Ground Surface Deformation of L'Aquila Earthquake Revealed by InSAR Time Series

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Key words: InSAR time series, L'Aquila earthquake, three dimension unwrapping, deformation field, evolution processes

SUMMARY :
We measured deformation field and its evolution processes of the Mw 6.3 L'Aquila earthquake occurred on 6 April 2009, using time series of ASAR ascending track images acquired from October 2008 to September 2009. We processed the time series using the Stanford method for persistent scatterers. On epicenter the significant deformations was observed: (1) Envisat ASAR satellite detected clearly the process of the displacement field change of the earthquake and the different deformation characteristics associated with focal rupture in different period, which included pro-earthquake creep displacement, obvious accelerating deformation, rapid rupture during the quake, and continuously and significantly decreased deformation in magnitude after the quake. (2) There existed a significant accumulation of regional stress and strain the period of the seismogenic zone become destabilizing before the seismogenic fault ruptured and dislocated. (3) The region of the strongest deformation and ground rupture located at a low depression area tending towards southeast. The cracking propagated with an orientation of 135° , along the NW striking and SW dipping Paganica-S. Demetrio normal fault. (4) The rupture was mainly formed at the epoch of earthquake and thereafter with a maximum subsidence of 210 mm in the line-of-sight, concentrating on a zone of 22 km x14 km, and a large subsidence bowl was formed.

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1. INTRODUCTION

An Mw 6.3 earthquake occurred On 6 April 2009 close to the city of L'Aquila in the central Appennines at a depth of about 9 km. The main shock was followed by thousands of aftershocks, of which two large events were Mw 5.6 and Mw 5.4 on April 7 and 9, respectively. It caused heavy damage in the town of L'Aquila with inhabitants of 73,000 and in many neighboring villages, and resulted over 300 fatalities and thousands of injures and tens of thousands homeless.

After the earthquake, researchers studied and interpreted this event using various methods and data sources from different fields, and a lot of results have been documented. Atzori S et al.(2009), defined the geometric and kinematic characteristics of the fault activated during the earthquake by finite fault inversion of DInSAR coseismic displacement interferograms, integrated with 30 GPS site displacements. The results shown that the best-fit solution for the main shock was addressed by a normal fault ~16km long and ~12km wide, with a small right-lateral component, dipping 47°SW with a maximum slip of ~90cm. Four days before the main quake, Anzidei M. at al.(2009) increased the existing permanent GPS network with five GPS stations bordering the L'Aquila basin. The maximum horizontal and vertical coseismic ground displacements surveyed at these stations were ~10.39cm and ~-15.64cm, respectively. And with a nonlinear inversion of the geodetic data, the source geometry was best fitted as a 13 km x 15.7 km rectangular fault, SW-dipping at ~55.3. Optimal source parameters of the earthquake from InSAR observations shown that this quake is associated with a buried SW-dipping normal fault with the epicenter at(13.4506°E,42.3580°N), a strike of 141.3°, a dip of 50° ,and the maximum slip of 1.2m at the depth of 6.1km (Feng W. P. et al.,2009). Walters R. J. et al.(2009) used InSAR and body-wave seismology to determine independent source parameters for the event and confirmed that the quake ruptured a SW-dipping normal fault with ~0.6-0.8m slip, and the L'Aquila earthquake occurred in an area with a marked seismic deficit relative to geodetically determined strain accumulation. Di Luccio F. et al.(2009) relocated the October 2008 to 6 April 2009 foreshocks and about 2000 aftershocks occurred between 6 and 30 April 2009 by applying a double-difference technique, and results shown that the events concentrate in the upper 15 km of the crust. And three main NW-SE TO NNW-SSE striking, 30°-45° and 80°-90° dipping faults were activated during the seismic sequence. Using high resolution foreshocks and aftershocks location, the geometry of fault segments was presented, the L'Aquila and Campotosto faults, forming an en-echelon system 40 km long (Chiaraluce L. et al., 2011). L'Aquila earthquake ruptured an approximately 18 km long SW-dipping normal fault. The aftershock area extended for a length of more than 35 km. Surface faulting occurred along the SW-dipping Paganica fault with a continuous extent of ~2.5 km(EMERGEO Working Group,2010).

