SURFACE DISPLACEMENT CAUSED BY THE 8 OCTOBER, 2005 KASHMIR EARTHQUAKE FROM SATELLITE RADAR IMAGERY

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KEY WORDS: SAR, Speckle tracking, Pakistan, earthquake, coregistration

ABSTRACT:

On October 8, 2005 a devastating earthquake occurred in the northern part of Pakistan with a magnitude of Mw 7.6, causing about 80.000 casualties and many more injured. Better understanding and monitoring of faults that may cause such earthquakes will help governmental agencies to improve their mitigation plans. The most important problem for such monitoring objectives is the lack of data, especially prior to an earthquake. In this respect, satellite radar interferometry is one of the strongest remote sensing technologies that enables the monitoring of surface displacements at cm precision. Unfortunately, due to topography, temporal decorrelation, and unfavorable satellite orbit conditions, conventional interferometric methods are limited in their capability to estimate coherent surface deformation. In rough and vegetated areas such as the Muzaffarabad fault, Kashmir, this leads to sparse patches of coherent phase information. Using the combination of speckle tracking techniques and reverse-heading orbits we estimate coarse scale deformation offset vectors, which are consecutively used to constrain the deformation field. We refined amplitude-based offset estimation algorithms, taking the rough topography of the region into account and implemented these in the radar interferometric processing software (Doris). Selecting a suitable combination of ascending and descending tracks of Envisat SAR imagery and applying dedicated range and azimuth offset algorithms, we obtained the three dimensional coseismic deformation field along the Muzaffarabad fault.

1 INTRODUCTION

The Himalayan orogenic belt was formed as a result of the ongoing collision between the Indian subplate and the Eurasian continental plate. On October 8 2005, this collision caused one of the most devastating earthquakes in the northwestern part of Himalayas, Kashmir region, causing about 80.000 casualties and many more injured. The earthquake caused slip along the reverse dextral strike-slip Muzaffarabad fault with the major shock of Mw 7.6.

This catastrophic event underlines the importance of monitoring and understanding the mechanisms of pre-existing active faults prior to an earthquake. Such information will help governmental agencies improve their mitigation plan and hazard assessment in order to make fast and reliable decisions to save precious human life. However, usually lack of such information especially prior to earthquakes hampers the efficiency of rescue and relief operations. In this respect, space-borne radar interferometry is an efficient tool for monitoring surface displacements due to subsidence, volcanic activities, earthquakes and glacial motions at cm level precision, see e.g. (Massonnet and Feigl, 1998, Hanssen, 2001). However, due to topography, temporal decorrelation, and unfavorable satellite orbit conditions, conventional interferometric methods are limited in their capability to estimate coherent surface deformation. In rough and vegetated areas such as Kashmir, this leads to sparse patches of coherent phase information. Due to the lack of coherent phase information and the high gradient of surface deformation, instead of relying on phase information, amplitude pixel offsets can be calculated to constrain the surface displacement field. This technique is based on speckle correlation, and often referred to as speckle tracking—initially developed for monitoring glacial motion (Gray et al., 1998).

Utilizing speckle tracking on reverse heading orbits it is possible to estimate the three dimensional displacement field. The precision of speckle tracking is limited to fractions of the resolution cell (sub-meter precision) in contrast to fractions of the radar wavelength (mm precision) for the phase information. Speckle offset observations are not limited to the line of sight (LOS) direction as compared to phase measurements. This technique has been successfully applied to construct three dimensional deformation field along faults zones (Fialko et al., 2001).

Fujiwara et al. (2006) showed that the LOS displacement of this earthquake has been estimated based on the image amplitude offsets of the descending tracks, where it was inferred that the topography and the deformation in the area were closely correlated. Pathier et al. (2006) demonstrated that using combinations of ascending and descending tracks can be used to capture the 3D displacement field along the Muzaffarabad fault, leading to slip distribution estimates along the fault plane. .

Here we compare estimating range and azimuth offsets using (i) a polynomial-based coregistration and (ii) a DEM-assisted coregistration method. For comparison, the estimated offsets are consecutively used to estimate the 3D displacement field along the Muzaffarabad fault.

2 MODEL AND ANALYSIS

2.1 Speckle tracking

Speckle tracking techniques are based on the estimation of local shifts through correlation between two amplitude images, i.e. master and slave images, and yield two offsets vectors: one parallel to the satellite track (azimuth) and the other in the line of sight (range) direction. If the backscatter from an area remains coherent, the speckle pattern will be correlated, allowing small windows within the two images to be registered with sub-pixel precision (Gray et al., 1998). In order to use these offsets to constructing the deformation field some corrections are required such as removal of earth curvature and the topographic effect. The main advantages of speckle tracking compared to interferometric SAR studies are, (i) No phase unwrapping is required, (ii) it is suitable for monitoring large deformations, when phase information would be lost due to undersampling, (iii) both line of sight displacements as well as azimuth displacements can be estimated, and (iv) displacement can be estimated even in areas with low coherence. The main disadvantage is of course the decreased sensitivity, leading to a sub-meter estimation precision.

