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Analysis of the evolution of ground movements in a low densely urban area by means of DInSAR technique

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ABSTRACT

This paper presents an application example of the use of the Differential Interferometry Synthetic Aperture Radar technique (DInSAR) for monitoring ground movements in a geologically complex area around the village of Súria (Ebro Basin, Catalonia, NE Spain), associated to underground mining activities and to the presence of a salt dome. The analysis has been mostly performed in a rural environment affected by ground movements with different patterns, magnitudes and causes. A total of fifty SAR images recorded between 1995 and 2007 were processed to generate the interferograms. In order to study the non-linear trends or changes of the ground surface behavior, the DInSAR technique was applied in two sets of images.

The interferometric results, in the form of vertical displacement rate maps, were checked against conventional surveying and GPS measurements. The results present a significant discrepancy in some location due to the wrapping of the phase when both fast and significant deformations occur. In order to avoid the latter effect and improve the accuracy of the results, all SAR images were reprocessed using topographic leveling and GPS data of different monitored points.

To support the DInSAR interpretation, a detailed geological reconnaissance of the study area was carried out as well as an inventory of ground movement indicators.

Four different patterns of ground movement have been identified: active shifting subsidence associated to the progression of the mining exploitation fronts; residual subsidence on abandoned galleries with a decreasing rate of closure; uplifting due to the intrusion of the salt dome; and sudden ground collapses (sinkholes) caused by the dissolution of soluble materials laying close to the ground surface.

1. Introduction

Ground surface movements commonly cause disturbance and damage in urban areas. The knowledge and prediction of the evolution of the temporal and spatial distribution of the movements are essential to delineate the most affected areas, to understand the mechanisms involved, and to establish counter measures to prevent damages.

The evaporite rocks are lithologies frequently found associated to ground displacements. In areas where salt domes are present, vertical movements (diapirism) may occur (Baer et al., 2002; Shimoni et al., 2002) while water infiltrated from either rainfall or rivers can dissolve rocks and originate subsidence, sudden collapses (sinkholes) or both (Gutierrez et al., 2007a, 2007b).

Underground mining activities may cause subsidence of the ground surface due to the advance of the excavation fronts and the progressive closure or collapse of the mineral extraction galleries. The magnitude of the displacements depends on different parameters, such as the depth of the mining galleries and the time elapsed since the onset and/or the abandonment of the excavation (Al-Rawahy, 1995; Bahuguna, 1995). The evolution of the subsidence of a point has been described by many authors (Alejano et al., 1999; Donnelly et al., 2001; Ambrožič and Turk, 2003) as a non-linear behavior which can be represented by a negative exponential curve.

During the last decade, Earth Observation techniques such as Differential Synthetic Aperture Radar Interferometry (DInSAR) have become an important tool for monitoring temporal and spatial ground movements. These techniques have been successfully applied to detect and measure ground subsidence in areas subjected to underground mining exploitation (Raucoules et al., 2003; Ge et al., 2004a; Biescas et al., 2007; Herrera et al., 2007; Baek et al., 2008; Miao et al., 2008; Gueguen et al., 2009). Moreover, the interferometric technique has been used to detect surface displacements caused by tectonic activity (Lanari et al., 2007; Martino et al., 2009), earthquakes (Hernandez et al., 2004), soil consolidation processes (Manunta et al., 2008), volcanic activity (Perlock et al., 2009), soil expansion (Vallone et al., 2008), subsidence caused by groundwater exploitation (Tomás et al., 2005; Cascini et al., 2006; Stramondo et al., 2007; Herrera et al., 2009a) and subsidence caused by ground dissolution (Gutierrez et al., 2011; Paine

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et al., 2012). Similarly, interferometric techniques have been used to estimate landslide displacements (Berardino et al., 2003; Fernandez et al., 2009; Herrera et al., 2009b, 2010; Iglesias et al., 2012).

DInSAR has some clear advantages over classical monitoring methods, such as the Differential Global Positioning System (DGPS) and ground-based instruments. The first one is its high spatial coverage. Classical techniques measure ground displacements at a few discrete points while DInSAR provides a more complete pattern of the displacements' field with measurements over a wide area. Another advantage of the technique is the existence of a historical database of SAR images, which was started more than 20 years ago, that enables the study of past situations.

The best performance of the DInSAR techniques is achieved in urban environments, because the quality of the interferometric phase is well preserved along time and many pixels of the image can provide reliable deformations. In addition, a proper selection and exploitation of stable natural reflectors or persistent scatterers increases the accuracy of the results (Ferretti et al., 2001).

DInSAR techniques have some well-known limitations. For instance, temporal and spatial phase wrapping problems may appear when the movement of the terrain surface is fast. The phase unwrapping is a critical step of the DInSAR signal processing, which has been the focus of a variety of approaches and algorithm development (Zebker and Lu, 1998; Pepe et al., 2011). In addition, when DInSAR is applied in non-urban environments the number of useful pixels can be dramatically reduced. This restriction usually can be eased by reducing the temporal separation between the images (Wegmüller et al., 2010) or using satellites with lower frequency more insensitive to vegetation (Wegmüller et al., 2007). Other additional techniques have been developed such as Persistent Scatterer (PS) InSAR technique (Chang et al., 2010) in order to reduce the noise and disturbances related to mountainous areas.

