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How second generation SAR systems are impacting the analysis of ground deformation☆

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ABSTRACT

In recent years, a second generation of Synthetic Aperture Radar (SAR) satellite sensor has been designed and, partially, put into operation, leading to an important breakthrough in Earth Science studies. The common characteristics of such new systems are, indeed, a reduced revisit time (as short as a few days) and, in most cases, an improved spatial resolution (as small as a few meters), providing scientists with unprecedented data for the mapping and monitoring of natural and human-induced hazards.

This paper provides an overview on the new observational capability offered by the second generation of SAR sensors, especially in the field of ground deformation analysis for mitigating the risk associated with natural and human-induced hazards. In particular, we exploit the high resolution X-band data acquired by the COSMO-SkyMed (CSK) constellation to show how deformation phenomena characterized by limited spatial extent and extremely fast dynamics can be detected and investigated in details.

Whenever possible, we compare the achieved results with those obtained by using data collected by the first generation ERS-1/2 and ENVISAT systems. A comparison with one ALOS satellite dataset is also included. Most of the results, based on the application of Differential SAR Interferometry (DInSAR) techniques, highlight how this technology is not anymore just a sophisticated tool for remotely studying surface deformation phenomena, but it is becoming an operational system for near-real time deformation monitoring.

Moreover, we also show how the improved spatial resolution extends the possibility to exploit SAR image amplitude, instead of phase, for direct comparison with optical data and for imaging large deformation episodes, typically associated with strong seismic events, for which DInSAR may fail.

1. Introduction

Synthetic Aperture Radar (SAR) has been one of the most important remote sensing tools for analyzing Earth's surface deformations since several decades. The "first generation" of SAR satellite sensors can be dated back to 1978, when SeaSAT was launched (see Table 1); however, it was with the launch of ERS-1 in 1991 that research activities in this field received a considerable pulse. As a matter of fact, although originally designed for studying ocean waves and sea ice, such a sensor became very popular when a systematic experimentation of SAR Interferometry (InSAR) (Zebker and Goldstein, 1986; Li and Goldstein, 1990) for topography mapping, and Differential SAR Interferometry (DInSAR) (Gabriel et al., 1989) for small elevation change measurement, was carried out in the 90s thanks to the availability of good quality data. In particular, the DInSAR technique produced very impressive results on ice sheet motion in the Antarctica region (Goldstein et al., 1993), on ground deformation induced by the Landers earthquake in California (Massonnet et al., 1993), and on the deflation of Mt. Etna volcano in Italy (Massonnet et al., 1995).

Since those early days, several advances have been achieved in this field, from both the algorithmic and the technological point of view. In the 2000s a set of "advanced" DInSAR techniques were developed in order to study not only a single deformation episode (e.g., a single eruption or earthquake), but also to follow the temporal evolution of the detected displacements through the generation of deformation time series (Ferretti et al., 2000; Berardino et al., 2002; Mora et al., 2003; Werner et al., 2003; Lanari et al., 2004; Hooper, 2008; Ferretti et al., 2011). As an important side effect, this also allows a more effective filtering of the atmospheric noise and a more accurate compensation of the topographic artifacts (which may impair single interferogram analyses), thus improving

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Table 1
Characteristics of satellite SAR systems.

Mission time lap	Satellite	Mode	Incidence angle (deg)	Band	Wavelength (cm)	Resolution (m)		Revisit time (day)
						Ground range	Azimuth	
1978–1978	SeaSAT	Stripmap	23	L	23.5	20	6.0	24
1991–1998	JERS-1	Stripmap	39	L	23.5	16	7.5	44
1991–2001	ERS-1	Stripmap	23	C	5.66	25	5	35
1995–2011	ERS-2	Stripmap	23	C	5.66	25	5	35
1995–today	Radarsat-1	Stripmap	20–50	C	5.66	20–30	7.5	24
		ScanSAR	20–46			25–40	25–35	
2002–2012	ENVISAT	Stripmap	15–45	C	5.63	25–50	5	35
		ScanSAR	16–44			25–50	100	
2007–today	Radarsat-2	Stripmap	20–49	C	5.55	20–30	7.5	24
		ScanSAR	20–45			25–40	25–35	
		Spotlight	20–49			2–5	1	
2006–2011	ALOS-1	Stripmap	8–60	L	23.6	9–30	5	46
		ScanSAR	18–43			15–75	50	
2007–today	COSMO-SkyMed	Stripmap	20–60	X	3.1	3–15	3	1–8
		ScanSAR	20–60			7–30	16–20	
		Spotlight	20–60			1	1	
2007–today	TerraSAR-X	Stripmap	20–45	X	3.11	1–3	2.4	11
		ScanSAR	20–45			2–3	16	
		Spotlight	20–55			1–3	1	
To be launched in 2014	Sentinel-1	Stripmap	18–46	C	3.1	5	5	12
		ScanSAR	30–46			5	20	
To be launched in 2014	ALOS-2	Stripmap	8–70	L	22.9	6–10	5	14
		ScanSAR				10–30	50	
		Spotlight				3	1	

