COMPARISON OF TWO METHODS IN MULTI-TEMPORAL DIFFERENTIAL INTERFEROMETRY: APPLICATION TO THE MEASUREMENT OF MEXICO CITY SUBSIDENCE

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ABSTRACT

In multi-temporal InSAR processing, both the Permanent Scatterer (PS) and Small BAaseline Subset (SBAS) methods are optimized to obtain ground displacement rates with a nominal accuracy of millimetres per year. The PS approach extracts deformation signals on point targets by modelling and analyzing their phase value that remains stable in time for all interferograms performed with a common master image. The SBAS approach is developped to maximize the spatial and temporal coherence by construction of small baseline interferograms. In this paper, we evaluate the performance of both approaches, their limitations and their complementarity through an inter-comparison. We apply both the Gamma-IPTA chain (PS approach) and the SBAS approach developped by Lopez-Quiroz et al. on 38 ENVISAT images from November 2002 to March 2007 to map the Mexico City subsidence. The subsidence rate maps obtained by both approaches are compared quantitatively and analysed at different steps of the PS approach. The difference is partly explained by errors in the spatial integration of subsidence rates in the PS approach. At a local scale, outside subsiding area, the difference standard deviation drops to 0.9 mm/yr, close to the nominal accuracy of both approaches. On the other hand, within the subsiding area, it increases to 3.6 mm/yr, that may be partly interpreted as punctual differential subsidence between various human-made structures unseen by the SBAS approach.

Key words: PS, SBAS, comparison, subsidence.

1. INTRODUCTION

Differential interferometry, using the phase difference between two radar images taken at two different dates and a digital elevation model (DEM), provides a measure of the ground movement with a pluri-centimetre accuracy. This technique has been successfully applied to the monitoring of landslides, earthquake deformations, volcanic activities and urban subsidence. However, its main limitations result from DEM errors, atmospheric propagation delays of the radar wave and decorrelation due to the increase of the temporal and spatial baseline between satellite passes. To overcome these difficulties and produce long time series of ground motion, the PS (Permanent Scatterer) and the SBAS (Small BAaseline Subset) approaches have been developed. The Permanent Scatterer technique has been developed in the late 1990s by Ferretti et al. [1] in order to overcome...
the major limitations of traditional differential interferometry: the temporal and geometric decorrelation and variations in atmospheric conditions. This technique distinguishes itself from other SAR interferometric processing by the fact that it uses a single master image to generate a stack of differential interferograms with all acquired images without limitations in temporal or spatial baselines. PS candidates, which a priori carry reliable phase information across the interferogram stack, are selected based on their backscattering properties. On these points, the PS technique adopts essentially a model-based, temporal unwrapping strategy. Accordingly, a priori information on the displacement is necessary, from which a deformation model can be established. In this model, the average velocity of the displacement and the DEM error are considered as two major parameters. As temporal unwrapping is performed on local phase differences, the PS approach includes schemes to integrate in space relative displacement rates and DEM errors.

The SBAS approach [2] [3] [4] [5] aims at increasing the spatial coverage over which one extracts reliable phase delay time series by selecting other pixels than "point-like" targets. To maximize coherence, interferograms are computed for image pairs separated by small temporal and spatial baselines. Interferograms form a redundant network linking between themselves images in the temporal and spatial baselines space. Decorrelation noise in interferograms is partly removed by range filtering of the non-overlapping part of the bandwidth spectrum and by applying a spatial filter. Interferograms are then spatially unwrapped. The inversion of the whole set of interferograms by Singular Value Decomposition (SVD) allows to obtain phase delay time series.