However, an earthquake case, from its seismogenic, to the rupture, and the effect after the quake, is a very complex geophysics process. For a long time, seismologists have been doing a lot of researches to explore the physical and tectonic mechanism of this process. In this paper, Based on previous work and by applying time series method to 9 repeat pass ASAR images, we represented the whole evolution processes of the displacement field of the L'Aquila earthquake. The results of this paper demonstrated the different deformation characteristics of the displacement field in the different phases caused by the earthquake during the imaging period. The deformation caused by different shocks(i.e., the main shock and significant aftershocks), and the deformation in preseismic、coseismic and postseismic of main shock were also analyzed. All of these results are consistent with the works derived by descending data(Luo Sanming et al., 2012), PS method(Luo Sanming et al., 2012) and SB method(Luo Sanming et al., 2011), respectively.

2. DATA PROCESSING

2.1. Data Description

In this paper, the available data contains 9 ascending ENVISAT ASAR images (ASA_IM_1) of track 401 spanning between October 2008 and September 2009(see Figure 1).Acquisition modes for ascending datasets are swath 2 (23 degrees), V/V polarization. Figure 1 shows the spatial and temporal repartitions of the data used for L'Aquila earthquake. Table 1 is the details about 9 scenes. During the imaging period, about 500 foreshocks from October 2008 to April 6 2009 occurred and about 2000 aftershocks occurred between April 6 and April 30 2009(Di Luccio, F. et al. , 2009), respectively.

2.2. Processing Method

The repeat-pass interferograms were derived using the Stanford method for persistent scatterers (StaMPS) time series analysis method developed by Hooper(2007) and precise orbit produced by the Delft Institute for Space research. The master image was selected based on the maximization of the stack coherence that is a function of temporal and perpendicular baselines and Doppler centroid frequency (Kampes 2005; Ketelaar, 2008). Ascending interferograms are then processed using the images acquired in 6 October 2008 as the master images (Table 1). Furthermore, the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was used to remove the main topographic contribution to the interferometric phase.

StaMPS method was used to select the pixels using two steps: amplitude and phase analysis. In the first step, the pixels whose amplitude dispersions are less than a threshold of 0.4, are selected as candidates. The phase stability of the candidates is investigated by temporal coherence estimation. In the next step, a smoothed model that is a representative of linear part of deformation for dataset was calculated. The coherence matrix for each pixel located in the deformation area was calculated using the estimation window. The coherence matrices were then averaged together to form a coherence matrix demonstrating a general behavior of the temporal decorrelation. The elements of the coherence matrix were ordered by the acquisition date.

The StaMPS can also increase the information on the slope and to better estimate the correlation between phase and elevation in non-deforming areas. A method incorporating both the Persistent Scatterers pixels (PS) (Hooper, A. et al., 2007) and Small Baseline pixels (SB) (Hooper, A., 2007) selection based on different scattering properties, which uses amplitude dispersion to select pixel candidates, were performed on single-look images. In order to increase the number of selected pixels, the SB method was applied on a subset of the data set (see Figure 1). Then combined both pixels sets derived by PS and SB methods, respectively.

2.3. Phase Unwrapping

Phase unwrapping is the process of recovering unambiguous phase values from phase data that are measured modulo a phase cycle. On the whole pixel set, a three dimension spatiotemporal unwrapping was performed (C. W. Chen, 2001; Hooper A. et al., 2007) if the sampling rate is high enough over most of the data set that aliasing is avoided.

In InSAR time series, however, the phase is undersampled in time for every point in space, due to the variation in atmospheric delay, which can vary by greater than half a phase cycle in much less than the time between acquisitions for all existing SAR data sets. There is also a phase term due to error in orbital estimation that approximates a ramp in space. Though often small, this term can also be greater than half a phase cycle in magnitude.

These terms are reduced to less than half a phase cycle over most of the image by estimating and subtracting the longer wavelength components of the phase change between each interferogram, which include most of the atmospheric and orbital error signal (R. F. Hanssen et al., 2001). For each pair of interferograms in time, the highest frequency component of spatially correlated phase is estimated. The complex phase difference between the interferogram pair is transformed to the frequency domain and iteratively low-pass filter, starting with a broad frequency response and decreasing the width until the filtered phase contains no residues. Unwrapping of the filtered phase is therefore unambiguous, and the estimation of the spatially-correlated look angle error was also used to help the unwrapping.

3. RESULTS AND ANALYSIS

First a fit study area shoud be selected. If study area is bigger, the efficiency of data processing is more inefficient, whereas the study area is smaller, a complete displacement field can not be obtained. In this work, the study area with 12500 pixels in direction and 2500 pixels in range, respectively, was defined. Of the selected pixels, within an area of 72 kmx58 km, 150468 pixels targets were identified by the StaMPS time series analysis method.

