ADVANCES ON REPEATED SPACE-BORNE SAR INTERFEROMETRY AND ITS APPLICATION TO GROUND DEFORMATION MONITORING-A REVIEW

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ABSTRACT:

Differential synthetic aperture radar interferometry (D-InSAR), is a remote sensing technique that could measure earth surface deformation and has gained extensive use along with its development as a technique and subject, from classical to advanced D-InSAR. The main principles of both were concisely depicted and the differences and relations between highlighted. Then an introductive review concerning applications of InSAR technology in China and obstacles therein to make the technique operational for coal-mining induced deformation was made. The other method developed for a more accurate InSAR application, consisting in GPS assisted and multi-platform SAR interferometry, atmospheric artefact modelling are introduced, and ended up with the conclusion part where the main limitations were put forward.

1. INTRODUCTION

Repeated SAR Interferometry (InSAR) technique, based on the combination of two radar images, has been exposed by Graham (Graham, 1974), allowing not only the retrieval of a Digital Elevation Model (Zebker et al., 1986), but also large-scale surface deformation monitoring (Differential InSAR, D-InSAR). The high density of measurement, with an accuracy of 1cm for single interferogram, allows generation of a map of ground deformation (Gabriel et al., 1989; Massonnet et al., 1993; Massonnet et al., 1995; Carnec et al., 1999).

The principle of D-InSAR(hereafter referred to as Classical D-InSAR, compared with the Advanced D-InSAR techniques to be detailed in Section 2) is to first obtain two interferograms of a study area, called Topo-defo interferogram and Topo respectively, and then make a difference between them to detect the deforming information if any. Just as the name implying, there are topographic and deforming information in the former, while topographic information only in the latter, which can be formed either through synthesizing an existed DEM (2-pass D-InSAR), or two SAR images acquired before the time deformation taking place.

Besides the above mentioned, Classical D-InSAR has gained extensive use elsewhere (Perski, 1998; Strozzi et al., 1999; Ge et al., 2008) and has become one of the efficient tools in surface deformation monitoring, among which there are GPS, VLBI□ conventional precise levelling and theodolite survey, EDM and remote electronic monitoring, to name a few.

Classical D-InSAR, however, faces several limitations essentially due to temporal and geometric decorrelation, atmospheric inhomogeneity, besides the presence of uncompensated topography due to the limited accuracy of DEM utilized. When random motion takes place within SAR-imaging pixels, such as those caused by crop growth, leaf fluctuation, interferometric phases will become noisy, thus causing temporal decorreltation, which will certainly prohibit us from accurate low-velocity deformation monitoring, where differential interferograms are forced to have large temporal baseline. Geometric decorrelation happens when there exists the excessive separation between satellites' orbits □ the perpendicular baseline, B□□, which will significantly reduce the number of image pairs suitable for interferometric application. (Jarosz et al., 2004). An additional limitation, atmospheric inhomogeneity, common to both large or small baseline interferograms, creates an atmospheric phase screen (APS) superimposed on each SAR image that can sometimes seriously degrade the quality of deformation estimation (Zebker 1997; Goldstein, 1995; Williams, 1998; Hanssen,1998; Carnec C. et al., 1996).

Fortunately, these limitations are well addressed in the advanced D-InSAR techniques, which will be introduced in the following.

2. ADVANCED D-INSAR TECHNIQUES

During several yeas of study, S.Usai et al (Usai et al., 1997; 1998;1999) found that some certain samples, mainly of anthropogenic nature, such as buildings, bridges, railways and roads, highly and reliably coherent in spite of the long-time interval, manifesting themselves as strong, nearly point-like bright dots in an almost completely decorrelated interferograms. The Advanced D-InSAR techniques then hunt for and utilize these pointwise targets to track the temporal evolution of the detected deformation, to which the scientific community has shown great interests.

Based on the coherent-target hunting strategy and the processing method for signal-of-interest isolation, the advanced techniques recently developed are classified as four types, i.e. Least Square approach, Permanent Scatterer SAR

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Interferometry, Small BAseline Subset, Coherent Pixel Technique, which will be introduced chronologically in some detail, together with the differences and relations between each.

