The PSIG chain: an approach to Persistent Scatterer Interferometry

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ABSTRACT

The PSIG procedure is a new approach to Persistent Scatterer Interferometry (PSI), which is implemented in the in-house PSI chain of the Geomatics Division of the CTTC. The PSIG procedure has been successfully tested over urban, rural and vegetated areas using X-band SAR data. This paper briefly describes the main steps of the procedure, mainly focusing on the two key processing steps of the approach. The first one is a selection of Persistent Scatterers (PS) consisting in a candidate Cousin PS (CPS) selection based on a phase similitude criteria that allows a correct phase unwrapping and a phase unwrapping consistency check. The second key element is a 2+1D phase unwrapping algorithm, which consists in a 2D phase unwrapping followed by a 1D phase unwrapping that allows the detection and correction of unwrapping errors. The results of the CPS selection and the 2+1D phase unwrapping obtained using a stack of 28 TerraSAR-X StripMap images over the metropolitan area of Barcelona are shown.

Keywords: Persistent Scatterer Interferometry; phase unwrapping; deformation measurement.

1. INTRODUCTION

Persistent Scatterer Interferometry (PSI) is a group of powerful techniques for deformation measuring and monitoring using interferometric Synthetic Aperture Radar (SAR) imagery. PSI represents an advanced type of Differential Interferometric SAR (DInSAR) techniques: it is based on large stacks of SAR images and suitable data modelling procedures that allow the estimation of different parameters. These parameters include the deformation time series, the average displacement rates and the so-called residual topographic error. Several approaches to PSI techniques have been proposed in the last 15 years, e.g. see [1-6]. This paper describes the PSIG processing chain [7], implemented at the Geomatics division of the CTTC. It includes three main processing blocks. In the first one, a set of correctly unwrapped and temporally ordered phases are derived. The key element of this block is given by the so-called Cousin PSs (CPSs), which are PSs characterized by a moderate spatial phase variation that ensures a correct phase unwrapping. This block makes use of flexible tools to check the consistency of phase unwrapping and guarantee a uniform CPS coverage. In the second block the above phases are used to estimate the atmospheric phase screen (APS) by means of a set of spatio-temporal filters [1-3,5]. The APS is later removed from the original unwrapped interferograms. The third block is used to derive the PS deformation velocity and time series. The key tool of this block is a new 2+1D phase unwrapping algorithm. The procedure offers different tools to globally control the quality of the processing steps. The PSIG procedure has been successfully tested over urban, rural and vegetated areas using X-band PSI data.
This paper focuses on the two key steps of the PSIG chain: the CPS selection and the 2+1D phase unwrapping. Section 2 describes the CPS selection step, section 3 is devoted to the 2+1D phase unwrapping and section 4 describes the main outputs of this last PSIG chain step and discusses the results obtained using 28 TerraSAR-X StripMap images over the metropolitan area of Barcelona. Finally, the conclusions are presented in section 5.

2. CPS SELECTION

This section is devoted to the selection of the so-called cousin PSs (CPSs), which are points characterized by moderate phase variation that allow obtaining a set of correctly unwrapped and temporally ordered phases that are then used to estimate the APS. The CPS selection consists in a candidate CPSs selection step, which is based on an iterative phase similitude criterion that works at full resolution and is suitable to cover wide areas, and a posterior phase unwrapping consistency check. These two main steps are described in next subsections.

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2.1 Candidate CPS selection

The CPS selection is based on an iterative search propagation criterion and a condition of phase similarity. The procedure starts with the selection of at least one seed PS located on the ground, with no motion or thermal expansion and characterized by small noise, i.e. with negligible contribution of the mentioned terms to the interferometric phase. The candidate CPSs are those PS candidates that satisfy the following condition:

$$\left|\Delta\varphi_{i,SEED}^{unw}\right|_{90\%} < Thr \tag{1}$$

where $\left|\Delta\varphi_{i,SEED}^{unw}\right|_{90\%}$ is the 90th percentile of the unwrapped phase differences between the seed and the ith PS candidate over the minimum independent interferogram configuration network, and *Thr* is the phase difference threshold. The phase differences are unwrapped following the simple rule of adding or subtracting 2π in such a way that the absolute value of the difference is $< \pi$. The operation is performed over a pre-selected set of PS candidates that fall within a given window. This pre-selection of points is performed using the DA criterion [1,2], i.e. a high DA threshold value is chosen to speed up the computation time. The window size is set to minimize the atmosphere contribution to the interferometric phase differences. The procedure is repeated recursively, using the new candidates CPSs as seeds and testing each point only once, until the area of interest is sufficiently covered by CPSs. Additional seeds might be required in order to cover isolated areas or to increase the CPS density in given areas.

