COSMO-SKYMED VS RADARSAT-2 FOR MONITORING NATURAL AND ANTHROPOGENIC COMPONENTS OF THE LAND MOVEMENTS IN VENICE

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ABSTRACT

We present the result of a test aimed at evaluating the capability of RADARSAT-2 and COSMO-SkyMed to map the natural subsidence and ground movements induced by anthropogenic activities in the historical center of Venice. Firstly, ground movements have been retrieved at quite long- and short-term by the Persistent Scattered Interferometry (PSI) on 2008-2015 RADARSAT-2 and 2013-2015 COSMO-SkyMed image stacks, respectively. Secondly, PSI has been calibrated at regional scale using the records of permanent GPS stations. Thirdly, considering that over the last two decades "in the historical center of Venice" natural land movements are primarily ascribed to long-term processes, and those induced by human activities act at short-term, we have properly resampled 83-month RADARSAT-2 C-band and 27-month COSMO-SkyMed X-band interferometric products by a common grid and processed the outcome to estimate the two components of the displacements. Results show that the average natural subsidence is generally in the range of 0.9 – 1.1 mm/yr and the anthropogenic ground movements are up to 2 mm/yr.

1. INTRODUCTION

The subsidence of Venice, one of the most beautiful and famous cities in the world, is well known not due to the magnitude of the ground movement but because it seriously compromised the heritage and the safety of the city in relation of its small elevation above the sea. For this reason, the frequent monitoring of land subsidence with millimetric accuracy is crucial for safeguarding the historical center of Venice. The new generation of TerraSAR-X and COSMO-SkyMed satellites (X-band), as their short revisiting time and high resolution, allow mapping the movements of single structures with a detail never obtained in the past. In particular, the use of X-band sensors in Venice has provided maps highlighting a large variability of the displacement rates which are likely not related to natural subsidence [1].
In-situ and satellites measures provide the total ground movements including natural and man-induced components of the displacements. Therefore, distinguishing between natural land subsidence and ground movements induced by anthropogenic activities is still a challenge.
A proper processing of the calibrated velocities obtained by Persistent Scattered Interferometry (PSI) on C- and X-band images (i.e. ENVISAT ASAR and TerraSAR-X) demonstrated to the possibility of separating the two components of the ground movements in Venice [2].
Our research is aimed at testing the capability of RADARSAT-2 and COSMO-SkyMed to estimate the natural land subsidence and the movements induced by anthropogenic activities in Venice using long- and short-term image datasets. We use RADARSAT-2 long-term C-band data to quantify the natural component of the land subsidence and COSMO-SkyMed short-term X-band data to highlight anthropogenic displacements.

2. METHODS

RADARSAT-2 images, Fine mode, 8 m nominal resolution, acquired from 2008 to 2015 and COSMO-SkyMed images, stripmap mode, 3 m resolution, from 2013 to 2015 have been processed by Interferometric Point Target Analysis (IPTA) method using GAMMA software [3, 4]. The two datasets consist of 19 RADARSAT-2 and 37 COSMO-SkyMed images acquired from 2008.06.18 to 2015.05.13 (83 months) and from 2013.02.07 to 2015.05.04 (27 months), respectively.
The interferometric solutions have been calibrated using the ground velocities recorded by permanent GPS stations [5] to mitigate the so-called flattening problem, i.e. the slight phase tilt resulting by the inaccuracy in estimation of the orbital baseline due to the not perfect knowledge of the satellite positions [2, 6]. The calibrated velocities have been validated by their comparison with those retrieved by ENVISAT-ASAR and TerraSAR-X, available from other research projects [2, 7]. Considering the different incidence angles, Line of Sight (LOS) velocities have been projected on the vertical direction (UP) in order to provide a reliable comparison among the displacements obtained by the different platforms. The uniform movement of the study area in the E-W direction supports this solution [8, 9].

3. RESULTS

3.1. Cumulative subsidence in Venice coastland and historical center

The IPTA calibrated solutions at regional scale are shown in Fig. 1.

