Land subsidence in the Firenze-Prato-Pistoia basin measured by means of spaceborne SAR interferometry

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Abstract — This work concerns the application of spaceborne SAR interferometry (InSAR) to the study of the land subsidence problem affecting the urban areas of the Firenze-Prato-Pistoia basin (Central Italy). Such phenomenon is mainly related to the large amount of ground-water pumped from the industrial activities of this area. The interferometric analysis has been carried out by means of both traditional Differential Interferometry (DInSAR) and Permanent Scatterers technique (PS) by using SAR data acquired by the ESA ERS1/2 satellites. Different patterns of terrain subsidence have been detected in the industrial areas of the monitored basin.

INTRODUCTION

This paper aims to study the subsidence phenomenon of the Firenze-Prato-Pistoia basin by space-borne SAR data. The analysis has interested an area having a spatial extension of about $400\ \mathrm{Km}^2$, representing the medium portion of the Arno River alluvial plain. From a geological point of view, this area represents a lacustrine basin, developed in the Villafranchian time, characterized by the presence of lacustrian and fluvial deposits, mainly consisting of orizontal levels of sand, clay and mud, settled on flysch formations. The hydrogeological setting of the area is related to the presence of three main acquifers, the Firenze-Signa groundwater, the Pistoia one and the Prato fan. Such acquifers supply the municipal aqueducts and the textile industries of the zone. They have been overexploited for more than twenty years and some of them are nearing exhaustion [1]. The measurements of the water level, made during the eighties, have shown an extensive deep cone in the piezometric surface, produced by the water pumping, minimally affected by seasonal recharges [1]. SAR interferometric (InSAR) technique has been used to analyse the effects of acquifers overexplotation on the terrain surface, so far not deeply studied through other traditional means. The study relies on SAR data acquired by the ESA ERS-1/2 satellites. The interferometric processing has been carried out following two strategies. Differential InSAR (DInSAR) has proven its potential for mapping ground deformations over wide areas spanning thousands of squared kilometers, supplying results on a dense $20\ \mathrm{m} \times 20\ \mathrm{m}$ grid [2]-[6] . This characteristic is of advantage when studying a subsidence phenomenon, because it provides information on the whole area interested by the deformation and not only in a few points as techniques such as geodetic levelling and GPS. The occurence of atmospheric disturbances and interferometric decorrelation are the main disadvantage of DInSAR [2]. Permanent Scatterers (PS) technique represents a useful way to overcome the above limitations of DInSAR, carrying out accurate interferometric measurements over a subset of image pixels corresponding to stable reflectors, namely PS [7, 8]. This technique is very effective in urban areas characterized by a high density of stable reflectors. In other areas, with a lower density of stable reflectors, the PS technique can be usefully combined with DInSAR applied to carefully selected inteferometric SAR images having a sufficient coherence. This approach increases the density of spatial information about the terrain movements.

DATA PROCESSING

Ten interferograms of the studied area have been generated by processing five ERS-1/2 SAR images spanning a time interval of two years (from August 1998 to July 2000). Spatial and temporal baselines range, respectively, from 1 to 522 m and from 34 to 700 days. We removed the topographic component by using a Digital Elevation Model (DEM) with a 10 m cell. A phase variation of 2π radians on the differential interferogram corresponds to a terrain movement of $28\ \mathrm{mm}$ measured along the radar's line-of-sigh (LOS). Being the ERS look angle $\vartheta \simeq 22^\circ$ and the Firenze-Prato-Pistoia basin practically flat, the $28\ \mathrm{mm}$ LOS movement is related to a terrain deformation of $30\ \mathrm{mm}$ along the vertical direction where it is expected to measure the effect of ground-water pumping. Atmospheric disturbances and phase decorrelation, due to temporal changes of the terrain properties, can affect the quality of interferograms. Atmospheric artifacts can be identified by analysing independent interferograms of the same scene. In fact, the atmosphere produces spatially coherent phase pattern which generally are not correlated in time [2]. Instead, the effect of land subsidence are recognized as they produce spatially correlated phase patterns which are temporally consistent. Decorrelation problems can be mitigated by choosing SAR images approximately acquired in the same season to reduce the occurrence of changes in the terrain properties. The PS technique gives another powerful means to exploite long temporal series of interferometric SAR images [7, 8]. The PS analysis has been performed by means of 24 ERS SAR images spanning a 7 year time period from July 1993 to August 2000. The atmospheric phase component is precisely estimated and removed so allowing for the detection and measurement, at the PS location, of the terrain subsidence.

RESULTS

Three interferograms of the studied area are shown in figure 1. They have been geolocated and overlaid to the intensity SAR images. The interferograms span time intervals from 315 to 700 days. Six bowl-shaped phase patterns possibly due to land subsidence have been recognized (encircled areas) in all of the interferograms. Their deformation rates goes from 2 to 9 cm/year. The result obtained by the PS technique is shown in figure 2. More than 57000 PS have been identified in the scene, mostly located in correspondence of urban areas. The reference point, assumed motion-less, is positioned near Firenze (green PS in figure 2.) High velocity values have been detected near Prato and Sesto Fiorentino, where some PS shows an average subsidence rate greater than 20 mm/year. In the urban area of Pistoia a slower subsidence is clearly visible, with an average displacement rate in the area of 3 mm/year. Two examples of PS time series are shown in figure 3 for a fast subsiding structure near Prato (point A in figure 2) and a very stable structure in Firenze (point B in figure 2).

