Source model of 18 September 2004 Huntoon Valley earthquake estimated from InSAR

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Abstract

On 18 September 2004, ~~an Mw 5.5~~a sequence of three Mw 5.2-5.6 earthquakes ~~earthquake~~ struck the Huntoon Valley, California, USA. To measure the coseismic deformation field, we applied interferometric synthetic aperture radar ~~(SAR)~~ (InSAR) technique on ascending and descending SAR images from the ENVISAT satellite. Multi-temporal InSAR images were stacked to reduce the atmospheric artifact and other noise. Deformation signals ~~are~~ were ~~obvious~~observed across the northeast-trending, left-lateral strike-slip fault that produced the earthquakes. Ascending and descending deformation maps allowed us to retrieve the east-west and vertical displacement components. Our results show that the displacement in the east-west component is between -3 cm and 3 cm while the vertical component is between -1 cm and 1 cm on both sides of the fault. To increase the temporal sampling and ~~more~~ the accuracy of deformation measurements~~modeling results~~, we applied small-baseline subset SBAS InSAR algorithm ~~and then we could retrieve pre-, coseismic, post deformation.~~to the observed interferograms.

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Modeling the ~~averaged~~ coseismic deformation ~~from SBAS results~~field ~~images from both descending and ascending tracks~~ with an elastic dislocation source resulted in a best-fit ~~8~~9-

km-long by 3-km-wide fault model that strikes northeast at a depth of about 4.7 km. The InSAR-derived source parameters are comparable with those from seismic catalogs. InSAR can provide accurate, independent locations of moderate-sized earthquakes and better constraints on the direction of strike if both descending and ascending interferograms are available. Since InSAR data can have high spatial resolution and can act as an independent remotely sensed data source, modeling InSAR-derived deformation field should improve fault parameters for moderate-sized earthquakes, particularly over remote areas where seismic network coverage is poor.

~~The magnitude calculated by InSAR data is Mw 5.6, which is similar to that from the local earthquake catalog and slightly larger than estimates from global earthquake catalogs. Moreover, the InSAR-derived depth is similar to that from the local catalog; both are shallower than those reported in the global catalogs. Besides, InSAR-derived fault source parameter provide independent earthquake location and strike earthquake geometry using deformation pattern. Our results suggest that the earthquake parameters based on global seismic catalogs can be improved by high-resolution InSAR imagery and modeling.~~

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1 Introduction

The Huntoon Valley is a ~~fault~~ fault-bounded basin within the Excelsior Mountains, California, USA. The valley trends northeast between the Adobe Hills to the southeast and the Excelsior Mountains to the northwest (Wesnousky, 2005) (Fig. 1). There is little sign of recent fault activity other than local occurrences of oversteepening at the base of the range front and a number of well-developed triangular facets on the northwest side of the valley (Wesnousky, 2005). Generally, reported slip rate has been less than 0.2 mm/yr (Adams and Sawyer, 1998).

The seismicity over the Huntoon Valley area has been stable before September 2004 (Fig. 2). ~~Based on the earthquake frequency plot during 1984 and 2010(Figure 2(a)), the increase of~~

~~seismicity during 2004-2006 consisted of several moderate sized earthquakes, including an Mw 5.2, an Mw 5.4 and an Mw 5.6 earthquake (Figure 2(b)).~~

On 18 September 2004, ~~at 23:02:17 (UTC),~~ ~~an earthquake of~~ ~~A~~a sequence of earthquakes including three Mw ~~5.4~~ 5.2-5.6 events occurred ~~just~~ east of Mono Lake and beneath the Adobe Hills of the Huntoon Valley area (Fig. 1) (Table 1). ~~There was no damage reported because this region is unsettled and the event was not so strong. On the other hand, the earthquake~~The earthquakes produced widely felt shaking in the area from Bridgeport to Bishop, California, while no damage was reported (USGS LVO, 2005). Several focal mechanism solutions were released by different organizations using seismic data (Table 1). In this study, we compiled the earthquake information from four catalogs, i.e. ~~:~~ National Earthquake Information Center Preliminary Determination of Epicenters (PDE), California Integrated Seismic network (CISN), Global Centroid Moment Tensor (CMT), and Double-Difference Earthquake Catalog for Northern California (NCAeeDD) (Waldhauser and Schaff, 2008)(~~Talbe~~Table 1). ~~Esepecially,~~The NCAeeDD ~~is~~has improved ~~the resolution~~estimates ~~i~~on hypocenter locations ~~by~~through waveform cross-correlation (CC) and double-difference (DD) methods (Waldhauser and Scaff, 2008).

~~However, the The focal mechnism~~ solutions ~~of four catalogs~~ ~~are~~ ~~were~~ ~~slightly different due to possible errors in the velocity model, the poor distribution of seismic stations, and different algorithms for parameter determination (Mellors et al, 2004). In other words, the reliability of the focal mechanism based on the seismic data mostly depends on many uncertain factors. However, on the other hand, InSAR can provide high resolution deformation samplings, therefore, InSAR can constrain the source parameters precisely. Thus,~~

comparing to seismic data, InSAR usually plays an important role in achieving earthquake source parameters.

Interferometric synthetic aperture radar (InSAR) utilizes SAR images acquired at different times to derive surface deformation at an unprecedented spatial resolution (e.g., Massonnet and Feigl, 1998; Lu, 2007; Lu and Dzurisin, 2014). Moreover, InSAR images from ascending and descending SAR tracks can be used to calculate the displacement components in the east-west and vertical directions (Wright et al., 2004). The focal mechanism solutions from the four earthquake catalogs (Table 1) were slightly different due to possible errors in the velocity model, the poor distribution of seismic stations, and different algorithms for parameter determination (Mellors et al, 2004). Therefore, high spatial-resolution InSAR imagery can provide additional constraints on the source parameters. The interferometric SAR (InSAR) images The InSAR technique can be used to derive source parameters associated with seismic, volcanic and other processes. For earthquake studies, InSAR provides independent information about the earthquake source parameters. This is can be particularly useful over areas where seismic stations are poorly distributed.