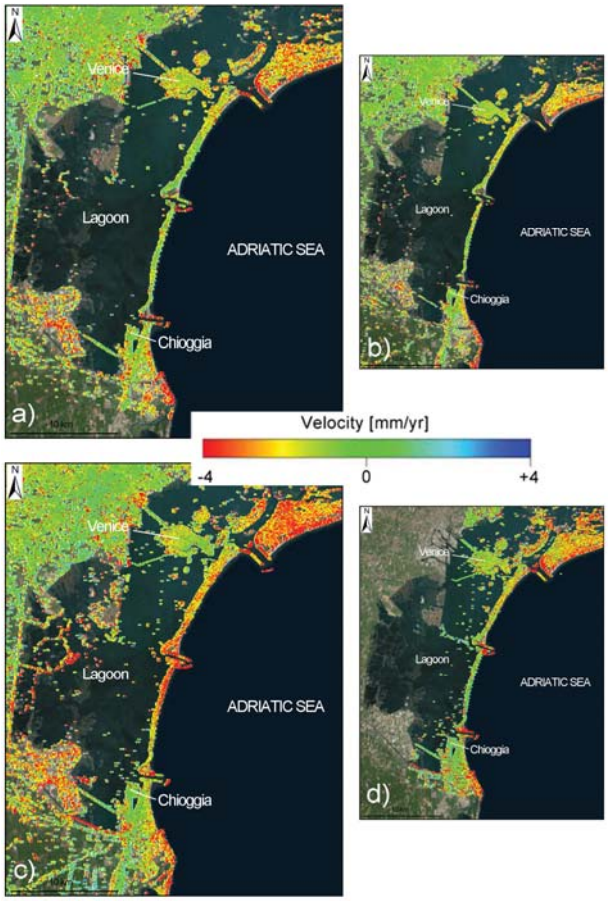

Figure 1. Calibrated average velocities in the Venice coastland: a) RADARSAT-2 2008-2015; b)ENVISAT-ASAR 2003-2010; c) COSMO-SkyMed 2013-2015; TerraSAR-X 2008-2011.

Data validation at regional scale points out similar rates in the RADARSAT-2 and ENVISAT-ASAR datasets. Conversely, significant differences between COSMO-SkyMed and TerraSAR-X are shown in some portions of the littoral strips. This is due to the presence of atmospheric noises in a few images, which is amplified by the limited number of acquisitions made available by the RADARSAT-2 and COSMO-SkyMed SOAR-ASI initiative.

Focusing on the more localized historical center of Venice, data validation points out the high accuracy of the calibrated IPTA products (Fig. 2). The statistical analysis of the displacement distributions in the Venice historical center points out that the average velocity rates are almost equal in RADARSAT-2 and COSMO-SkyMed to those of the previous studies (Fig. 3). The standard deviation is 0.9 mm/yr both for RADARSAT-2 and COSMO-SkyMed. In the RADARSAT-2 solution, a number of measurable points larger than with ENVISAT ASAR is available because of the higher range resolution and the more recent advanced processing chain.

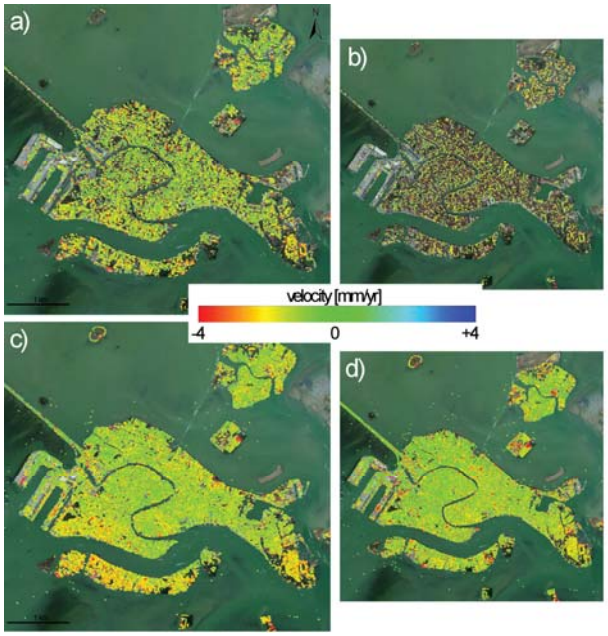

Figure 2. Calibrated average velocities in the Venice historical center: a) RADARSAT-2 2008-2015; b)ENVISAT-ASAR 2003-2010; c) COSMO-SkyMed 2013-2015; TerraSAR-X 2008-2011.