2.1 Least Square database approach (LS approach)

After analyzing the phase stability of some man-made features, S.Usai et al (Usai et al., 1997,1999,2000) presented a new approach, known as Least Square approach (LS), for the long-term monitoring of terrain deformations with D-InSAR. This method uses a database of interferograms, and by solving all the deformation velocities as a unique least squares problem provides a chronologically ordered sequence, describing the evolution of the deformation pattern in time (Usai, 2002).

2.1.1 Main principle

The input for the least squares adjustment is a set $y=[I_1,\ldots,I_N]$ of N unwrapped interferometric deformation maps(i.e., the unwrapped interferograms are compensated for topographic and flat-earth phases), all coregistered at subpixel level, generated from M SAR images taken at days $x=[d_1,\ldots, d_M]$. The day d_1 corresponding to the first image is taken as reference and the deformations at each of the other (M-1) days relative to this day considered as solutions of the problem:

$$y=Ax \qquad (1)$$

where in x the element d_1 not been considered.

In the system matrix A, each row corresponds to an interferogram, while the columns correspond to the days. For interferogram $I_k=I_{di}-I_{dj}$, the values on row k are all zero except at columns i and j, being +1 and -1 respectively and A an incidence like matrix, directly depending on the set of interferograms generated form the M SAR images.

The unweighted least squares solution x of Eq.1 is straightforward:

$$x=(A^TA)^{-1}A^Ty \qquad Qx=(A^TA)^{-1} \qquad (2)$$

2.1.2 Some notes on LS approach

The LS approach has been applied to measure terrain displacements in the period 1993-1999 at the Phlegrean Fields (Naples, Italy), using a set of 20 ERS-1/2 SAR images, and 43 interferograms generated(Usai, 2002; Usai, 2003). The authors made use of an external DEM to obtain the differential interferograms and found that residual topography had caused systemtic effects in the data. In addition, during the processing, a closed-loop method was used to detect and remove image- and interferogram-related biases. In fact, according to Usai, (Usai, 2001) two kinds of biases can be identified: the image-related ones, like for example those caused by atmospheric disturbances; and the interferogram-related ones, i.e. those which have been produced in the interferometric combination of two images, most probably by phase-unwrapping errors.

2.2 Permanent Scatterer (PS)

The Permanent Scatterer technique, developed at the 'Politecnico di Milano' (Milan, Italy) (Ferretti et al., 1999; 2000; 2001), is the first of a family of similar advanced interferometric techniques-Permanent Scatterer Interferometry (PSI).

Given N+1 images, a set of N differential interferograms is generated with respect to a single master. High temporal and normal baseline interferograms (affected by a high decorrelation noise) are, thus, part of the dataset. The approach focused on privileged image pixels that, even in these 'extreme conditions', still exhibit a low noise term, thus the so-called Permanent Scatterers. With PS technique, pixels are selected from the study of its amplitude stability along the whole set of images (typically >30). Therefore, the maximum resolution of the SLC images is preserved (Ferretti et al., 2001)

After PS candidates selection, a linear model is adjusted to the data to estimate the deformation linear velocity and possible DEM errors for each PS Candidate. Then the atmospheric phase screen (APS) for the master image and the nonlinear motion contribution and APS for each image are computed through a spatio-temporal filtering. After estimation and removal of all the APS superimposed on the data, one can identify more PSs and repeating the previous steps allows getting the whole deformation time series and average LOS displacement rate of every single PS, and a refining DEM with sub-metric precision of the exact height of the object corresponding to the PSs.

2.3 Small BAseline Subset (SBAS)

The Small Baseline Subset (SBAS) approach, proposed by Berardino et al. (2001; 2002), extends the Least Squares approach (Usai, 2001; 2002; 2003; Lundgren et al, 2001) to the case of multiple small baseline acquisition subsets. The key point, in addition to the use of multi-look interferograms, is that the data pairs involved in the generation of the interferograms are carefully selected in order to minimize the spatial baseline, thus mitigating the decorrelation phenomenon and topography errors. The Singular Value Decomposition (SVD) method is applied to link otherwise independent SAR datasets separated by large baselines. The SBAS method was originally used to investigate large scale deformations with spatial resolution of about 100m*100m, calculating the time sequence deformation and estimating DEM error and the atmospheric artifact in a similar way as PS. O.Mora et al (O.Mora et al., 2002) promoted a complementary approach, utilizing two different sets of data generated at low (muliti-look) and full resolution (single-look) respectively, to monitor localized deformation. The former are used to identify and estimate possible atmospheric phase artifacts and low-wavenumber deformation patterns based on SVD SBAS method or CPT(Mora et al., 2003); the latter to detect, on the high-resolution residual phase components, structures highly coherent over time like buildings, rocks, lava structures, etc.

