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Using multi-band InSAR data for detecting local deformation phenomena induced by the 2016–2017 Central Italy seismic sequence

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ABSTRACT

In this work we exploit X- and C-band InSAR data for detecting local deformation phenomena induced by the 2016–2017 Central Italy seismic sequence. Our goal is to highlight the usefulness of multi-band InSAR analysis for Hazard assessing and Rapid Mapping purposes when in-situ investigations are difficult or dangerous to be performed. Indeed, local seismic-induced effects (such as landslides, avalanches, subsidence, etc.) could severely impact the environment and the population in the surrounding of areas hit by earthquakes. We focused on four areas, named *Monte Vettore*, *Podalla*, *Bolognola* and *Cicconi*, where InSAR outcomes revealed how the main seismic events of the sequence activated several landslides and secondary faults interested by deformation of ~2–3 cm along the satellite Line-of-Sight (LoS). The use of multi-band InSAR data allows the observation of multi-scale deformation phenomena with both different spatial resolution and coverage, highlighting the limits and constraints of different SAR sensors. Moreover, it ensures the crosschecking of displacement patterns retrieved through different InSAR products, especially when no ground truth or in situ ancillary data are available for validation purposes. As a result, the retrieved InSAR information can support the Scientific Community and the Institutions in the management of crisis emergencies.

1. Introduction

The 2016–2017 Central Italy seismic sequence has been a long sequence consisting of > 60 earthquakes with magnitudes greater than Mw 4.0 spanning from August 2016 to January 2017. Because of the density of villages and towns as well as the persistence and concentration in the same Central Apennine area, the impact of the sequence on population and buildings was highly devastating. It caused > 300 casualties and many buildings were destroyed or severely damaged, such as in Accumuli and Amatrice villages (Masi et al., 2016). Also the historical-artistic heritage of the area was affected by the earthquakes, which for example caused the collapse of the Basilica of San Benedetto and the Co-Cathedral of Santa Maria Argentea in Norcia and the Sant'Agostino church in Amatrice.

The sequence we have analyzed consists of 4 mainshocks characterized by a normal fault mechanism and located among Marche, Umbria, Lazio and Abruzzo regions (http://cnt.rm.ingv.it/): the Mw 6.0 Amatrice earthquake occurred on August 24th 2016 (Bignami et al., 2016; Cheloni et al., 2016), the Mw 5.9 Visso earthquake occurred on October 26th 2016, the Mw 6.5 Norcia earthquake occurred on October 30th 2016 (Cheloni et al., 2017), and the Mw 5.5 Montereale earthquake occurred on January 18th 2017. Many foreshocks and aftershocks (with Mw even > 5.0) were also observed during this temporal span. The four mainshocks have been located at a depth of ~10 km in an area of ~70 km of extension (http://cnt.rm.ingv.it/). Because of the relatively shallow depth of the earthquakes, they produced significant surface deformation fields, reaching up to ~70 cm of ground displacement (e.g. the Norcia earthquake), as clearly highlighted by Synthetic Aperture Radar Interferometry (InSAR) data (Fig. 1). The capability of InSAR data in constraining the co-seismic deformation induced by seismic events was extensively demonstrated by considering both large scale earthquakes (Chini et al., 2010; Massonet et al., 1993) and smaller scale events (Polcari et al., 2016; Stramondo et al., 2014). Nowadays, SAR systems operating at different frequencies are included in Earth Observation (EO) programs of several space agencies for risk mitigation purposes, such as the L-band ALOS-2 mission of the Japan Aerospace eXploration Agency (JAXA), the C-band Sentinel-1 (S1) mission from the European Space Agency (ESA) and the X-band COSMO-SkyMed (CSK) mission of the Italian Space Agency (ASI). Therefore, depending on the scale of the observed phenomenon, it is possible to exploit L- (1–2 GHz), C- (4–8 GHz) or X-band (8–12 GHz) SAR data. In Fig. 1, the displacement maps due to the

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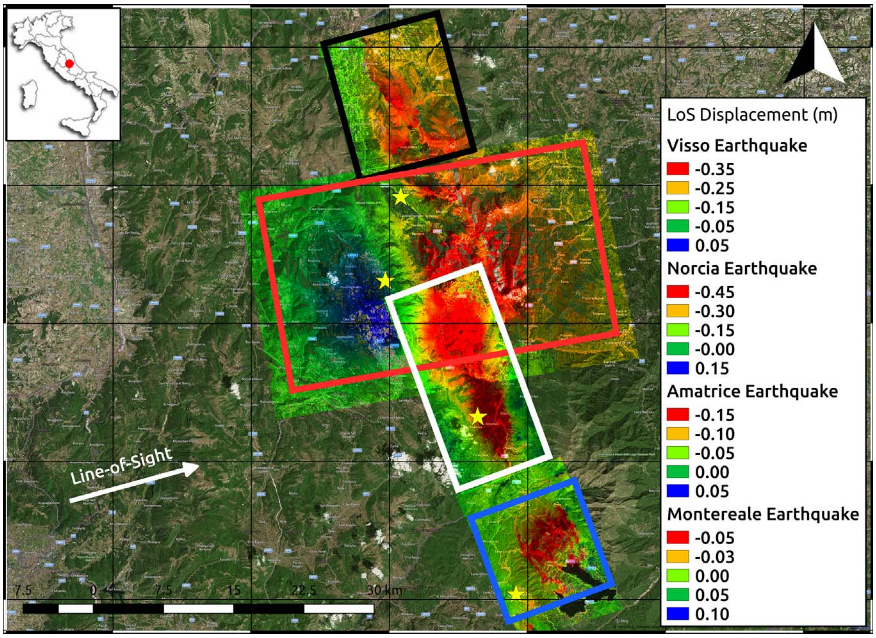