Numerous studies have attempted to derive earthquake mechanisms in spite of InSAR limitations such as decorrelation, atmospheric errors and low temporal resolution (e.g., Weston et al., 2011). However, Weston et al. (2011) reported that there were 57 earthquakes occurred from of 1992-to--2007, for which there are both GCMT and InSAR reportderived source parameters. Among these earthquakes, only In case of6 moderate-sized earthquakes about (less than Mw 5.56) were studied by , only 6 earthquakes used for InSAR modeling due to atmospheric noise and, data incoherence. In this respect, importantlypaper, we studied the , Huntoon Vvalley earthquakes (Mw 5.2-5.6) with detailed InSAR analysis and modelinghas been studied for the first time with modeling.

~~For the Huntoon Valley earthquakes,~~ Bell et al. (2008) showed the line-of-sight (LOS) deformation field due to the 19 September 2004 Huntoon Valley earthquakes using only 1 interferogram from a descending track. In this paper, we processed a ~~large~~ number of SAR images from both descending and ascending tracks. We stacked ~~many~~ interferograms to improve the signal-to-noise ratio of the final deformation images. We derived the deformation field in the east-west and vertical directions using the ~~averaged~~ stacked descending and ascending ~~InSAR images.~~interferograms. ~~Even if the earthquake was moderate Mw size, this method may have risk to~~W~~ include pre-, post- deformation and effect to modeling. Therefore, we~~ used ~~SBAS(~~s~~S~~mall-~~—BA~~baseline s~~S~~ubset (SBAS) InSAR processing ~~A~~algorithm (Berardino et al., 2002) to obtain deformation time series and evaluate any possible pre- or post-seismic displacement. ~~make the best use of temporal resolution.~~ Finally, we modeled the observed deformation images from the descending and ascending tracks jointly using an elastic dislocation source and compared the InSAR-derived source parameters with those from various seismic catalogs.

2 Data Processing and InSAR Results

2.1 Data Processing

To measure the coseismic surface deformation, we obtained ascending and descending SAR images from the European Environmental Satellite (Envisat) operating at C-band with a wavelength of 5.6 cm. We used the two-pass InSAR approach (e.g., Massonnet and Feigl, 1998) to generate interferograms with perpendicular baselines less than 350 m and temporal baselines less than 5 years from one ascending and one descending tracks, respectively. We then chose 5 descending (Table 2) and 8 ascending (Table 3) co-seismic deformation interferograms whose coherence values are greater than 0.3. We used a 1-arc-second digital elevation model to correct for the topographic phase contribution in the interferograms. Interferograms were created by using a complex multilook operation with 2 looks in the range and 10 looks in the azimuth directions, resulting in a pixel dimension of about 40 m by 40 m. After that, each pairinterferogram was smoothed using an adaptive filter with a window size of 32 to reduce phase noise (Goldstein et al., 1998). Finally, a minimum cost unwrapping algorithm iwas used to unwrap the interferometric phase (Costantini, 1998).

The averaged deformation mapsThe iInterferograms from the ascending and descending tracks then can allow us to retrieve the east-west and vertical displacement components (Wright et al., 2004; Jung et al., 2011). Because both the ascending and descending tracks of Envisat are near-polar orbits, we couldn't resolve the deformation field in the north-south direction based on two LOS InSAR observations (Wright et al., 2004; Jung et al., 2011).

Let $\mathbf{d}=(d_x, d_y)^T$ be the 2-dimensional deformation vector in a local (east, up) reference frame. If **u** is tThe unit LOS deformation vector in the same local reference frame, then **u** is $(\sin\theta\cos\varphi, \cos\theta)^T$, where θ is the radar incidence angle from the vertical and φ is the satellite track angle from north, respectively. **u** is a matrix containing unit LOS vectors (u_asc, u_dsc) which can be calculated based on the corresponding θ and φ from the ascending and descending tracks, respectively. **r** is a vector representing the LOS deformation measurements (observations) from interferograms of both ascending and descending tracks. Thus, the unit vector u (u_{asc}, u_{dsc}) is calculated by θ and φ from ascending and descending tracks, respectively. If we produceThe deformation r (r_{asc}, r_{dsc}) measured from InSAR interferograms (observations) from both descending ascending and ascending descending tracks, Then, we can obtain the deformation vector $\mathbf{d} = -(\mathbf{u}^T\mathbf{u})^{-1}(\mathbf{u}^T\mathbf{r})$, where **u** and **r** are given by $\mathbf{u}=(u_{\_asc}, u_{\_dsc})^T$ and $\mathbf{r}=(r_{\_asc}, r_{\_dsc})^T$, respectively. At lastFinally, the interferograms and deformation maps were precisely georeferenced to a geographic coordinate system.

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2.2 InSAR results

The coherence of a repeat-pass interferogram highly depends on its perpendicular and temporal baselines. Fortunately, the study area maintains interferometric coherence value greater than 0.3 in spite of large perpendicular baseline and temporal baseline (Tables 2 and 3). This is because that Huntoon Valley is located in an arid semi-desert region with little vegetation. Fig. 3 shows coherence images which were calculated from original (not filtered) interferograms. Clearly, Fig. 3(b) and Fig. 3(d) have higher coherence because of short perpendicular or temporal baselines (Table 2). Other interferogram pairs used in this study have coherence value greater than 0.3 (Fig 3). The higher coherence of interferograms in this study allowed us to interpret the deformation results reliably.

NCAeeDD catalog reported three earthquakes: Mw 5.6 (3.26 km depth), MW 5.2 (7.15 km depth), and MW 5.4 (8.76 km depth). Generally, ground surface deformation produced by an earthquake is highly controlled by its magnitude and depth (Okada, 1985). Moreover, based on the simulation study of Dawson et al. (2007), InSAR is generally insensitive to the deformation of an earthquake with magnitude less than 5.5 and depth larger than 6 km. The surface deformation from the Mw5.6 earthquake is much larger than the combined deformation from the other two events. So, the observed deformation is mainly due to the Mw 5.6 event. Therefore, in this study, we focused on the Mw 5.6 earthquake which occurred at 23:02:17 (UTC) and compared the InSAR-derived source model parameters with those from the Mw 5.6 event.