Figure 2 and Figure 3 are the interferograms time series of wrapping phas e and unwrapping phase, respectively. Figure 4 is the displacement field reveal ed by pixels selected by StaMPS analysis method . Faults in Figure 4 were cit ed from Atzori et al. (2009). Reference pixels A, B, C and D for time sequen ce analysis in Figure 5 located in rupture area, and their time series curves ar e shown in Figure 5. The UU' and VV' indicate the positions of two profiles across the rupture area in Figure 4, and their profiles are shown in Figure 6 (a) and (b), respectively. Figure 7 are the distribution of foreshocks in L'Aquil a area between October 2008 and April 2009 (following Di Luccio F. et al, 2 009). Figure 8 is the statistics of the main shock and aftershocks higher than magnitude 1.5 (http://portale.ingv.it/primo-piano-1/news-archive/2009-news/april-6-earthquake/).

Figure 3 and Figure 5 show that a complete process of the deformation field change of L'Aquila earthquake was observed clearly in rupture zone. And a creep course before the main shock occurred on 6 April was also measured in the same area from October 2008 to February 2008, while a seismic swarm with amount of 140 occurred at this area in the four months(Di Luccio F. et al. , 2009). Furthermore, the displacement field appeared in image on 30 March 2009 began to accelerate change, while the frequency of seismic swarm previous appeared also increased significantly with 220 number of times in two months, and the greatest event was Mw4.4 occurred on 30 March 2009(Di Luccio F. et al. , 2009). The change characteristics of the displacement field before the main shock indicated that these changes were related to the activities of seismic swarm(Figure 7) and suggested the area stress and strain began to accumulate quickly during this period.

The results measured between March and May 2009 in Figure 3 and Figure 5 also show that the displacement field changed rapidly during the shocking and subsequence. The variation of deformation in LOS at rupture zone achieved 100 mm, the majority of which was formed in this phase. Meanwhile, the main shock was followed by thousands of aftershocks, the 7 of which with magnitudes greater than Mw 5.0 (Chiarabba, C. et al. ,2009)(Figure 8). The increasing changes of the displacement field can be the results of the combined effect of the main shock and thousands of aftershocks, included the 7 large aftershocks.

The results measured from May to September 2009 in Figure 3 and Figure 5 show that the change of the displacement field decreased sharply in four m onths. Meanwhile, the times of aftershocks also reduced rapidly, most of which with magnitudes less than Mw2.0(http://protale.ingv.it/primo-pano-1/news-archiv e/2009-news/april-6-earthquake). Analysis of this paper indicated that the charac teristics of the displacement field change is relative with the action frequency of aftershocks after the main shock.

The results from reference pixels time series Figure 5 also shows ~160 mm displacement away from the satellite in LOS was measured, this is consistent with GPS measurements(Anzidei et al.,2009).

Figure 4 shows that the surface faulting within a zone of about 22 km x14 km, with an orientation of 135°, occurred along the NW-striking and SW-dipping Paganica-S. Demetrio normal fault. This is agreement with field investigations carried out by EMERGEO Working Group(EMERGEO Working Group,2010), and also well fitting with the conclusions using DInSAR and GPS data(Atzori et al., 2009; Anzidei et al., 2009; Chiarabba et al., 2009).

4. DISCUSSION AND CONCLUSIONS

The Apennine area surrounding the L'Aquila town is a mountain region formed by ridges of prevailing carbonate rocks and intramountain tectonic depressions filled by continental deposits. The main structure of this part of the Apennines was shaped between the Late Miocene (Messinian) and the Early-Middle Pliocene by SW–NE directed compressional tectonic forces, which initiated NE-verging fold-and-thrust structures. Since Late Pliocene–Early Pleistocene times, the compressional structures have been displaced by normal faults driven by SW–NE oriented tensional forces, creating the intramountain tectonic depressions (Lavecchia et al. 1994). The extensional tectonics is presently active along the entire axial zone of the Apennines, as testified by field geology and paleoseismology (Bosi 1975; Galadini and Galli 2000; Bosi et al. 2003; Galli et al. 2008; Messina et al. 2009), geodetic data (D'Agostino et al. 2008) and seismotectonic studies (Pace et al. 2002; Boncio et al. 2004). The active normal faults strike on average NW–SE, with local variations to □W–E or WNW–ESE, and dip to the SW or to the SSW (Figure 4). Most of the historical earthquakes of the Apennine area can be linked to normal faulting, and the L'Aquila 2009 seismic sequence is the most recent expression of such an active tectonic process(Pace et al.,2011). From this paper, we obtained the following initial thought.

