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Understanding land subsidence in salt marshes of the Venice Lagoon from SAR Interferometry and ground-based investigations

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ABSTRACT

The existence of salt marshes and tidal morphologies is strictly connected to their elevation with respect to the mean sea level. Quantifying land subsidence of these high-valued transitional environments is therefore crucial to investigate their long-term possible survival, also in view of the expected climate changes. However, monitoring with a certain accuracy their movements has been challenging until now due to the peculiar features of these morphological forms: they are difficult to access, made of largely unconsolidated deposits, without anthropogenic structures, relatively far from anthropogenic facilities, and become submerged by the sea water twice a day. For these reasons, they have never be linked to traditional levelling and GPS networks, and also standard Interferometric SAR applications returned very poor results in terms of spatial and temporal coverage. An advanced Persistent Scatterer Interferometry (PSI) technique on a 5-year long stack of X-bandwidth SAR acquisitions of the Venice Lagoon is here presented. The regularity of the acquisitions, the short satellite revisiting time (11 days), the high image resolution (~3 × 3 m), and the strategies used in the PSI application have allowed us to detect thousands of measurable persistent targets (PTs) in the Venice Lagoon salt marshes. The measured displacements range from small uplifts to subsidence rates of more than 20 mm/yr. The analyses of the observed displacements point out that land subsidence is much larger on man-made than natural salt marshes, with a significant negative correlation with the marsh age. In addition, land subsidence with the presence of halophytic vegetation species is generally smaller than on unvegetated marshes. Finally, at a few selected sites, the integration of the PSI outcome with local ground-based measurements, such as multi-depth benchmarks, feldspar marker horizons and surface elevation tables, has allowed quantifying the displacement variability versus depth and therefore developing a first conceptual model of the salt marsh consolidation and accretion processes.

1. Introduction

Salt marshes are parts of the tidal platform generally exposed to the atmosphere and submerged only during high tides or in particular meteo-climatic conditions, depending on morphological setting of the landforms and the hydrodynamic and physiographic features of the sea/lagoon basin. Generally, the lowest parts of the salt marshes, i.e. the inner portions toward the mudflats, pannes and pools, are flooded at every tide, while the highest sectors are submerged only during particularly high tides, storm surges, or wind-driven tidal inundations (e.g., Rizzetto and Tosi, 2011).

Salt marsh morphologies represent the result of the interactions between climate changes (e.g., sea-level rise and storm surge) and sedimentary processes (deposition and erosion, early and late post-depositional consolidation, geological subsidence), in which the presence of halophytic vegetation species and the related production of organic matter play a key role (e.g., Morris et al., 2002; Marani et al., 2007; Marani et al., 2010). Accelerated sea level rise and human activities occurred over historical time influenced the natural evolution of many lagoon, delta and estuary marshes, leading to mutations that are often irreversible (e.g., Blum and Roberts, 2009; Carrasco et al., 2016; Jankowski et al., 2017). Among the main anthropogenic factors, the margin erosion due to the waves generated by boat traffic and land subsidence due to exploitation of underground resources are those that more strongly jeopardize the survival of salt marshes.

Sea level rise and land subsidence (i.e. relative sea level rise, RSLR) act at different spatial and temporal scales. The former is essentially global in extent with a constant trend over quite long period and large

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areas. Especially in transitional coastal environments, the latter is usually highly variable in time and heterogeneous in space because of the superposition of regional and local–scale processes such as tectonics, natural sediment compaction, subsurface fluid withdrawals. The quantification of land subsidence in salt marshes has been always challenging because of the complexity, often impossibility, to use accurate ground-based methods (e.g., levelling, GPS) over these vulnerable environments with difficult access. More recently, the use of airborne sensors, such as LIDAR, has provided good results in term of ground elevation of tidal morphologies (e.g., Chassereau et al., 2011; Buffington et al., 2016; Fernandez-Nunez et al., 2017); however, applications for detecting ground displacements in the range of a few mm/year accuracy are not yet available. SAR-based Interferometry has been extensively adopted for retrieving ground velocities (e.g., Teatini et al., 2011; Crosetto et al., 2016). Nevertheless, its application on salt marshes rarely has led to satisfactory outcomes, especially when the displacement rates are in the order of a few mm/year because of the lacking of man-made structures and rock outcrops, which are required in order to provide high accuracy measurements.