2.4 Coherent Pixels Technique (CPT)

Developed by O.Mora et al (2003), original CPT gained its first use (Mora et al., 2001) in the long-term subsidence monitoring of an area of small town in Spanish, choosing the temporal-coherence as criterion for permanent scatterers selection only to make flexible the SAR images requirement in PS. The results, utilizing seven SAR images, turned out to be satisfactory and coincided well with the DGPS measurements.

Recently, CPT has been improved (Blanco et al., 2007; Duque et al., 2007) into an operational advanced technique for terrain deformation mapping, in terms of linear and nonlinear deformation extraction, robustness with DEM error, thus allowing DEM refining, and atmospheric phase screen (APS) removal. P.Blanco et al (2008) concluded this approach and detailed the main steps, such as optimal interferogram sets selection, coherent pixels selection, linear and nonlinear blocks for a full deformation extraction. The related algorithms consist of Delaunay triangulation and Minimum Spanning Tree (MST) for best combination of interferograms selection, Conjugate Gradient Method (CGM) for Phase Unwrapping, multi-layer for liable estimation of linear deformation. What's more, by integrating the amplitude-based criterion for pixels selection, CPT can provide full-resolution deformation. In some sense, we can say CPT is a well-integrated technique of the main PSI techniques.

2.5 Other techniques

Some other multiple-interferogram techniques for deformation monitoring emerge and gained many uses as well, including, Interferometric Points Targets Analysis (IPTA) developed by GAMMA remote sensing research group (Wegmüller et al., 2000; Werner et al., 2003) in Switzerland, Spatio-Temporal Unwrapping Network (STUN) (Kampes et al., 2005) and phase gradient approach to stacking interferograms (Sandwell et al., 1998; Raucoules et al., 2003; Rocca, 2007). Moreover, there is STBAS (Small Temporal BAseline Subset) for monitoring of wetland's water level changes (Hong et al., 2008).

2.6 Remarks on Advanced D-InSAR techniques

Compared with Classical D-InSAR, which employs several SAR images (4 at most for the 4-pass version D-InSAR) to analyze a single deformation episode, Advanced D-InSAR technique fully exploits the SAR archives available, and we may consider it a postprocessing step (Usai, 2003; Berardino et al., 2002) applied to the set of D-InSAR interfrograms that may be generated via already available interferometric data processing tools. Based on this, several considerations are in order.

2.6.1 Foundation of Advanced D-InSAR

The input of Advanced D-InSAR is a set of Differential interferograms. Therefore, a careful D-InSAR processing has to be implemented, controlling the quality of all major processing steps (e.g. image co-registration, phase unwrapping, etc.), guaranteeing a high quality set of input data for the Advanced techniques. This is of particular significance for PS method, where no compulsive constraints are enforced on temporal and spatial baseline and any noisy area existed will introduce mis-registration problems. Phase unwrapping, on the other hand, always remaining the most delicate issue, behaves as a sparse and irregularly sampled data unwrapping problem in advanced techniques, and can be performed following a two-step algorithm (Ghiglia et al., 1998)□
1) estimation of the unwrapped phase differences between neighboring pixels; 2) integration of the gradient using one of the known techniques, such as minimum cost flow (Costantini, 1998), weighted least mean squares (Ghiglia et al., 1998; Spagnolini, 1995), and branch and cut (Goldstein et al., 1988).