Then, we analyzed the interferograms (Fig. 4) to ensure the observed signal is real deformation other than atmospheric artifacts. Indeed, most of the descending interferograms are noisy, including some atmospheric influences. However, the signals with lobe patterns

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persist in all the interferograms were unlikely due to atmospheric artifacts, because some interferograms were produced from independent SAR images acquired on different dates (e.g. Fig. 4a, 4c, 4g, 4i). Considering some of the interferograms were contaminated by atmospheric artifacts, we then carried out stacking method (Biggs et al., 2007) to obtain the co-seismic deformation by reducing atmospheric noise. Stacking is a technique that can extract subtle deformation signals out of multiple interferograms. By averaging many interferograms over the same area, random noise such as atmospheric signals can be subdued (Biggs et al., 2007). For earthquakes of this size, it should be noted that the postseimic deformation is negligible compared to the co-seismic part (Segall, 2010). Thus, in this study, the stacked interferogram is dominated by the co-seismic deformation. In addition, we applied SBAS processing to obtain deformation time-series, confirming that the post seismic deformation from the Mw 5.6 event could not be measured from our InSAR datasets. **Formatted:** Font: (Asian) Chinese (PRC)

~~Averaged~~ Stacked interferograms from both descending and ascending tracks are shown in Fig. ~~2(a)~~ 5(a) and Fig. ~~2(b)~~ 5(b), respectively. The deformation signals are ~~more~~clearly visible ~~with less noise~~ across the northeast-trending fault that produced the earthquake. The deformation reached about 2 cm in LOS on both sides of the fault. The east-west and vertical displacement components based on the ~~averaged~~ stacked deformation images from the descending and ascending tracks are shown in Fig. ~~2c~~ 5(c) and Fig. ~~2d~~ 5(d), respectively. Fig. ~~3~~ 6 shows the horizontal and vertical displacements along the profile AB labeled in Fig. ~~2~~ 5. The displacement in the east-west component is between -3 cm and 3 cm on both sides of the fault. Meanwhile, the deformation of the vertical component is between -1 cm and 1 cm on both sides of the fault. From ~~the~~ this analysis ~~of the profile~~ we can conclude that the horizontal component dominated the deformation ~~pattern~~field.

3 Modelling & Analysis

3.1 ~~InSAR deformation modelling~~Time-series Deformation and Coseismic ~~Modeling~~Modelling

~~Stacking approach is a reliable method to make the deformation signal stronger and measures surface deformation when limited coseismic interferogram sets are available. Then~~Next, we tried to obtain deformation time-series ~~figure out the local deformation variation evolved with time~~ via SBAS ~~(Small BAseline Subset)~~ approach (Berardino et al., 2002). By doing this, we ~~can~~might discern the pre- and ~~,~~post-seismic –deformation ~~that related~~associated with the Huntoon valley earthquake sequence. The SBAS InSAR processing ~~algorithm~~ adopts spatially low-pass and temporally high-pass filters to mitigate atmospheric effects. ~~Moreover, the method removed topographic error using irrelevant signal appearance due to hypothesis of baseline . At last, it~~The algorithm uses the ~~simgular~~singular value decomposition (SVD) to obtain deformation time series from temporally disconnected ~~differential~~ interferograms ~~. By using SVD, the interferograms are adjacently linked and increase the temporal sampling of the time-span. From 2003 to 2010, we used 15 and 19 scenes acquired from ascending and descending tracks, respectively. These were distributed in two small-baseline subsets, respectively~~ (Fig.7).

Deformation ~~SBAS algorithm is applied to convert~~ time -series ~~surface deformation and Fig 8 shows~~that include the pre-, cos~~esimic~~-, post-seismic deformation results are shown in Fig. 8. We plotted the time-series ~~Dispacement~~displacements ~~of earthquake along the LOS has different impact on ascending and descending tracks. Therefore, we have selected~~over two points (P1, P2) which ~~is~~ have the maximum deformation ~~pixel~~ from the ascending and descending tracks, respectively~~(Fig 8(1), Fig 8(2))~~. ~~The time series variations of these points is show that coseismic deformation interferograms include some pre- and postseismic deformation. Even though we take into accout the fact that typical~~In lieu of typical SBAS accuracy is of 5.6 mm in amount of SAR data available(Casu et al., 2006), the pre- and post-seismic partsdeformation are not negligible comparing to the coseismic part as shown Fig 8can't be distinguished outside the coseismic part due to the poor temporal-resolution of SAR datasets as well as the relatively small size of the earthquake (Fig. 8). So, the postseismic deformation, if any, should be included in the coseismic interferograms.Indeed, preseismic period have detected anti-coseismic signal (Fig 8 (a),(b)), these signal are affected to coseismic signal.

To reveal retrieve the focal mechanism parameters of the -18 September 2004 earthquake (Mw 5.6), we jointly modeled the -averaged interferograms coseismic deformation images measured byfrom SBAS resultsprocessing of from the ascending and descending InSAR tracks. We using used an elastic dislocation source (Okada, 1985) because the eartuqhake has shown simple fault geometries(Wang et al., 2013)to model the displacement field. The rectangular elastic dislocation source consists of 10 model parameters: two location coordinates for the center of source (x, y), depth (z), length, width, three components of slip (strike, dip, tensile), and strike and dip of the dislocation plane. We used the downhill simplex method and Monte Carlo simulations (Press et al., 1992) to estimate optimal parameters and their uncertainties, and the root mean square (RMS) errors between the observed and modeled interferograms as the prediction-fit criterion. The best-fit parameters and their uncertainties are listed in Table 4. Figure 4 9 shows the observed (Fig. 4a 9(a) and Fig. 4d 9(d)), modeled (Fig. 4b 9(b) and Fig. 4e 9(e)), and residual (Fig. 4c 9(c) and Fig. 4f 9(f)) interferograms from descending and ascending tracks, respectively. RMS misfits are 4 mm and 6 mm for the ascending and descending interferograms, respectively. The descending interferogram has a slightly larger RMS misfit than the ascending one due to relatively stronger atmospheric artifacts in the descending interferograms. The best-fit fault model strikes approximately N-E with a length of about 8 9 km and a width of 3 km centered at a depth of 4.7 km.

3.2 Comparison of source parameters from InSAR and seismology

After we obtained the best-fit parameters for the dislocation source, we calculated the earthquake moment magnitude (Mw) based on the formula by Hanks and Kanamori (1979): $Mw = 2/3\log_{10}(M_0) - 10.7$. The seismic moment, M_0, is equal to μAS (Table 4), where μ is the shear strength of the country rock, about $3x10^{11}$ dyne/cm^2 for typical continental crust, A is the area of the fault, and S is the average displacement along the fault plane. The moment magnitude calculated for this earthquake based on InSAR modeling is Mw 5.6.