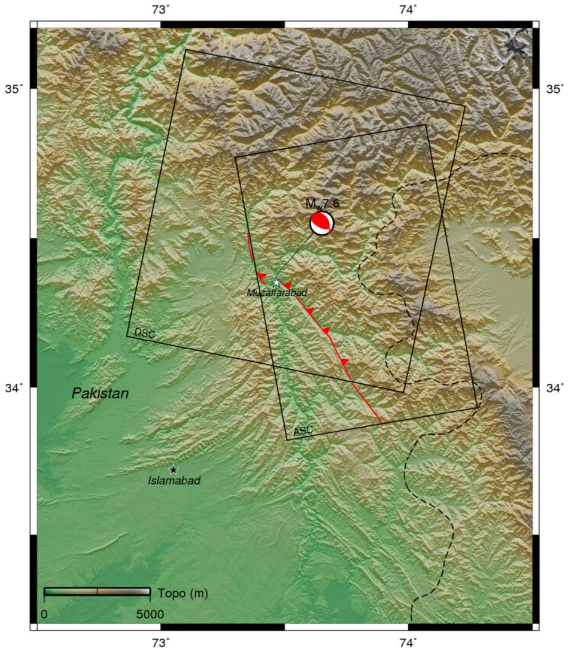


Figure 1: Shaded relief map of the study area in the Kashmir region, Pakistan. Solid rectangles outline the area covered by the ascending (ASC) and descending (DSC) scenes. The red line indicates the Muzaffarabad fault location.

2.2 Estimation of range and azimuth offsets

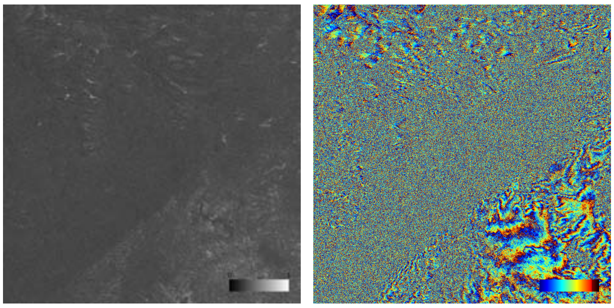
To start with the amplitude offset analysis Envisat ASAR images were used, acquired by European Space Agency (ESA) before and after the 8 October 2005 earthquake event. The available acquisitions were examined and selected based on their suitable temporal baseline and perpendicular baseline. For the ascending (Image Swath IS2) and descending (IS6) tracks, a coseismic image pair was identified, see table 1. Even though the temporal baseline between each coseismic image pairs spans only 35 days, the scenes are significantly decorrelated near to the epicentral area indicating the effect of large deformation gradients rather than topographic influence (see Fig. 2).

Using the maximum overlapping crop size between reverse heading orbits, two processing approaches are defined for comparison, (i) standard polynomial-based coregistration to estimate sub-pixel offsets, and (ii) coregistration together with removal of topography effect to estimate sub-pixel offsets. For the first step we have used already implemented algorithms available in the Delft Object-Oriented Interferometric Software (DORIS) and for the latter step we have developed new algorithms that additionally consider the topographic contribution using a digital elevation model, i.e. the 3 arcseconds SRTM DEM, and estimate the possible azimuth time shift during coregistration.

In both processing approaches, first we have used precise orbits (Scharroo and Visser, 1998) to estimate the coarse shift between master and slave within an accuracy of 30 pixels, followed by using this resulting shift as input to coarse cross-correlation, leading to an estimated shift within the accuracy of 1 pixel. Finally, knowing the shift at the pixel level, fine cross-correlation estimation is used to estimate the sub-pixel shift between image pairs before the estimation of the coregistration polynomial coefficients in order to transform the slave to the master coordinate system. In the polynomial-based approach, a polynomial of degree 3 has been used to estimated the topographic contribution to a certain extent. Additionally, we have considered the elevational undulations between the SAR acquisitions and the SRTM DEM. In the former one, elevations are referenced to WGS86 ellipsoidal heights, while in the latter one, heights are referenced to the Earth Geodetic Model 96 (EGM96). The height undulations were corrected assuming a constant height change all over the cropped scene. Using online tools provided by NGA (Agency and NASA, 1996), we estimated the height undulation for the center of the scene which is about -40 meters at average.