(i) In the half year before the earthquake, the surface of the epicenter has already begun to change slowly, after the earthquake, subsidence in the fracture zone increased with the large magnitude. The cracking propagated along the epicenter in the southeast direction. A large subsidence bowl was formed in the epicenter.

(ii) In 2003 Hunstad I. et al. processed the GPS data and triangulation network observation data since 1860, and their results show the significant strain accumulated over the past 130 years may not have been released in the past earthquakes in the Apennines (Hunstad I. et al., 2007). Although the L'Aquila earthquake that occurred on 6 April 2009 is the strongest event since the M7.0 Fucino earthquake in the central of Italy in 1915(E. Falcucci et al., 2009), the results in this paper suggest that this area might be susceptible to a stronger earthquake in the future since the L'Aquila shock was not strong enough to release the long-term strain accumulated in the area.

(iii) Synthetic aperture radar interferometry can obtain the change information and evolution processes of surface "field" without any artificial targets. This promises the continuity of data chain, and the continuous information can be obtained even in the rupture zone. This is impossible using conventional geodetical methods. Thus, the work in this paper has provided a comprehensive case for understanding new methods for earthquake forecasting with time sequence DInSAR.

Acknowledgments

We wish to thank the European Space Agency (ESA) for providing ENVISAT ASAR data, the Netherlands Delft University of Technology and Mr Andrew Hooper for providing open source software.

Tab. 1 Processed Information from Ascending Orbit Data for L'Aquila Earthquake(Track: 401)

No	Orbit	Date	Sensor	$B_{\perp}$ (m)	f_{DC} (Hz)	Days
1	34523	2008-10-06	Envisat	0	-560.63	0
2	35204	2008-11-10	Envisat	467	-551.44	35
3	36026	2009-01-19	Envisat	437	-555.95	105
4	36527	2009-02-23	Envisat	-3	-550.54	140
5	37028	2009-03-30	Envisat	581	-553.11	175
6	37529	2009-05-04	Envisat	-145	-557.86	210
7	38030	2009-06-08	Envisat	-144	-564.12	245

8	38531	2009-07-13	Envisat	400	-549.31	280
9	39533	2009-09-21	Envisat	626	-548.84	350

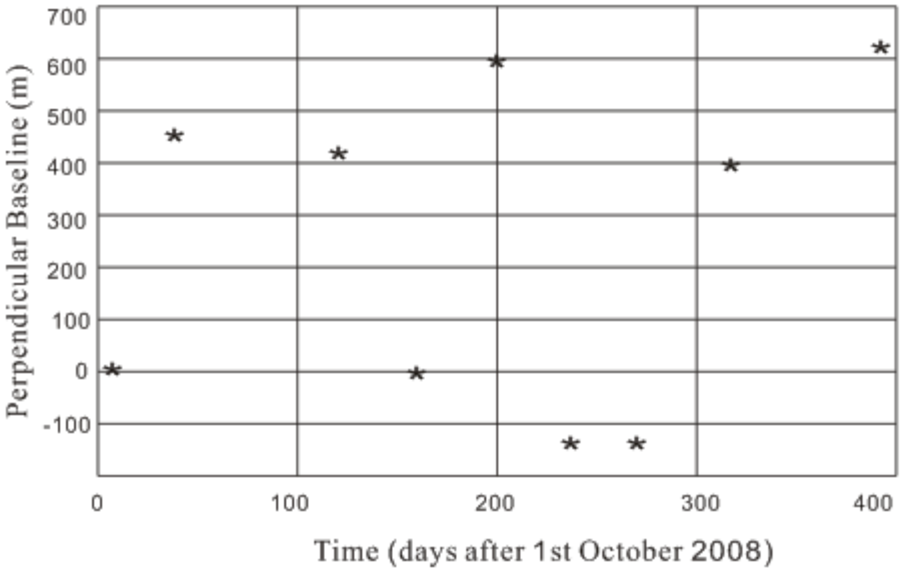

Figure 1 Acquisition geometry of available data in the L'Aquila area: temporal baselines against perpendicular baselines (ascending track 401).