~~Next, we compared the InSAR-derived earthquake parameters with those from several existing earthquake catalogs: National Earthquake Information Center Preliminary Determination of Epicenters (PDE), California Integrated Seismic Network (CISN), Global Centroid Moment Tensor (CMT), Double-Difference Earthquake Catalog for Northern California (NCAeeDD) (Waldhauser and Schaff, 2008).~~ Overall, InSAR and seismic data agree well regarding the location, moment magnitude, strike and dip of the earthquake (Tables 1 and 4). The difference in earthquake location is less than 3 km (Tables 1 and 4), and InSAR-derived source location is about 3 km away from those from earthquake catalogs (Fig. 9). ~~However, NCAeqDD and CMT have a clear resemblance to location. Similarly, PDE and CISN have shown slightly difference in location. Possibly, for these reasons, these catalogs locations rely on dependent seismic data based on relative location method. On the other hand~~So, it suffices to say that InSAR can provides independent ~~accurate~~ location ~~based on independent measurement~~estimate for a moderate-sized earthquake.

The InSAR-derived earthquake magnitude is Mw 5.6. This estimate is the same as that from NCAeqDD catalog, but ~~smaller than those from~~ both are slightly larger than those from other ~~seismic~~earthquake catalogs ~~such as PDE and CMT~~ (Table 1). The InSAR-derived source depth is about 4.7 km (Table 4), which is slightly shallower than most of estimates

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from earthquake catalogs (Table 1). This is consistent with a global survey that InSAR-derived depth is generally shallower than the estimates from global seismic catalogs (Weston et al., 2011). However, the depth estimate from CMT catalog (12.0 km) represents a significant departure from the other catalogs and the InSAR result, suggesting the depth estimate from the global catalog CMT is probably an outlier (Table 1). The strike dip of the fault from InSAR is nearly identical to those from PDE and CISN catalogs. Notably, all of which are similar to the strike of the three catalogs are similar, however, InSAR-derived strike has a difference with catalogs about 2017º degree. The Ddashed-line shown in Fig 9(a)(d)(e), redash-line presents the catalogs strike direction (239º degree) from earthquake catalogs. In contrast to catalogs, , while the solid- lines representsed the InSAR-derived strike direction (222º degree). We found that a strike of 239º (from the earthquake catalogs) could not fit the InSAR observations well (In Fig 9). We believe the two-dimensional deformation mapping from InSAR provides better constraints on the strike direction of the fault plane.

, the deformation shows left-lateral strike-slip fault and this is agree well regarding InSAR-derived strike than catalogs strike sources. Supposedly, this Our results indicate that the seismic signal of moderate--sized earthquakes could be captured by InSAR a. And the causative fault parameters can be constrained strictlyprecisely. On the other hand, in this case, the fault parameters was constrained loosely by using seismology methods probably because of sparse distributed seismic stations. is not enough to decide strike pattern and distribution of seismic stations affected to calculate the fault source parameter. For that reason, InSAR-derived fault source parameter could improve fault geometry using deformation pattern in moderate size earthquake. As a consequence, in the case of moderate size earthquake, InSAR-derived deformation field and modeling fault source parameters can provide at least provide independent estimates of position datafault parameters, and might supply more reliable source geometry such as strike using deformation patternestimates of source geometry over remote areas where the coverage of seismic network is poor. all of which are similar to the strike of the mapped faults in the area (Figure 1). The strike from the CMT catalog (339 degrees) is much different from InSAR and other earthquake catalogs, suggesting CMT's estimate on strike is also a biased one. However, InSAR imagery suffers poor temporal resolution, atmospheric artifacts, and sometimes loss of interferometric coherence, making it difficult to resolve postseismic signal.Based on the above analysis, we believe the quality of source parameters from the CMT catalog for the 18 September 2004 earthquake is poorer than the others.

3.3 Seismicity over Huntoon Valley area

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Finally, we investigated the seismicity over the Huntoon Valley area during 1984 and 2010 using NCAecDD catalog. The minimum magnitude completeness for earthquakes over this area is about 0.8 (Wiemer and Wyss, 2000). Based on the earthquake frequency plot (Figure 5), the seismicity over the Huntoon Valley fault area has been stable before 2004. The increase of seismicity during 2004-2006 consisted of several moderate-sized earthquakes, including an Mw 5.2, an Mw 5.4 and an Mw 5.6 earthquake (Figure 5). Therefore, we suspect that the observed InSAR deformation field likely represents the cumulative effect of these events. This explains in part why the InSAR derived moment magnitude is slightly larger than most of the seismic catalogs.

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4 Conclusions

Using both descending and ascending Envisat InSAR images, we investigated the 18 September 2004 Mw 5.6 earthquake over Huntoon Valley, California. We stacked multi-temporal InSAR images to improve the signal-to-noise ratio of the averaged deformation images. We then used the averaged stacked deformation images from both descending and ascending tracks to retrieve the east-west and vertical displacement components. Our results show the displacement in the east-west component is between -3 cm and 3 cm on both sides of the fault. The deformation of the vertical component is estimated is between -1 cm and 1 cm on both sides of the fault.

We applied a dislocation source to jointly model the averaged deformation images from the descending and ascending tracks. To increase the temporal sampling and more accuracy of modelingdeformation results, we applied SBAS algorithm- to the observed interferogramsand then we could retrieve pre-, coseismic, post deformation. We concluded that the pre- or post-seismic deformation can't be distinguished outside the coseismic part due to the poor temporal-resolution of SAR datasets and the relatively small size of the earthquake. Finally, we We applied a dislocation source to jointly model the coseismic deformation fields from the descending and ascending tracks,. The best-fit source model determined by InSAR indicates a northeast-trending, left-lateral strike-slip fault with a length of about 8 9 km and a width of 3 km centered at a depth of 4.7 km. The InSAR-derived source parameters are comparable with those from seismic catalogs and can allowed us to judge biased source parameter estimates in the CMTthe earthquake catalogcatalogs. Moreover, these catalogs locations rely on dependent seismic data, while InSAR— can provides accurate, independent locations and better constraints on the direction of strike for a moderate-sized earthquake if both descending and ascending interferograms are availablebased on independent measurement. Besides, InSAR-derived fault source parameter such as strike could improve fault geometry using deformation pattern in moderate size the earthquake. Since InSAR data can have a high spatial resolution and can act as an independent remotely sensed data source, modeling InSAR-derived deformation field can improve fault parameters derived in global catalogs, particularly when

~~the distribution of seismic stations is poor.~~ for moderate-sized earthquakes, particularly over remote areas where the coverage of existing seismic network is poor.

