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Earth observation advancements in a changing world

Edited by Chirici G. and Gianinetto M.

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Contents

EXPLOITATION OF GNSS FOR CALIBRATING SPACE-BORNE SAR FOR THE STUDY OF LANDSUBSIDENCE

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KEY WORDS: GNSS; SAR; Persistent Scatterers Interferometry; deformation map; Calibration, InSAR

ABSTRACT:

Nowadays advanced multi-temporal interferometric approaches such as PSI (Persistent Scatterers Interferometry) derived from the processing of space-borne SAR (Synthetic Aperture Radar) images represent an effective tool to detect terrain movements and provide millimetric ground measurements over large scenes thanks to their wide-area coverage, non-invasiveness, and high accuracy. Nevertheless, PSI data lack of absolute reference both in time and space, as they are relative estimates measured along the sensors-to-target line of sight and referred to a chosen stable motionless reference point. In this work, a methodology to fix relative InSAR results into conventional geodetic reference systems through calibration with GNSS (Global Navigation Satellite System) data acquired from permanent stations is proposed. In particular, mean yearly velocities of PSI radar benchmarks are corrected with GNSS values by means of procedures commonly used in geodesy for combining crustal and local deformation studies. The operative method is tested in the area of Ravenna and Ferrara cities on the north-western Adriatic coast within the eastern alluvial plain of Po River, extensively affected by subsidence with strong spatial and temporal variations. The outcomes reveal the usefulness of the presented methodology for generating unique ground deformation maps over wide are using geodesy for aligning PSI data before SAR maps stacking.

1. INTRODUCTION

Land subsidence is commonly defined as sudden sinking or gentle and gradual lowering or sudden sinking of the ground surface (Galloway & Burbey, 2011). Natural or anthropogenic processes, as well as their combination, and endogenic or exogenic phenomena, which refer to geological-related motions and the removal of underground materials, respectively, (Prokopovich, 1979) can be caused subsidence, sometimes with consequences. Subsidence phenomena mainly affect urban and greenhouses or nurseries areas (Tomas et al., 2014; Del Soldato et al., 2018) because of water overexploitation, with serious consequences such as damage to linear infrastructures, e.g., bridges, roads or railways, and building stability issues due to differential settlement (Del Soldato et al., 2016; Tomas et al., 2012). The monitoring of these phenomena plays a key role in the management of natural hazards for mitigating and minimizing the disaster losses and consequences. For land subsidence monitoring, classical techniques such as levelling networks (Teatini et al., 2005) or GNSS/GPS (Global Positioning System) techniques (Béjar-Pizarro et al. 2016) are traditionally used. In the last several decades, the Earth Observation (EO) technique, especially SAR (Synthetic Aperture Radar) remote sensing methods have rapidly grown. These techniques can profitably support risk reduction strategies by taking advantage of their wide area coverage associated with a high cost/benefit ratio. The PSI (Persistent Scatterers Interferometry) techniques (e.g. Ferretti et al., 2001and 2011), has been successfully adopted for a wide range of applications in disaster management, and it has extensively proven to be a valuable tool to detect ground deformations due to landslides (Solari et al., 2018; Del Soldato et al., 2018a; Ciampalini et al., 2016) or subsidence (Bonì et al., 2017; Da Lio & Tosi, 2018a).

PSI is commonly applied to satellite SAR images based on the recognizing on ground points characterized by long-term stability of the electromagnetic backscattered signal and high reflectivity Persistent Scatterers (PS) (Ferretti et al., 2001, Crosetto et al. 2016). By using the interferometric technique on the signal phase reflected by PS, the velocities of these points can be studied thought the time-series analysis of their displacements. Such as all the interferometric techniques, the velocity measured are relative to some points of the SAR image that is supposed to be stable.The lack of an absolute reference frame can be supplied by GNSS (Global Navigation Satellite System) measurements (Farolfi et al., 2018, 2019) as this is a geodetic network that provides rates and precise geographic location. In literature, many works exploited both SAR and GNSS data (i.e. Bovenga et al., 2012; Casu et al., 2006; Del Soldato et al., 2018b) for local terrain movements. In this work, we exploit SAR data acquired by historical ENVISAT data supported and calibrated by means of GNSS data throughout a methodological procedure for combining the two source datasets. We apply this approach to Ravenna and Ferrara cities located in the Po Plain in Central Italy, as this area is historically affected by subsidence due to natural and anthropogenic causes (Carminati and Martinelli, 2002). The merging of SAR products with GNSS reveals to be fundamental especially in the case of land subsidence where the velocity rates play an important role to understand and quantify the phenomena.