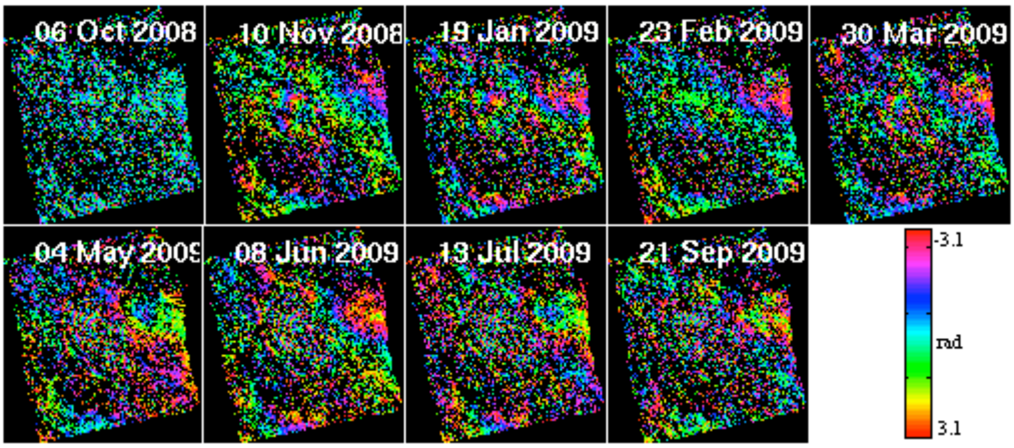

Figure. 2 Wrapped interferograms in radar coordinates formed from ascending orbit data acquired over L'Aquila, with 4 looks taken in range and 20 in azimuth. The master acquisition date is 6 October 2008. Each color fringe represents 2.8 cm of displacement in the LOS, and the intensity reflects interferogram amplitude.

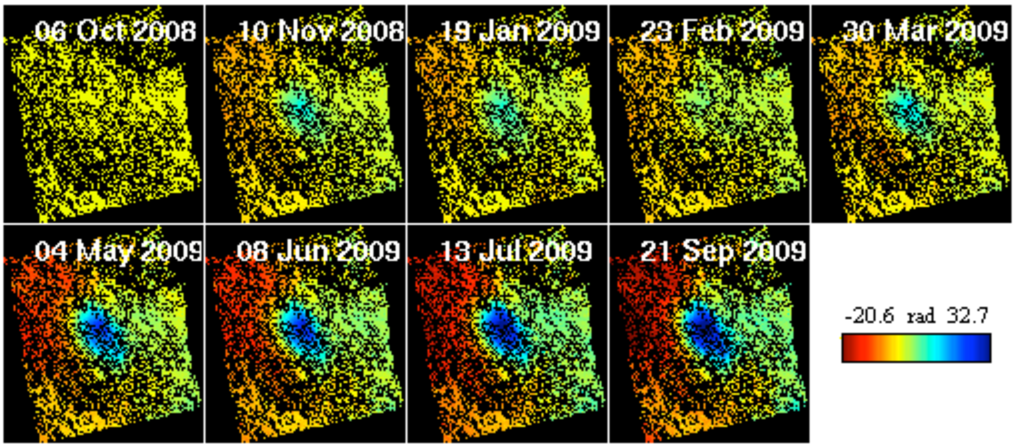

Figure.3 Pixels time series displacement field unwrapped phase formed from ascending orbit data over L'Aquila, dark blue section represents rupture zone.

