Review Article

Crustal Deformation Studies using Synthetic Aperture Interferometry

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Satellite based Synthetic Aperture Radar interferometry (InSAR) is a well known remote sensing technique to generate digital elevation models of meter-scale accuracy. The technique also enables to measure ground deformation with sub-centimeter level accuracy at a spatial resolution of few meters covering on large areas. In this article we review recent studies from India on crustal deformation related to earthquakes using InSAR technique. We also briefly discuss limitations and recent technological advances of this technique with a future perspective.

Keywords: InSAR; Crustal Deformation; Case Studies from India

Introduction

Active microwave remote sensing using Synthetic Aperture Radar (SAR) sensors has become an important tool for wide variety of earth observations. Geophysical applications of SAR interferometry (InSAR) to measure changes in the Earth's surface have been explored since last two decades. InSAR is a method to combine the phases of two different radar images gathered simultaneously or at different times with slightly different looking angles from the satellites. This technique calculates the interference pattern caused by the difference in phase between these images, which can measure the topography or minute changes in the topography of the order of few millimeters along the satellite look direction between two image acquisitions. InSAR has been used to measure surface deformations caused by a variety of sources like earthquakes, landslides, mining etc. The potential of InSAR for seismological application was demonstrated (Massonnet *et al.*, 1993) to map co-seismic deformation caused by the 1992 Landers earthquake. Further, they proved that InSAR could be used as an alternative tool to obtain location, magnitude and type of an earthquake which otherwise could be only possible with seismological observation. Since then, several studies have been attempted for demonstrating the application of InSAR for

earthquake deformation studies (Burgmann *et al.*, 2000; Prati *et al.*, 2010 and references therein).

InSAR principle

A SAR image is a two-dimensional record of both the amplitudes and the phases of the returns from targets within the imaging area. The amplitude is a measure of target reflectivity, whereas the phase encodes changes at the surface. Phase of two SAR images, gathered simultaneously or at different times with slightly different look angles from space can be combined to produce a radar interferogram. The geometry of a typical repeat pass InSAR is provided in Fig. 1. The spatial distance between two orbits of the repeat pass SAR acquisition is called baseline (Fig. 1). Interferometric phase difference between two SAR images could be expressed as (Ferretti *et al.*, 2007)

$$\Delta\phi = \frac{4\pi}{\lambda} \frac{B_n}{R \sin \theta} h + \frac{4\pi}{\lambda} \frac{B_n}{R \tan \theta} S + \frac{4\pi}{\lambda} d + \Delta\phi_{\text{atm}} + \Delta\phi_{\lambda} \quad (1)$$

where, h is the topographic height, s is the relative slant range position, d is the LOS of the relative displacement, B_n is the perpendicular baseline, R is the SAR-target distance, θ is the "off-nadir" angle,

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$\Delta\phi_{\text{atm}}$ is the differential tropospheric delay phase contribution and $\phi\gamma$ is the phase noise that depends on temporal and geometric decorrelation of targets.

The first two-phase terms in Eq. (1) represent the phase component due to Flat-earth and surface topography it can be eliminated with the availability of the precise orbital information (baseline, sensor-target distance and off-nadir angle) and precise DEM respectively. The residual phase component, phase, is then proportional to the terrain motion component along the LOS plus atmospheric and decorrelation noise. The decorrelation is typically caused by ground surface changes between image acquisitions and plays a major role in controlling the accuracy and spatial converges of the InSAR measurements. Atmospheric contribution to the InSAR introduces long wavelength signals and can be modeled by either using atmospheric models or radiometers on-board satellite.

It should be noted that the InSAR measures a change in range along the look direction but is not capable of determining the full three-dimensional displacement vector as in the case of Global Position System (GPS) measurements. On the other hand, InSAR and GPS are fully complementary as GPS provides precise three-dimensional displacements with high temporal sampling intervals, while InSAR provides spatially distributed one dimensional range-change measurements.

