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SENSING THE LAND SUBSIDENCE IN THE VENICE LAGOON BY INTERFEROMETRIC POINT TARGET ANALYSIS

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Abstract

Land subsidence is a severe geologic hazard threading the lowlying coastal areas worldwide. Monitoring land subsidence has been significantly improved over the last few years by space borne earth observation techniques based on SAR (Synthetic Aperture Radar) Interferometry. Within the INLET Project, funded by Magistrato alle Acque di Venezia – Venice Water Authority (VWA) and Consorzio Venezia Nuova (CVN), we have used the Interferometric Point Target Analysis (IPTA) to characterize the ground displacements within the Venice Lagoon. IPTA measures the movement of backscattering objects (point targets, PT) at the ground surface which persistently reflect radar signal emitted by the SAR antenna. For this study 80 ERS-1/2 and 44 ENVISAT scenes recorded from 1992 to 2005 and from 2003 to 2007, respectively, have been processed by IPTA. High reliable land subsidence data have been detected for thousands of PT located on the lagoon margins, along the littorals, in major and small islands, and on single anthropogenic structures scattered within the lagoon. On the average, land subsidence ranges from less than 1 mm/year to 5 mm/year, with some PT that exhibit values also larger than 10 mm/year depending on both the local geologic conditions and anthropogenic activities. A network of few tens of artificial square trihedral corner reflectors (TCR) has been established before summer 2007 to monitor land subsidence in the inner lagoon areas where natural reflectors completely lack (e.g., on the salt marshes). The first interferometric results on the TCR appear very promising.

1 Introduction

With the end of the aquifer over-exploitation in the early 1970, the component of the Venice land subsidence due to groundwater pumping was arrested [Carbognin *et al*., 1977]. The relative land stability of the historical center was monitored by leveling surveys in 1993 [Carbognin *et al*., 1995], 2000 [Tosi *et al*., 2000], and lately verified with the integration of different techniques by Tosi *et al*. [2002]. In this work, a Synthetic Aperture Radar (SAR)-based technique was applied for the first time in the Venice area to measure the vertical land displacements of the historical center. The analysis was carried out by the Differential InSAR approach that is used in geophysical sciences since the late 1980s [Gabriel *et al*., 1989]. With DInSAR two (or more) SAR images taken from very close orbital positions at different times are combined (interferometric processing) to exploit the phase difference of the radar signals which is related only to the earth surface displacement occurring between the acquisition of the image pair, once the surface topography contribution is removed and the atmospheric disturbance mitigated (e.g., by average of a stack of interferograms). The interferogram phase noise ("decorrelation") restricts the DInSAR use. Major contributions to the phase noise are the temporal and the spatial decorrelation, the former due to the temporal change of the scatterers, as is the case of densely vegetated areas, and the latter to the slightly different viewing positions (interferometric baseline) related to the orbits.

More recently, an alternative approach known as IPTA or PSI (Persistent Scatterer Interferometry) has been developed taking advantage from the fact that, when the dimension of a reflecting target is smaller than the image resolution cell, the coherence is good irrespective of the image pair baseline [Usai and Klees, 1999; Ferretti *et al*., 2001; Werner *et al*., 2003]. Consequently, more observations are available, thus allowing for a reduction of temporal decorrelation errors. IPTA interferometric phases are thus interpreted only for a number of selected single pixels that are coherent over long-time intervals and cover the monitored area as a sparse "natural" benchmark net. By the IPTA technique, the interferometric SAR-based subsidence survey can be performed in rural areas as well using existing pointwise reflectors (e.g. buildings, bridges, etc.), with the requirement of a PT density larger than 1 km^{-2}.

