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Uncovering deformation processes from surface displacements

Salvatore Stramondo[a,*], Elisa Trasatti[a], Matteo Albano[a], Marco Moro[a], Marco Chini[b], Christian Bignami[a], Marco Polcari[a], Michele Saroli[a,c]

[a] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy
[b] Luxembourg Institute of Science and Technology, 5, avenue des Hauts-Fourneaux, L-4362 Esch sur Alzette, Luxembourg
[c] Department of Civil and Mechanical Engineering (DICeM), University of Cassino and Southern Lazio, Via G. di Biasio, 43, 03043 Cassino, Italy

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A B S T R A C T

Today, satellite remote sensing has reached a key role in Earth Sciences. In particular, Synthetic Aperture Radar (SAR) sensors and SAR Interferometry (InSAR) techniques are widely used for the study of dynamic processes occurring inside our living planet. Over the past 3 decades, InSAR has been applied for mapping topography and deformation at the Earth's surface. These maps are widely used in tectonics, seismology, geomorphology, and volcanology, in order to investigate the kinematics and dynamics of crustal faulting, the causes of postseismic and interseismic displacements, the dynamics of gravity driven slope failures, and the deformation associated with subsurface movement of water, hydrocarbons or magmatic fluids.

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* Corresponding author.
E-mail address: salvatore.stramondo@ingv.it (S. Stramondo).

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This review aims at providing the state of art of InSAR research activities and outcomes with a particular emphasis on applications involving new and most recent satellite missions.

1. Introduction

Nowadays, Earth observation by remote sensing sensors on board of spacecraft has reached a key role in understanding the dynamic processes of our living planet. A huge number of techniques, methods and algorithms have been developed over the last decades, with the objective of deeply exploiting information encrypted in the satellite images.

Among these techniques, the role of the Synthetic Aperture Radar (SAR) sensors in detecting and measuring surface movements has been widened. Today, Earth Sciences have available innovative tools to generate a huge number of observations that better constrain ground deformations in order to improve the understanding of the physical processes beyond these natural phenomena.

The processes producing surface deformation cover a wide range of causes. Roughly, we can separate such deformations into two classes of causes: "natural" and "anthropogenic". In a non-exhaustive list, natural deformation includes the seismic cycle and the deformation of volcanic edifices, while anthropogenic deformation includes land subsidence in urban areas due to urbanization and to overexploitation of water resources, the deformation related to fluid injection or withdrawal, the deformation of civil infrastructures (dams, buildings, nuclear power plants, etc.).

The accurate measurement of surface deformation is one of the most relevant parameters for studying the seismic cycle and, in particular, for modeling the mechanisms of tectonic stress accumulation and release. Displacements analyses at large scale through the synoptic capabilities of space sensors, foster the opportunity to study inter-seismic, pre-seismic, co-seismic, and post-seismic phases of the tectonic process, over its temporal and spatial behaviour.

Ground deformation is a phenomenon commonly observed in connection with volcanic activity. It is usually interpreted to reflect changes of pressure in shallow magma reservoirs or to be caused by the occurrence of intrusion events. The study of surface deformation is one of the key methods of inferring the geometrical and dynamical parameters characterizing buried magma bodies, especially if associated with the study of local seismicity. Volcanic uplift is a common precursor to eruptions, but, for some volcanoes, uplift of meters or more has not yet led to an eruption. The continuous monitoring that quantifies the spatial and temporal evolution of the deformation is therefore an essential and powerful tool for near real time volcano hazard estimates.

Satellite measurements are the best way to provide a fast, systematic and synoptic view of the Earth surface over large areas and long-term period, especially in remote areas where the setup of a monitoring network is not feasible. For such aims, SAR is the most relevant instrument today.

In this paper, the InSAR technique is discussed by reviewing its development since the 1992, and then is addressed its powerful contribution by showing several case studies of seismic and volcanic surveillance and crisis.

2. InSAR: improvements on science and technology

2.1. SAR satellite missions: from past to present day

The history of civilian satellite SAR systems began with the 1978 NASA Seasat satellite, which has been the first satellite equipped with a SAR sensor, operating at L band (24 cm of wavelength) of the electromagnetic spectrum. The mission has been designed for remote sensing of the Earth's oceans to demonstrate the feasibility of global satellite monitoring of oceanographic phenomena and to help determining the requirements for an operational ocean remote sensing satellite system. Specific objectives were to collect data on sea-surface winds, sea-surface temperatures, wave heights, internal waves, atmospheric water, sea ice features, and ocean topography. In addition, it has been also used to image the land in several areas but, unfortunately, the satellite lifetime has been about three months. The first application of SAR Interferometry (InSAR) technique exploited Seasat data to detect vertical motions over a few days caused by soil swelling of irrigated fields in the Imperial Valley, California (Gabriel et al., 1989). The authors affirmed that InSAR "*can measure accurately extremely small changes in terrain over the large swaths associated with SAR imaging, especially since the sensor can work at night and through clouds or precipitations*".

In 1991 the European Space Agency (ESA) launched its ERS-1 satellite with a C-band (5.6 cm wavelength) SAR system, which has been joined by ERS-2 a few years later (1995) (see Fig. 1).

The applications using data from both SAR satellites spanned most of the Earth Sciences, and in 1993 the capability to apply the InSAR technique to ERS data has been demonstrated for the case of the deformation due to the Mw 7.3 Landers earthquake in California (Massonnet et al., 1993) and ice motion in Antarctica (Goldstein et al., 1993). In parallel, the National Space Development Agency of Japan (NASDA, now JAXA – Japan Aerospace Exploration Agency) developed an L-band SAR sensor that has been launched into orbit onboard the JERS-1 satellite, in 1992. The applications of JERS-1 have been mostly focused on earthquakes and volcanic eruptions in Japan (Ozawa et al., 1997) or Asia in general (Tobita et al., 1998), while less used in Europe or America (Murakami et al., 1996) due to limited data coverage. In 1995, the Canadian Space Agency (CSA) launched RADARSAT-1, an advanced Earth observation satellite (http://www.asc-csa.gc.ca/eng/satellites/radarsat1/default.asp) to monitor environmental changes and to support resource sustainability. This C-band SAR sensor had a number of different radar imaging modes, including wide-swath for large area imaging. RADARSAT-1 has been used in a wide range of applications: sea-ice monitoring – daily ice charts (Kim et al., 2009), extensive cartography (Oliveira and Paradella, 2008), flood mapping and disaster monitoring in general (Zang et al., 2002), glacier monitoring (Jezek, 1999), forest cover mapping (Parmuchi et al., 2002), oil spill detection (Solberg et al., 2007), assessment of the likelihood of mineral (Daneshfar et al., 2006), oil and gas deposits (De Beukelaer et al., 2003), urban planning (Corbane et al., 2008), crop production forecasts (McNairn et al., 2002), coastal surveillance (erosion) (Barbosa et al., 1999), and surface deformation detection (Bignami et al., 2012). Many of these missions are now out of operation. JERS stopped collecting data in

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