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Table 1. Summary of source parameters for the 18 September 2004 earthquake from four catalogs: PDE, CISN, CMT, NCAeqDD

Source	Latitude (Deg.)	Longitude (Deg.)	Depth (km)	Mw	Strike(°)	Dip(°)
PDE	38.004	-118.677	5.0	5.4	239	89
CISN	38.009	-118.679	7.6	5.5	239	89
CMT	38.020	-118.690	12.0	5.4	~~339~~238	~~76~~81
NCAeqDD	~~38.0119~~ 38.020	~~118.69099~~- -118.691	3.2	5.6	-	-

Note: PDE and CMT are global catalogs whereas CISN and NCAeqDD are local catalogs.

Table 2. ENVISAT SAR interferograms (track No.485, descending)

No.	Master Date	Slave Date	Bperp[m]	Btemp[day]
1	20031019	20050710	50	630
2	20040620	20041003	-5	105
3	20040620	20050814	-29	420
4	20040829	20041003	-248	35
5	20040829	20050814	-272	350

Table 3. ENVISAT SAR interferograms (track No.120, ascending)

No.	Master Date	Slave Date	Bperp[m]	Btemp[day]
1	20031029	20050720	-189	630
2	20031029	20071003	82	1435
3	20031029	20080917	4	1785
4	20040630	20060531	54	700
5	20040908	20071003	-95	1120
6	20040908	20071107	94	1155
7	20040908	20080709	-55	1400
8	20040908	20080917	-174	1470

Table 4. Parameters for the best-fitting dislocation model. Uncertainties correspond to the 95% confidence level.

Latitude (Deg)	Longitude (Deg)	Depth (km)	Strike (°)	Dip (°)	Length (km)	Width (km)	Strike-slip (mm)	Dip-slip (mm)	Tensile-slip (mm)
~~38.0258~~ 38.026±0.003	~~118.6661~~ -118.663±0.003	4.7±0.6	~~229~~222.5±2.9	~~82.7~~ 89.9±5.4	~~8.0~~ 9.3±0.9	3.1±0.4	~~322~~ 301±9	~~-16~~ -9±4	0

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Figure Captions

Figure 1. Shaded relief map of Huntoon Valley and surroundings. Primary geographic features in the region are labeled. Quaternary faults over Huntoon Valley are shown by black lines inside the dashed box. Red star represents the earthquake of Mw 5.~~5~~ 6 on 18 September 2004.

Figure 2. Distribution of (a) frequency and (b) magnitude of earthquakes occurred near the Huntoon Valley area from NCAeqDD catalog.

The minimum magnitude completeness for earthquakes over this area is about 0.8 (Wiemer and Wyss, 2000).

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Figure 3. ~~(a)~(e)~~ Coherence maps from a descending track (a - e) and ~~(f)~(m) from~~ an ascending track (f – m).

Figure 4. ~~(a)~(e)~~ Wrapped Interferogram from a descending track (a - e) and ~~(f)~(m) from~~ an ascending track (f – m).

Figure ~~2~~ 5. (a) LOS deformation image acquired from a descending track. (b) LOS deformation image acquired from an ascending track. (c) East-west component of the deformation field. (d) Vertical component of the deformation field.

Figure ~~3~~ 6. East-west (a) and vertical (b) components of the deformation along a profile AB labeled in Fig. 5~~2(c). (b) Vertical deformation along the profile~~.

Figure 7. Perpendicular baselines used for ~~small baseline subset (~~SBAS~~)~~ InSAR processing from~~.~~ (a~~) Two different small baseline subsets from)~~ descending track~~,~~ and (b) ~~Two different small baseline subsets from~~ ascending track.

Figure 8. (Middle panels) Time-series surface deformation of P1 from the ~~(1)~~ descending track and P2 ~~(2)~~from the ascending track, respectively. [(a), (d)], [(b), (e)], [(c), (f)] ~~are~~ shows pre-, co-~~seismic~~, and post-seismic deformation measurements from the descending ~~track~~ and the ascending tracks, respectively.

Figure 9. ~~4.~~ Observed deformation images from (a) descending track and (d) ascending track. (b, e) Synthetic ~~inteferograms~~interferograms for the descending and ascending track geometries based on the best-fit source model. (c, f) Residual interferograms from the

descending and ascending tracks, showing the difference between observed and modeled interferograms. ~~White~~ Black star represents the center of the best-fit earthquake source while black circles represent earthquake center of earthquake source from catalogs. ~~the~~ The solid line represents the projection of the modeled fault ~~that caused the 18 September 2004 earthquake.~~ w~~W~~hile the dashed line represents the projection of the fault from earthquake catalogs ~~that caused the 18 September 2004 earthquake~~.

Source model of 18 September 2004 Huntoon Valley earthquake estimated from InSAR

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Abstract

On 18 September 2004, a sequence of three Mw 5.2-5.6 earthquakes struck the Huntoon Valley, California, USA. To measure the coseismic deformation field, we applied interferometric synthetic aperture radar (InSAR) technique on ascending and descending SAR images from the ENVISAT satellite. Multi-temporal InSAR images were stacked to reduce the atmospheric artifact and other noise. Deformation signals were observed across the northeast-trending, left-lateral strike-slip fault that produced the earthquakes. Ascending and descending deformation maps allowed us to retrieve the east-west and vertical displacement components. Our results show that the displacement in the east-west component is between -3 cm and 3 cm while the vertical component is between -1 cm and 1 cm on both sides of the fault. To increase the temporal sampling and the accuracy of deformation measurements, we applied small-baseline subset InSAR algorithm to the observed interferograms. Modeling the coseismic deformation field with an elastic dislocation source resulted in a best-fit 9-km-long

by 3-km-wide fault model that strikes northeast at a depth of about 4.7 km. The InSAR-derived source parameters are comparable with those from seismic catalogs. InSAR can provide accurate, independent locations of moderate-sized earthquakes and better constraints on the direction of strike if both descending and ascending interferograms are available. Since InSAR data can have high spatial resolution and can act as an independent remotely sensed data source, modeling InSAR-derived deformation field should improve fault parameters for moderate-sized earthquakes, particularly over remote areas where seismic network coverage is poor.