1. AREA OF STUDY

The paper focuses on the eastern portion of the Po River plain, a narrow area of Italian peninsula between Northern Apennines, Southern Alps and along the northern Adriatic coast where Ravenna and Ferrara cities are located. The Po River sedimentary basin is filled by Alpine and Apennine sediments. From the structural point of view, the north-verging Apennine fold-and-

* Corrisponding author

thrust belt system is overlapped by Plio–Quaternary sediments (Carminati, 2002). In this area, vertical deformation is known and the subsidence is driven by the combination of anthropogenic, geological and tectonic processes. The main factor responsible for land subsidence in the Po plain is the human extraction of deep no-rechargeable ground waters (Gambolati et al., 1999). The industrial growth, the modern extensive agricultural and zootechnical techniques and the population increase that took place in the second half of the 20th century in Italy induced a dramatic intensification in groundwater demand. Some authors state that these factors produced a near quadrupling of groundwater withdrawal compared with the first half of the century (Gonella et al., 1998). In addition to water pumping, gas exploitation is also greatly performed in this area during the last century (Teatini et al. 2005, Tosi et al. 2010). Regarding the components of natural subsidence in the Po Plain, the ground lowering is also sediment loading and compaction (Sclater and Christie, 1980) as well as post-glacial rebound and tectonic loading. Geologically, Holocene sediments include sandy and clayey silty level often rich in organic matter and they can suffer from compaction problems by loads and in case of water over-pumping (Rizzetto et al., 2003). Moreover, the effects of the last deglaciation, still impacting the Po Plain (Mitrovica and Davis, 1995), and active tectonics linked to a buried anticline under the Ferrara area are considered additional factors to the long-term geological subsidence (Carminati et al. 2003).

2. DATASETS

2.1 GNSS Dataset

The velocity field for the eastern Po Plain area was derived by the combination of two independent solutions (Palano 2014, Farolfi et al., 2016, 2017) consists of a subset of 35 sites determined for a period that runs from 2008 to 2014. The two velocity solutions were combined involving a rigid Helmert transformation that minimizes the differences of GNSS site velocities that the two datasets have in common, by using a least squares approach. The resulting horizontal velocity field were referred into the European Terrestrial Reference Frame ETRF2008.

2.2 PS dataset

The velocity field determined with SAR satellites were calculated by involving with using PSInSAR technique (Ferretti et al., 2001) by using all available ENVISAT data from the Italian peninsula resulting from the program "Not-Ordinary Plan of Remote Sensing" developed by the Italian Ministry of the Environment available from the Italian Geoportale Nazionale (www.pcn.minambiente.it). The European ENVISAT mission covered a long-term continuous period from 2003 to 2010 with a temporal solution or satellite's repeating cycle of 35 days.

3. METHODOLOGY

The PS displacements and velocities calculated with GNSS and SAR show differences due to the different LOS direction in which they are recorded. Since the deformation PS velocity is acquired a LOS of the satellites with determined parameters, it must be re-projected and decomposed in vertical and horizontal components to be compared with the velocity components derived by GNSS. For this reason, the LOS displacements and velocities of the ENVISAT PS data was decomposed into horizontal and normal components with respect to the international ellipsoid. After this procedure, the InSAR displacements and velocities can be compared to GNSS dataset.

The velocity v_{LOS} measured by the SAR satellite for a ground velocity v with components $v = [v_N, v_E, v_V]$ is determined by the direction cosine or unit vector $S = [S_N, S_E, S_V]$ in the direction from the ground to the satellite along the LOS direction:

$$v_{LOS} = V_N S_{N,LOS} + V_E S_{E,LOS} + V_V S_{V,LOS} \,. \qquad (1)$$

The unit vector S for ascending (S_A) and descending (S_D) orbits are derived by the inclination of the orbits with respect to the equator $\delta = 98.5°$, and the mean off-nadir θ:

$$\begin{pmatrix} S_A \\ S_D \end{pmatrix} = \begin{pmatrix} -\sin\theta_A \cos\delta & -\sin\theta_A \sin\delta & \cos\theta_A \\ \sin\theta_D \cos\delta & \sin\theta_D \sin\delta & \cos\theta_D \end{pmatrix} \qquad (2)$$

For ENVISAT mission the LOS angles for both ascending and descending geometry is given the same value of θ =23.3° Eq. 1 can be written for the ascending (V_A) and descending (V_D) velocities with the direction cosine:

$$\begin{pmatrix} V_A \\ V_D \end{pmatrix} = \begin{pmatrix} S_{N,A} & S_{E,A} & S_{V,A} \\ S_{N,D} & S_{E,D} & S_{V,D} \end{pmatrix} \begin{pmatrix} V_N \\ V_E \\ V_V \end{pmatrix} \qquad (3)$$

Eq. 3 is a system of two equations with three variables and is thus not solvable. Considering that the displacements along the north–south direction are almost parallel to the ENVISAT satellite orbit and for this reason cannot be detected along the LOS for both the ascending and descending orbits, then eq. 3 can be approximated as:

$$\begin{pmatrix} V_A \\ V_D \end{pmatrix} \cong \begin{pmatrix} S_{E,A} & S_{V,A} \\ S_{E,D} & S_{V,D} \end{pmatrix} \begin{pmatrix} V_E \\ V_V \end{pmatrix} \qquad (4)$$

and be solved. The two components of velocity v can be derived as follows:

$$V_E \cong \frac{V_D - V_A}{2.|S_E|}, \qquad V_V \cong \frac{V_D + V_A}{2.|S_V|} \qquad (6)$$

where the modules of unit vectors of S for ENVISAT are $S = [S_N, S_E, S_V]$= [0.05,0.38,0.92] . The availability of GNSS site velocity in the Area of Interest (AoI) permits to align the PS velocities to the ETRS89 reference frame. In fact, PS velocities are calculated respect to one or more reference points chosen during the processing phase of the SAR images.