2.6.2 Data acquisition

Besides the large stack of SAR images required, uniform distribution of temporal and spatial baselines are always preferred in order to acquire more accurate and reliable information about the ongoing deformation. However, global availability of SAR acquisitions is somewhat limited. Many areas have few or no acquisitions unless the area of interest was previously tasked for imaging. For example, there are subsiding areas in Mexico and in the People's Republic of China that have significant aquifer-system compaction problems, however, with limited ERS SAR coverage. For Envisat SAR coverage, the various selectable polarizations of the transmitted electromagnetic SAR signal may limit the availability of SAR-image pairs suitable for InSAR processing (Galloway et al., 2007).

2.7 Difference and similarity among Advanced techniques

Besides several differences among the techniques detailed above, mainly relying in data requirements (minimum number of SAR images, more than thirty needed for PS for a well statistics estimation of phase stability), the limitations on baseline length (SBAS, LS, CPT), the need of multilooking (SBAS, LS, CPT), the multi-pair approach (SBAS, LS, CPT) for interferogram formation, there exist several similarities among them.

2.7.1 Deformation extraction strategy

All the techniques extract deformation through a two-step way, linear and nonlinear. In fact, we'd better regard the introduction of a linear model as a way to clean phase to make easier nonlinear estimation. Such a strategy, dividing and conquering, running through the whole signal isolation process, does help a lot (Blanco et al., 2007).

2.7.2 APS estimation and removal

The output of Advanced D-InSAR includes LOS displacement rate, DEM error, and Atmospheric disturbance, with the latter two byproducts indicating great superiority compared with Classical D-InSAR, and in some way justifying the need of a large number of images (Ferretti et al., 2000).

After the estimation and removal of linear phase (linear deformation and DEM error phases), theoretically, three contributions still remain: APS, nonlinear deformation and noise. In practice, however, the noise contribution was mitigated to the minimum either due to the multilooking process in SBAS and CPT, or due to the neighboring differencing in PS and CPT, thus only APS being the target to be cleaned. Based on the observation that the atmospheric signal phase component is characterized by a high spatial correlation and exhibits a significantly low temporal correlation (random), the desired nonlinear deformation is estimated as the result of the cascade of a spatial low-pass and a temporal high-pass filtering operation, with APS removed(Ferretti et al., 2001; Berardino et al., 2002; Mora et al.,2003).

2.7.3 Multi-plantform interferometry

The frequency difference between ERS and EnviSAT, although a small shift, limits the possibilities of the generation of useful cross-interferograms (Monti et al., 2000). For a flat surface, theoretically, it's possible to compensate for the 31 MHz center frequency difference unless the normal baseline reaches 2100m (Gatelli et al., 1994). Although some researchers found several pairs of images for successful crossing-interferometry by searching, with delicacy, the whole archives(Santoro et al, 2007) , we should note that the consequence of such large baselines are, on the one hand, the restrictive elevation of ambiguity with respect to the image, around 4.5m, which makes the interferograms sensitive to topography. On the other hand, interferograms with large baseline are extremely sensitive to volumetric decorrelation, which poses great limitation in urban areas.

Again, Advance DInSAR techniques circumvent the above dilemma elegantly, exploiting pointwise targets, as in the case of the Permanent Scatterer approach (Arrigoni et al., 2003; Ferretti et al., 2004; Wegmuller et al., 2005) that allows investigating the temporal evolution of the detected displacements by analyzing full-resolution (single look) interferograms, or in the SBAS and CPT cases, by considering ERS and EnviSAT as independent subsets, searching for a least squares solution with a minimum norm deformation velocity vector constraint (Berardino et al., 2004; Pepe et al., 2005; Mallorquí et al., 2005; Blanco et al., 2006)

3. APPLICATION OF INSAR TECHNOLOGY IN CHINA

InSAR technique has penetrated through almost every surface-deformation related monitoring, thanks to the Advanced D-InSAR technique. In general, InSAR has evolved to be able to monitor and track deformation, with great elegance, of different causes including tectonic seismic and volcanic activity, ice and rock glacier motion, slope instability, and subsidence caused by ground water pumping, mining, hydrocarbon extraction, and natural compaction in high precision and reliability.

