Available online at www.sciencedirect.com

ScienceDirect

Remote Sensing of Environment 109 (2007) 20–28

Remote Sensing of Environment

www.elsevier.com/locate/rse

Application of the SBAS-DInSAR technique to fault creep: A case study of the Hayward fault, California

Riccardo Lanari [a,*], Francesco Casu [a,b], Mariarosaria Manzo [a,c], Paul Lundgren [d]

[a] *Istituto per il Rilevamento Elettromagnetico dell'Ambiente, Consiglio Nazionale delle Ricerche, Napoli, Italy*
[b] *Dipartimento di Ingegneria Elettrica ed Elettronica, Università degli Studi di Cagliari, Cagliari, Italy*
[c] *Dipartimento di Ingegneria e Fisica dell'Ambiente, Università degli Studi della Basilicata, Potenza, Italy*
[d] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA*

Received 4 July 2006; received in revised form 31 October 2006; accepted 3 December 2006

Abstract

We present a quantitative assessment of the capability of the differential SAR interferometry (DInSAR) technique referred to as Small BAseline Subset (SBAS) approach to investigate fault creep phenomena. In particular we have computed, via the SBAS-DInSAR algorithm, time series of the surface displacements relevant to the Hayward fault zone, within the San Francisco Bay Area (California), from the European Space Agency's ERS-1/2 satellite radar data for the 1992 to 2000 time period. Starting from the DInSAR time series we measured the relative displacements across the fault with no need for any atmospheric filtering step. These results have been systematically compared to the measurements available from the alignment arrays that are located along the fault. Our analysis shows that the standard deviation of the differences between the DInSAR and the *in situ* measurements is on the order of 2 mm. Moreover, the estimated mean deformation rates have an accuracy that is better than 1 mm/year.

Keywords: DInSAR; SBAS; Surface creep; Hayward fault; Alignment arrays

1. Introduction

Differential SAR interferometry (DInSAR) is a microwave remote sensing technique that exploits the phase difference (interferogram) between SAR image pairs acquired at different times, in order to extract information on the radar line-of-sight (LOS) projection of the surface displacements that occurred between the acquisitions (Rosen et al., 2000). The DInSAR methodology was originally applied to investigate single deformation events (Massonnet et al., 1993; Peltzer & Rosen, 1995). However, more recently, several advanced DInSAR approaches (Berardino et al., 2002; Ferretti et al., 2000; Mora et al., 2003; Werner et al., 2003) have been developed to analyze the temporal evolution of the surface displacements via the generation of deformation time series. Among these techniques, we used the one referred to as Small BAseline Subset (SBAS) approach (Berardino et al., 2002) and exploited its capability to investigate fault creep phenomena, i.e., aseismic fault slip events. This study is focused on the Hayward fault running beneath the eastern San Francisco Bay Area, California, which has been the focus of other studies aimed at understanding its fault mechanics and earthquake potential.

The Hayward fault is creeping by varying amounts along most of its length and is capable of moderate size (M 6.8) earthquakes directly beneath an urban area (Bakun, 1999; Yu & Segall, 1996). The large number of alignment arrays and other geodetic measurements, coupled with extensive seismic and geologic observations, allowed the development of a fairly detailed representation of the fault in three dimensions (3-D). Of particular interest has been the identification of the distribution of locked and creeping patches and the relationship of the geodetically inferred locked and slipping portions of the fault and the background seismicity (Schmidt et al., 2005; Waldhauser & Ellsworth, 2002). Moreover, in February 1996, several

* Corresponding author. Tel.: +390815707999; fax: +390815705734.
E-mail address: lanari.r@irea.cnr.it (R. Lanari).

0034-4257/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2006.12.003

alignment arrays along the southernmost 10 km of the fault experienced up to 2 cm right-lateral creep. Several studies have looked at this event in terms of the timing of the event and the spatial location of this segment of the Hayward fault in relation to the 1989 Loma Prieta earthquake (Lienkaemper et al., 1997; Lienkaemper et al., 2001).

