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Vertical and horizontal displacements of Los Angeles from InSAR and GPS time series analysis: Resolving tectonic and anthropogenic motions

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ABSTRACT

We resolve the complex ground deformation associated with tectonic and anthropogenic activities in Los Angeles, California by combining Interferometric Synthetic Aperture Radar (InSAR) and Global Positioning System (GPS) measurements acquired from 2003 to 2007. The three-dimensional (3-D) cumulative displacement velocity field is first derived based on Weighted Least Squares (WLS) InSAR analysis of both ascending and descending ENVISAT ASAR data aided by GPS measurements at 54 Southern California Integrated GPS Network (SCIGN) stations. Clear subsidence can be observed from the results in the Pomona and San Gabriel areas, respectively, while uplift in the Santa Fe Springs. The displacements are mainly due to the extraction and injection of groundwater or oil. The northwestern horizontal displacement detected also suggests that the area had experienced interseismic strain accumulation related to the San Andreas Fault. The varying northeastern displacement magnitudes indicate increasing displacement accumulation away from the San Andreas Fault. The results are validated with GPS measurements at 15 independent stations, with the root mean squares (RMS) residuals of the discrepancies being 2.4, 1.5 and 0.9 mm/yr in vertical, northern and eastern directions, respectively. The seasonal displacement in Santa Ana Basin due to anthropogenic activities is examined with eight pairs of ascending and descending InSAR LOS displacement estimations selected from the WLS InSAR solution. It is clear that almost the entire Santa Ana Basin experiences significant seasonal vertical displacement with the maximal displacement reaching 43 mm. The Newport-Inglewood Fault forms a sharp boundary of the seasonal vertical displacement field. In addition, seasonal oscillations of 10–20 mm in east direction are detected near the margin of the Santa Ana Basin, across the Newport-Inglewood Fault. Strong correlations are found between the groundwater levels and the seasonal displacements at three wells, yielding an average elastic skeletal storage coefficients of 5.9×10^{-4}. This indicates that the Santa Ana basin is dominated by the elastic deformation.

1. Introduction

It is well known that Los Angeles in Southern California, USA has experienced complicated crustal motion. The interseismic strain accumulation due to the San Andreas Fault, whose nearest distance to the Los Angeles metropolitan is about 35 km, has induced contracting surface displacements over Los Angeles with respect to the southern part of the San Gabriel Mountains (Argus et al., 2005; Fialko, 2006). The aquifer systems in the Los Angeles basin also cause the ground to experience seasonal oscillation (Watson et al., 2002).

In the past two decades or so, several seismic events have occurred in Los Angeles and its neighboring regions, including the 1992 Landers (Massonnet et al., 1993; Fialko, 2004a), the 1994 Northridge (Murakami et al., 1996) and the 1999 Hector Mine earthquakes (Sandwell et al., 2000). The SCIGN that consists of approximately 250 continuously observing GPS sites has been established for studying the tectonic activities of the region (Hudnut et al., 2002). Interferometric Synthetic Aperture Radar (InSAR) measurements have also been used to study the long-term surface displacements in Los Angeles (e.g., Watson et al., 2002; Lanari et al., 2004; Zhang et al., 2012; Hu et al., 2013a; Tymofyeyeva

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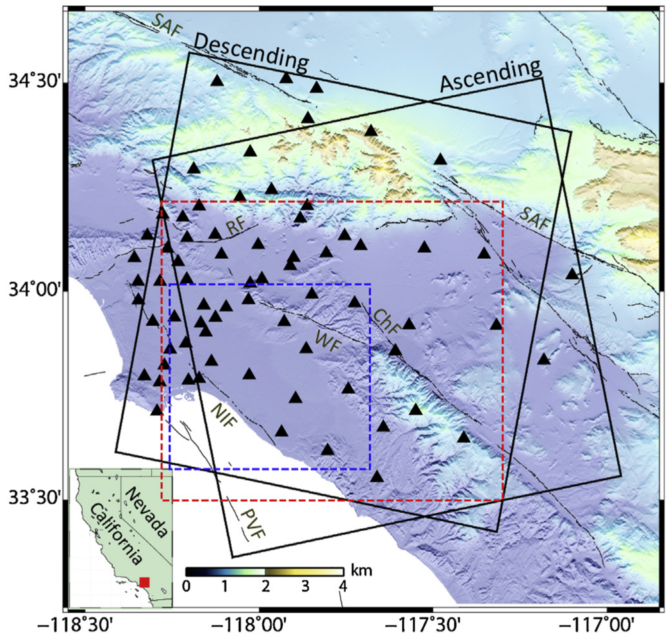

Fig. 1. Topographic map of the study area generated from SRTM DEM data. The solid outlines show the coverages of the ascending and descending EVNISAT ASAR images used. The red and blue dashed outlines indicate areas investigated for cumulative displacement and seasonal oscillation, respectively. The triangles show the locations of the 69 SCIGN GPS sites. The inset map indicates the study area in California. SAF: San Andreas fault. RF: Raymond fault. ChF: Chino fault. WF: Whittier fault. NIF: Newport-Inglewood fault. PVF: Palos Verdes fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

