap regions are calculated and unwrapped. Based on their coherence and phase statistics weights are determined and used in the weighted averaging of the unwrapped double difference phases. The resulting average phase is then converted to an azimuth offset. Typically, this estimation is iterated once or twice until the residual correction in azimuth direction falls below a 1/2000 of an azimuth pixel.

2.1. S1 TOPS IW1 SLC phase correction for an ESA processor update effect

As a consequence of an S1 processor update around 15-Mar-2015 a phase anomaly relevant for interferometry using IWS data was observed. For S1 IWS interferograms between a scene acquired before 15-Mar-2015 and one acquired after this date, a constant phase offset of 1.25 radian was observed at the interface between the sub-swaths IW1 and IW2. This anomaly is corrected by adding a constant phase offset to the IW1 sub-swath SLC of the scene acquired before 15-Mar-2015.

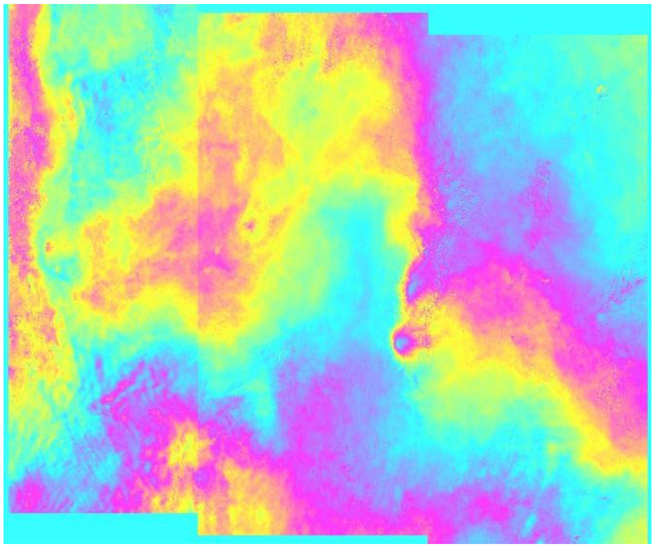

Figure 1 S1 IWS differential interferogram in slant range geometry over Mexico City, 8-Mar-2015 and 20-Mar-2015. One color cycle corresponds to one phase cycle. The data was not corrected for the ESA processor update effect discussed in the text and consequently a phase jump of about 1.25 radian is observed between IW1 and IW2.

3. S1 IWS INTERFEROMETRIC TIME-SERIES ANALYSIS

There is a broad range of different interferometric time series analysis approaches, using either single or multi-looked interferometric phase and using either single reference or multi reference stacks to derive the deformation time series. For early tests with S1 IWS data we used a stack over Mexico City, consisting of a relatively small number of 12 repeat observations [4]. Because of the small stack and the very significant ground motion in the Mexico City area we used at the time multi-reference stacks for both the SBAS and PSI processing done. In the following we describe this initial SBAS processing done as well as a PSI processing that was updated considering further S1 acquisitions. At present (Dec. 2015) the stack available includes 35 scenes, but significantly more scenes are expected until IGARSS’2016 in July 2016.

As input to the time series analysis we co-registered all the S1 IWS SLC to one selected reference scene. This was done using the procedure described in section 3, including the refinement with the spectral diversity method and applying a phase correction to the IW1 SLC for the processor update effect discussed in Section 2.1. The differential interferogram mosaics without visible phase jumps at burst interfaces and between sub-swaths and with generally very high coherence over urban areas confirm the quality of the co-registered SLC stack.

3.1. SBAS time series analysis over Mexico City

We followed an SBAS procedure similar to the one described in [5,6]. In particular we considered multi-looked differential interferometric phases using 10 range and 2 azimuth looks. For the entire stack all the baselines are below 250m and so all spatial baselines are short. To maximize the temporal coherence but also to facilitate the phase unwrapping by minimizing the deformation phase we considered the shortest time intervals possible. As we wanted to include redundant observations we decided to include all pairs between scenes that are up to 3 positions away from each other in the time series (i.e. 1-2, 1-3, 1-4, 2-3, 2-4, 2-5, 3-4, …), which resulted in a total of 30 pairs for the initial stack of 12 scenes.