The analysis of fault creep phenomena and in particular of those relevant to the Hayward fault already has been the subject of DInSAR studies (Bürgmann et al., 2000; Bürgmann et al., 2006; Schmidt et al., 2005). However, although some comparisons between the DInSAR and geodetic measurements have been provided, no extensive analysis on the accuracy of the SAR products has been carried out. Accordingly, the main goal of this work was to provide a quantitative assessment of the expected accuracy when investigating creep phenomena by applying DInSAR techniques and, in particular, by using the SBAS approach. The Hayward fault was selected as a case study area because of the large set of *in situ* measurements available from the alignment arrays along the fault, to be used as reference data; moreover, the availability of a long series of SAR images acquired by the ERS sensors between 1992 and 2000 was also crucial for our analysis. We further remark that this work complements the study of Casu et al. (2006) where an extended comparison between DInSAR and GPS and leveling measurements was presented.

2. Methods

2.1. Short description of the SBAS approach

The algorithm we used for our analysis is the SBAS approach that relies on an appropriate combination of multilook DInSAR interferograms (Berardino et al., 2002).

The first step of the SBAS procedure involves the selection of the SAR data pairs used to generate the interferograms; they are characterized by a small temporal and spatial separation (baseline) between the orbits in order to limit the noise effects usually referred to as decorrelation phenomena (Zebker & Villasenor, 1992). Accordingly, this data selection allows us to preserve the temporal and spatial coherence characteristics of the interferograms computed, via a complex averaging (multilooking) operation (Rosen et al., 2000), from the selected SAR data pairs.

The second step of the procedure involves the retrieval of the original (unwrapped) phase signals from the modulo-2π restricted (wrapped) phases directly computed from the interferograms. This operation, referred to as phase unwrapping, is based on the minimum cost flow algorithm (Costantini & Rosen, 1999), which is integrated with a region growing procedure to improve the performances in areas with low signal to noise ratio.

The core of the SBAS approach is the inversion of the unwrapped interferograms for the deformation time series retrieval. The interferograms are inverted by using the Singular Value Decomposition (SVD) method which allows us to easily “merge” the information available through the computed interferograms.

Finally, the availability of space/time information permits to apply the last step of the procedure: the detecting and subsequently filtering of possible atmospheric artifacts. This filtering is based on the observation that the atmospheric phase signals are highly correlated in space but poorly in time (Ferretti et al., 2000). Accordingly, the undesired atmospheric artifacts are identified via the cascade of a low-pass filtering implemented in the two-dimensional spatial domain, followed by a temporal high-pass filtering (Berardino et al., 2002). This operation also allows us to detect possible orbital ramps caused by inaccuracies in the SAR sensors orbit information. Following their identification, the atmospheric artifacts and the orbital ramps are finally removed.

As a result of the SBAS algorithm, we can generate spatially dense deformation maps and produce deformation time series for each coherent pixel identified in the imaged scene.

Table 1
ERS SAR acquisitions for descending orbits (track 70, frame 2853)

Mission	Orbit	Day	Month	Year
ERS1	4223	6	5	1992
ERS1	4724	10	6	1992
ERS1	5225	15	7	1992
ERS1	5726	19	8	1992
ERS1	7730	6	1	1993
ERS1	10235	30	6	1993
ERS1	20098	19	5	1995
ERS1	21601	1	9	1995
ERS2	2429	7	10	1995
ERS1	22 603	10	11	1995
ERS1	24 607	29	3	1996
ERS2	4934	30	3	1996
ERS1	25108	3	5	1996
ERS2	5435	4	5	1996
ERS2	7940	26	10	1996
ERS2	11948	2	8	1997
ERS2	12449	6	9	1997
ERS2	12950	11	10	1997
ERS2	13952	20	12	1997
ERS2	15455	4	4	1998
ERS2	15956	9	5	1998
ERS2	16958	18	7	1998
ERS2	17459	22	8	1998
ERS2	17960	26	9	1998
ERS2	18461	31	10	1998
ERS2	18962	5	12	1998
ERS2	19463	9	1	1999
ERS2	19964	13	2	1999
ERS2	20465	20	3	1999
ERS2	20966	24	4	1999
ERS2	21467	29	5	1999
ERS2	21968	3	7	1999
ERS2	22469	7	8	1999
ERS2	22970	11	9	1999
ERS2	23471	16	10	1999
ERS2	23972	20	11	1999
ERS2	24473	25	12	1999
ERS2	24974	29	1	2000
ERS2	25475	4	3	2000
ERS2	25976	8	4	2000
ERS2	26978	17	6	2000
ERS2	27479	22	7	2000
ERS2	27980	26	8	2000
ERS2	28982	4	11	2000
ERS2	29483	9	12	2000