1 Introduction

The Huntoon Valley is a fault-bounded basin within the Excelsior Mountains, California, USA. The valley trends northeast between the Adobe Hills to the southeast and the Excelsior Mountains to the northwest (Wesnousky, 2005) (Fig. 1). There is little sign of recent fault activity other than local occurrences of oversteepening at the base of the range front and a number of well-developed triangular facets on the northwest side of the valley (Wesnousky, 2005). Generally, reported slip rate has been less than 0.2 mm/yr (Adams and Sawyer, 1998). The seismicity over the Huntoon Valley area has been stable before September 2004 (Fig. 2).

On 18 September 2004, a sequence of earthquakes including three Mw 5.2-5.6 events occurred east of Mono Lake and beneath the Adobe Hills of the Huntoon Valley area (Fig. 1) (Table 1). The earthquakes produced widely felt shaking in the area from Bridgeport to Bishop, California, while no damage was reported (USGS LVO, 2005). Several focal mechanism solutions were released by different organizations using seismic data (Table 1). In this study, we compiled the earthquake information from four catalogs, i.e. National Earthquake Information Center Preliminary Determination of Epicenters (PDE), California

Integrated Seismic network (CISN), Global Centroid Moment Tensor (CMT), and Double-Difference Earthquake Catalog for Northern California (NCAeeDD) (Waldhauser and Schaff, 2008)(Table 1). The NCAeeDD has improved estimates on hypocenter location through waveform cross-correlation (CC) and double-difference (DD) methods (Waldhauser and Scaff, 2008).

Interferometric synthetic aperture radar (InSAR) utilizes SAR images acquired at different times to derive surface deformation at an unprecedented spatial resolution (e.g., Massonnet and Feigl, 1998; Lu, 2007; Lu and Dzurisin, 2014). Moreover, InSAR images from ascending and descending SAR tracks can be used to calculate the displacement components in the east-west and vertical directions (Wright et al., 2004). The focal mechanism solutions from the four earthquake catalogs (Table 1) were slightly different due to possible errors in the velocity model, the poor distribution of seismic stations, and different algorithms for parameter determination (Mellors et al, 2004). Therefore, high spatial-resolution InSAR imagery can provide additional constraints on the source parameters. This can be particularly useful over areas where seismic stations are poorly distributed.

Numerous studies have attempted to derive earthquake mechanisms in spite of InSAR limitations such as decorrelation, atmospheric errors and low temporal resolution (e.g., Weston et al., 2011). Weston et al. (2011) reported 57 earthquakes of 1992-2007, for which there are both GCMT and InSAR derived source parameters. Among these earthquakes, only 6 moderate-sized earthquakes (less than Mw 6) were studied by InSAR due to atmospheric noise and data incoherence. In this paper, we studied the Huntoon Valley earthquakes (Mw 5.2-5.6) with detailed InSAR analysis and modeling.

Bell et al. (2008) showed the line-of-sight (LOS) deformation field due to the 19 September 2004 Huntoon Valley earthquakes using only 1 interferogram from a descending track. In this paper, we processed a number of SAR images from both descending and ascending tracks. We stacked interferograms to improve the signal-to-noise ratio of the final deformation images. We derived the deformation field in the east-west and vertical directions using the stacked descending and ascending interferograms. We used small-baseline subset (SBAS) InSAR processing algorithm (Berardino et al., 2002) to obtain deformation time series and evaluate any possible pre- or post-seismic displacement. Finally, we modeled the observed deformation images from the descending and ascending tracks jointly using an elastic dislocation source and compared the InSAR-derived source parameters with those from various seismic catalogs.

2 Data Processing and InSAR Results

2.1 Data Processing

To measure the coseismic surface deformation, we obtained ascending and descending SAR images from the European Environmental Satellite (Envisat) operating at C-band with a wavelength of 5.6 cm. We used the two-pass InSAR approach (e.g., Massonnet and Feigl, 1998) to generate interferograms with perpendicular baselines less than 350 m and temporal baselines less than 5 years from one ascending and one descending tracks, respectively. We then chose 5 descending (Table 2) and 8 ascending (Table 3) co-seismic deformation interferograms whose coherence values are greater than 0.3. We used a 1-arc-second digital elevation model to correct for the topographic phase contribution in the interferograms. Interferograms were created by using a complex multilook operation with 2 looks in the range and 10 looks in the azimuth directions, resulting in a pixel dimension of about 40 m by 40 m. After that, each interferogram was smoothed using an adaptive filter with a window size of 32 to reduce phase noise (Goldstein et al., 1998). Finally, a minimum cost unwrapping algorithm was used to unwrap the interferometric phase (Costantini, 1998).

Interferograms from ascending and descending tracks can allow us to retrieve the east-west and vertical displacement components (Wright et al., 2004; Jung et al., 2011). Because both the ascending and descending tracks of Envisat are near-polar orbits, we couldn't resolve the deformation field in the north-south direction based on two LOS InSAR observations (Wright et al., 2004; Jung et al., 2011).

Let $\mathbf{d}=(d_x, d_y)^T$ be the 2-dimensional deformation vector in a local (east, up) reference frame. The unit LOS vector in the same local reference frame is $(sin\theta cos\varphi, cos\theta)^T$, where θ is the radar incidence angle from the vertical and φ is the satellite track angle from north, respectively. **u** is a matrix containing unit LOS vectors (u_asc, u_dsc) which can be calculated based on the corresponding θ and φ from the ascending and descending tracks, respectively. **r** is a vector representing the LOS deformation measurements (observations) from interferograms of both ascending and descending tracks. Then, we can obtain the deformation vector $\mathbf{d} = -(\mathbf{u}^T\mathbf{u})^{-1}(\mathbf{u}^T\mathbf{r})$, where **u** and **r** are given by $\mathbf{u}=(u\_{asc}, u\_{dsc})^T$ and $\mathbf{r}=(r\_{asc}, r\_{dsc})^T$, respectively. Finally, the interferograms and deformation maps were precisely georeferenced to a geographic coordinate system.

2.2 InSAR results

The coherence of a repeat-pass interferogram highly depends on its perpendicular and temporal baselines. Fortunately, the study area maintains interferometric coherence value greater than 0.3 in spite of large perpendicular baseline and temporal baseline (Tables 2 and 3). This is because that Huntoon Valley is located in an arid semi-desert region with little vegetation. Fig. 3 shows coherence images which were calculated from original (not filtered) interferograms. Clearly, Fig. 3(b) and Fig. 3(d) have higher coherence because of short perpendicular or temporal baselines (Table 2). Other interferogram pairs used in this study have coherence value greater than 0.3 (Fig 3). The higher coherence of interferograms in this study allowed us to interpret the deformation results reliably.

