Time Series Investigation of Land Subsidence Using a Weighted Least Squares Adjustment Based on Image Mode Interferometric Data

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Abstract

This study presents the weighted least squares method based on Interferometric Synthetic Aperture Radar (InSAR) images to retrieve spatial-temporal evolution of land subsidence in Mashhad Valley, northeast Iran. Using the analysis of a few interferograms covering the 2003-2005 period, Motagh et al (GJI 2006) presented a preliminary analysis of the subsidence in this area. Here we extend this study and use additional SAR data to retrieve time-dependent deformation in Mashhad Valley We utilize 17 SAR images acquired by the ENVISAT satellite in a descending orbit during Jun. 2004-Nov. 2007, make 53 differential interferograms spanning different long- and short-term intervals, and do a time series analysis to extract deformation signals out of differential interferograms. Time series analysis suggests that the subsidence occurs within a northwest-southeast elongated elliptical shaped bowl along the axis of Mashhad valley. The maximum accumulated subsidence during 1260 days reaches about 86 cm, located northeast of Mashhad City. The comparison between InSAR time series results with continuous GPS station in the city of Tous, northeast of Mashhad, yields comparable results at the level of 1 cm.

1 Intoduction

Differential Synthetic Aperture Radar (DInSAR), using the phase difference of two correlated synthetic aperture radar (SAR) images, has the ability to detect surface displacements to within a centimeter-to-millimeter accuracy [1-2]. The technique has become an important remote sensing tool over the last decade for detection of land subsidence in developed groundwater basins. This paper investigates the ground surface deformation in Mashhad Valley using differential SAR Interferometry (InSAR).

The valley of Mashhad is oriented in an approximately northwest-southeast (NW-SE) direction in the Northeast Iran. It is bounded to the south by the Binaloud Mountains and to the north by the Hezar-Masjed Mountains (see Figure 1). The area is subsiding due to the excess water withdrawal for the industrial and agricultural purposes [4].

Motagh et al. [4] presented a preliminary analysis of the subsidence in this area using stacking method over a few interferograms covering the 2003-2005 period. We extend this study by using additional SAR data that allow us to perform a time-series analysis using least squares adjustment over a database of short and long-term interferograms [4-6]. This method allows us to retrieve spatial-temporal evolution of the deformation for a time period and to generate spatially dense ground deformation maps chronologically [6].

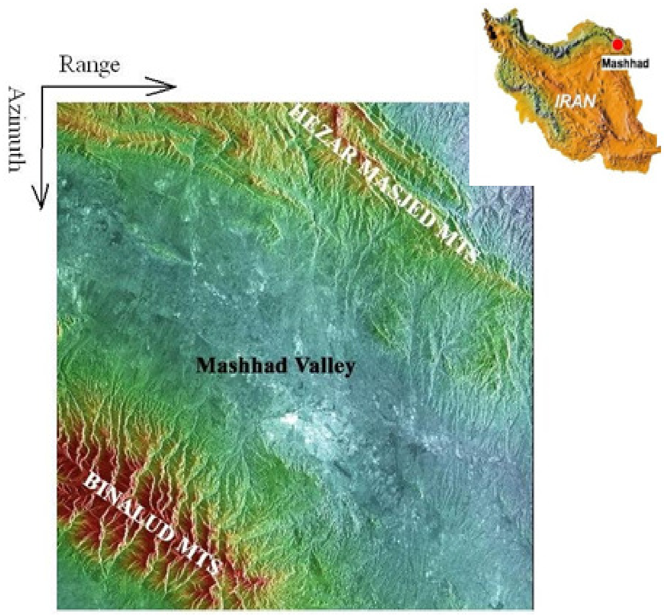

Figure 1 Overlay of ENVISAT image of Mashhad Valley on topography generated from the 3-arcsecond SRTM data. The inset shows the location of the Mashhad Valley within Iran.

2 InSAR Processing

To investigate land subsidence in Mashhad Valley, we use 17 SAR Single Look Complex (SLC) images (see **Table 1**) from a descending orbit (track 392) acquired by the European ENVISAT satellite in image mode (I2) spanning a time interval from June 2004 to November 2007, and enabled the investigation of the temporal evolution of displacements detected at this area. Each interferometric SAR image pair has been chosen with consideration of their spatial baselines and we take those interferometric pairs having a perpendicular baseline value smaller than 400 m and with a maximum time interval of 3 yr.