For each pair we calculated the differential interferogram using the SRTM height as topographic reference and unwrapped the phase. The unwrapped phases were then converted to a time-series using a weighted least-squares algorithm that minimizes the sum of squared weighted residual phases. The residuals are the differences between input phases (the observations) and the differential phases derived from the time-series solution. Smoothing of the time series solution is achieved by introduction of constraints on the change in velocity [7]. Besides, height corrections were simultaneously estimated. The phase standard deviation from the time series is used to identify areas where an unwrapping error occurred and mask those from the solution. The main results are the average deformation rate and the deformation time series (Figures 2,3). Converting the line-of-sight values to a vertical displacement rate (assuming the movement is in the vertical direction) we observed subsidence rates up to more than 40cm/year. No anomalies were observed at the interface between subsequent bursts or between adjacent sub-swaths.

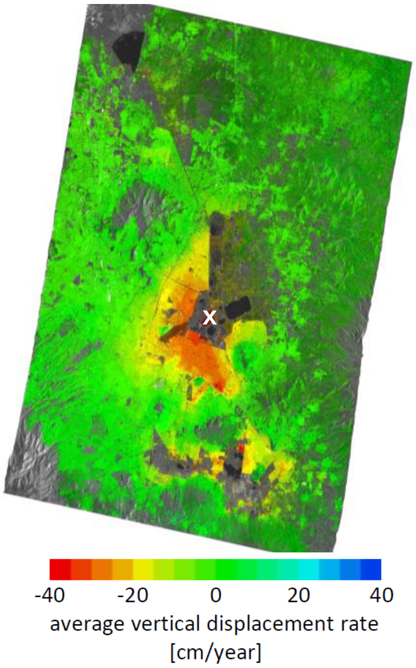

Figure 2 Average vertical displacement rate derived from a stack of 12 S1 IWS SLC over Mexico City using an SBAS procedure (linear color scale)

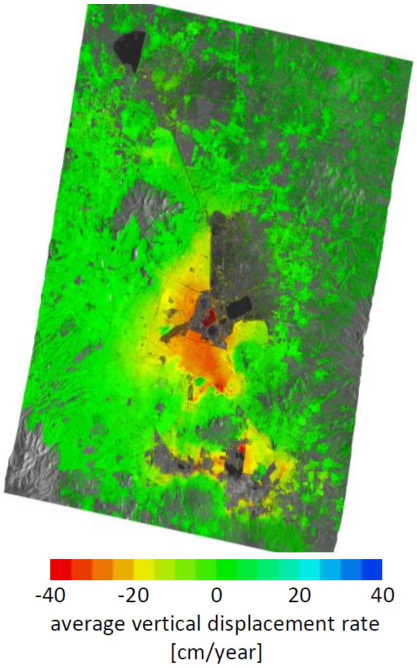

Figure 4 Average vertical displacement rate derived from a stack of 22 S1 IWS SLC over Mexico City using an PSI procedure (linear color scale)

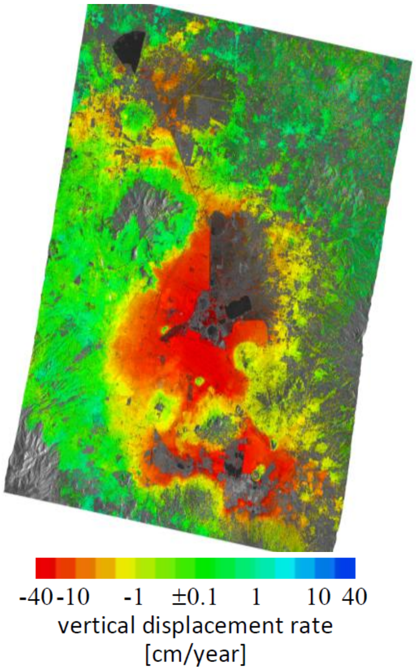

Figure 5 Average vertical displacement rate derived from a stack of 22 S1 IWS SLC over Mexico City using an PSI procedure (logarithmic color scale).