Master(Date)	Slave(Date)	$B_\perp$(m)	B_{temp}(day)	Heading
2005-09-19	2005-10-24	300.1	35	ASC
2005-09-17	2005-10-22	300.7	35	DSC

Table 1: List of datasets used in the study



(a) Coherence image (b) Interferogram

Figure 2: (a) Estimated coherence for the descending pair using a 10×2 window. Brighter tones show high coherence. (b) Interferogram of descending pair, phase filtered. The decorrelation close to the epicentre and along the fault is clearly visible. Both images are in the radar coordinates of descending track.

After the coregistration step, the output products are used to estimate the two components of displacements, i.e. azimuth offsets and range offsets, in the corresponding coseismic image pair. This is implemented using a correlation window of 64×64 pixels, which is used to estimated the sub-pixel offset of the full resolution images with steps of 16 pixels in range and 80 pixels in azimuth direction, yielding approximately 100000 offsets vectors for each orbit direction. In order to reduce noise in the offset estimates we have defined thresholds based on the histograms and the statistics for each offsets, as the speckle tracking technique has it own noise characteristics. Finally the offset estimates in the radar coordinates are transferred to a geographical coordinate system for further analysis.

2.3 Mapping 3D deformation field

The speckle tracking measurements are the projections of the actual three dimensional surface displacement vectors to the satellite line of sight (range) and the along track (azimuth) directions. Let the ground deformations orthogonal components be $d = (d_e, d_n, d_u)$ in east, north, and vertical directions, respectively, for a given point at the earth surface. Then, the projection of the surface displacement vector d to the line-of-sight and azimuth directions can be formulated as.

$$d_r = (d_e \cos\alpha_h - d_n \sin\alpha_h) \sin\theta - d_u \cos\theta \qquad (1)$$

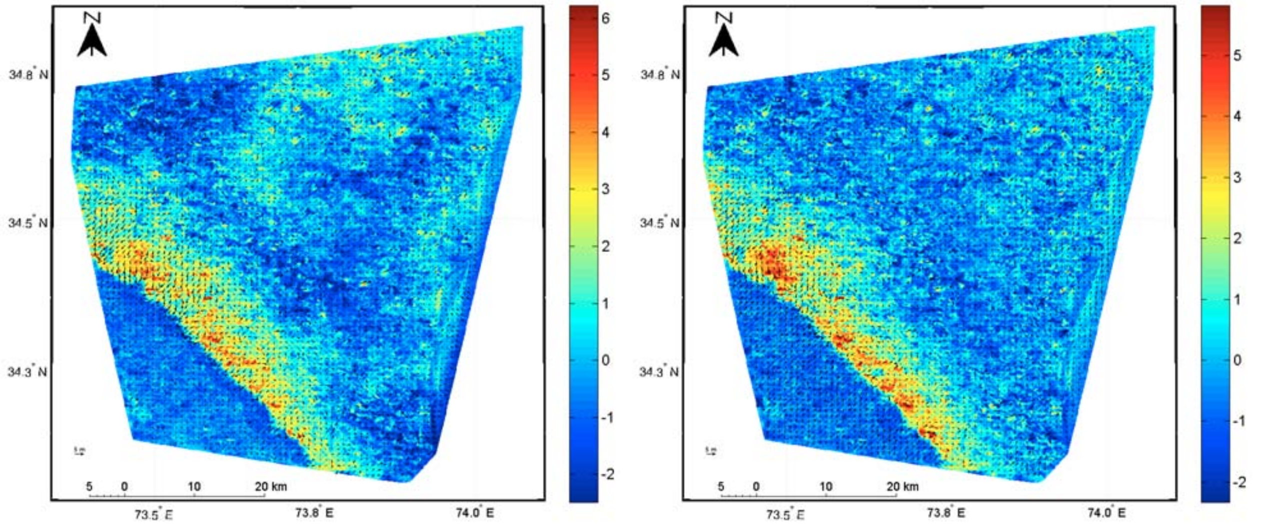


Figure 3: (a) Coseismic displacement field inverted from the amplitude offsets estimated by polynomial-based coregistration. (b) Coseismic displacements inverted from the amplitude offsets estimated by DEM-assisted coregistration. Colors denote the vertical displacement in meters, and arrows show horizontal displacement field.

and

$$d_a = d_e \sin\alpha_h + d_n \cos\alpha_h. \qquad (2)$$

where θ and α_h denote the radar indicidence at reflection point and the azimuth angle of satellite measured positive clockwise from the North, respectively. It is worth noting that the range vector is positive in eq.(1) for increasing range displacement and the azimuth vector is positive in eq. (2) for increasing azimuth displacement. The satellite LOS displacement vector has a higher sensitivity to vertical displacements than to the other two components of a surface displacement, i.e. east and north, due to the near-polar satellite orbits and the incidence angle of $\theta \approx 23$.