The most important parameter of the candidate CPS selection is *Thr*, which is defined as a function of the distance from the seed to account for the APS effects. The choice of this value is a trade-off between low phase variation, which ensures a correct phase unwrapping, and the need to connect all parts of a given area of interest. This is critical when the area of interest includes rural and vegetated areas where the PS density can be very low.

Figure 1 shows the performance of the candidate CPS selection using 28 TerraSAR-X images over the metropolitan area of Barcelona using 9 seeds and a *Thr* defined with the following values: 0.8 rad at a distance of 0 m, 1.1 rad at 100 m, 1.35 rad at 200 m and 1.52 rad at 300 m. A total of 611 813 candidate CPS were selected in an area of 1019 km^2, i.e. a mean density of 600 candidate CPS/km^2 was obtained, see Figure 1a. All the urban areas of the full scene were homogeneously covered and connected, as shown in Figure 1b, where the zooms over the roads connecting different urban nucleus are presented. 87% of the candidate CPS satisfied the condition of the phase unwrapping consistency check, i.e. the final CPS set includes 532 277 points.

2.2 Phase unwrapping consistency check

In this second step, the phase unwrapping is performed over the selected candidate CPSs. The phase unwrapping is performed spatially, interferogram by interferogram, over the M interferograms, using an implementation of the Minimum Cost Flow [8,9]. A phase unwrapping consistency check is performed to determine if the unwrapping has been correctly performed over the selected CPS candidates. The CPSs that satisfy this check constitute the final network of CPSs. The check uses a pixel wise Least Square (LS) estimation based on the following observation equation:

$$\Delta\varphi_{MS} = \varphi_S - \varphi_M \tag{2}$$

where $\Delta\varphi_{MS}$ is the unwrapped interferometric phase (the observation), *S* and *M* are the slave and master images and φ_S and φ_M are the corresponding unknown phases.

For each pixel, a system of M equations with N-1 unknowns can be written, where M is the number of interferograms and N is the number of images. The phase of the first image φ_0 is set to zero, due to the differential nature of the observations. The system of observation equations can be expressed as:

$$b = A \cdot x \tag{3}$$

where *b* is the M-dimensional observation vector, *A* is the design matrix that expresses the set of scalar equations in matrix form and *x* is the N-1 dimensional vector of unknowns. A stochastic model is associated with the functional model, which is represented by weight matrix *P*. The LS solution is given by:

$$\hat{x} = -(A^t \cdot P \cdot A)^{-1} \cdot A^t \cdot P \cdot b \tag{4}$$

where $\hat{x}$ is the vector of estimated unknowns.