Table 1 Acquisition date of the SAR data used in this study

day	Acquisition Data	Orbit	Mission
d1	2004.06.14	11969	ENVISAT
d2	2004.07.19	12470	ENVISAT
d3	2004.11.01	13973	ENVISAT
d4	2004.12.06	14474	ENVISAT
d5	2005.01.10	14975	ENVISAT
d6	2005.02.14	15476	ENVISAT
d7	2005.03.21	15977	ENVISAT
d8	2005.04.25	16478	ENVISAT
d9	2005.05.30	16979	ENVISAT
d10	2005.07.04	17480	ENVISAT
d11	2005.08.08	17981	ENVISAT
d12	2005.09.12	18482	ENVISAT
d13	2005.10.17	18983	ENVISAT
d14	2005.11.21	19484	ENVISAT
d15	2006.11.06	24494	ENVISAT
d16	2007.03.26	26498	ENVISAT
d17	2007.11.26	30005	ENVISAT

All differential interferograms with favorable baselines and temporal coverage were computed using the two-pass method implemented in the Doris software [5]. Precise satellite orbital information produced by the Delft Institute for Earth-Oriented Space Research (DEOS) for correction of orbital separation and the 90 m resolution digital elevation model (DEM) generated by the NASA Shuttle Radar Topography Mission (SRTM) to remove the topographic phase contribution from the interferometric phase have also been used. A complex multilook operation with 4 looks in the range direction and 20 looks in the azimuth one was done, with a resulting pixel dimension of about 100*100 m. To obtain reliable unwrapped data, in this study firstly we consider a threshold of 0.2 on coherence values and restrict the unwrapping operation in the SNAPHU to involve only those pixels exhibiting an estimated coherence of higher than this value. Image pixels with coherence values less than 0.2 are ignored in the final unwrapped results. The unwrapped interferograms were then interpolated, geocoded and calibrated with respect to an area of known (zero) displacement (pixels to the south of the deformation field) to obtain absolute deformations.

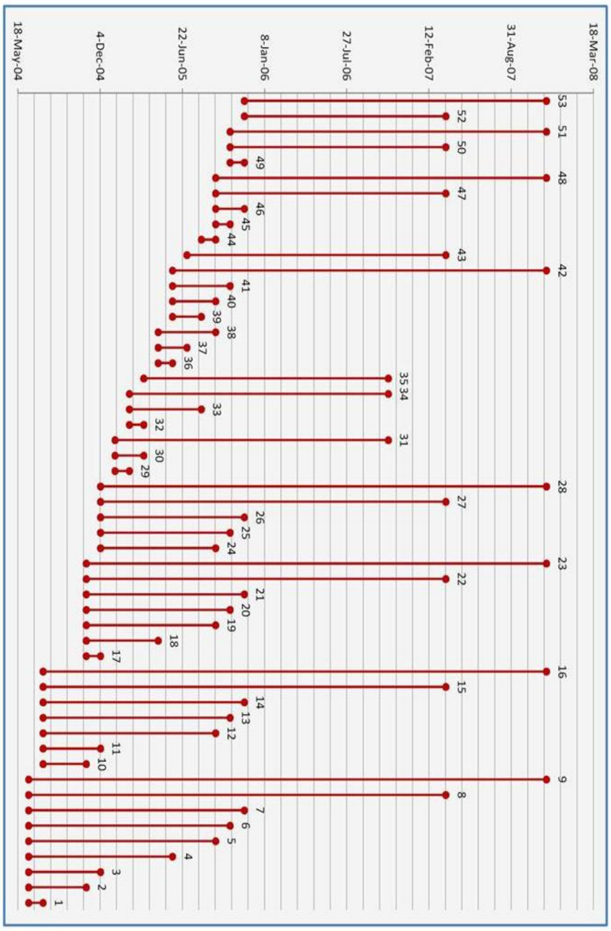

Figure 2 set of suitable interferograms for time series analysis along with their time spans as horizontal bars on a linear scale