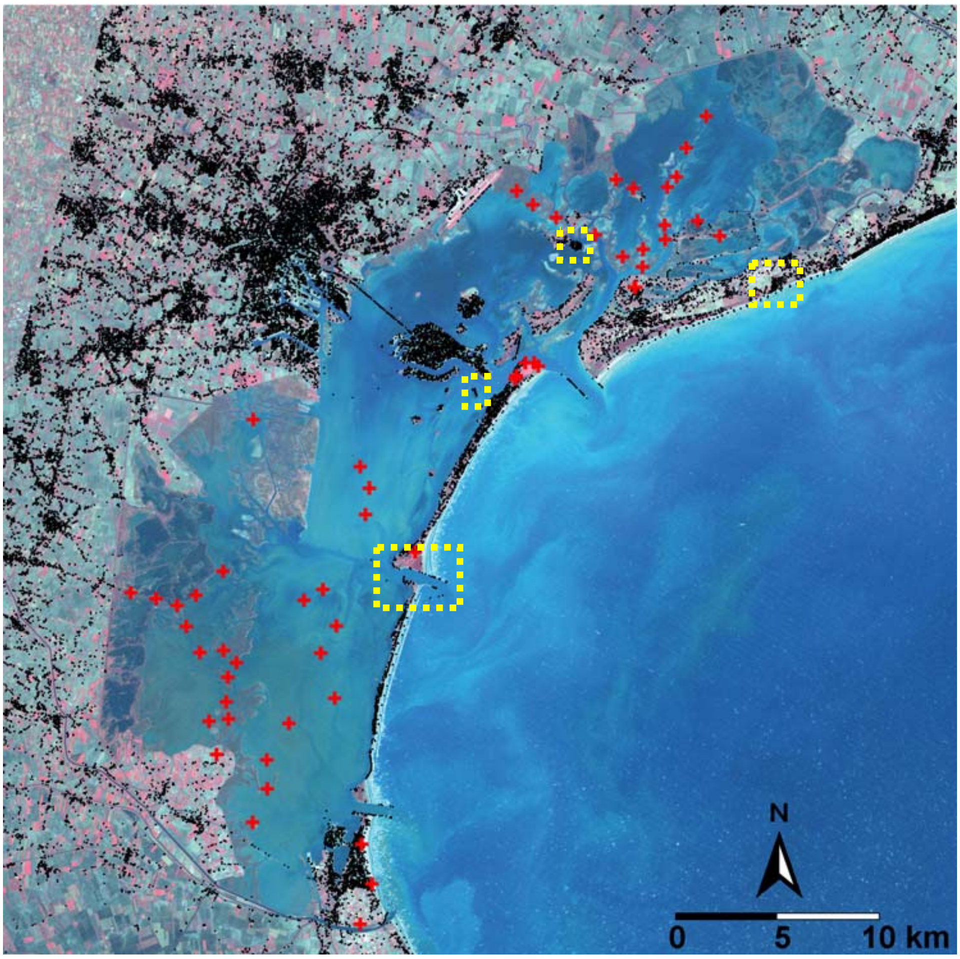

Fig. 1. Satellite image of the Venice Lagoon with the location of the natural PT (black points) detected by IPTA from ENVISAT scenes and the network of artificial TCR (red crosses) established in the framework of the INLET Project. The dashed boxes highlight the areas where the IPTA results are presented at the local scale

DInSAR and IPTA have been applied on the Veneto region within the "VENEZIA Project: Subsidence monitoring service in the lagoon of Venice for regional administrative and water authorities" funded by ESA (European Space Agency). Land displacements have been retrieved at the regional scale and for three local areas of major interest (Venice, Chioggia, the Zennare Basin) using 59 ERS SAR data from 1992 to 2000 [Teatini *et al*., 2005, 2007].

In 2006 VWA and CVN have funded the INLET Project with the main goals of (*i*) extending the IPTA investigation in the Venice Lagoon till to 2007 using the ENVISAT satellite and (*ii*) experimenting artificial TCR within the lagoon where IPTA has failed to retrieve subsidence information (Fig. 1). After a short description of the IPTA methodology and its peculiar application to the study area, the paper provides some representative results showing the strong capability of IPTA to monitor the land displacements in coastal environments and its promising applicability on the TCR.