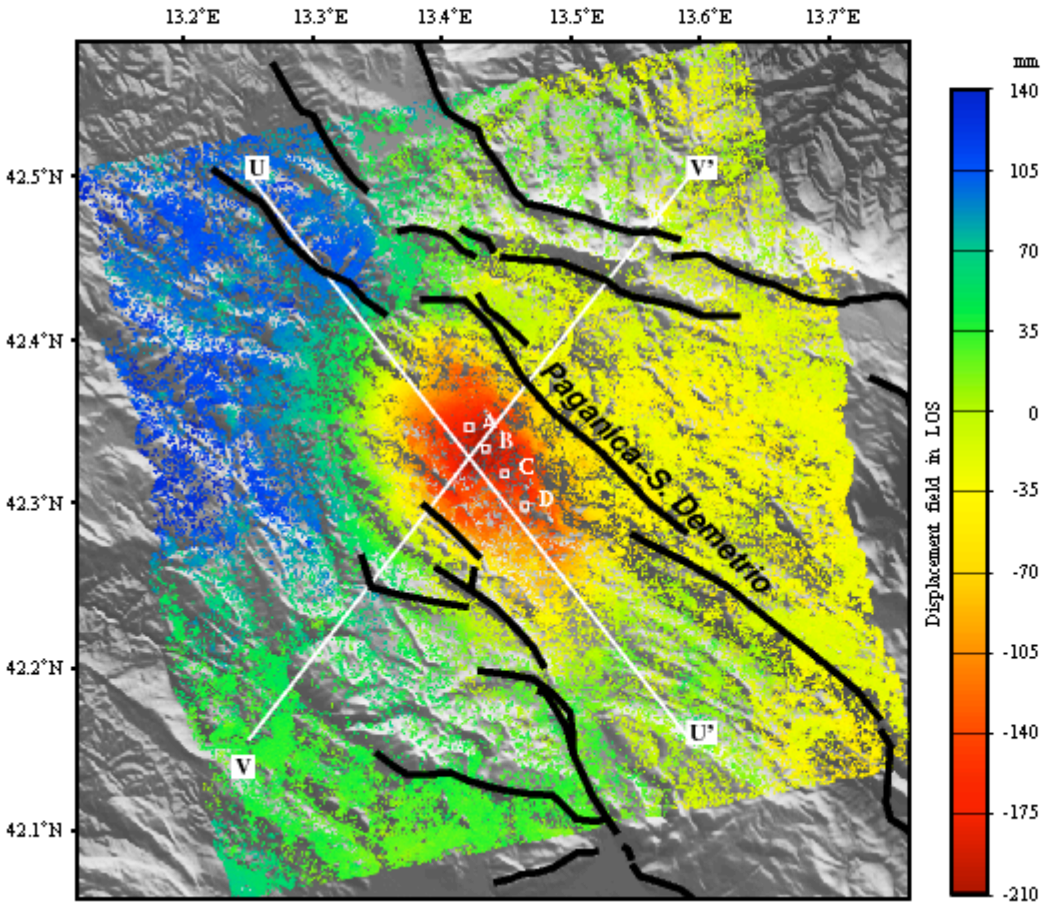

Figure.4 Pixels displacement field(LOS) over L'Aquila zone from 6 Oct 2008 to 21 Sep 2009