In the late 1990s, InSAR technology was introduced into China and gained firstly an experimental use and then became operational mainly on the subsidence taking place in urban area due to either water pumping and/or underground construction, besides the active tectonic caused deformation (Zhao et al.,2009; He et al.,2006; Xu et al.,2008) and co-seismic deformation extraction and modeling (Shan et al., 2002; Ji et al., 2009). Recently, Advanced D-InSAR techniques gain their use in long-term series deformation monitoring in urban areas (Fang et al., 2009; Li et al., 2009; Jiang et al., 2009; Huang et al., 2008).

InSAR technique has also been used to monitor mining-induced subsidence, with the main squeeze being coal mining in China (Cao et al., 2008) in a cost-effective way due to the vast area influenced, which could be considered a startup and experimental and there’s certainly a long way to go for the operational use. The main reasons may consist in the limited data acquisition and the inherent limitation of InSAR for large-gradient and/or vegetated surface subsidence monitoring.

4. GPS AND D-INSAR INTEGRATION

Due to the unknown phase ambiguity number and the limited knowledge of the satellites’s position, measurements from D-InSAR are essentially relative ones. In order to relate these measurements to a reference datum, a priori information is required, such as Ground Control Points, absolute deformations from GPS or other geodetic techniques. What’s more, both atmospheric artifacts and orbital fringes feature high spatial correlation, since their correlation typically exceeds 1km. Local spurious components are compensated for by the double difference computation inherent in any Advanced DInSAR analysis, but regional signals affecting hundreds or even thousands of square kilometers can be difficult to discriminate without a priori information, thus justifying the complementariness between GPS and DInSAR data, which can be used in synergy to map surface deformation (Prati et al., 2009).

The idea of InSAR and GPS integration was perhaps first suggested in 1997 (Bock et al., 1997; 1998). Ge et al (1997, 2000) proposed a DIDP approach for this integration. A methodology that uses Markov Random Field (MRF) based regularization and simulating annealing optimization was then proposed by Sverrir Guemundsson(2000) to unwrap InSAR images, obtaining a high-resolution 3-D motion field from combined GPS and interferometric observations. With GPS, MODIS and MORIS data, Li et al (Li, 2005a; Li et at., 2005b) produced regional water vapor model with a spatial resolution of 1km*1km, which, applied to the ERS-2 repeat-pass data, assisted in discriminating geophysical signals from atmospheric artifacts. Doin et al. (2009) proposed another approach, using global atmospheric models (GAM), to model and remove the stratified tropospheric delay efficiently.

5. DISCUSSIONS AND CONCLUSION

D-InSAR technology has demonstrated unsurpassed capabilities of the technique in terms of deformation monitoring, and has embedded itself one of the most widely used geodesy techniques, combining the characteristics of large-scale imaging and high-accuracy quantitative observations, particularly of dynamic processes. However, there still exist several limitations at present, related as follows:

A) Excessive subsidence (i.e., big phase gradient) taking place in one repeat cycle of satellite makes impossible deformation measurement without a priori information;

B) A systemtic errors introduced during the D-InSAR process, such as caused by mis-coregistration, orbit perturbation, inaccurate topography model, phase unwrapping, atmospheric artifact, remains unknown, and the precision evaluation of the end-product at present only comparatively known through a so-called Quantitative Analysis step (i.e., making comparisons with respect to traditional implementation geodetic method);

C) Characteristics of PSs, utilized in PSI techniques, require a thoroughly study, in order to geocode and interpret the studied PS deformation more accurately to the local structure;

D) In some cases, such as the coal mining influenced area, where typically displacement in all the 3-D takes place, making subsidence not so dominating, chances are unpractical deforming information will be acquired.

With the newly launched satellites and some ongoing research activity, the above-mentioned limitations can be addressed, to a certain extent at least, if not completely. For example, the newly launched four SAR satellites, operating at X-band, feature short repeat cycles: three belong to the dual-use Cosmo-SKymed constellation operated by the Italian Space Agency, with a 4-day cycle, and one is the German TerraSAR-X, with the cycle of 11 days could make less likely excess subsidence. What’s more, some ongoing research activity are aiming at the study of the nature of PSs, and striking results have already been reported (Ferretti et al., 2005). With more knowledge of PSs, cross-frequency and/or cross-incidence angle could be possible and extremely promising. We are surely convinced that all these existed and upcoming efforts will lead to an operational and routine use of Spaceborne InSAR technology for ground surface deformation monitoring.

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