For retrieval of the 3D displacement field, we have two observations from each orbit, i.e. a range vector and an azimuth vector, which are sufficient to solve the three unknown orthogonal components of displacement field. Therefore, using eqs. (1) and (2) we have obtained a set of four equations for both descending and ascending orbits to calculate the orthogonal components of the displacement using least-squares estimation. For the sake of simplicity we assumed that the observations are uncorrelated, acknowledging the good angular separation between ascending and descending line-of-sight directions, and orthogonal azimuth and range directions.

For inversion of the 3D displacement field, we have interpolated range offsets and azimuth offsets with a grid spacing of 3.6 arc seconds using a linear interpolator for each coseismic pair. Then, from the interpolated data we have estimated the east, north, and vertical components of the deformation field.

3 RESULTS AND DISCUSSION

Using the speckle tracking technique on both ascending and descending image pairs, we have obtained sufficient observation to construct the three dimensional deformation field of the 2005 Mw 7.6 Kashmir earthquake. Fig. 3 shows the vertical component of the deformation estimated using amplitude offsets from polynomial-based coregistered image pairs and the DEM-assisted coregistered image pairs, respectively. The vertical component clearly indicates the deformation and the fault boundary within the data coverage of overlapping scenes.

Fig. 4 shows the difference of the vertical components of the two coregistration approaches, and the topographic contribution to the estimated vertical components can be clearly observed from the figure. Nevertheless, away from the epicentral area, we still observed offsets which are due to topographic effect. It is clear that the polynomial-based coregistration was not suitable for areas where we have high topographic differences—depending on topographic conditions, it can underestimate or overestimate LOS offsets (see Fig. 3). The new proposed coregistration is less sensitive to deformation and preserves deformation related offsets while eliminating topographic contribution. It is worth noting that the polynomial-based coregistration may also remove displacement offsets to a certain extent. In order to overcome this drawback of polynomial coregistration approach we have used the largest possible crop size in order to eliminate removal of deformation.

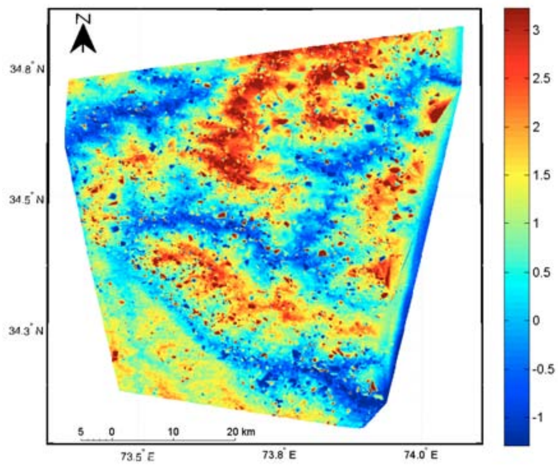


Figure 4: Difference image of vertical component of displacement between two coregisration approaches. Colors denote vertical displacement.

The ground displacement measurements shows that towards Muzaffarabad, i.e. NW along the fault, the deformation intensity increases which explains the significant damages in neighboring settlements such as Muzaffarabad. This large deformation, especially in the vertical direction, triggered large scale land slides in the region. Maximum deformation estimated along the fault is 6 meters in vertical direction.

4 CONCLUSIONS

In this paper, we have shown that using amplitude-offset measurements and reverse heading orbits, it was possible to retrieve the complete 3D deformation field within sub-meter accuracy levels. The main advantage of using amplitude-offsets is that we don't need to consider coherence between image pairs as much as we do for interferometric measurements. Coherence estimations are sensitive to topography, temporal decorrelation, satellite orbit conditions and deformation gradients, which limits conventional interferometric methods in their capability to estimate coherent surface deformation.

Coregistration with removal of topography effect is important to get an improved estimate of the deformation field. We have successfully implemented new algorithms to eliminate the topographic contribution to amplitude offsets. Our results also confirm that Muzaffarabad fault is a reverse dextral strike slip fault with uplift mainly in the NW segment.

The 2005 Kashmir earthquake underlines the importance of monitoring and understanding the mechanisms of pre-existing active faults prior to an earthquake. Without such in-situ information, SAR observations provide reliable estimates of surface deformation to governmental agencies in order to improve their mitigation plan and hazard assessment.

ACKNOWLEDGEMENTS

The authors would like to thank S. Samiei Esfahany, G. Ketelaar, P. Marinkovic, F. van Leijen and Z. Perski for valuable discussions during development and implementation of algorithms. We are grateful to The European Space Agency (ESA) for providing ENVISAT data. Interferometric data were processed using the public domain SAR processor DORIS, and satellite orbits from Delft University of Technology.

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