2 IPTA application in the Venice coastland

A stack of 80 ERS-1/2 and 44 ENVISAT scenes recorded from October 10, 1992, to August 24, 2005, and from February 4, 2003, to December 12, 2007, respectively (Fig. 2), have been commercially acquired by the VWA and processed by IPTA on the whole lagoon area.

For each PT within the study area IPTA has provided the time series of the land displacement along the line of sight between the satellite and the target, which slope is 23° with respect to the vertical direction, over a time interval of about 15 years. The SAR analysis has been carried out separately for the ERS-1/2 and the ENVISAT images because of a certain difference between the frequency of the radar mounted in the two satellites. A total number of 80 and 42 interferograms has been computed using the images dated October 15, 1997, and December 12, 2004 for the ERS-1/2 and ENVISAT acquisitions, respectively, as central reference.

The PT detected in the study area amount to about 90'000 and 190'000 for the ERS-1/2 and ENVISAT images, respectively (Fig. 1). The difference is related to the criteria used to select the targets on which develop the phase investigation. With ERS-1/2, the interferometric analysis has been focussed on the displacement processes occurring at a large (regional) scale by using a relatively strict condition on the coherence of the PT response in order to derive only very accurate measurements. A smaller coherence threshold has been used with the ENVISAT data to obtain a larger number of PT, even if in part characterized by a more noisy displacement history, on which develop a detailed interpretation at a local scale.

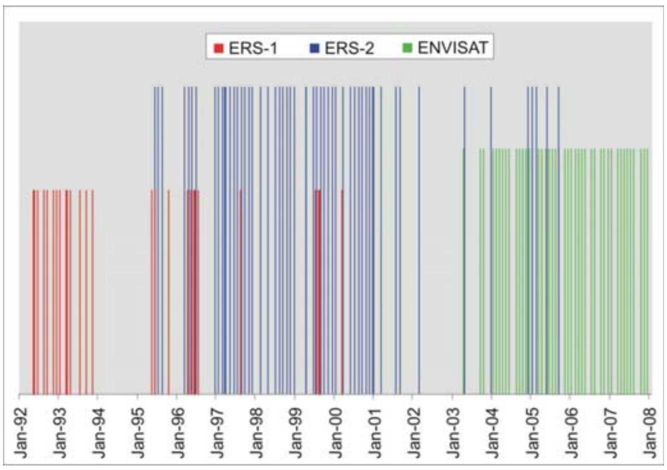

Fig. 2. SAR images from ESA satellites available on the Venice Lagoon area and used by IPTA

IPTA provides for each PT the target coordinates in the SAR reference image and in the Italian cartographic system (Gauss-Boaga, zone 2, datum Roma 1940), an estimate of the target height, the average displacement rate over the investigated time period, the standard deviation of the residual phase, the estimated height and displacement rate uncertainty, and the displacement history with respect to the reference image. It is important to point out that the average displacement rate and the displacement history are two different outcome of the IPTA. The average velocity is calculated first; Then, the nonlinear contribution to the displacement is computed from the phase residual that includes also the atmospheric phase and error terms. The discrimination of the three effect is based on their differing spatial and temporal dependencies.

Presently, for large scale SAR investigation such as the one carried out in this study, the inaccuracy in estimation of the baseline due to the not perfect knowledge of the satellite position results in a phase tilt. This yields that the "right solution" in term on PT average velocity is rotated on a slightly inclined plane, with the relative displacement rate for PT some tens of kilometres apart that is characterized by an uncertainty of 1-3 mm/year.

To overcome, or at least mitigate, this flattening problem, the IPTA solutions have been calibrated using leveling and GPS measurements available in the study area. The substantial stability of the Treviso, Marghera, and Brondolo areas pointed out by the ISES leveling survey carried out in 2000 (compared to the 1993 measurements) [Carbognin *et al*., 2004] has been used to constrain the IPTA outcome on the ERS-1/2 acquisitions. Concerning ENVISAT, the calibration of the IPTA results have been carried out using the stable area of Treviso and the subsidence rates measured by the GPS stations established by the VWA at Cavallino and Marghera [MAG.ACQUE - Morgan, 2007].