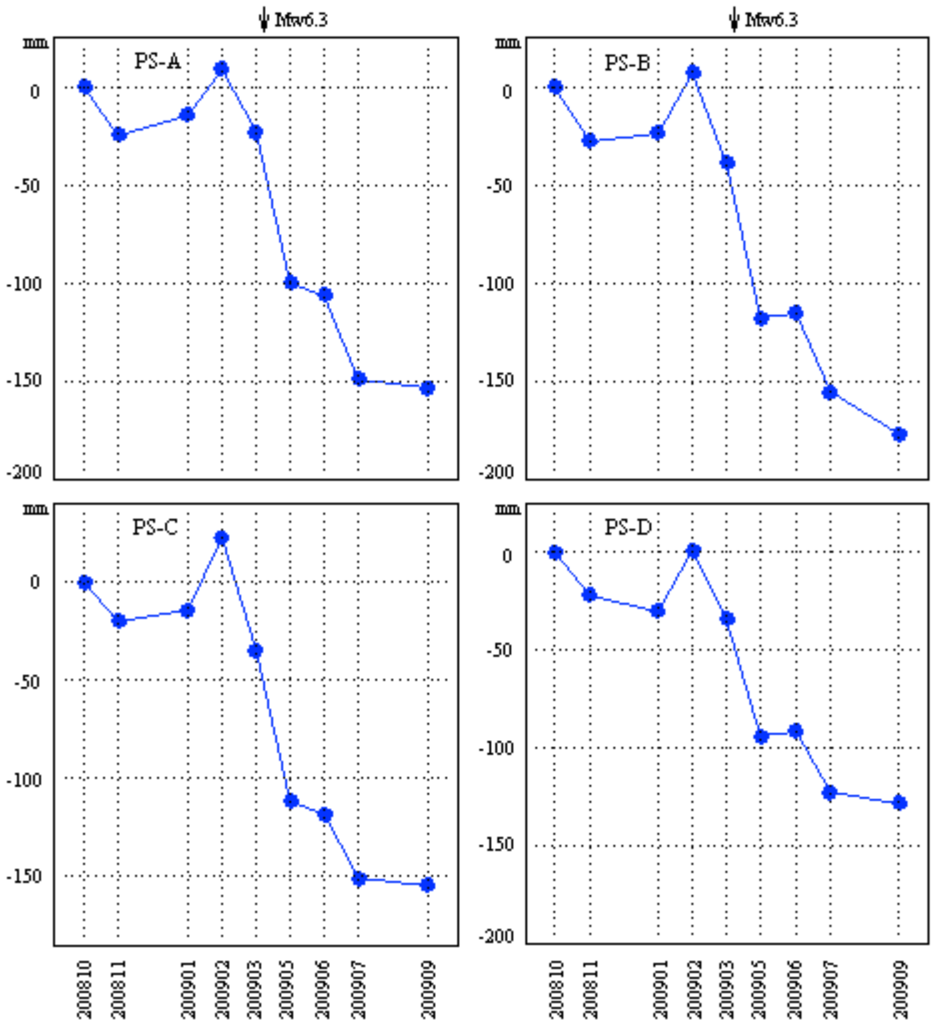

Figure 5 Reference Pixels time series displacement(LOS)

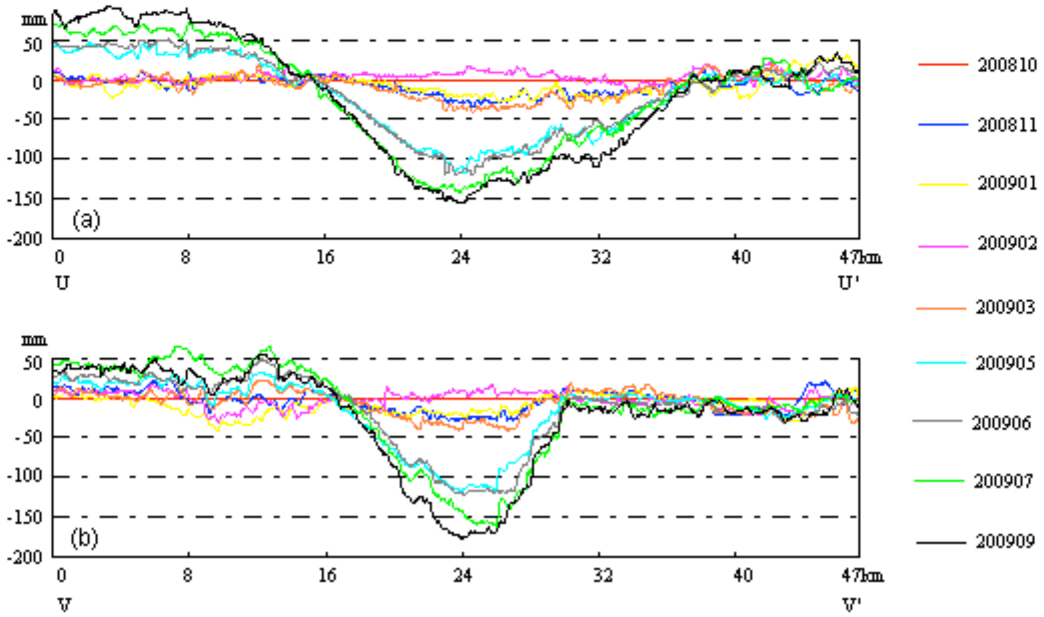

Figure 6 Displacement field profiles across the rupture area. Figure (a) shows the profile along the UU′ and (b) along the VV′ in Figure 3, respectively.