InSAR Studies for Crustal Deformation – Indian Scenario

InSAR technique have been successfully used to study co-seismic deformation associated with the 1995 Chamoli earthquake (Satyabala and Bilham, 2006), Killari earthquake (Satyabala, 2006) and Lushan earthquake (Mathew *et al.*, 2015). The technique was also utilized to map post seismic deformation associated with the 2001 Bhuj earthquake (Chandrasekhar *et al.*, 2009; Saraf *et al.*, 2011; Rastogi *et al.*, 2012, Zia *et al.*, 2014) and low magnitude ($M=5$) earthquake in Chamman fault (Furuya and Satyabala, 2008). Bhattacharya *et al.* (2012) estimated interseismic deformation along parts of Himalayan Frontal thrust using InSAR technique. Further, this technique was also used to map surface deformation associated with fluid extraction (Chatterjee *et al.*, 2006), land mining (Chatterjee *et al.*, 2015), landslide motion (Bhattacharya *et al.*, 2015;

Fig. 1: InSAR acquisition geometry

Bhattacharya and Mukherjee, 2016), geomorphic changes (Majumdar, 2013) and glacier dynamics (Rao, 2011; Saraswat, *et al.*, 2013; Satyabala, 2016). In this article we report and review the recent contributions on earthquake deformation studies from Indian researchers using the InSAR technique. We particularly discuss on the recent InSAR based studies of the 2015 Gorkha, Nepal earthquake (Sreejith, *et al.*, 2016a,b) and the 1992 $M_w = 6$ Kohat Plateau earthquake and associated tectonics (Satyabala, *et al.*, 2012).

M_w 7.8 Gorkha, Nepal, Earthquake

The catastrophic 25 April 2015, Gorkha, Nepal earthquake of magnitude M_w 7.8 located between Pokhara and Kathmandu (28.147° N and 84.708° E after U.S. Geological Survey National Earthquake Information Center (NEIC), 2015 and Global Centroid Moment Tensor Catalogue (GCMT), 2015) is one of the largest earthquakes to have struck Nepal since the 1934 Bihar Nepal earthquake of M_w 8.2 (Sapkota, *et al.*, 2012). The earthquake caused widespread destruction in Nepal and parts of India and China with a total death toll exceeding 9000 and injuring 23000 in an area inhabited by about 8 million people. Moment tensor solutions from tele-seismic data suggest that the Nepal earthquake occurred on a $10\text{--}20^\circ$ dipping sub-horizontal blind thrust fault at about 15 km depth with a strike of 290° from the north (NEIC, 2015). The M_w 7.8 event was followed by 18 aftershocks with magnitude > 5 including two events having magnitudes 6.1 and 6.6 on the same day. The largest aftershock occurred on 12 May 2015 about 150 km east of the main shock (Fig. 2).

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Fig. 2: Map showing the epicenter locations of the 25 April 2015 (M_w 7.8) Gorkha, earthquake and 12 May 2015 (M_w 7.3) aftershock (red stars) along with other aftershocks [after Adhikari *et al.*, 2015] in circles. Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust faults (MCT) are shown as black lines. The inset map represents the present study area in rectangle with great and large earthquakes since 1505 in stars

carried out detailed analysis of the co-seismic and early post-seismic deformation of the Gorkha earthquake using InSAR and GPS techniques as a part of the Disaster Management Support Program (DMSP) of the Indian Space Research Organization (ISRO). The results of the studies have provided new constraints on the coseismic and early post-seismic slip on the causative that has important implications in seismic hazard assessment of the Nepal Himalaya.

SAR data from Sentinel-1 satellite and near-field GPS data from 4 stations (CHLM, KKN4, NAST, and SNDL) of Nepal Geodetic Network were utilized for the coseismic and postseismic investigations of the Gorkha earthquake. The deformation map generated from the coseismic

interferogram (Fig. 3A) suggests an upliftment of about 1 m near Kathmandu and a subsidence of about 0.8 m towards north along the LOS of the pertinent satellite. The most striking feature of the early postseismic deformation is the reversal in the direction of ground motion with respect to the coseismic deformation (Figs. 3A-3E). Further, it is observed that the postseismic deformation pattern is broader in wavelength and appears to be asymmetric with upliftment towards north of 0.05-0.15 m (corresponding to the coseismic subsidence) and a subsidence up to 0.07 m towards south (corresponding to the coseismic upliftment) along the LOS (Figs. 3B-3E). The InSAR observations are well supported by the GPS observations. The complementary nature of coseismic and postseismic deformation, the broader