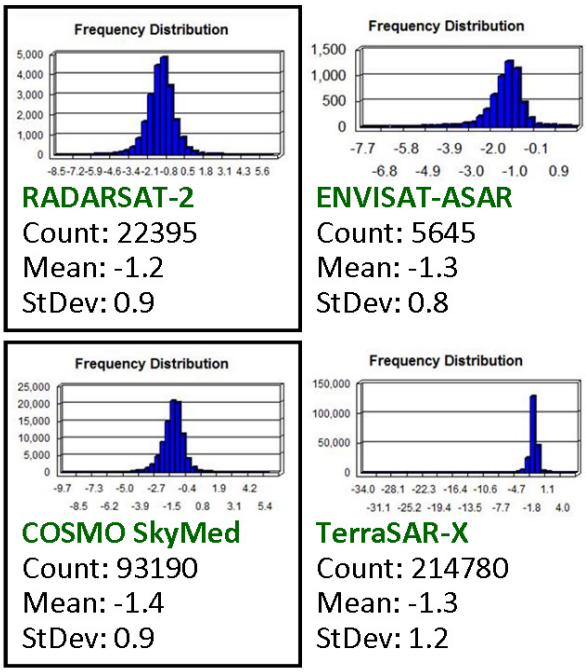

Figure 3. Frequency distributions of the ground movement in the Venice historical center.

3.2. Natural subsidence *versus* induced ground movements in Venice historical center

The natural subsidence varies over geological periods, while it can be assumed constant at centennial - decadal temporal scales in areas with negligible tectonics and the absence of seismicity. On the other hand, nowadays, induced displacements in the historical center of Venice act in shorter period and generally at local scale. Therefore, the long-term map obtained by processing the interferometric outcome of RADARSAT-2 can be interpreted as a reasonable picture of the present natural subsidence. In fact, PSI requires a coherent target response in the whole image dataset, i.e. a radar reflector must rest on the soil over the entire monitoring period. In addition, the induced short-term movements are "smoothed" in the map of the average long-term C-band dataset.

The short 2013-2015 analysis based on high spatial resolution and revisiting time X-band data detects more effectively the total ground movements, including the natural and anthropogenic activities. As C- and X-band analyses show similar average displacement rates (Fig. 2 and Fig. 3), i.e. the average natural subsidence, it is reasonable to assume that the difference between RADARSAT-2 and COSMO-SkyMed datasets is likely representative of the effects caused by anthropogenic activities. A proper processing of the two C- and X-band measurements supports this hypothesis.

The two datasets are interpolated by the Kriging method on the same regular grid covering the whole city (Fig. 4).

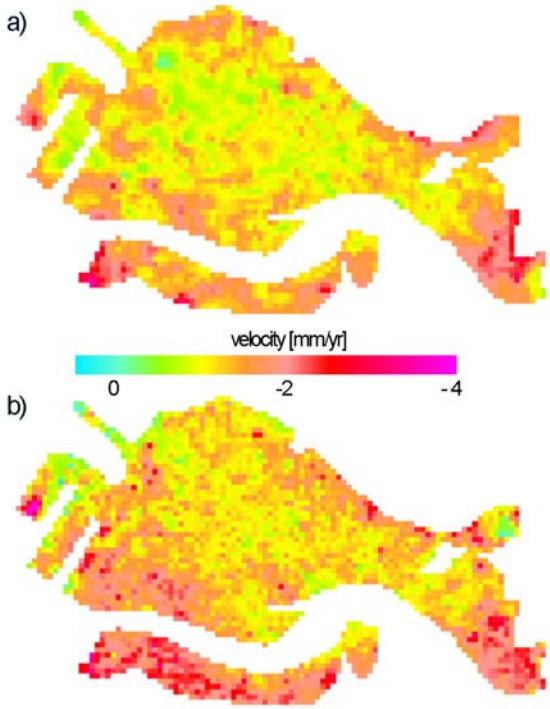

Figure 4. Interpolated displacements obtained from a) RADARSAT-2 and b) COSMO-SkyMed.

The grid spacing, fixed at 50 m, has been appropriately tuned to simultaneously:

- filter out the outlier values provided by the C-band analysis; these outliers are referred to a few (~5%) unstable targets, generally due to human effects, scattered within the majority of the solution representing the natural processes
- keep the heterogeneity of the displacements detected by the X-band investigation.

Comparing the two maps showed in Fig. 4, it must be noticed the quite uniformity of the long-term subsidence rates (0.9 - 1.1 mm/yr) obtained by RADARSAT-2 data (Fig. 4a) and the large variability of the X-band short-term movements superposed to a background velocity similar to that given by the C-band data (Fig. 4b).