The joint analyses of figures 1 and 2 shows a general agreement. In particular, PS technique is able to measure land subsidences with a slow deformation rate as the one close to the Firenze area. This ground movement, even if present on interferograms of 1, can not be easily distinguished from other interferometric artifacts being the interferometric phase a small fraction of the 2π cycle. On the contrary, land subsidences with a fast dynamics, such as the bowls in the Prato fan, are much easier identifiable and measurable by using DInSAR. Terrain deformation rates in these zones can reach peaks up to 8-9 cm/year. These velocities are close to the maximum deformation rate which can be accurately followed by PS analysis.

Future work will consist in matching the terrain deformations rates estimated by interferometric SAR data with hydrogeological analysis. In fact, the amount of water pumped in the last years can be calculated taking into account the hydrologic balance of the acquifer [1, 9].

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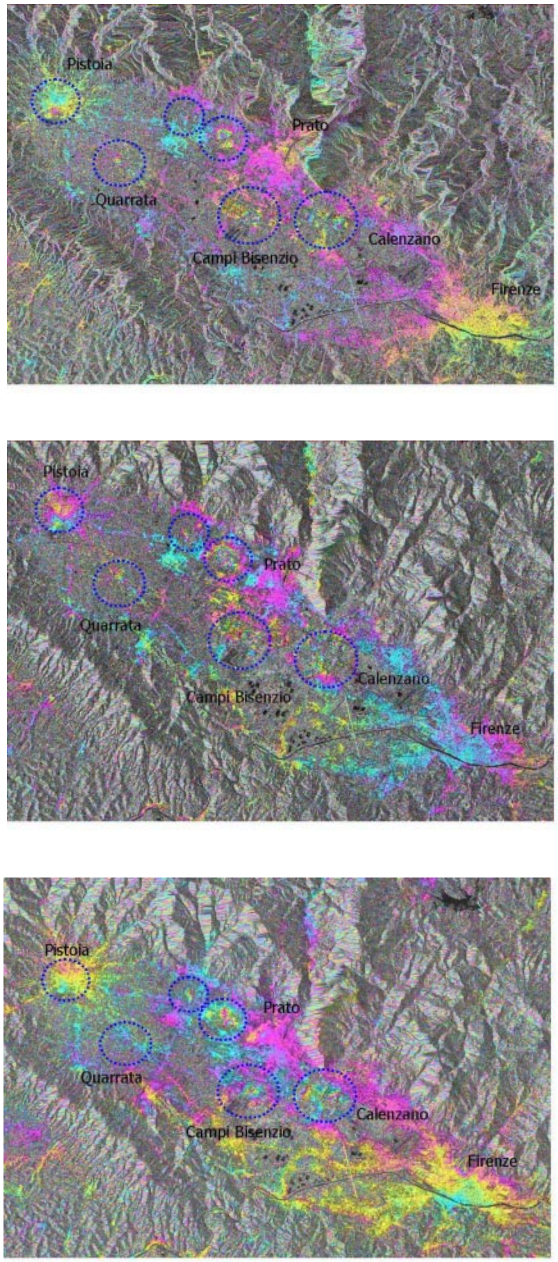

Figure 1: Differential interferograms of the Firenze-Prato-Pistoia basin overlaid to the intensity SAR image of the same scene. From the top to the bottom, interferograms refer to the following time intervals: 13.08-98/02-09-99 (385 days, $B = 1$ m); 13-08-98/13-07-2000 (700 days, $B = 186$ m); 13-07-2000/02-09-99 (315 days, $B = 185$ m).

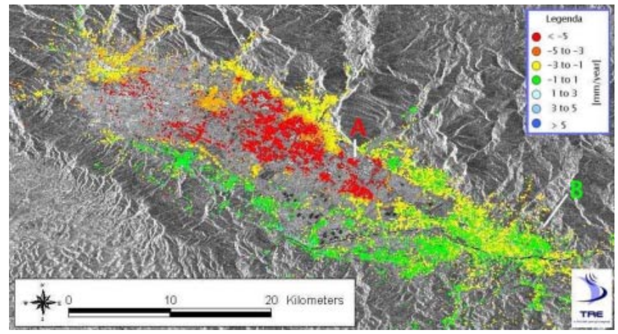

Figure 2: Terrain velocity field of the Firenze-Prato-Pistoia basin as computed from the PS technique. The map has been overlaid over an intensity SAR image of the scene. Ground deformations are measured along the LOS direction and refer to the time period from July 1993 to August 2000. Negative and positive signs denote subsidence and uplift movements, respectively. The temporal evolution of the terrain velocity in points A and B is given in figure 3.

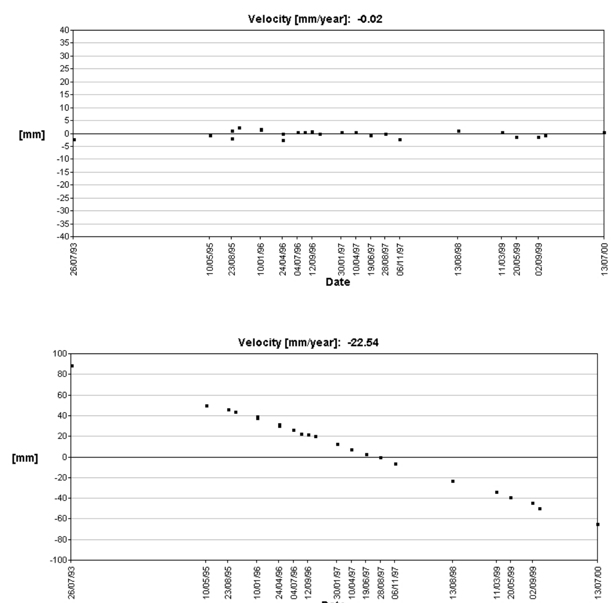

Figure 3: Temporal evolution of the terrain velocity in points A and B shown in figure 2.