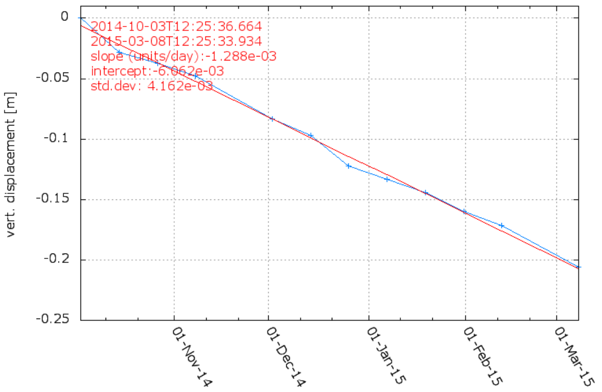

Figure 3 Displacement history of an area near the international airport (see white x in Figure 2) derived using the described SBAS procedure.

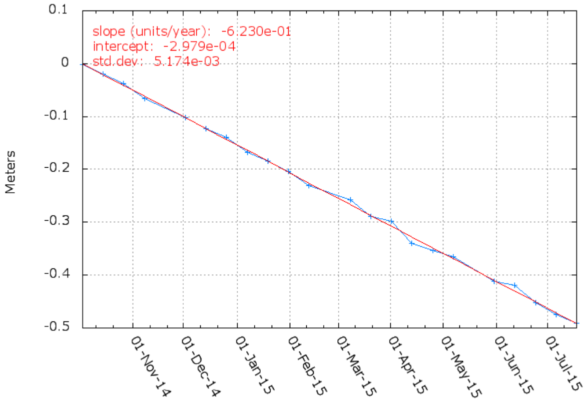

Figure 6 Displacement history of an area near the international airport (see white x in Figure 2) derived using the described PSI procedure.

3.2. PSI time series analysis over Mexico City

Using the co-registered deramped SLC mosaic stack over Mexico City a PSI processing was done in the same way as for conventional stripmap mode data. In the identification of persistent scatterer candidates, we applied a spectral diversity criteria as well as criteria on the backscatter variability and level [8]. To be able to use the spectral diversity method available in the GAMMA software for the identification of point-like scatterers it was necessary to deramp the SLCs for the azimuth spectral trend.

Thanks to the good range resolution of the S1 IWS SLC a relatively high number of suited persistent scatterers is found in urban areas. To make the PSI processing more efficient, especially when processing large areas, we initially reduced the candidate list size using a point-density-adaptive methodology described in [9]. The data for the point candidates are stored as vector data stacks making the processing much more efficient.

The average deformation rate derived in the PSI processing (Figures 4) corresponds closely to the result of the SBAS processing (Figure 2). To better visualize the result at low deformation rates a logarithmic color scale is used in Figure 5. This clearly shows significant deformation also to the north and south of the main subsidence bowl. Furthermore, considering stable areas shows that mm/year precision is not reached with this C-band stack of 22 scenes between October 2014 and July 2015. 2) These Sentinel-1 IPTA based average deformation rates are affected by a significantly higher noise than what we are used to from ASAR based result. The reason for this is the much shorter total time span covered by the data in the Sentinel-1 case (< 1 year as compared to 5 years). Nevertheless, the observed noise of the order of 1-3mm/year, seems acceptable in this area that includes fast deformation rates up to several dm/year.

In the Mexico City PSI result no anomalies were observed at the interface between subsequent bursts.

4. CONCLUSIONS

Sentinel-1 IWS interferometric time series analysis (SBAS and PSI) procedures applied and results obtained over Mexico City, a mega-city subject to very substantial ground deformation, were presented. The main differences to "normal" strip map mode data are the organization of the IWS SLC data in 3 sub-swaths and by burst. Because of the strong along-track Doppler Centroid variation, an extremely accurate co-registration is required for interferometry to avoid phase jumps between consecutive bursts. The results achieved confirm that the S1 IWS data are well suited for interferometry and interferometric time series analysis.

Besides the presented SBAS and PSI approach other time series approaches, e.g. working with a single reference stack or methods combining single and multi-look interferometric phases [10] are also applicable, especially with larger stacks becoming available.

The applicability of interferometric time series analysis was found to be good with some advantages over former C-band sensors as ENVISAT ASAR thanks to the shorter time interval (12-day at present with S1A, 6-day in the future in combination between S1A and S1B), the overall short spatial baselines (< 250m), and the high slant range resolution (2.3m) of the S1 IWS data.

5. ACKNOWLEDGMENTS

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