The quantification of man-induced displacements obtained by removing the C-band interpolated map from the X-band interpolated solution (Fig. 5) shows that most of the city is subsiding only due to natural components (transparent color scale). However, 20-30% of Venice has experienced in 2013-2015 some movements due to anthropogenic causes.

Figure 5. Quantification of man-induced ground movements obtained by removing the C-band interpolated map from the X-band interpolated solution.

4. DISCUSSION

The natural subsidence is strictly related to the reference period (i.e. geological- and modern- term) and its quantification in Venice was obtained through various methodologies and not uniquely quantified. However, for the safeguarding of Venice, it is much more crucial to evaluate the natural displacements over the last few decades, i.e. the present natural land subsidence, than that averaged over geological periods.

Although subsidence due to groundwater pumping ceased in the 1970s [e.g., 10, 11], others anthropogenic activities such as restoration works for the conservation of the historical palaces and the embankment walls, and the waves induced by the boat and ship traffic, increased in the last decades, potentially inducing "local ground movements".

PSI provides the cumulative land displacements (natural plus anthropogenic) on the investigated area. Using

decade-long observations from the C-band sensors and short-time (e.g., annual) displacement records by high resolution X-band satellites, the land movement components primarily ascribed to natural processes and those induced by human activities can be distinguished in Venice [2].

The proper tuning of the interferometric RADARSAT-2 product (C-band) allows to estimate the average natural subsidence in 0.9 – 1.1 mm/yr, a range comparable with those provided by previous studies. Notice the occurrence of a certain variability (Fig. 4a) correlated with both the evolution of the urban growth over the centuries and the subsoil architectures (Fig. 6). In fact, the subsoil of the younger parts of the city is less consolidated than those corresponding to the primeval human settlement [12]. Moreover, different consolidation rates characterize the upper Pleistocene and Holocene sediments consisting of sands, silts, and clays, and peat layers with buried features such as channel-levee systems [13, 14].

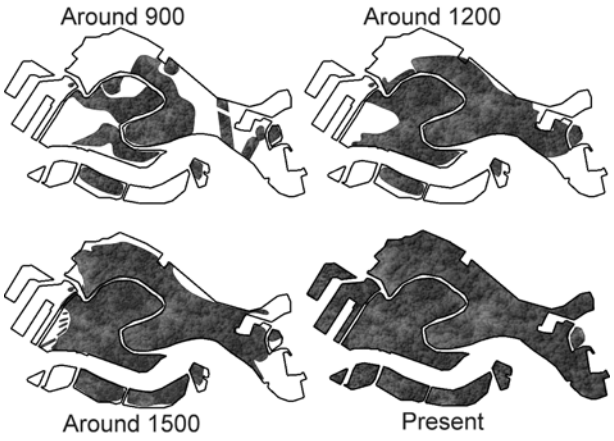

Figure 6. Sketch of the growth in area of Venice from 900 A.D. to present

The ground movements due to human activities amount to up to 2 mm/yr. They develop at local scale and their distribution well correspond with the sites interested by activities linked to the restoration of buildings (Fig. 7), e.g., new loads, consolidations, jet grouting, well-points. We can observe that the magnitude of the induced ground movements due to anthropogenic activities obtained in this study is lower of about 30-40% than that published by [2]. The actual smaller rates can be explained considering that the 27-month period of COSMO-SkyMed acquisitions (2013-2015) is likely too long for a proper detection of the average short-term movements, and the number of available images is not sufficient to remove the atmospheric noises and obtain sub-millimetric accuracy within the two analysed period. However, a punctual comparison between the magnitude and distribution of the induced ground movements is not correct because these two studies refer to different periods of analysis, i.e. restoration works involved different sectors of the city over the years.

Figure 7. Aerial photographs of buildings before and after restoration works: a) Hospital area; b) Arsenale area; c) Hilton Molino Stucky area; d) Tronchetto area (touristic harbour terminal). The position of areas (a-d) is in Figure 5.

5. CONCLUSIONS

The combined use of long-term C-band and short-term X-band SAR investigations offers a unique opportunity to discriminate between natural and anthropogenic land subsidence in Venice. However, the number of archive images made available from the COSMO-SkyMed/RADARSAT-2 Initiative has resulted to be not adequate for an accurate quantification of the induced and natural ground movements. Nevertheless, this test has provided interesting results with an acceptable uncertainty in distinguishing the two components of the land movements.

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