3 Time Series Analysis

After InSAR processing, in which 53 unwrapped interferograms with relatively little noise remained, we used a least-squares adjustment approach in order to analyze the spatio-temporal evolution of land subsidence in Mashhad. To derive the time series of the deformation field, we first constructed a network of interferograms, and then applied the least-squares adjustment approach as discussed in [6]. The first acquisition date, June 14, 2004, was taken as reference and the adjusted displacement maps for the other SAR data acquisition dates with respect to this day were found as solutions of the problem.

$$Y = AX \tag{1}$$

where Y=[I1,I2,I3,…,I53] and X=[X1,X2,X3,…,X16] are the set of interferograms and the unknown mean velocities between acquisition dates, respectively. The design matrix A is the mathematical representation of

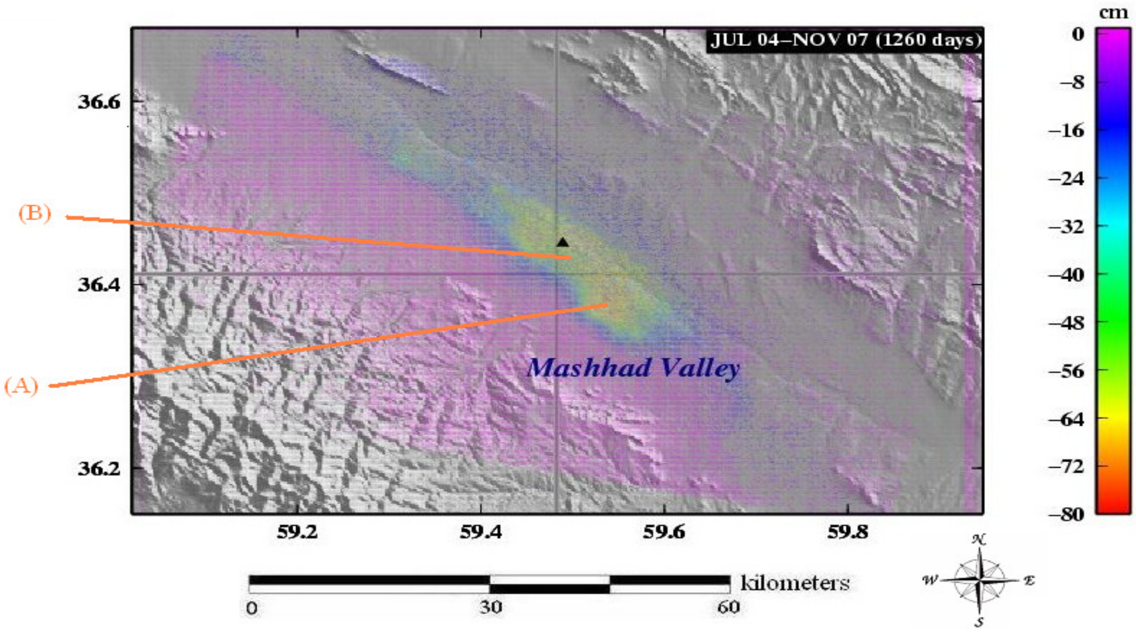

Figure 3 Accumulative ground displacement map in a LOS direction for 1260 days overlaid on DEM

Figure 2, excluding the rejected interferograms. For each row (i.e., for each interferogram), the values (partial derivatives) are 1 or −1 at the corresponding column of acquisition dates for slave and master, respectively. The remaining columns of each row are subscripted by 0. The weighted least square solution of (1) is straightforward

$$X = (A^T PA)^{-1}(A^T PY) \quad (2)$$

where P is the weight matrix of the observations and is determined based on the value of coherence in each pixel and the atmospheric disturbances in relevant interferogram according to the following relation:

$$P(i,j) = (1/\sigma^2)_k + \gamma_c(i,j) \quad (3)$$

4 Experimental Results

Figure 3 shows accumulative maps resulted from least squares adjustments of interferograms. This map represents the deformations, in centimeters, with respect to the reference day, June 14, 2004 (d1). **Figures 4a, 4b** shows the evolution of subsidence during the period of observation (Jun. 2004- Nov. 2007) at two locations in Mashhad, which are indicated by A and B in **Figure 3.** The deformation history of point A demonstrates surface deformation about 79 cm of in SAR sensor Line of Sight (LOS) in this period located in the area of maximum subsidence/downlift of the