3 Results

3.1 Natural reflectors

Several thousands of targets with measurable displacement information have been detected by IPTA in the lagoon area. Fig. 1 shows that the PT are densely distributed in the mainland, along the littorals, in the historical center of Venice, and in the main islands (e.g., Burano, Murano, Sant'Erasmo). Moreover, land displacements have been measured on some reflectors detected also in the several small islands (e.g., San Michele, San Lazzaro degli Armeni, San Francesco) scattered in the central and northern parts of the lagoon where anthropogenic structures were established in the past.

Some examples are provided in the following. Fig. 3 shows the IPTA results at the Burano island in term of the average movement rates computed for the two periods monitored by ERS-1/2 and ENVISAT. A first important outcome is that the subsidence rates and the displacement history for the PT identified with both satellites are coherent. The average subsidence rate is of the order of 2 mm/year, ranging between 0.5 and 3 mm/years depending on the specific conditions of the structure/building reflecting the radar signal. The left part of Fig. 4 shows the 2003-2007 displacement velocity measured at the island of San Servolo. The map points out a substantial stability in the northern part of the isle and significant settlements, up to 10 mm/year, in the central and southern portions. The movement distribution is somehow consistent with the restoration work of the island buildings; started a few years ago, the works was completed at the end of the 1990s for the main monumental complex at the northern tip and only recently for the other buildings distributed in the park. The 2003-2007 subsidence rates in a portion of the Cavallino littoral are illustrated in Fig. 4 (right). Tens of PT are detected in the tourist village, on recreational infrastructures along the shore, the farmer houses between the greenhouses (upper-left corner), and the jetties built along the

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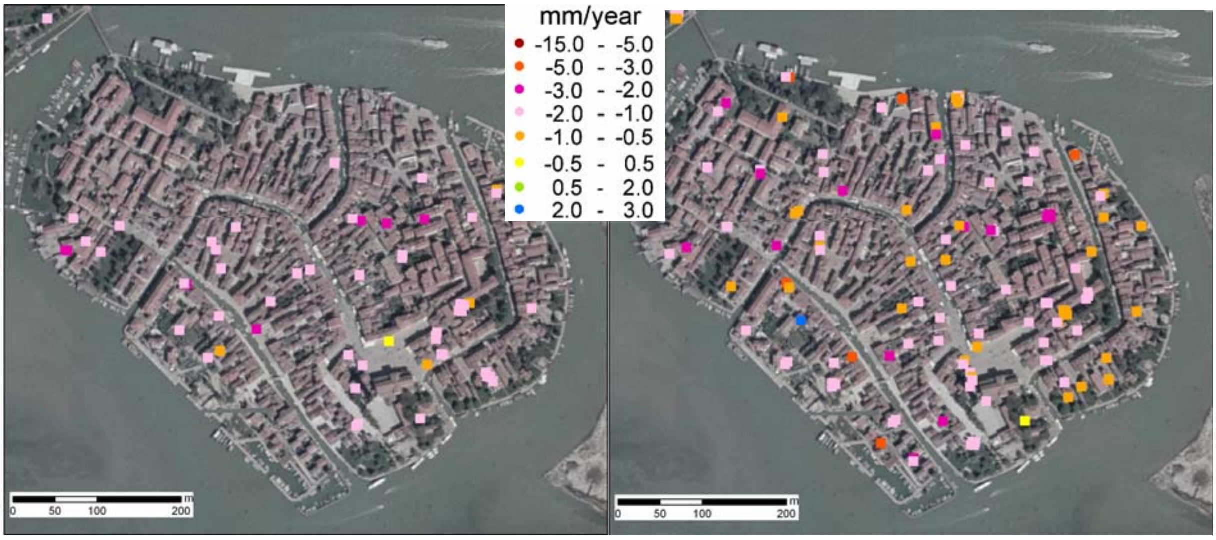