In both PS and SBAS approaches, further steps are generally designed to filter out residual orbital trends, stratified atmospheric delays and turbulent atmospheric patterns. In this paper, we apply both approaches on 38 ENVISAT images from November 2002 to March 2007 centred on the Mexico City basin. The subsidence in Mexico basin is characterized by its wide spatial extent (it covers the whole Mexico Basin), very large rate (reaching 38 cm/yr), and its extreme subsidence gradients (up to 15 cm/yr in 200 m). Outside the city, the interferometric coherence decreases quickly with time due to vegetation and soil occupation changes. These characteristics are challenging for the application of multi-temporal interferometry. We use both the Gamma-IPTA chain [6] and the SBAS method developed by Cavalié et al. (2007) [7] and by Lopez Quiroz [8] and their results. We describe below the application of the PS Gamma-IPTA chain to the Mexico City data set, and analyse the results associated to each step. Furthermore, a series of synthetic tests are carried out on the temporal phase unwrapping step after the PS technique processing. This allows on one hand to quantify uncertainties associated to temporal unwrapping, particularly in the presence of non linear motion, on the other hand, to explain the temporal aliasing effect observed during PS processing. We then describe shortly the SBAS method designed by Lopez Quiroz et al. [8] to solve the specific problem of unwrapping the interferograms on Mexico City (due to the large number of fringes, and the rapid coherence loss). Their results are used as a precise knowledge where running the PS software. For both approaches, we analyse how specific data processing procedures may impact the accuracy of the subsidence rate maps. Finally we present a quantitative, step by step comparison between the two approaches, and analyze the sources of errors in both cases.

2. METHODS

2.1. Permanent scatterer processing

We describe here the application of the Gamma-IPTA chain on the Envisat Mexico City data set. First, one produces a stack of SLC radar images co-registered to the same master image, chosen in the middle of the temporal and spatial baseline space. PS candidates are then identified based on the temporal variability and the intensity of the backscattered echo. 1.3x10^5 pixels are selected, the vast majority in the flat Mexico Basin covered by the city and a few on human made structures on the lower parts of the volcanoes flanks surrounding the Basin. The wrapped differential phase of PS candidates on the multi-temporal data stack is then computed using an interpolated SRTM DEM [9] and the DELFT precise orbits data [10]. The unwrapped differential phase delay ϕ^k for a point target in interferogram k can be expressed as:

$$
ϕ^k = \frac{4π}{λ} \frac{B^k}{R \sin θ} h + \frac{4π}{λ} T^k \nu + ϕ_{atmo}^k + ϕ_{orb}^k + ϕ_{nl}^k + ϕ_{noise}^k
$$

(1)

where the first term corresponds to the DEM error h, the second term corresponds to the linear displacement rate ν, ϕ_{atmo}^k is the atmospheric phase delay, ϕ_{orb}^k is the residual orbital error, ϕ_{nl}^k is the non-linear ground motion and ϕ_{noise}^k is the decorrelation noise, assumed low on PS candidates. The topographic phase varies linearly with the perpendicular baseline B^k∥, with a proportionality coefficient depending on the wavelength of the radar carrier signal λ, on the radar to ground distance R, and on the incidence angle θ. The displacement phase is written as a function of the temporal baseline T^k. In order to extract the displacement time series from the wrapped differential phase ϕ^k, the PS softwares in general start with a local unwrapping in the (T^k, B^k) space leading to increments in DEM error and displacement rate (δν, δh) then integrate the locally modelled δν and δh through space to get a global (ν, h) solution. The phase residuum ϕ_{res}^k, is then integrated in space assuming that it remains included in the [-π, π] interval. As the phase residuum includes residual orbital trend, atmospheric delay, and non-linear motion, their progressive filtering could in theory lead to a more accurate solution of displacement time series by iterations. The Gamma IPTA software includes such iterative steps that are described below:

1. Temporal unwrapping. A first estimation of the displacement rate (Figure 1) and DEM error (Figure 2) is obtained on PS candidates through a 2D linear re-
gression on the wrapped differential phase as a function of the perpendicular baseline and of the time interval of temporal series. During the first step, only 34 interferograms whose perpendicular baseline is inferior to 800 m are used. The image is divided into 2x2 km² wide patches. The regression is performed on the phase of each PS of a given patch with respect to the patch reference phase, the phase difference at short distance including only small contributions from ϕ_{orb}, ϕ_{atmo} and possible ϕ_{nl}. The phase standard deviation of the regression σ is given as an assessment of the quality of the modelled (δv, δh) and reflects the point decorrelation noise, plus other terms not taken into account in the regression. We keep 12.6x10^4 points with a σ below the threshold of 1.2 radian. Beginning with the global reference point, the patch reference points are unwrapped by connecting each point with the nearest other points in a propagating way. The local velocity and height differences, together with residual phase differences, are then propagated across the image and referenced to the global reference point. In order to reduce aliasing described in section 2.2, we choose a global reference point in an area subsiding at a velocity of 20 cm/yr. A detailed visualization of the velocity map shows “patch” errors, both with small velocity steps of about 0.5 cm/yr, and with large velocity steps of 28 cm/yr. Half of the residual interferograms display unwrapping errors in form of patches which are expected due to residual orbital ramp and atmospheric phase screen. 16 interferograms whose residuals are relatively uniform are identified as correctly unwrapped, and are used in the next step.