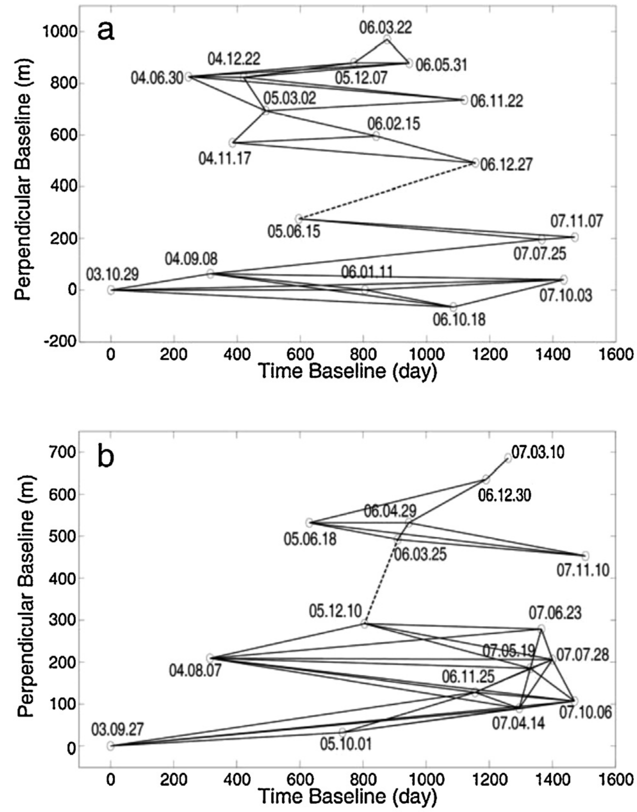

Fig. 2. Spatial-temporal baselines of (a) ascending and (b) descending interferometric pairs. The circles represent the scenes as labeled by the acquisition time. The solid lines indicate interferograms with perpendicular baselines shorter than 130 m and dashed lines represent the additional interferograms for linking the independent subsets of interferograms.

and Fialko, 2015). InSAR can measure ground displacements with high spatial resolution (e.g., 5 m × 20 m for ENVISAT ASAR data), but low temporal resolution (e.g., 35 days for ENVISAT ASAR data). Besides, only the projection of surface displacement in the line-of-sight (LOS) direction can be measured with InSAR.

Recent years many efforts had been made to distinguish between the tectonic and anthropogenic motions over Los Angeles by combining InSAR and GPS measurements for their complementary features. Bawden et al. (2001) estimated the tectonic contraction across Los Angeles from a series of SAR interferograms after removal of groundwater pumping effects with GPS observations. Watson et al. (2002) deployed ERS-1/2 interferograms and GPS to infer the seasonal displacements related to groundwater withdrawal in the Los Angeles basin. Fialko (2004b) investigated the transient postseismic deformation due to the 1992 Landers earthquake using stacked InSAR data and GPS measurements from 1992 to 1999. Argus et al. (2005) separated interseismic strain accumulation from anthropogenic motion in Los Angeles by combining the GPS and InSAR measurements. Lundgren et al. (2009) constrained the southern San Andreas-San Jacinto fault system slip rates by using GPS and InSAR observations. Meng et al. (2010) measured the interseismic crustal deformation near Los Angeles by integrating GPS and InSAR data where a spatial high-pass filter was used to suppress InSAR long wavelength errors. Tong et al. (2013) integrated InSAR and GPS observations to evaluate the fault creep rates along the San Andreas Fault. However, the InSAR measurements in these studies have been limited to one dimension only in the radar LOS direction, which cannot provide a full picture on the ground displacements.

We will in this study propose to resolve the tectonic and anthropogenic motions over the Los Angeles area (as shown in Fig. 1) by estimating the spatial-continuous vertical and horizontal displacements with the InSAR and GPS time series observations. First, both ascending and descending ENVISAT ASAR data during 2003–2007 are processed with the weighted least squares (WLS) InSAR approach to derive time series of displacement fields in the respective LOS directions. The horizontal displacements observed at the SCIGN GPS sites are then interpolated to derive preliminary horizontal displacement fields corresponding to the time of the SAR acquisitions. Finally, the InSAR and the GPS time series results are combined to determine both the three-dimensional (3-D) cumulative displacements and the seasonal oscillations in the vertical and east directions, which provide a great insight into the tectonic motions and the anthropogenic activities over Los Angeles.

2. Data and methods

2.1. InSAR time series analysis

18 ascending and 16 descending ENVISAT ASAR scenes over Los Angeles acquired during 2003–2007 are interferometrically processed, respectively (Table 1). 32 and 38 interferograms are generated initially with perpendicular baselines limited to 130 m (established according to Berardino et al. (2002)) for the ascending and descending data, respectively. Both of the ascending and descending interferogram series are separated into two independent subsets (see Fig. 2). The problem caused by the data gaps between the subsets is resolved in the conventional Small BAseline Subsets (SBAS) approach by the singular value decomposition (SVD) method (Berardino et al., 2002). Following the WLS InSAR approach proposed in Hu et al. (2013a), we choose to use an additional interferogram with baseline longer than the set baseline threshold to link the subsets so that SVD is not required. For the ascending orbit,