Fig. 3. Displacement rates from IPTA at the Burano island from 1992 to 2002 (left) and from 2003 to 2007 (right) derived from the ERS-1/2 and ENVISAT images, respectively. Negative values mean subsidence

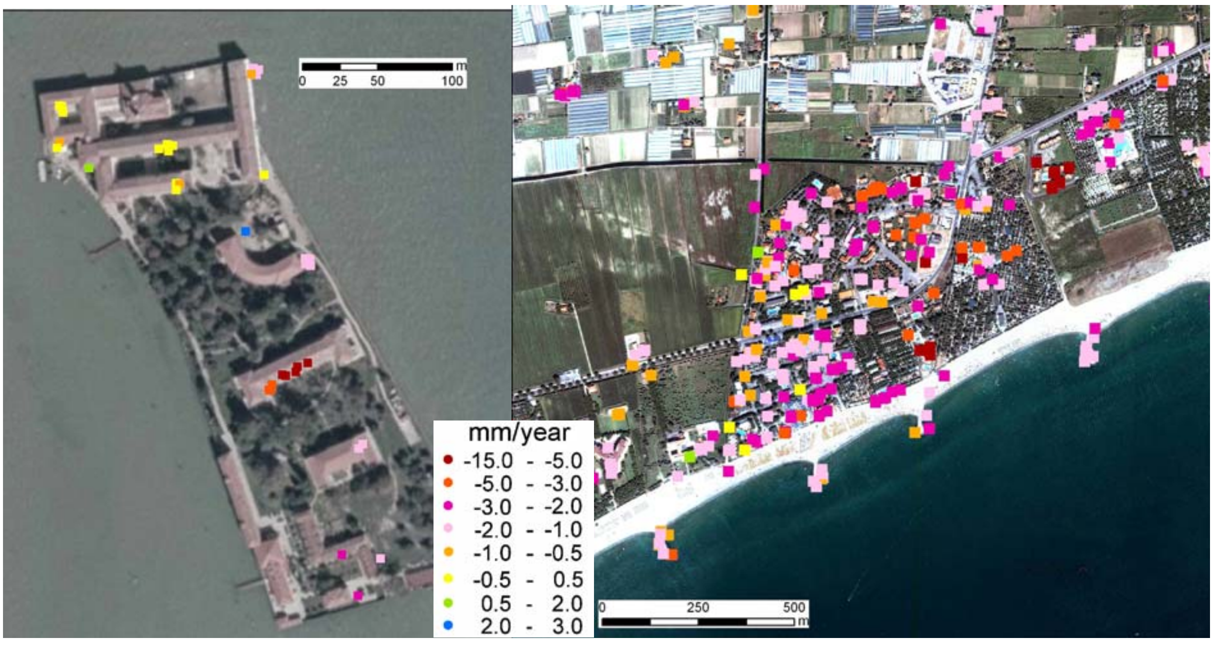

Fig. 4. Displacement rates from IPTA at the San Servolo island (left)and along the Cavallino littoral (right) averaged over the 2003-2007 period. Negative values mean subsidence

coastline to protect the beach. The subsidence velocity averages 2 mm/year, increasing to more than -5 mm/year on the tourist complexes that have been recently constructed. In this part of the Cavallino strip, the jetties are moving at a rate ranging between -1 and -2 mm/year. Finally, Fig 5 shows the strong utility of IPTA from both the environmental and engineering point of views to control land subsidence in the work areas of the MOSE system at the inlets and to check the movement of anthropogenic structures constructed for the lagoon protection from the high tides. Several PT at the Malamocco inlet confirm the stability of this part of the lagoon strips over the last years. Also the two inlet jetties are almost stable except the heads whose reinforcement is responsible for a local consolidation of the underlying subsurface with a displacement rate of about -3 and -5 mm/year for the southern and the northern structure, respectively. Very interesting is the possibility to control the displacements of the breakwater in stone blocks and acropods completed outside the inlet. The structure, which is about 1300 m long and 3-4 m high above the mean sea level, is settled at an average 10 mm/year rate. The displacement time series of a PT pair located on the breakwater show the typical behaviour of a consolidation process, with a significant reduction of the sinking rate over year 2007.