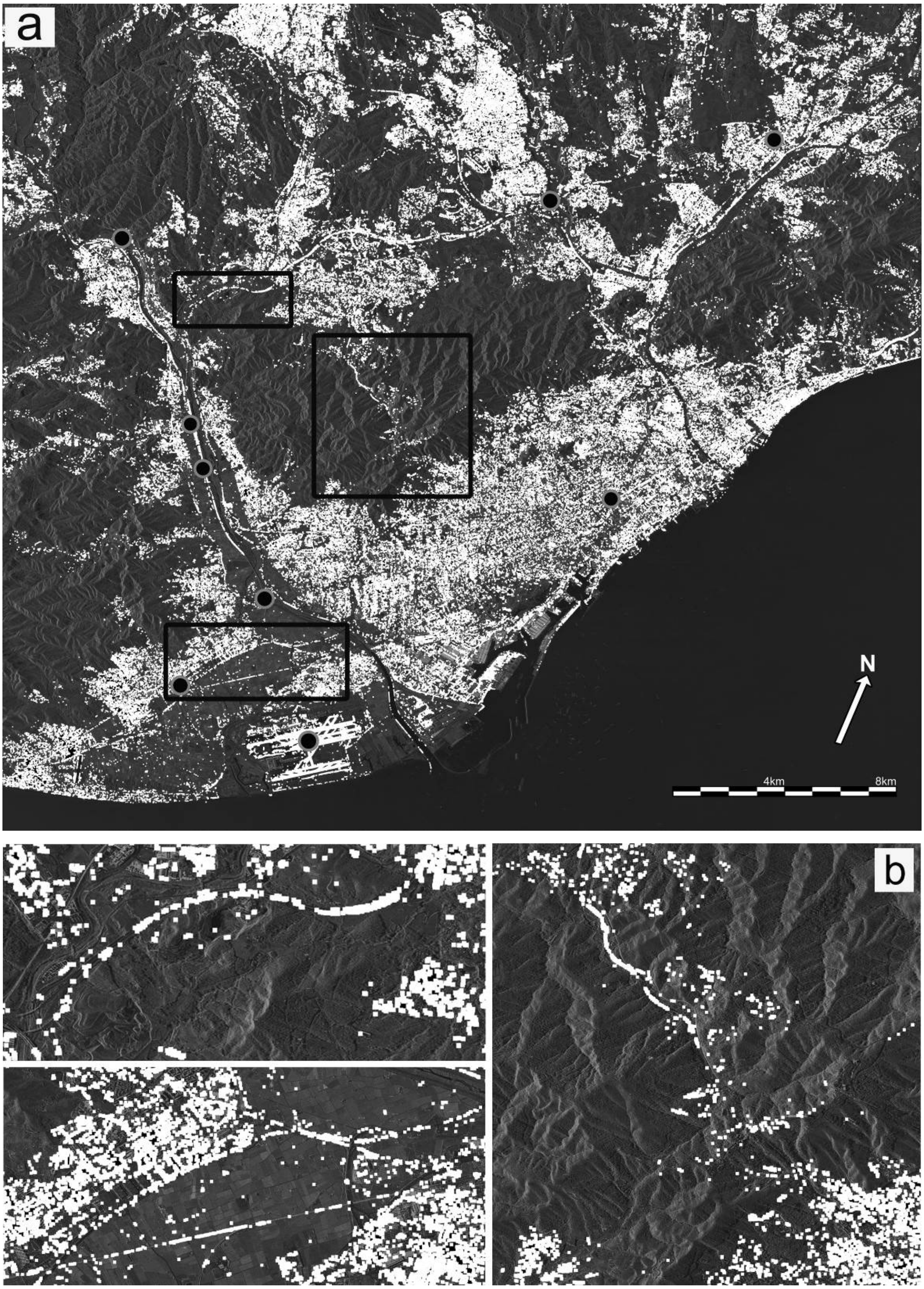

Figure 1. a) Distribution of candidate Cousin PSs (CPSs) selected over an area of 1019 km^2 were 611813 candidate CPSs (white points) were found from 9 seeds (black points). b) Zoom of the squares shown in Figure 1a.

The vector of the a posteriori estimated observations $\widehat{b}$ are re-estimated from $\widehat{x}$, and the residual vector $\widehat{\varphi}_{res}$ is derived:

$$\widehat{b} = A \cdot \widehat{x} \tag{5}$$

$$\widehat{\varphi}_{res} = b - \widehat{b} \tag{6}$$

A candidate CPS is finally selected if the vector of residuals satisfies the following condition:

$$\widehat{\varphi}_{res} = \vec{0} \tag{7}$$

This condition ensures a spatial and temporal consistency of the phase unwrapping. A check of the distribution of the CPSs needs to be carried out to ensure a homogeneous density over the entire area of interest. If this is not accomplished, the procedure is resumed using new seeds to look for new candidate CPSs.

3. 2+1D PHASE UNWRAPPING

The 2+1D phase unwrapping is the last step of the PSIG chain. Its goal is to retrieve the deformation time series (TS) of the densified net of PSs and some quality index tools of the estimations. A spatial 2D phase unwrapping is performed separately on each interferogram using the Minimum Cost Flow method [8,9]. Following this step, a 1D phase unwrapping is performed pixel wise over the M interferograms. This last step is able to detect and correct the errors generated in the 2D phase unwrapping stage, and provides tools to control the quality of the derived TS. For this purpose, it uses an iterative LS procedure [10-12], which fully exploits the integer nature of the unwrapping errors. It is based on the estimation of the following system of equations:

$$\Delta\varphi_{MS} = \widetilde{\varphi}_S - \widetilde{\varphi}_M \tag{8}$$

$$\widetilde{\varphi}_0 = 0 \tag{9}$$

The system is solved by means of an iterative LS driven by two key parameters: the residuals $\widehat{\varphi}_{res}$ and the redundancy of the network. The residuals of the first LS estimation are computed and used to select the outliers candidates (the highest absolute residuals), which are removed from the network. A new LS estimation is performed: if the residual of the outlier candidate is multiple of 2π, the observation is corrected and reaccepted. In this way, it is possible to correct the unwrapping errors. Otherwise, the decision of re-entering or rejecting the outlier candidate is based on the comparison of its old and new residuals. A new LS is performed again, computing the residuals and restarting the procedure, which is executed iteratively until there are no remaining outlier candidates. Thus, the correction of the unwrapping-related errors is extended to all the residuals that, within a given tolerance, are multiple of 2π.