2. In the second step, the velocity and DEM error are re-estimated on the unwrapped phase of the 16 interferograms correctly unwrapped in the first step. Note that in this second regression without unwrapping, a single patch processing is applied to avoid the patch errors.

3. In the third step, temporal unwrapping (as in step 1) is again performed only to refine the solution found in step 2, therefore allowing only a variation of 0.5 cm/yr for the velocity and of 3 m for the DEM error. To provide a good accuracy, 37 interferograms are used. After this step, 22 interferograms are qualitatively considered as correctly unwrapped based on the visualisation of the residue. Errors, although small locally, propagate by spatial integration through the whole area.

4. The fourth step is devoted to the spatial unwrapping of residual interferograms which can not be unwrapped correctly by temporal unwrapping. The residues are easier to unwrap than the differential interferograms. We rewrap the residual phase, filter the wrapped phase and unwrap them again spatially using a Minimum Cost Flow (MCF) algorithm. An addition of 10 interferograms is then considered as correctly unwrapped. Note however that spatial phase unwrapping is not perfect, some errors more or less significant can still be there. Finally, 32 differential interferograms considered as correctly unwrapped by the combination of temporal and spatial unwrapping are included in the 2D regression analysis by a single patch method, to obtain a new estimation of the displacement rate and of the elevation correction.

5. At this step, we eliminate the residual ramp on the interferogram stack. This is done by optimizing the baselines such that the deviations between modelled and differential phases are minimal in a least square sense. This optimization is applied on all PS whose subsidence velocity is lower than 2 cm/yr. A new regression analysis results in new velocity and DEM error maps. Surprisingly, the areas which were observed as very stable in the SBAS velocity map and as relatively stable at PS step 2, now appears with subsidence gradients. In fact, we face here a problem associated with the very small number of PS outside the deformation area, and their dissymmetric localisation: they are almost entirely located on the western side of Mexico City on the gentle slopes of the mountains. Either the applied mask is strict but we retain PS exclusively on the western part of the image, or we include PS with some deformation, but there remains a trade-off between the modelled orbital ramp and the deformation.
6. In the sixth step, we evaluate and remove the atmospheric phase screen associated with changes in water vapour stratification. This term is simulated as a linear function of elevation. However, as noted previously, the small number of PS on volcanoes flanks, and mostly located on the western side of the basin, results in a trade-off between this term and both the deformation field and the orbital trend. The application of this step is thus found unsatisfactory. Nevertheless, new velocity and DEM error maps are constructed.

7. Finally, in order to remove the turbulent effect of atmosphere, we filter the corrected phase delay time series by a weighted temporal filter.

2.2. Synthetic tests of temporal unwrapping

A particularity of the Mexico City subsidence is the very high subsidence rates, reaching 35 cm/yr in the line of sight (LOS) direction, and the high subsidence gradients across lithological boundaries between lacustrine deposits and volcanoes flanks. As the minimum temporal sampling is of 35 days, the problem of aliasing arises during the temporal phase unwrapping. In this section, we use synthetic tests to study the aliasing phenomenon during the temporal unwrapping step and to test the effect of non-linear motion and noise presence. That for, we construct synthetic time series of phase differences between two points $\delta \phi^k$, wrap them, and then adjust the synthetic wrapped phases by a model, $\delta \Phi^k$, expressed as:

$$\delta \Phi^k = \frac{4\pi}{\lambda} (\delta \upsilon T^k + \delta h \frac{B^k}{R \sin \theta})$$

where $\delta \Phi^k$ is the modelled phase difference between two points, $\delta \upsilon$ is the incremental ground velocity between two points and $\delta h$ is the contribution associated to relative DEM error between two points. Both $\delta \upsilon$ and $\delta h$ are estimated by maximizing the norm of complex coherence $\gamma$:

$$\gamma = \frac{1}{N} \sum_{k=1}^{N} e^{i(\delta \phi^k - \delta \Phi^k)}$$

where $N$ is the number of SAR data (N=38).