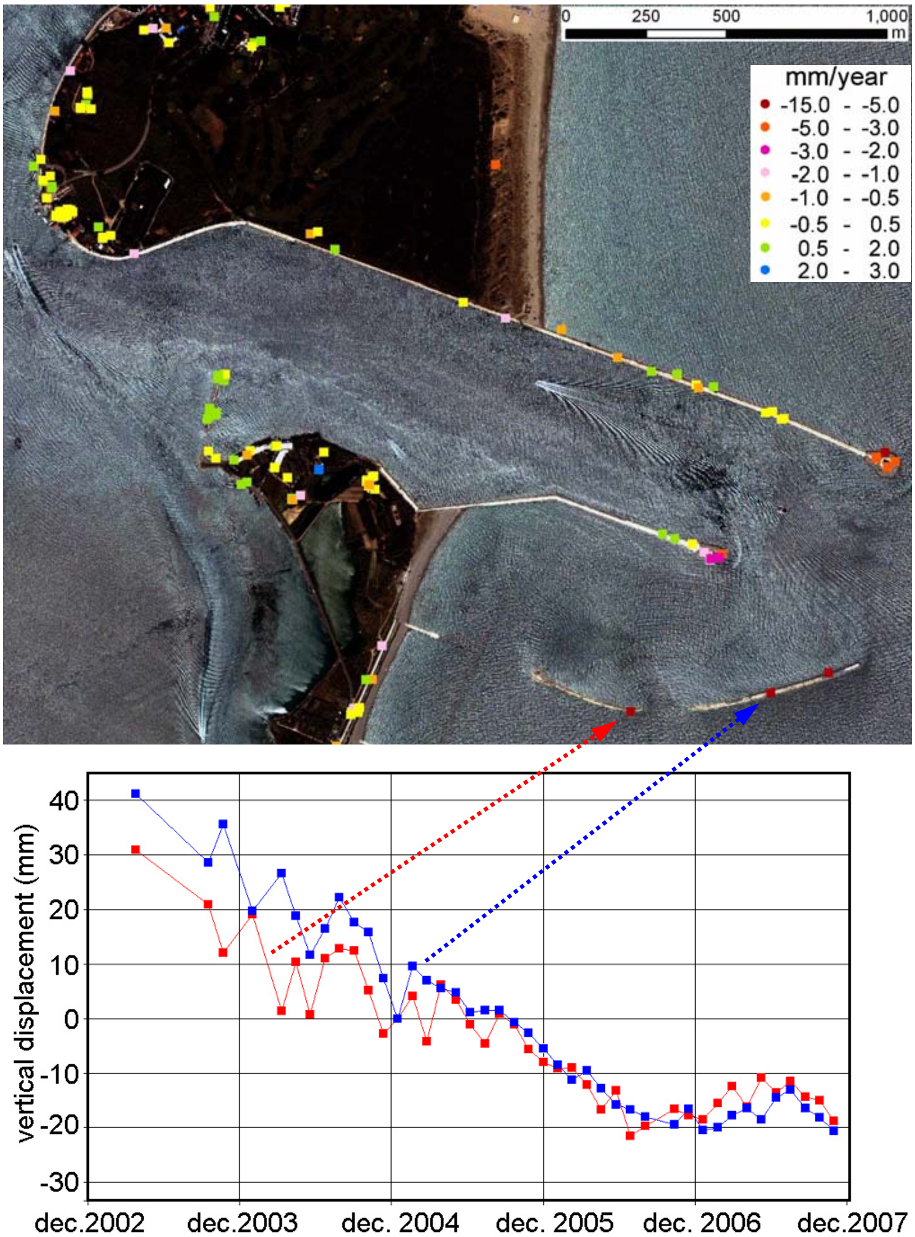

Fig. 5. Displacement rates from IPTA at the Malamocco inlet over the 2003-2007period (above); negative values mean subsidence. Displacement history of a pair of PT located on the offshore breakwater constructed in front of the inlet (below)