the overall precision of the methods (Casu et al., 2006). An overview of the applications of such techniques can be found in Sansosti et al. (2010).

More recently, the DInSAR scenario has been characterized by a considerable technological development thanks to the advent of a "second generation" of SAR sensors, which are either already operational (TerraSAR-X, COSMO-SkyMed, Radarsat-2) or will be launched in the near future (Sentinel-1, ALOS-2). Although operating at different frequencies and with variable ground resolutions (see Table 1), all these sensors exhibit two common characteristics: a reduced revisit time (as small as a few days) and an improved spatial resolution (as small as a few meters and even less, in the spotlight mode).

The aim of this work is to provide a comprehensive overview on how the availability of data gathered by such new systems is impacting the present DInSAR scenario and, more in general, how it is opening new perspectives in the field of Earth Observation. To this end, we exploit a large set of X-band data acquired by the COSMO-SkyMed (CSK) constellation and demonstrate, through the discussion of a number of selected case studies, their capability to detect and analyze deformation phenomena characterized by limited spatial extent and extremely fast dynamics.

In particular, we first show how the improved spatial resolution is making SAR amplitude images more and more comparable to optical ones from a geometrical point of view, thus opening new application scenarios of such remote sensing systems. Indeed, a simple visual comparison between two images, which needs no specific expertise in processing and interpreting radar data, can significantly support the phases of emergency response as well as the risk assessment and mitigation activities.

Next, we present some significant results achieved by applying the Small BAseline Subset (SBAS) algorithm, which allows producing ground deformation time series at a regional scale with reduced resolution (Berardino et al., 2002), as well as at the full sensor resolution (Lanari et al., 2004). We perform the low resolution analysis on two test sites, the Napoli Bay area (which includes two volcanic complexes, the Campi Flegrei Caldera and the Mt. Somma-Vesuvius) and the Mt. Etna, both located in Southern Italy, in order to highlight the advantages arising from the use of second generation SAR sensors for the assessment and mitigation of volcanic risk.

Subsequently, we apply the full resolution SBAS algorithm to the Napoli urban area (Italy) to show how the high resolution DInSAR data allow mapping, with a unique level of detail, deformation phenomena affecting single buildings and man-made features.

The last case study shows some results relevant to the earthquake that struck Haiti in 2010, causing severe socio-economic damage. In this case, conventional and advanced DInSAR techniques cannot be directly used because the co-seismic displacements that occurred in the area are too large and coherence is low in the tropical vegetation. Therefore, we apply the Pixel Offset (PO) approach (Fialko and Simons, 2001; Casu et al., 2011) that is able to measure ground displacements with magnitude comparable to the image resolution. Such a technique exploits the amplitude images, only (without using the phase) and the achievable accuracy in the displacement measure is in the order of 1/30th of the resolution cell (Casu et al., 2011). As a consequence, the use of very high resolution data, such as those acquired by the CSK spotlight mode (1 meter resolution, in both azimuth and range), extends the possibility to use such a technique also to measure deformation phenomena with a centimetric accuracy, significantly smaller than in the past.

Finally, we compare the obtained results, whenever possible, to those achieved by using ERS-1/2 and ENVISAT data, to further point out how the new SAR scenario is moving from deformation analysis to near-real time monitoring, thanks to the recent technological improvements. A comparison with satellite ALOS data is also included for the Etna study area.

2. Use of single amplitude images: the Giampilieri area experiment

The significant improvement in spatial resolution achieved by the second generation SAR sensors, in particular by the X-band systems, is making SAR images more and more geometrically comparable to optical ones. On one hand, this relevant feature encourages human interpretation of SAR data in a way similar to