The core of the proposed algorithm is given by the so-called redundancy matrix R. The LS is not a robust estimation method, considering that a given error is spread out through the network according to the characteristics of A and P. In order to identify correctly the residuals that are multiple of 2π, it is necessary to analyse how the errors are distributed in the network. This is contained in the redundancy matrix R [11]:

$$R = I - A \cdot (A^t \cdot P \cdot A)^{-1} \cdot A^t \cdot P \tag{10}$$

R is only related to A and P, i.e. it is not affected by the observation vector. This matrix is used to correct the LS residuals by the redundancy of the corresponding observations:

$$\widehat{\varphi}^*_{res\_i} = \frac{\widehat{\varphi}_{res\_i}}{r_{ii}} \tag{11}$$

where $\widehat{\varphi}^*_{res\_i}$ is the corrected ith residual and r_{ii} is the ith diagonal element of R, which is called the local redundancy. The procedure to correct the unwrapping errors explained above is performed on the corrected residuals. If there is sufficient system redundancy, the LS spreading of errors is mitigated and the unwrapping errors are properly identified. However, it is worth emphasising that this requires that the majority of the interferograms connected to a given image are correctly unwrapped. The algorithm checks the available local redundancy at each iteration and leaves a given outlier candidate untouched if its redundancy is too low. If this occurs, the corresponding parts of the network have to be checked off-line after concluding the automatic analysis. That is, the 1D phase unwrapping only works over the redundant parts of the analysed network.

4. 2+1D PHASE UNWRAPPING OUTPUTS

In addition to the TS, the 2+1D phase unwrapping step creates some outputs that allow to check the quality of the measurements: (i) the plots of the residuals at the first and last iterations, (ii) the number of observations corrected per point and (iii) a 3-class quality index associated with each deformation time series, defined as "Good", "Fair" and "Warning". They are derived, per each image of a given time series, by computing the ratio (Cor_%) between the corrections and the interferograms connected with the image at hand. The following classes are used: "Good" indicates that Cor_% is less than 30% for all the images; "Fair" is when Cor_% is between 30 and 40%; and "Warning" is when at least one image has Cor_% above 40%.

The 2+1D phase unwrapping outputs obtained from the set of 28 TerraSAR-X Stripmap images over the metropolitan area of Barcelona are discussed. The 2+1D phase unwrapping was performed over 375 interferograms generated from the stack of 28 images covering the period 2007-2009. The PS time series and the above mentioned quality check tools were derived over a dense network of 5.4 million PSs. More than 30 major deformation phenomena were found over the entire frame, with several examples of deformation caused by soil compaction, water abstraction, landslides, underground construction works (metro line and metro stations), etc. They represent a valuable source of information, together with the quality index map of the mentioned areas, useful to obtain a preliminary and concise overview of the quality of the estimated PSs. 98.4% of the PSs are classified as "Good", while 1.2% are "Fair" and 0.38% "Warning". The "Fair" and "Warning" PSs are in some cases clustered over deformation areas and isolated (*i.e.*, not well connected) areas, where the phase unwrapping is more error-prone. The rest of them are scattered points, most probably caused by noisy PSs.
It is worth comparing the proposed 2+1D phase unwrapping method with the classical LS solution, i.e. the LS solution without outlier rejection. The classical LS solution yields the following results: all residuals are zero for 85% of the PSs, i.e. both solutions coincide; while the rest of PSs have at least one aliasing that affects the time series estimation. By contrast, this does not occur in the 2+1D phase unwrapping solution, which properly detects and corrects the unwrapping errors. Figure 2 shows four examples of corrected TSs, where the first iteration TSs is represented with triangles and the last iteration with circles. The number of corrected observations per image is represented with squares. The first example corresponds to a "Good" PS and the other examples are "Fair" PSs. The examples shown at the top correspond to stable PSs, while the examples at the bottom show PSs displaying displacements away from the satellite. The TSs were properly corrected in the last iteration in all cases.