The simulation is performed for synthetic data sets without noise and with an added Gaussian noise. In each case, we have three assumptions for the deformation temporal behaviour: (a) linear deformation, (b) linear deformation with added acceleration, (c) linear deformation with added periodic displacement. The dates $T^k$ and perpendicular baseline $B^k$ are given by the 38 acquisitions of Mexico City. The wrapped phase differences are constructed from an input velocity (10 cm/yr) and an input DEM error (5 m). The tested values of the acceleration and the period of the periodic displacement are based on the results of SBAS approach.

(a) In the case of linear deformation, the retrieved coherence for one simulation is displayed on Figure 3: Coherence map as a function of searched velocity and DEM height error. In these three cases, no noise is added to the constructed phase series. (a) The deformation is assumed linear in time. (b) The deformation also presents an acceleration. (c) A sinusoidal displacement with an amplitude of 0.75 cm is superimposed on the linear rate.
In the first iteration, the raw differential interferograms in three successive iterations: bital trend, and inversion of interferograms are performed. Correction of stratified atmospheric delays plus residual or-
months. These small baselines allow maximizing the spa-
tial interferograms are constructed with perpendicular only outline its main characteristics. Firstly, 72 differ-
mation, is explained in detail in their paper. We will here a SBAS approach by Lopez-Quiroz et al. (2009) [8]. The Envisat Mexico City data set has been processed with

2.3. SBAS processing

The Envisat Mexico City data set has been processed with a SBAS approach by Lopez-Quiroz et al. (2009) [8]. Their method, designed specifically to solve the unwrapping problem in areas of large and relatively stable deform-
formation area, e.g., outside the flat portion of the basin. Then, a SVD inversion allows examining the closure of the redundant interferometric network and to quantify and identify unwrapping errors. The next two iterations repeat the previously described procedure, however with a “guide” to the unwrapping step. Lopez-Quiroz et al. (2009) [8] pick the 5 best interferograms with high signal to noise ratio and no phase unwrapping error, and stack them to represent an average deformation rate. An adap-
tative filter is applied to the stack to decrease its noise. This deformation “model” is then scaled by least square adjustment to each interferogram unwrapped in the previous iteration. Residual orbital ramp and stratified atmos-
pheric delays are also estimated from the unwrapped inter-
ferograms obtained in the previous iteration. All these terms are removed from the raw differential wrapped in-
terferograms. Therefore, the constructed residual inter-
ferograms present a limited number of fringes, includ-
ing turbulent atmospheric patterns, the deformation that does not follow the “model”, and noise. After applica-
tion of a slight adaptive filter, they are unwrapped by SNAPHU [12]. A new inversion allows again examining closure errors and quantifying unwrapping errors. The latter decreases significantly. This unwrapping “help” is repeated twice, because the “model” scaling, the estima-
tion of stratified atmospheric delay and the residual or-
bital contribution are not very reliable at the first step. Fi-
nally, a further mask is applied to interferograms where the residual phase exceeds 4 radians. Lopez-Quiroz et al. (2009) [8] verify that the interferometric system mis-
closure drops at each iteration. Finally, they obtain a set of 71 unwrapped interferograms, successfully corrected from stratified atmospheric delay and orbital residual contribution, and with a phase on average referenced to zero outside the flat basin, and masked in noisy areas. After inversion, the phase de-
lay time series in general show a remarkably linear subsi-
dence through time. However, in some areas, a non neg-
ligible acceleration or deceleration occurs. Furthermore, for some pixels, the matrix for inversion has a rank de-
ficiency, i.e. at least a critical link in the interferometric network is missing. In these cases, the acquisition data set is split into two or more independent image groups. One additional constraint stating that the phase varies as a quadratic polynomial in time and linearly with perpen-
dicular baseline is then added to the design matrix with a sufficiently small weight that it only fixes the offsets between phase delay time series of independent image groups.