For its peculiarity, the lagoon of Venice and this unique city are a well-known site affected by land subsidence and most of the satellites equipped with SAR sensors has been used to monitor the city and lagoon movements (e.g., Tosi et al., 2002; Teatini et al., 2005; Teatini et al., 2007; Tosi et al., 2010; Bock et al., 2012; Teatini et al., 2012a). However, a detailed evaluation of land displacements within this transitional zone is still far from being satisfactorily achieved. Most of the lagoon is occupied by water, partly by salt marshes, with urbanized islands (Venice historic center included) that represent a minor portion (Fig. 1). Consequently, not only the in-situ techniques (levelling, GPS) cannot be used, but also the potentiality of the common SAR-based interferometric processing chains can be exploited only partially because of i) the limited extent of exposed lands with respect to the whole lagoon and ii) the absence of “traditional” targets, i.e. anthropogenic structures or rock outcrops, suitable for reflecting radar signal in salt marshes (Strozzi et al., 2013).

In order to overcome this limitation at least in part, Strozzi et al. (2013) established a network of about 50 passive reflectors within the Venice Lagoon and applied Persistent Scatterer Interferometry (PSI) on ENVISAT ASAR and TerraSAR-X images. Although limited in the spatial coverage, the results provided a first clear quantification of the land subsidence in inner marshes revealing a certain variability in the displacement trends. More recently, Tosi et al. (2016), by taking advantage of the high spatial resolution and measurement accuracy provided by the X-band on single structures and the effectiveness in retrieving information in vegetated areas made available by the L-band, developed a combination of multi-band COSMO-SkyMed and ALOS-PALSAR SAR data on the Venice coastland. This application led to a significant improvement on the measurement of the ground movements in the lagoon environment and allows one also to detect some displacements in the salt marshes. Nevertheless, a thorough quantitative detection of the salt marshes displacements with high accuracy and coverage is still lacking because of the difficultly previously mentioned, and a comprehensive description of marshes landscape vertical dynamic is still proving elusive.

In this study we present a step forward in the characterization of land subsidence of salt marshes, with an application to the Venice Lagoon. We take advantage of the long-term temporally-regular stack of TerraSAR-X scenes acquired between 2008 and 2013, which has been

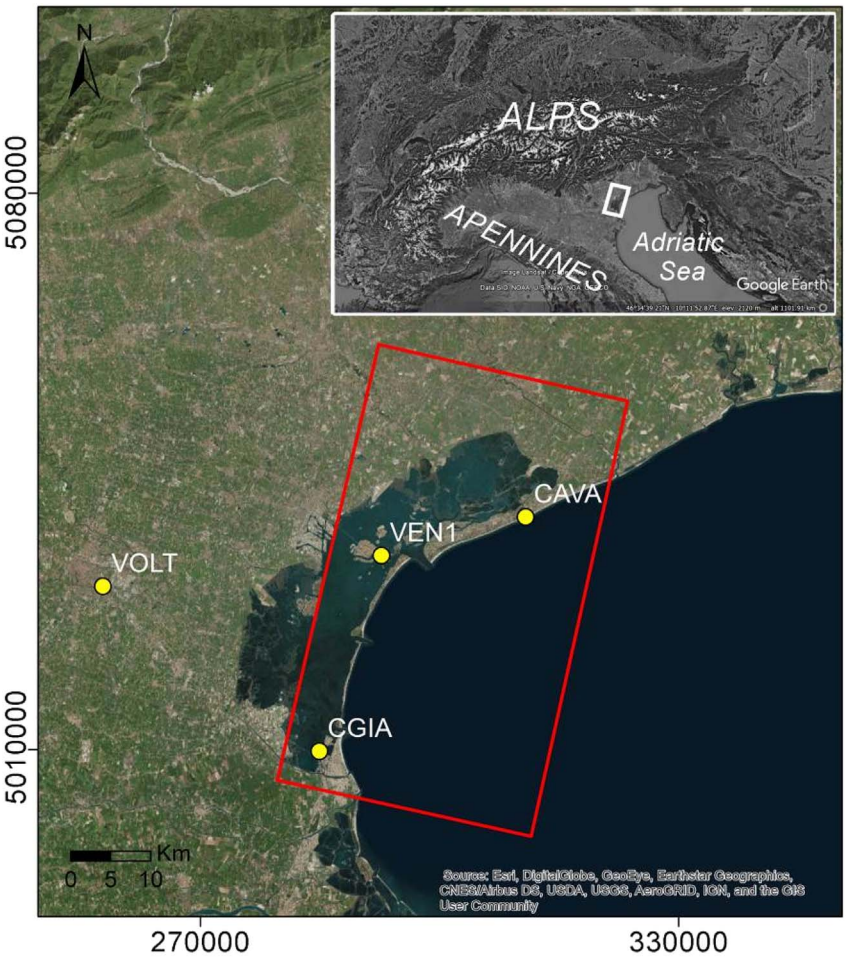

Fig. 1. Satellite image of the Venice Lagoon on the coast of the northern Adriatic Sea, Italy. The footprint of the TerraSAR-X frame (beam strip_006R) is represented by a red box. Yellow dots indicate the position of the CGPS stations used to calibrate the SAR solution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)