Fig. 3: (A) Coseismic and postseismic deformation maps at different epochs (B, C and D) generated by InSAR analysis (Sreejith *et al.* 2016). GPS data off-sets corresponding to InSAR epochs in horizontal (black arrow) and vertical (white arrow) directions are shown. Figure 2e indicates the profiles of InSAR data during coseismic (left Y axis) and different postseismic epochs (right Y axis) as indicated by respective color codes along the section AB. Postseismic deformation along section AB obtained from ALOS interferogram [Lindsey *et al.*, 2015] is also shown (Gray dots)

wavelength of later and the logarithmic fit to the postseismic time series GPS data together indicate afterslip at deeper parts of the causative fault.

The observed deformation pattern of the coseismic deformation was explained by a simple forward model (Sreejith, *et al.*, 2016a) consisting of planar dislocation buried in elastic half-space (Okada, 1985). The model revealed that the overall rupture occurred on a 170 km long, 60 km wide fault along the strike (286°) and dipping north ($\text{dip}=15^\circ$) with large amount of slip (4.5 m) confined to the center (95×22 km²) and less slip (0.25 m) on the surrounding part of the fault plane (Fig. 4). The best fit fault plane has a $\text{dip} = 15^\circ$ and $\text{rake} = 98^\circ$ with fault centroid at 85.45°E and 27.85°N located at a depth of 20 km. The slip model obtained from the forward computations is comparable to those obtained from inversion of seismic and geodetic data (Lindsey *et al.* 2015; Wang and Fialko 2015; Galetzka *et al.*, 2015, Grandin *et al.*,

2015, Avouac *et al.*, 2015). However, the forward model suggests a steeper dip angle (15°) for the causative fault compared to 7° – 11° as suggested by the earlier studies. They further noted that the area, depth and dip of the modeled fault plane are fairly consistent and overlap with the location of mid-crustal ramp in MHT with a dip angle $\sim 16^\circ$ at a depth of 10–25 km imaged from the seismic reflection and receiver function stacking studies. The mid-crustal ramp structure is known to have accumulating stress in the inter-seismic period as suggested by micro-seismic and geodetic observations (Pandey *et al.*, 1995; Avouac, 2003). Keeping these observations in view, Sreejith *et al.*, 2016a have suggested that the Gorkha earthquake was possibly caused by the release of inter-seismic strain energy accumulated in the environs of mid-crustal ramp due to plate boundary forces. However, it appears that the hypothesis put forward in this study need to be verified using more sophisticated models.

Fig. 4: Forward modeling results of the coseismic deformation caused by the Gorkha earthquake (modified after Sreejith *et al.*, 2016a). LOS deformation along profile AB (± 50 km either sides) is shown as gray dots. The black line indicates the best fit modeled deformation along the profile AB (dip= 15° and depth 20 km). Deformation models along the profile AB for dip= 7° depth 20 km (dashed line), dip 15° and depth=12 km (dotted line) are also shown for comparison. The topography along the profile (middle) and trace of model fault (bottom) are shown. Fault plane solutions obtained from InSAR and that of GCMT are also shown in the bottom panel

Sreejith, *et al.*, 2016b presented a more realistic fault model for the Gorkha earthquake by joint inversion of InSAR and GPS data (Fig. 5). Their model fault consists of four connected fault segments of variable widths (10-65 km) and dip angles (5 - 30°) representing the complex geometry of MHT as obtained from geophysical studies (Avouac, 2003). The strike of the fault segments considered is 292° and has variable rakes (90° - 100°). InSAR and GPS data were jointly inverted to constrained least-squares optimization to solve for the dip-slip and strike-slip components. The coseismic rupture of the Gorkha earthquake is dominated by thrust slip with a maximum value of 5.65 m along with a minor component from right-lateral slip (0.6 m). The maximum coseismic slip is about 5.7 m at a depth of 12 km (Fig. 5). The coseismic slip model suggests that the nucleation of the earthquake appears to have initiated at the lower bend portion of the flat-mid-crustal ramp transition. The down-dip propagation of the rupture along the steep ramp must have been restricted due to sharp changes in frictional and rheological properties along the ramp, whereas the shallow portion of the MFT remained uninterrupted during the earthquake. Further, they noticed that the lateral extend of the co-seismic rupture is defined by the NE-SW trending Trisouli transfer zone towards west and the rupture area of the M_w 8.2, 1934 Nepal-Bihar earthquake towards