The average ground motion rate is shown in Figure 4 (a), whereas a zoom on the RMS maps of the inconsistencies in the interferometric network is showed in Figure 4 (b). The accuracy of the subsidence velocity is given equal to 0.7 mm/yr, for pixels without unwrapping error (RMS value lower than 0.35 radian) and for which the interfer-
ometic set is complete. Slightly larger uncertainties are expected if less images or interferograms are available.
for a given point. Note also that, due to the slight adaptive filtering applied to interferograms, the solution can be considered as regularized in space, and thus cannot provide subsidence velocity of an individual target that would subside differently from its neighbors.

3. APPLICATION TO MEXICO CITY SUBSIDENCE

Both approaches are applied on 38 ENVISAT images from November 2002 to March 2007 with the aim to map the Mexico City subsidence rate. The displacement rate estimated at each step of the PS technique is compared to the average velocity obtained by SBAS. They show a general agreement, however with some exceptions. The closest agreement is obtained at PS step 2, with a velocity standard deviation of 3.0 mm/yr. The difference standard deviation is already relatively low at step 1 (4.0 mm/yr), decreasing at step 2 (3.0 mm/yr), but increases from step 3 (3.4 mm/yr) onwards (step 4 at 4.6 mm/yr). At step 5, because of the small coverage of PS targets outside the subsiding area, the residual orbital ramp correction is not satisfactory. Therefore, the PS result at this step is not reliable. As a result, we discuss here only the comparison at PS steps 1 to 4, before the residual orbital ramp correction.

To analyse the dispersion of the SBAS-PS results, we use three additional data sets, the PS phase standard deviation \( \sigma \), the map of non-linear deformation derived from the SBAS analysis \( \varphi_{nl} \), and the SBAS RMS mis-closure, \( \varphi_{RMS} \). In the 9.2x10^4 PS finally selected, 4.9% have \( \varphi_{RMS} \) greater than 1.07 radian, 6.6% are in areas with non-linear deformation greater than 1.3 radian, and 1.4% have a \( \varphi_{RMS} \) greater than 0.35 radian (with a possible unwrapping error from SBAS). Let us first analyse the points presenting large differences. We observe that the aliasing problem was mostly avoided, with only \( \sim 300 \) points in two separate patches affected by velocity differences of \( \sim 28 \) cm/yr. Apart from these points, 850 points present differences larger than \( \sim 2.5 \) cm/yr. It would be interesting to know whether they represent isolated points unseen by the SBAS approach, whose subsidence differs from the neighbouring points. An analysis shows that 57% of these points may be explained by large \( \sigma \) (48% with \( \sigma > 1.07 \) radian) and/or large \( \varphi_{nl} \) (21% with \( \varphi_{nl} > 1.3 \) radian) and/or large \( \varphi_{RMS} \) (7% with \( \varphi_{RMS} > 0.35 \) radian), these proportions being much larger than in the ‘normal’ PS population. Therefore, we can hardly be positive that the remaining 367 points carry specific subsidence information as isolated points. We will now focus on the ‘normal’ PS population which displays moderate PS-SBAS differences, lower than 2 cm/yr.

It is interesting to map the PS-SBAS difference at a local scale and with some spatial smoothing, because the PS approach can retrieve punctual deformation with accuracy, but may not propagate well spatially the solution, whereas the SBAS approach, due to slight adaptive spatial filtering, does not recover punctual deformation. The difference maps are thus displayed, after averaging the point velocity difference in 450 m wide sliding windows (low-pass filter, hereafter called LP), and after removing the LP map (high-pass filter, hereafter called HP).

For the PS step 1, we observe on the low-pass difference map (Figure 5 (a), \( \sigma_{LP} = 3.3 \) mm/yr) differences that can be mostly explained by patch errors from the PS technique. On the high-pass difference map (Figure 5 (d), in stable areas with null or low subsidence rate, the variability is small (standard deviation of 1.1 mm/yr). By contrast, in the areas where the subsidence is large, as in Mexico City centre, the variability is relatively large (standard deviation of 4.2 mm/yr). This can be explained by slightly heterogeneous deformation behaviour depending on the characteristic of roads and buildings. As mentioned above, the SBAS method provides a slightly spatially filtered measurement without taking into account the possible point-like displacement of individual targets. Figure 5 (b) shows the LP difference at PS step 2. The same observations hold, however the LP map appears better constrained and without patch errors (with \( \sigma_{LP} = 2.2 \) mm/yr). Whereas the HP map has larger standard deviation in the stable area (1.6 mm/yr). Indeed, at this step, only half of the interferograms, considered as correctly unwrapped at the first step, are used,
thus decreasing the local measurement accuracy. At PS step 3, temporal unwrapping re-introduces some patch errors, visible in the LP map (Figure 5 (c), bimodal distribution with $\sigma_{LP} = 3.1$ mm/yr), but the HP variability in stable areas drops again to 0.9 mm/yr and in subsiding areas to 2.7 mm/yr. Excluding points with $\sigma > 1.07$ radian, $\varphi_{nl} > 1.3$ radian and $\varphi_{RMS} > 0.35$ radian does not reduce the observed variability.