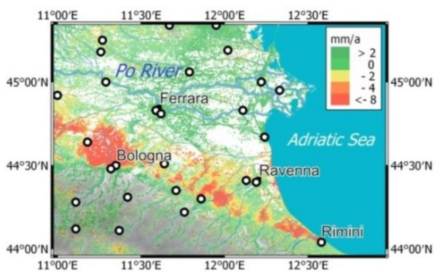
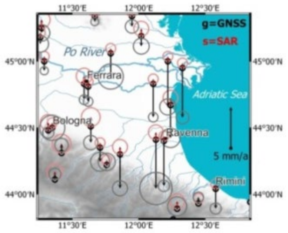


Figure 1 - Map of PS vertical velocity from InSAR images. Green represents represents stable points, yellow represents points with mild downward movement around -2mm/a, and red represents points of downward movement lower than -8.0 mm/a. Black circles represent the position of GNSS sites.

The lack of an absolute reference frame of PS dataset can be supplied by the comparison of ground point velocities determined using both techniques (Fig.2). The differences between the two velocity datasets were interpolated with an exponential inverse distance weighting to determine the map of correction for PS velocities (Fig.3).



*F*igure 2 - Comparison of vertical velocities and their circles of uncertainties determinate with GNSS (black arrows) and PSInSAR (red arrows) for each GNSS site (black circles).

4. RESULTS

The GNSS stations displaced in the Po River Delta and in the city of Ravenna record important values lower than -5 mm/a of subsidence. The limit of this lowering ~ -2 mm/a is close to Ferrara. The GNSS stations present in Bologna are stable since they are located out from the wide subsidence area. Rimini show mild values of subsidence ~ - 2mm/y. The comparison between the PS and GNSS vertical velocity shows different rates (Fig. 2) that reach -5 mm/a in the area of Po River Delta and Ravenna, -2 mm/a around Ferrara and Rimini.

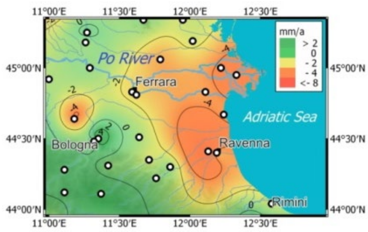


Figure 3 - Calibration map for PS vertical velocity to apply to PS to obtain "absolute" and corrected vertical velocity rates.

The area of the Po River Delta shows subsidence rate with values ~ - 5 mm/y (Figure 4). The coastal area from the north of Ravenna town to the city of Rimini shows a bend of subsidence with values variable from -8 mm/a to -4 mm/a confined by stable sector. In the western area of Bologna, is located a big bowl with subsidence rates lower than - 10 mm/a. The area of Ferrara town and its surrounding show values of velocity of displacement into the stable span (~2 mm/a).

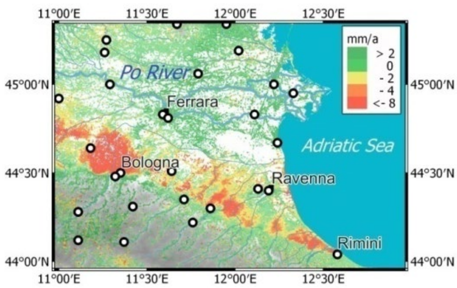


Figure 4 - Vertical velocities of PSI points after the calibration performed by GNSS (absolute velocity). Green represents points with a stable or light uplift, yellow represent points with a mild downward movement, orange represent points with downward movement less than -4 mm/a and red represents points of downward movement less than -8.0 mm/a.

5. CONCLUSIONS

The combination of the GNSS with the PS data deeply improved the investigation of the displacement of the ground. In this way, all the problem of the choice of a stable points for PS processing based on geological and signal features, can be an overpass. The determination of correct vertical velocity rates play an important role in subsiding areas for avoiding damage to structures and infrastructure (e.g. Bianchini et al., 2015; Del Soldato et al., 2016). Moreover, the combination of GNSS and SAR produces new maps of surface movements where velocities at both a detailed and a wider scale are geodetically correct.

CONTRIBUTIONS

Intellectual content to conception and project coordination are contributions of G. Farolfi and N. Casagli. G. Farolfi developed mathematical models and performed the geodetic analysis. S. Bianchini and M. Del Soldato provide SAR analysis, geological settings, geodynamic analysis and the writing of the manuscript. Drafting the article came from the contribution of all the authors.
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