It is advisable to support interferometric data with classical surveying techniques, for example to compare both data to get a better understanding of the problem (Finnegan et al., 2008). Other authors use GPS data for monitoring landslides with large three-dimensional effects, where the phase information in line-of-sight (LOS) can be projected back onto the direction provided by the GPS displacement field (Samsonov et al., 2007; Peyret et al., 2008), or in earthquakes combining GPS and interferometric methods in a joint inversion procedure that couples horizontal displacement from GPS measurements and vertical displacements from interferometric data (Hernandez et al., 1999; Pedersen et al., 2003). GPS data can also be used to correct the atmospheric disturbance in DInSAR results (Ge, 2000; Ge et al., 2004b). The combination of different techniques takes advantage of the complementary strengths of each method by overcoming their inherent limitations.

In mining districts, delineating the area affected by ground movement is very important for knowing which buildings or structures may be at risk. In these areas, the degree of damage depends mainly on the ground slope change or angular distortion of the terrain (Skempton and MacDonald, 1956; Bell, 2004; Son and Cording, 2005). First of all, it is essential to determine the magnitude and trend of the movement. DInSAR techniques allow the detection of zones affected by ground movements, but clearly they are not able to explain by themselves the causes of such displacements. These can only be determined by an integrated analysis of data from multiple sources.

In this work, we present the results of the analysis of the DInSAR images in Súria (Ebro Basin, NE Spain). This area is subjected to an intensive underground exploitation of a salt dome. Ground disturbance and/or structural damage on buildings have been observed in different locations around the village but their relation with the mining activities has not been well established so far. The objectives of this work are fourfold: (1) improve the reliability and accuracy of the DInSAR measurements with the support of other monitoring techniques (conventional surveying and GPS); (2) test the feasibility of the DInSAR techniques for the spatio-temporal analysis of ground movements in a low densely urbanized environment; (3) assess the performance of the DInSAR techniques in complex geological contexts where different types of ground movement may coexist; (4) analyze the temporal evolution of ground surface movements using two data sets of SAR images covering different time intervals (1995–2000 and 2003–2007), which facilitates the detection of changes in the displacement rates (increase or stabilization tendency).

2. Materials and methods

In order to achieve the objectives mentioned above, the following activities have been carried out:

a) Prepare a geological model of the area in order to properly interpret the monitoring results. Detailed geological and historical studies as well as published information have been collected. Available core logs from boreholes that cross the salt dome have been used to prepare detailed geological cross-sections. Field work has been carried out in order to search for ground surface movement indicators such as recent ground collapses, ancient sinkholes filled with either alluvial or colluvial material, tilted river terraces and damaged structures. Finally, a search of historical information about the mining in the area has been compiled, but the exact location and advancement plans of the extraction galleries were not provided by the mining company.
b) Collect available monitoring data in order to check and calibrate the DInSAR measures. On the one hand, the mining company has supplied a topographic leveling survey while the Geological Institute of Catalonia (from now on IGC) has facilitated a data set of ground GPS located above an exploited sector. On the other hand a topographic leveling survey of the urban area of Súria has been collected from the Cartographic Institute of Catalonia (from now on ICC).
c) Process of historical SAR images (from 1995 to 2007) using DInSAR technique. Because the used radar systems (ERS-2 and ENVISAT) were not operational for 2 years (from 2000 to 2002) there is a gap of SAR images for this period. Different considerations have been taken into account in deciding whether the images should be processed in a single set or separately in two sets. The subsidence induced by mining activities is usually modeled with non-linear functions (i.e. Alejano et al., 1999; Sheorey et al., 2000). In Súria, the topographic measurements obtained between 1954 and 1999 also show a long-term non-linear trend. In order to test and highlight of the non-linearity on the processing results we have compared the results for the two sets of images (from 1995 to 2000 and 2003 to 2007). The low quality of the interferometric data in non-urban areas requires the processing of the SAR images with a linear model. However, it is expected that the non-linear behavior of the ground displacements will reveal from the average velocities of the two sets.
d) The previous step allowed the generation of ground displacement rate maps. In order to generate the final results only vertical movements have been assumed in the area. This means that the phase measurement along LOS is supposed to be a projection of a vertical displacement field. This hypothesis is assumed in this work because both the geology of the studied zone (existence of a shallow salt dome and soluble materials) and the presence of underground mining activity suggest that ground deformation must have a predominant vertical component. The GPS measurements are consistent with this assumption.
e) Calibrating DInSAR results, with available monitoring data sets and subsequent reprocessing by considering the displacement rates of known points (seeds). Finally, the discussion and interpretation of the results have been done by consideration and the integrated analysis of multidisciplinary data.