THE LAND SUBSIDENCE OF THE VENICE HISTORICAL CENTER: TWENTY YEARS OF MONITORING BY SAR-BASED INTERFEROMETRY

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The subsidence of Venice, one of the most beautiful and famous cities in the world, is well known not by reason of the magnitude of the ground movement, which amounts to less than 15 cm over the last century, but because it has seriously compromised the ground safety level of the city in relation of its small elevation above the sea.

The RSLR, i.e. subsidence plus eustacy, calculated for the last century is about 25 cm. This produced a significant increase in frequency of the “acqua alta” events (**Fig. 1**).

Fig. 1 – San Marco Square during a high tide (“acqua alta”) event

MATERIAL AND METHODS

Over the last two decades, satellites instrumented with SAR sensors provided excellent data for detecting land displacements by inteferometric processing. In particular, the accuracy achieved by Persistent Scatterer Interferometry (PSI) and the impressive number of detected measurement points have progressively reduced the use of in situ traditional measurements, i.e. leveling survey, for monitoring land displacements of Venice. In fact, the intensive urban development makes the historical center an optimal site for PSI. On the other hand, the correct interpretation of the PSI outcomes, which provide the relative movement of single churches, palaces, bridges with millimetric precision and metric spatial resolution, require a deep knowledge of the city and its subsoil due to the peculiarity of this urban area developed over the centuries within the sea. We investigate the movements of Venice by Interferometric Point Target Analysis (IPTA) over the last 20 years using SAR acquisitions of the ERS-1/2, ENVISAT, TerraSAR-X, and Cosmo-SkyMed satellites. The density of detected scatterers is one order of magnitude larger with the newest very high resolution X-band sensors from TerraSAR-X and Cosmo-SkyMed, but by reason of the larger observation period the accuracy of the mean displacement rate of the C-band ERS and ENVISAT is higher (**Tab. 1**)

Satellite	Period	# Images	# PS	Venice average displacement (mm/yr)	Standard Deviation (mm/yr)
ERS-1/2	1992-2002	73	3’532	-0.8	0.7
ENVISAT	2003-2010	72	5’960	-0.5	0.8
TerraSAR-X	2008	30	167’310	-1.0	1.6
Cosmo-SkyMed	2009-2011	31	121’407	-1.1	1.0

Tab. 1 – Main characteristics of the processed satellite images and the results from IPTA