Fig. 1. InSAR LoS overall displacement induced by the 2016–2017 Central Italy seismic sequence. The map was retrieved by L-band ALOS-2 ascending SAR data. From north to south, the displacement fields due to the Visso (black rectangle), Norcia (red rectangle), Amatrice (white rectangle) and Montereale (blue rectangle) earthquakes are shown, respectively. In the same order, the epicenters are indicated as yellow stars. The different color scales used for the displacement range values are due to the different magnitude of seismic events. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Amatrice, Visso, Norcia and Montereale earthquakes are estimated by the L-band ALOS-2 SAR data. Thanks to its long wavelength ($\lambda \sim 24$ cm), the L-band SAR data are less affected by temporal decorrelation problems. Moreover, using X- and C-band data, an occurred large surface displacement could lead to coherence loss and unwrapping phase errors, especially in proximity of the deformation peak and fault location. However, besides the large co-seismic deformations, the long seismic sequence further induced several local deformation phenomena, such as landslides or avalanches (Emergeo et al., 2016). Although considered "secondary effects" induced by earthquakes, these local phenomena severely impact the interested areas, causing dangerous landscape and structural changes, thus increasing the risk for the surrounding villages, inhabitants and critical infrastructures (e.g. dams, bridges). They can provide non-negligible losses in terms of human life, building damages, environmental instabilities, transport facilities and financial resources. As a result, an effective InSAR-based monitoring strategy could be suitable not only to detect and monitor such phenomena at local scales, but also to provide useful information for the seismic risk mitigation of the affected areas in short and medium terms.

The aim of this paper is to investigate such local effects by means of X- and C-band InSAR data, exploiting the different sensors characteristics on the base of resolution and the orientation of the phenomenon with respect to the geometry of the satellite Line-of-sight (LoS). The scale of the investigated phenomena is generally few centimeters, then the X- ($\lambda \sim 3.1$ cm) and the C-band ($\lambda \sim 5.6$ cm) SAR data are the only able to image them. These dual band InSAR data confirmed to be suitable and very useful in detecting the "secondary effects" of an earthquake, especially when the complex and rugged topography makes complicated the in-situ analysis.

In this work, the attention was focused on 4 case studies located in the surroundings of the epicenters, respectively the *Monte Vettore*, *Bolognola*, *Podalla* and *Cicconi* sites. They were selected since InSAR data revealed localized deformations occurring after the main events of the seismic sequence. Hence, they are interesting to study and monitor for security and safeguarding purposes.

2. Seismotectonic framework and geological setting

Since Neogene geologic period, the Central Apennine chain developed as an east-verging fold and thrust belt, (Bally et al., 1987) accreted in consequence of the contemporaneous flexural-hinge retreat of the Adria plate and the back-arc opening of the Tyrrhenian basin (Meletti et al., 2000 and references therein). This portion of Apennines is characterized by the superposition of two main tectonic phases, evidenced by the presence of a complex pattern of thrusts, strike-slip faults, folds and normal faults (Barchi et al., 1998; Lavecchia et al., 1994; Tavarnelli, 1999). The first compressional phase took place during the Upper Miocene-Lower Pliocene and is responsible for the formation of the E-NE verging fold and thrust belt. The second and latter phase superimposed during the Upper Pliocene and Quaternary, generating extensional basins bounded by NW-SE to N-S trending normal faults.

The present-day NE trending extensional stress field revealed by geodetic data (D'Agostino et al., 2011; Devoti et al., 2011), focal mechanisms (Chiarabba et al., 2009) and borehole breakout (Mariucci et al., 2010), is related to the persistence of back-arc extension, with deformation occurring on active normal faults NW-SE trending, SW-dipping. Active extension, earthquakes and evidence of active faulting are mainly concentrated along the axial belt, close to the main topographic ridge, where the strongest historical (Intensity = XI) and instrumental seismicity ($M > 5.8$) occurs (Barchi et al., 2000 and reference therein).

From a geological point of view, the observed phenomena described below are located in a portion of the Umbria-Marche Apennines known as Inner Ridge (Lavecchia and Pialli, 1980; Scarsella, 1951), a carbonate multilayer sequence constituted by rift and passive margin environment sediments. This stratigraphic sequence is represented by a Lower Liassic massive carbonate platform (Calcare Massiccio fm), superimposed by Middle Lias-Middle Eocene pelagic sequence of cherty limestones (Corniola fm, Calcari Diasprigni fm, Maiolica fm, Scaglia Bianca fm, Scaglia Rossa fm) and marly formations (Rosso Ammonitico fm, Marne a Fucoidi fm, Scaglia Variegata fm, Scaglia Cinerea fm).

3. X- and C-band data

The SAR data adopted in this study were acquired by the CSK and S1 missions (Table 1). The choice to use CSK and/or S1 data relies on the scale, the size and the spatial extension of the phenomena to observe. S1 uses a wavelength of 5.66 cm (f = 5.33 Ghz) and the SAR data are characterized by a pixel posting of $\sim 3 \times 15$ m in the Interferometric Wide Swath (IW) acquisition mode. This is a new form of ScanSAR imaging, namely the Terrain Observation with Progressive Scan SAR