NCAeeDD catalog reported three earthquakes: Mw 5.6 (3.26 km depth), MW 5.2 (7.15 km depth), and MW 5.4 (8.76 km depth). Generally, ground surface deformation produced by an earthquake is highly controlled by its magnitude and depth (Okada, 1985). Moreover, based on the simulation study of Dawson et al. (2007), InSAR is generally insensitive to the deformation of an earthquake with magnitude less than 5.5 and depth larger than 6 km. The surface deformation from the Mw5.6 earthquake is much larger than the combined deformation from the other two events. So, the observed deformation is mainly due to the Mw 5.6 event. Therefore, in this study, we focused on the Mw 5.6 earthquake which occurred at 23:02:17 (UTC) and compared the InSAR-derived source model parameters with those from the Mw 5.6 event.

Then, we analyzed the interferograms (Fig. 4) to ensure the observed signal is real deformation other than atmospheric artifacts. Indeed, most of the descending interferograms are noisy, including some atmospheric influences. However, the signals with lobe patterns persist in all the interferograms were unlikely due to atmospheric artifacts, because some interferograms were produced from independent SAR images acquired on different dates (e.g. Fig. 4a, 4c, 4g, 4i). Considering some of the interferograms were contaminated by atmospheric artifacts, we then carried out stacking method (Biggs et al., 2007) to obtain the co-seismic deformation by reducing atmospheric noise. Stacking is a technique that can extract subtle deformation signals out of multiple interferograms. By averaging many interferograms over the same area, random noise such as atmospheric signals can be subdued (Biggs et al., 2007). For earthquakes of this size, it should be noted that the postseimic deformation is negligible compared to the co-seismic part (Segall, 2010). Thus, in this study, the stacked interferogram is dominated by the co-seismic deformation. In addition, we applied SBAS processing to obtain deformation time-series, confirming that the post seismic deformation from the Mw 5.6 event could not be measured from our InSAR datasets.

Stacked interferograms from both descending and ascending tracks are shown in Fig. 5(a) and Fig. 5(b), respectively. The deformation signals are clearly visible across the northeast-trending fault that produced the earthquake. The deformation reached about 2 cm in LOS on both sides of the fault. The east-west and vertical displacement components based on the stacked deformation images from the descending and ascending tracks are shown in Fig. 5(c) and Fig. 5(d), respectively. Fig. 6 shows the horizontal and vertical displacements along the profile AB labeled in Fig. 5. The displacement in the east-west component is between -3 cm and 3 cm on both sides of the fault. Meanwhile, the deformation of the vertical component is between -1 cm and 1 cm on both sides of the fault. From this analysis we can conclude that the horizontal component dominated the deformation field.

3 Modelling & Analysis

3.1 Time-series Deformation and Coseismic Modelling

Next, we tried to obtain deformation time-series via SBAS approach (Berardino et al., 2002). By doing this, we might discern the pre- and post-seismic deformation associated with the Huntoon valley earthquake sequence. The SBAS InSAR processing adopts spatially low-pass and temporally high-pass filters to mitigate atmospheric effects. The algorithm uses the singular value decomposition (SVD) to obtain deformation time series from temporally disconnected interferograms (Fig.7).

Deformation time series that include the pre-, co-, post-seismic deformation results are shown in Fig. 8. We plotted the time-series displacements over two points (P1, P2) which have the maximum deformation from the ascending and descending tracks, respectively. In lieu of typical SBAS accuracy of 5.6 mm (Casu et al., 2006), the pre- and post-seismic deformation can't be distinguished outside the coseismic part due to the poor temporal-resolution of SAR datasets as well as the relatively small size of the earthquake (Fig. 8). So, the postseismic deformation, if any, should be included in the coseismic interferograms.

To retrieve the focal mechanism parameters of the 18 September 2004 earthquake (Mw 5.6), we jointly modeled the coseismic deformation images from SBAS processing of the ascending and descending InSAR tracks. We used an elastic dislocation source (Okada, 1985) to model the displacement field. The rectangular elastic dislocation source consists of 10 model parameters: two location coordinates for the center of source (x, y), depth (z), length, width, three components of slip (strike, dip, tensile), and strike and dip of the dislocation plane. We used the downhill simplex method and Monte Carlo simulations (Press et al., 1992) to estimate optimal parameters and their uncertainties, and the root mean square (RMS) errors between the observed and modeled interferograms as the prediction-fit criterion. The best-fit parameters and their uncertainties are listed in Table 4. Figure 9 shows the observed (Fig. 9(a) and Fig. 9(d)), modeled (Fig. 9(b) and Fig. 9(e)), and residual (Fig. 9(c) and Fig. 9(f)) interferograms from descending and ascending tracks, respectively. RMS misfits are 4 mm and 6 mm for the ascending and descending interferograms, respectively. The descending interferogram has a slightly larger RMS misfit than the ascending one due to relatively stronger atmospheric artifacts in the descending interferograms. The best-fit fault model strikes approximately N-E with a length of about 9 km and a width of 3 km centered at a depth of 4.7 km.

3.2 Comparison of source parameters from InSAR and seismology

After we obtained the best-fit parameters for the dislocation source, we calculated the earthquake moment magnitude (Mw) based on the formula by Hanks and Kanamori (1979): $Mw = 2/3\log_{10}(M_0) - 10.7$. The seismic moment, M_0, is equal to μAS (Table 4), where μ is the shear strength of the country rock, about 3×10^{11} dyne/cm^2 for typical continental crust, A is the area of the fault, and S is the average displacement along the fault plane. The moment magnitude calculated for this earthquake based on InSAR modeling is Mw 5.6.