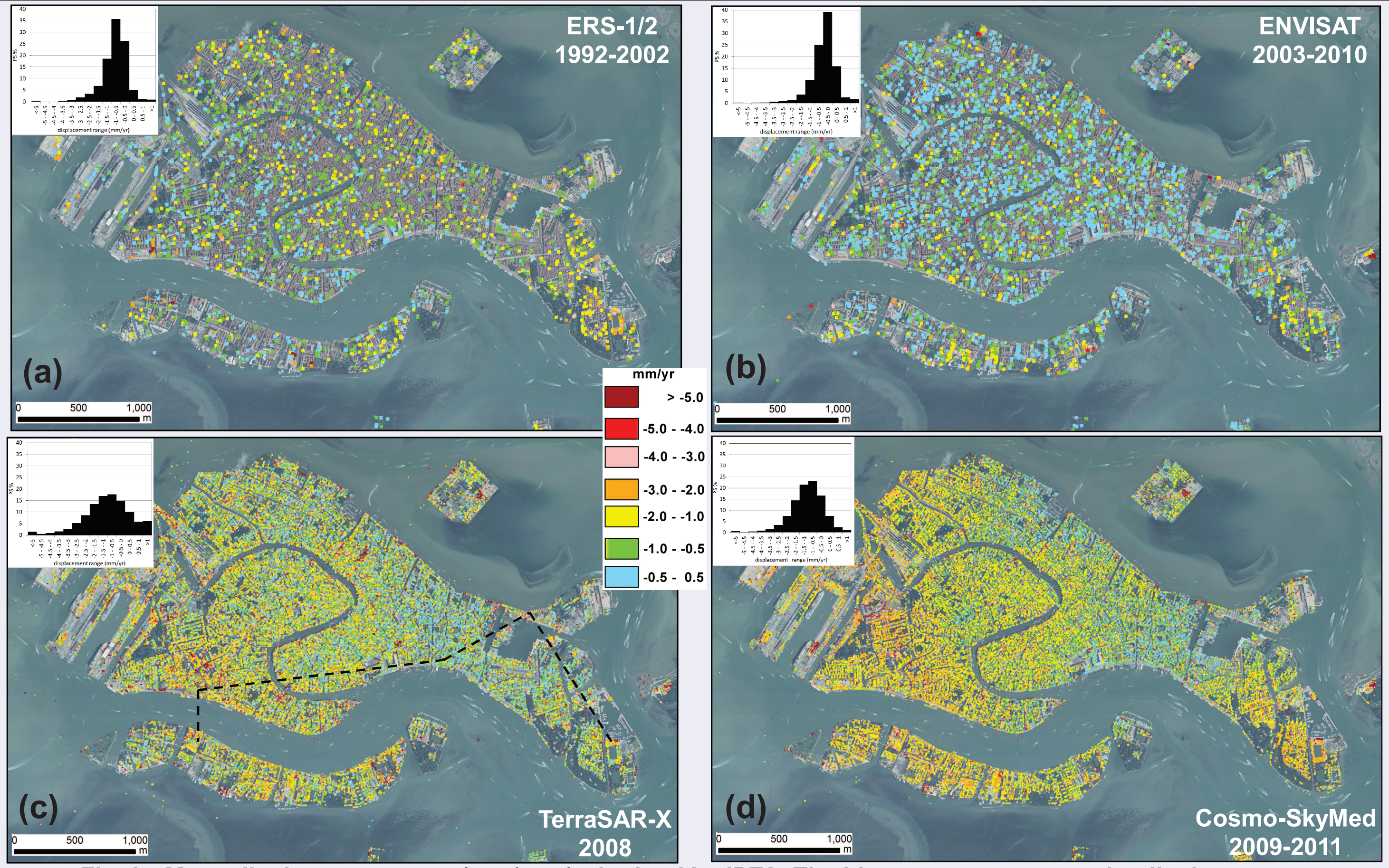


Fig. 3 - Mean displacement rates (mm/year) obtained by IPTA. The histograms represent the displacement frequency distribution computed for the whole city.

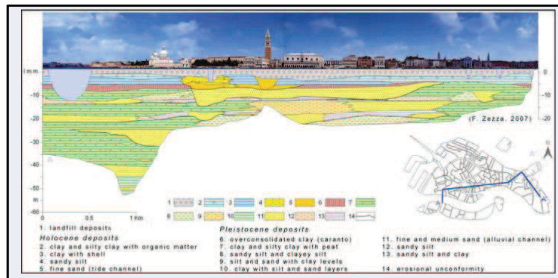


Fig. 4 – Stratigraphic section of the Late Quaternary subsoil of Venice along the trace shown in Fig. 3c (after Zezza, 2010)

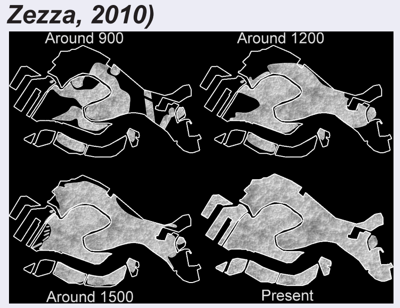


Fig. 5 – Sketch of the growth in area of Venice from 900 AD to present (after Tosi et al., 2002)

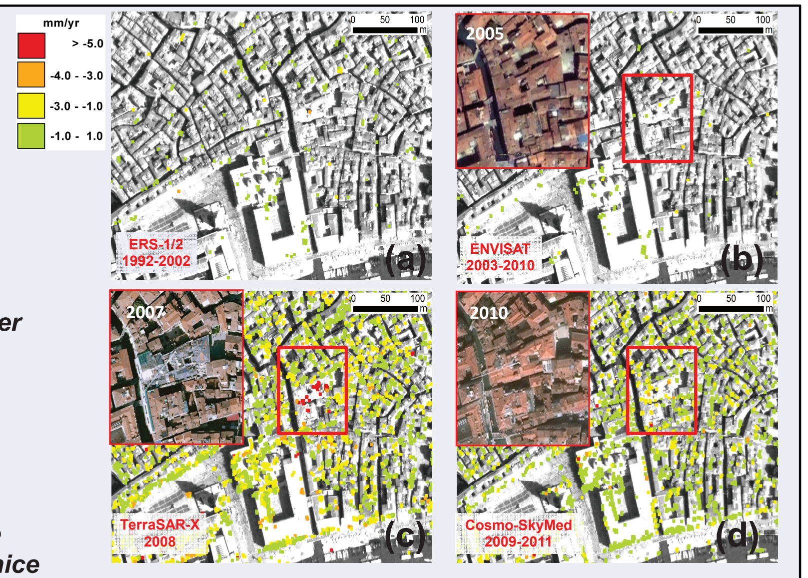
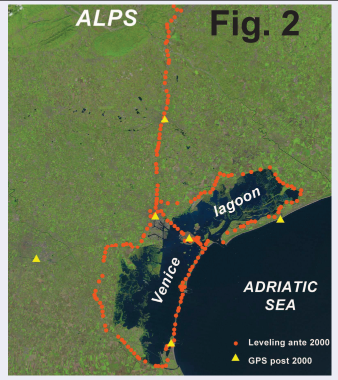


Fig. 6 – Example of temporary high sinking rate due to restoration work of single palaces



IPTA CALIBRATION/VALIDATION

IPTA results have been calibrated using leveling and permanent GPS stations to correct 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 (**Fig. 2**).

Fig. 2 – Map of the leveling benchmarks and permanent GPS stations used for IPTA CAL/VAL

RESULTS

The comparison between the measurements covering the period from 1992 to 2011 confirms the substantial stability of the city in its whole, with a subsidence rate averaging 1 mm/yr (**Figs. 3a-d**). However, the PSI measurements also provide evidence of local zones and single structures that are subsiding at faster rates due to the heterogeneous nature of the of the upper Holocene lagoon subsoil, different load and foundation of the historical palaces, and restoration works along the canals. In particular, the occurrence of a buried sandy paleo-channel (perhaps the primeval Canal Grande) fits well with the more stable sectors. Conversely, the portions with both silty/clayey alluvial/tidal plain deposits are characterized by a higher settlement (**Fig.4**). Also the age of the landfill are well correlated with the subsidence rates. In fact, the city developed over ancient well-consolidated sandy islands during the first millennium, and the following expansions were done by reclaiming and filling parts of the lagoon and channels. Stable sectors generally correspond with the city extension before 1500 (**Fig. 5**). Finally, the highest sinking rates are detected in correspondence of restoration works, as shown in **Fig. 6**.

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