Fig. 5: (A) Coseismic slip model of the 25 April 2015, Gorkha earthquake. Depth to the fault (Dashed white lines) and aftershocks during 25/04/2015-11/05/2015 (Gray dots) and 12/05/2015-07/06/2015 (Black circle) are shown, (B) Postseismic slip model for the 25 April 2015, Gorkha earthquake with co-seismic slip contours (White). (Modified after Sreejith *et al.*, 2016b)

east. The four segment fault model presented in this study has provided a better insight to the subsurface slip distribution along the MHT compared to highly simplified fault model presented in previous studies (Wang and Fialko, 2015; Lindsey *et al.*, 2015).

The post-seismic motion has significant contribution from right-lateral slip, particularly along the down-dip patch, where the maximum right-lateral slip is about 0.23 m and accounts for about half of the dip-slip component (Fig. 5). Comparison of coseismic and postseismic slip models clearly suggests that the coseismic slip occurred along the upper part of the mid-crustal ramp, whereas majority of the postseismic slip (0.1–0.2 m) occurred below the lower edge of the mid-crustal ramp (Fig. 5), where relatively ductile inter-seismic creeping zone exists (Ader *et al.*, 2012). This clearly indicates that the afterslip is predominantly aseismic in nature. It turns out that the segment of MHT where comparatively steep mid-crustal ramp interacts with flat fault segments acted as a barrier for stress build-up in central Nepal Himalaya and seems to spawn earthquakes.

The 2015 Gorkha earthquake occurred on a seismic gap between the 1934, 1833 and 1505 events (Fig. 1) and ruptured the deeper portion of the MHT towards east-southeast direction. However, the afterslip model in the present study suggests that the postseismic relaxation is confined to the down-dip and eastern portions of the coseismic asperity. This indicates that a large stress field induced by the thrust motion towards south during the Gorkha earthquake

Fig. 6: Map showing rupture area of the Gorkha earthquake (purple), rupture area of 1934 and 1505 earthquakes (yellow) and unruptured portions (blue dashed lines) (After Bilham, 2015). Area of early postseismic slip (Sreejith *et al.*, 2016b) is marked with red shade

is not relaxed immediately in the early postseismic period. It increases the risk of another major event as postulated by Bilham (2015) (Fig. 6). However, continued geodetic observations, particularly time series InSAR measurements, are much needed to understand the detailed postseismic behavior of the MHT towards south.

The 1992 Kohat Plateau Earthquake

On 20 May 1992 an unusual $M_w = 6$ earthquake occurred beneath the Kohat Plateau (Fig. 7) approximately 30 km north of the Surghar range that bounds its southern edge. The earthquake was larger than any in the historical record and caused damage to nearby cities and loss of life in Kohat. The earthquake is particularly interesting as it occurred on a viscous, sub-horizontal décollement, where aseismic slip dominates over earthquakes in response to stress. The earthquake was captured by InSAR data (Fig. 8) (Satyabala, *et al.*, 2012). Elastic dislocation modeling of the InSAR data suggests that the seismic rupture occurred on a 1° , NNW dipping basal décollement underlying the Kohat Plateau. About 30 cm slip was occurred on $8 \times 9 \text{ km}^2$ a fault plane resulting a moment magnitude of $M_w = 5.9$. The model derived fault parameters are in agreement with that derived from 26 broadband seismic waveform observations.