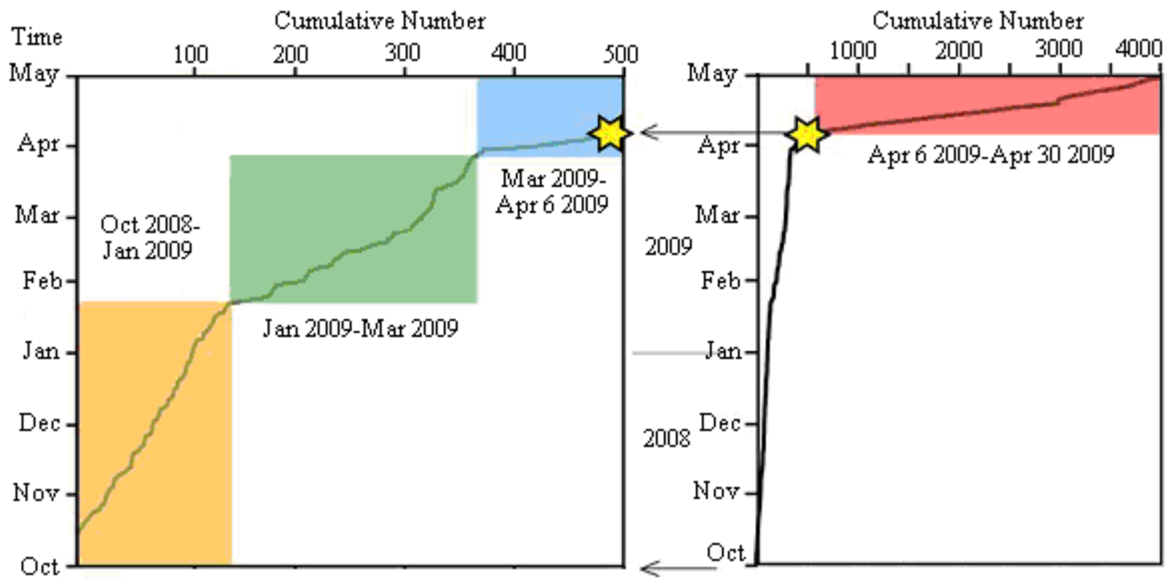

Figure 7 Time versus cumulative number of earthquakes for the period October 2008-April 2009, yellow star represents mainshock of April 6(following F. Di Luccio et al.).

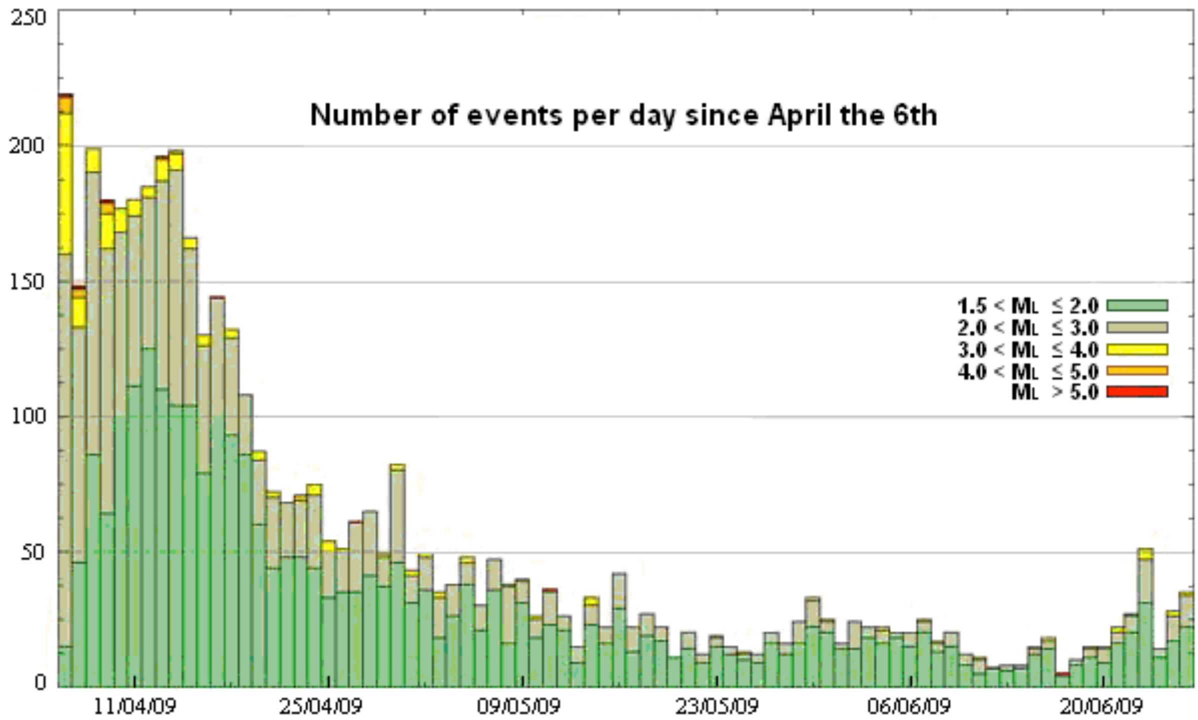

Figure 8 Aftershocks charts of L'Aquila earthquake from 6 April 2009 to 26 June.

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