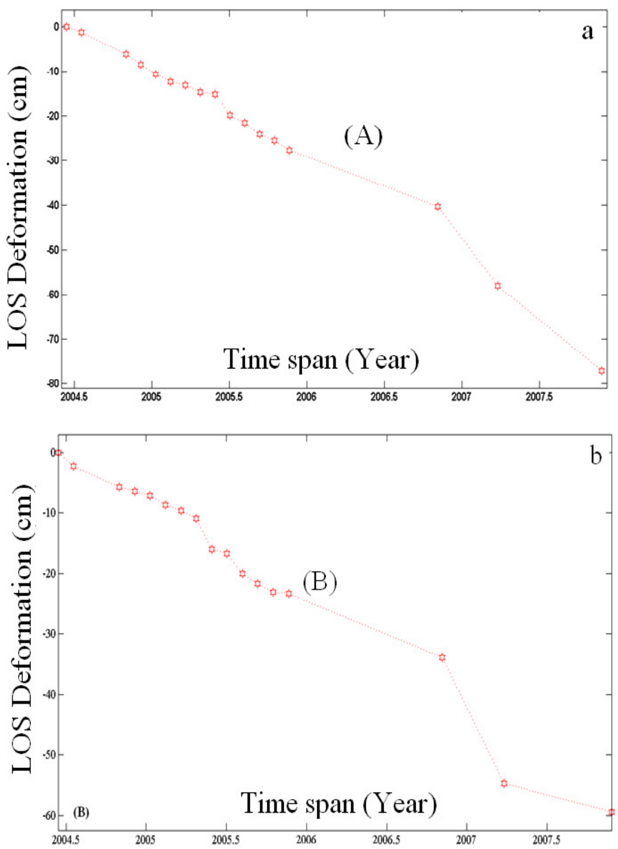

Figure 4 Time series plots of deformation at the points A, and B. The locations of the points are shown in Figure 3.

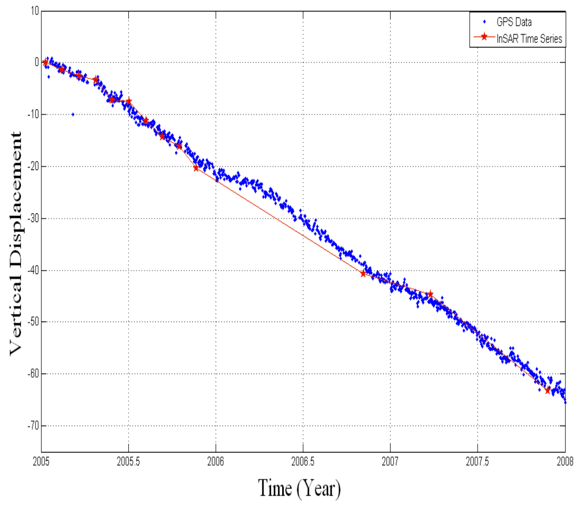

Figure 5 the comparison between InSAR time series results with continuous GPS station in the city of Tous marked by a triangle in Figure 3.

Mashhad valley. The deformation history of point B demonstrates surface deformation about 59 cm of in LOS direction. These results are confirmed by geodetic observations carried out by the National Cartographic Center of Iran (NCC).

The comparison between InSAR time series results with continuous GPS observations at Tous station, northeast of Mashhad, (triangle in **Figure 3**) between 2005 and 2008 yields comparable results at the level of 1 cm. InSAR results also show consistency with the average subsidence rate of 22 cm/yr at the station (See **Figure 5**).

Motagh and et al in 2006 presented a preliminary analysis by relying on only 13 interferograms and stacking method for the period 2003 to 2005 and showed that the northeastern part of Mashhad city has been subsiding with rate of 15 cm/yr and maximum rate of 30 cm/yr. This study shows that there is a bias in amount of 5 cm in these results. Considering the high precision of time-series analysis and the number of used interferograms it can been claimed that the results of this study are closer to reality.

5 Conclusion

This study presented an application of the InSAR time series analysis to derive spatio-temporal evolution of land subsidence in Mashhad Valley. The least-squares inversion was applied for a dataset of 53 interferograms and a time-series of subsidence was retrieved. The results of InSAR time-series analysis is in good agreement with geodetic measurements and improve the knowledge of subsidence histories in this region.

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