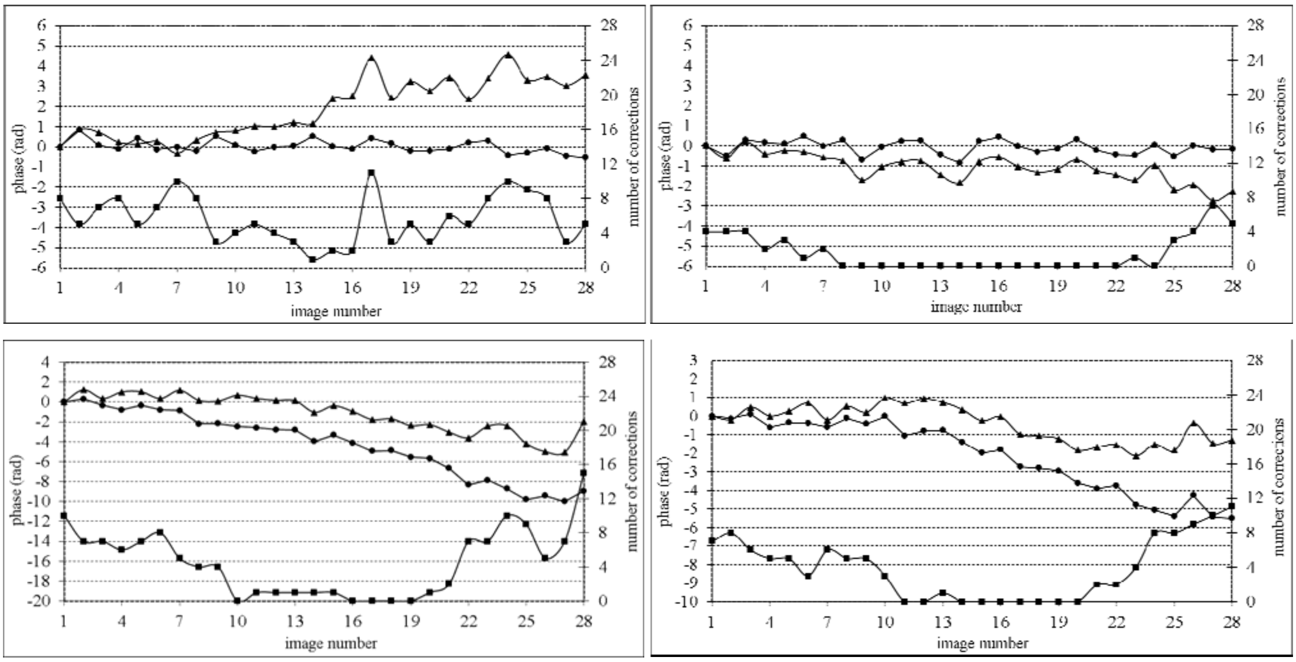

Figure 2. Examples of time series produced at the first iteration (triangles), last iteration (circles) and the associated corrections per image (squares). These examples were derived from a network of 28 TerraSAR-X StripMap images over the metropolitan area of Barcelona.

5. CONCLUSIONS

In this paper, the two main processing steps of the PSIG chain have been described in detail: the CPS selection and the 2+1D phase unwrapping. An overview of the PSIG chain has been provided. It consists of three main processing blocks. In the first block, a set of unwrapped and temporally ordered interferometric phases are derived. The second block uses the above phases to estimate the atmospheric phase screen by means of a set of spatio-temporal filters. The PS deformation velocity map and time series are estimated in the third block over a densified network of PSs using the APS filtered interferograms.

The key steps of the first block are the candidate CPS selection, based on a phase similitude criterion, and a phase unwrapping consistency check. The results of the candidate CPS selection obtained over the entire TerraSAR-X StripMap Barcelona scene have been presented. In this case, 611813 candidate CPSs were selected in an area of 1019 km^2, i.e. a mean density of 600 candidate CPS/km^2 was obtained. 87% of the candidate CPS satisfied the condition of the phase unwrapping consistency check, i.e. they were included in the CPS network.

The 2+1D phase unwrapping algorithm is the key tool of the third processing block. This algorithm is a 2D phase unwrapping that uses the Minimum Cost Flow method and a 1D phase unwrapping that allows detecting and correcting the errors generated during the 2D phase unwrapping stage. The procedure provides tools to control the quality of the derived TS. Some results over the Barcelona TerraSAR-X dataset have been presented and analysed.

ACKNOWLEDGEMENTS

This work has been partially funded by the Fundación Ciudad de la Energía (http://www.ciuden.es). 20 of the 28 TerraSAR-X SAR images used in the Barcelona case study were acquired within the Project “Evaluation of DEM derived from TerraSAR-X data, LAN0634”, of the TerraSAR-X Science Service Program.

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