At PS step 4, some interferograms unwrapped temporally are replaced by interferograms unwrapped spatially. However, the MCF algorithm used by the spatial phase unwrapping obviously does not succeed in eliminating the phase unwrapping errors that inherit from the temporal phase unwrapping, as the LP map difference at step 4 shows increased discrepancies ($\sigma_{LP} = 3.5$ mm/yr).

Note that the LP patterns are changing from one step to the other. They are best constrained at PS step 2, despite the restricted use of only 16 interferograms, uncorrected from orbital errors, and covering only two years over the original 4.3 year span. In stable areas, the high-pass difference is reduced to 0.9 mm/yr at step 3, which is compatible with the combined nominal accuracy of the SBAS method and PS technique. Therefore, the standard deviation of 2.7 mm/yr in strongly subsiding areas, minus the variability in stable area of 0.9 mm/yr, can be seen as an upper bound for the local variability, for the ground motion of a point relative to its neighbouring area. As a consequence, the amplitude of local point-like displacements is of the order of $\pm 2$ mm/yr.

Because the deformation model in the PS temporal unwrapping step is linear in time, the non linear contribution appears as noise during the 2D regression analysis and increases the $\sigma$ value (Figure 6 (a)). For non linear motion larger than 2.5 radian, the chances for the PS to be rejected are extremely high, as seen from the lower PS density in Figure 6 (a), where the non-linear residue is large (Figure 6 (b)). Furthermore, when the non-linear motion has non negligible but lower amplitude, the standard deviation of the regression is quite large and the HF difference map presents anomalously high variability.

We conclude that the present PS analysis fails to retrieve non-linear subsidence temporal behaviour in the Mexico Basin.

4. CONCLUSION

In this paper, the results of the two main multi-temporal InSAR processing approaches are compared on a specific data set to measure the Mexico City subsidence, characterized by very high subsidence rates and large deformation gradients. The SBAS approach has been optimised in order to adjust to this situation, developing some particular strategy of data processing to ensure the measure quality. On the other hand, the PS technique of Gamma Software provides a processing chain that aims at measuring the ground motion with a great accuracy in general cases. Therefore, the deviation of the PS results from those of the SBAS approach should not just be interpreted as resulting from deficiencies of one approach, but em-
phasizes the importance of tuning a method to each specific setting and data set.

However, despite its spreading application, the PS technique cannot provide optimal estimation under certain circumstances, particularly in cases when assumptions on the displacement model are not valid. Furthermore, some errors relative to spatial integration of the local temporal unwrapping results can not be get rid of because of technological reasons. In addition, without a priori knowledge on the deformation, it is very difficult to evaluate the quality of the results obtained by PS approach.

As for SBAS approach, it provides a reliable measurement of subsidence rate with a precision of a millimetre per year over an extended area; however, it cannot capture punctual deformation rates that are also extremely interesting in urban setting. Moreover, the processing is heavy in terms of complexity and number of intermediate results. Finally, it necessitates a data set with a sufficiently dense sampling in terms of temporal and perpendicular baseline to avoid spatial coherence loss due to decorrelation noise. As a result, potential improvements could be derived by combining these two approaches [13], as the PS technique provides punctual deformation, while the SBAS method can greatly extend the measurement coverage by spatial regularization. The combination of these two methods appears promising in multi-temporal InSAR processing, from which a more detailed measurement and a wide range of application can be expected in the future.

**ACKNOWLEDGMENTS**

This work was supported by the EFIDIR project (http://www.efidir.fr) granted by the French National Agency (ANR) (ANR-07-MDCO-004). The authors wish to thank the ANR for their support.

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