Overall, InSAR and seismic data agree well regarding the location, moment magnitude, strike and dip of the earthquake (Tables 1 and 4). The difference in earthquake location is less than 3 km (Tables 1 and 4), and InSAR-derived source location is about 3 km away from those from earthquake catalogs (Fig. 9). So, it suffices to say that InSAR can provide independent location estimate for a moderate-sized earthquake. The InSAR-derived earthquake magnitude is Mw 5.6. This estimate is the same as that from NCAeqDD catalog, but both are slightly larger than those from other earthquake catalogs (Table 1). The InSAR-derived source depth is about 4.7 km (Table 4), which is slightly shallower than most of estimates from earthquake catalogs (Table 1). This is consistent with a global survey that InSAR-derived depth is generally shallower than the estimates from global seismic catalogs (Weston et al., 2011). However, the depth estimate from CMT catalog (12.0 km) represents a significant departure from the other catalogs and the InSAR result, suggesting the depth estimate from the global catalog CMT is probably an outlier (Table 1). The dip of the fault from InSAR is nearly identical to those from PDE and CISN catalogs. Notably, the strike of the three catalogs are similar, however, InSAR-derived strike has a difference about 17º. The dashed-line shown in Fig 9(a)(d)(e) represents the strike direction (239º) from earthquake catalogs while the solid line represents the InSAR-derived strike direction (222º). We found that a strike of 239º (from the earthquake catalogs) could not fit the InSAR observations well

(Fig 9). We believe the two-dimensional deformation mapping from InSAR provides better constraints on the strike direction of the fault plane.

Our results indicate that the seismic signal of moderate-sized earthquakes could be captured by InSAR and the causative fault parameters can be constrained precisely. InSAR-derived deformation field and modeling can at least provide independent estimates of fault parameters, and might supply more reliable estimates of source geometry over remote areas where the coverage of seismic network is poor. However, InSAR imagery suffers poor temporal resolution, atmospheric artifacts, and sometimes loss of interferometric coherence, making it difficult to resolve postseismic signal.

4 Conclusions

Using both descending and ascending Envisat InSAR images, we investigated the 18 September 2004 Mw 5.6 earthquake over Huntoon Valley, California. We stacked multi-temporal InSAR images to improve the signal-to-noise ratio of the deformation images. We then used the stacked deformation images from both descending and ascending tracks to retrieve the east-west and vertical displacement components. Our results show the displacement in the east-west component is between -3 cm and 3 cm on both sides of the fault. The deformation of the vertical component is estimated is between -1 cm and 1 cm on both sides of the fault.

To increase the temporal sampling and accuracy of deformation results, we applied SBAS algorithm to the observed interferograms. We concluded that the pre- or post-seismic deformation can‘t be distinguished outside the coseismic part due to the poor temporal-resolution of SAR datasets and the relatively small size of the earthquake. Finally, we applied a dislocation source to jointly model the coseismic deformation fields from the descending and ascending tracks. The best-fit source model determined by InSAR indicates a northeast-trending, left-lateral strike-slip fault with a length of about 9 km and a width of 3 km centered at a depth of 4.7 km. The InSAR-derived source parameters are comparable with those from seismic catalogs and can allow us to judge biased source parameter estimates in the earthquake catalogs. InSAR can provide accurate, independent locations and better constraints on the direction of strike for a moderate-sized earthquake if both descending and ascending interferograms are available. Since InSAR data can have high spatial resolution and can act as an independent remotely sensed data source, modeling InSAR-derived deformation field can improve fault parameters for moderate-sized earthquakes, particularly over remote areas where the coverage of existing seismic network is poor.

Acknowledgements

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Note: PDE and CMT are global catalogs whereas CISN and NCAeqDD are local catalogs.

Table 2. ENVISAT SAR interferograms (track No.485, descending)

No.	Master Date	Slave Date	Bperp[m]	Btemp[day]
1	20031019	20050710	50	630
2	20040620	20041003	-5	105
3	20040620	20050814	-29	420
4	20040829	20041003	-248	35
5	20040829	20050814	-272	350

Table 3. ENVISAT SAR interferograms (track No.120, ascending)

No.	Master Date	Slave Date	Bperp[m]	Btemp[day]
1	20031029	20050720	-189	630
2	20031029	20071003	82	1435
3	20031029	20080917	4	1785
4	20040630	20060531	54	700
5	20040908	20071003	-95	1120
6	20040908	20071107	94	1155
7	20040908	20080709	-55	1400
8	20040908	20080917	-174	1470

Table 4. Parameters for the best-fitting dislocation model. Uncertainties correspond to the 95% confidence level.

Latitude (Deg)	Longitude (Deg)	Depth (km)	Strike (^{o})	Dip (^{o})	Length (km)	Width (km)	Strike-slip (mm)	Dip-slip (mm)	Tensile-slip (mm)
38.026±0.003	-118.663±0.003	4.7±0.6	222.5±2.9	89.9±5.4	9.3±0.9	3.1±0.4	301±9	- -9±4	0

Figure Captions

Figure 1. Shaded relief map of Huntoon Valley and surroundings. Primary geographic features in the region are labeled. Quaternary faults over Huntoon Valley are shown by black lines inside the dashed box. Red star represents the earthquake of Mw 5.6 on 18 September 2004.

Figure 2. Distribution of (a) frequency and (b) magnitude of earthquakes occurred near the Huntoon Valley area from NCAeqDD catalog. The minimum magnitude completeness for earthquakes over this area is about 0.8 (Wiemer and Wyss, 2000).

Figure 3. Coherence maps from a descending track (a - e) and an ascending track (f – m).

Figure 4. Wrapped Interferogram from a descending track (a - e) and an ascending track (f – m).

Figure 5. (a) LOS deformation image acquired from a descending track. (b) LOS deformation image acquired from an ascending track. (c) East-west component of the deformation field. (d) Vertical component of the deformation field.

Figure 6. East-west (a) and vertical (b) components of the deformation along a profile AB labeled in Fig. 5.

Figure 7. Perpendicular baselines used for SBAS InSAR processing from (a) descending track and (b) ascending track.

Figure 8. (Middle panels) Time-series surface deformation of P1 from the descending track and P2 from the ascending track, respectively. [(a), (d)], [(b), (e)], [(c), (f)] show pre-, co-, and post-seismic deformation measurements from the descending and the ascending tracks, respectively.

Figure 9. Observed deformation images from (a) descending track and (d) ascending track. (b, e) Synthetic interferograms for the descending and ascending track geometries based on the best-fit source model. (c, f) Residual interferograms from the descending and ascending tracks, showing the difference between observed and modeled interferograms. Black star represents the center of the best-fit earthquake source while black circles represent earthquake center of earthquake source from catalogs. The solid line represents the projection of the modeled fault while the dashed line represents the projection of the fault from earthquake catalogs.