The seismic and InSAR data thus provide compelling evidence that the décollement slipped

Fig. 7: Topography of Kohat Plateau (yellow polygon) and adjoining regions. Rupture area of 20 May 1992 $M_w = 6.0$ earthquakes shown as green rectangle in map. InSAR tracks numbered as inclined rectangles. (Figure adopted from Satyabala *et al.*, 2012)

Fig. 8: InSAR data and synthetic model for 1992 earthquake, (A) Coseismic interferogram for 157 days after the Kohat earthquake, (B) Residual after subtracting synthetic model from A, (C) Synthetic interferogram of best-fitting model. Line-of-sight displacement scales in mm (A–C), (D) Topography for the region and (E–G) Profiles identified in C. Continuous line, model; red and black symbols, coseismic and residual data, respectively. (Figure adopted from Satyabala *et al.*, 2012)

seismically in 1992. The significance of this is that, for horizontal rupture to have occurred, the patch that was stuck must have been loaded by preseismic stresses developed 30 km north of the frontal thrusts of the Surghar range, and a yet greater distance south of the Kohistan Ranges, where currently 80% of India's convergence with the Eurasian plate is manifest geodetically (Mohadjer, *et al.*, 2010). Thus the asperity is not located at a transition zone between locked seismic rupture and steady creep, as, for example, occurs in subduction zones or near the base of the high Himalaya. The process is similar to that associated with repeating earthquakes on asperities on creeping faults in central California and elsewhere (Templeton *et al.*, 2008). Creep processes apparently permit the plateau to stream around basal asperities, with strain developing upstream and along their sides.

The cumulative slip of the plateau occurs partly by aseismic slip on a viscous décollement, and partly by seismic slip on one or more asperities where the sediments of the plateau lie directly on the crystalline

or sedimentary basement. The décollement beneath the Potwar Plateau is known to consist of Cambrian salt (Yeats *et al.*, 1984), providing weak layer of compliant rheology must exist throughout much of the décollement for aseismic slip to have stressed the 1992 rupture zone. Presumably, the plateau at the location of the 1992 earthquake has been welded to the underlying basement by increased local friction, or has occurred, as in the Potwar Plateau, by the evacuation of viscous materials to the surrounding décollement or into the cores of anticlines developing in association with ramp thrusts. Postseismic interferograms reveal slip of 10 mm on the décollement in an annulus surrounding the rupture zone (Fig. 9).

The study suggests that the southern Kohat Plateau advances over India partly as a result of creep on a viscous décollement, and partly by stick slip processes on one or more asperities that for prolonged periods are welded to the underlying basement. Thus this part of the plateau does indeed slip with a

Fig. 9: Afterslip 17–402 d after the 1992 Kohat earthquake from time-series analysis of a post-seismic 30-fold stack spanning 1992–93. (Figure adopted from Satyabala et al., 2012)

caterpillar-like motion. Thus this hybrid seismic and aseismic behaviour represents an evolution of the mode of slip of the plateaux from steady creep towards increasingly widespread seismic rupture.

Future Perspectives

The InSAR technique has been effectively used to study earthquake induced deformation studies as demonstrated by several case studies. However, lack

of seamless data availability, atmospheric distortions and decorrelation effects make the technique more challenging for geophysical applications. Development of regional atmospheric correction models for InSAR, particularly for tropical regions, is important for effective use of the technique. Recent advances in time series InSAR techniques such as Small Baseline Subset Interferometry (SBAS) and Persistent Scatterer Interferometry (PSInSAR) have greatly improved the accuracy of measurement and could be effectively useful in monitoring inter-seismic deformation across active faults and volcanic processes. Further, availability of new high resolution SAR sensors with a short revisiting time such as TerraSAR-X, ALOS-2, Sentinel-1 have provided great opportunity to get precise surface ground motion on a high density of measurement points covering large areas. The joint SAR mission between NASA and ISRO scheduled to be launched in 2020 is expected to provide seamless SAR data in both L and S band with a 12-day interferometric orbit that will provide systematic global coverage over all the landmass. These data sets would be particularly useful in understanding the dynamics of the solid earth, cryosphere and ecosystem with unprecedented level of accuracy and coverage.

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