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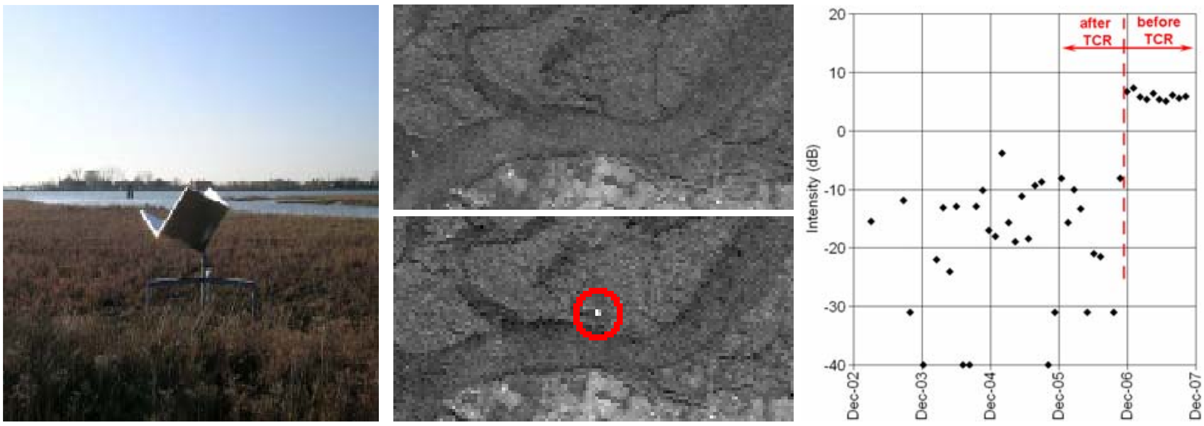

Fig. 6. The TCR established within the San Felice salt marsh in December 21, 2006: photo of the reflector (left); comparison between two ENVISAT backscattering intensity images obtained before and after the TCR installation that proves the good reflector visibility (centre); time behaviour of the backscattering intensity at the TCR position plotted as a function of all the ENVISAT acquisitions

3.2 Artificial reflectors

Although improved co-registration, more efficient computational techniques, and an advanced experience have allowed the detection of a number of PT larger than that found within the VENEZIA Project, also in the INLET Project IPTA misses to infer displacement information on "natural" targets in the inner lagoon and in some limited portions of the farmland bounding the lagoon margins due to absence of persistent reflectors. In order to fill this gap, a network of 55 artificial square trihedral corner reflector (TCR) have been established from September 2006 to July 2007 on natural and anthropogenically rebuilt marshes, small isles (known as "motte"), along the lagoon margins and the banks bounding the fish farms. The TCR are characterized by a 60 cm long edge (Fig. 6, left) and made of aluminum to reduce their weight. The TCR network has been planned taking into account the location of the “natural” PT and keeping to a value of about 1 km the maximum distance between them or between an “artificial” and the adjacent “natural” reflector.

Fig. 6 shows a preliminary result on the TCR located in the San Felice salt marsh. The comparison between the average ENVISAT backscattering intensity image acquired before and after December 2006 when the corner were establish confirms its very good visibility. The constant high intensity in all the images acquired before the installation confirms the possibility of applying the interferometric process on this targets when a sufficient number of SAR scenes will be available. Unfortunately, acts of vandalism recently occurred on a few TCR located in the central and southern parts of the lagoon are likely to threaten their use.

Conclusions

IPTA is a powerful technique to map land displacement in coastal environments. Its application in the Venice Lagoon has allow to quantify the vertical displacements of thousands of persistent reflectors scattered on the urbanized islands, the lagoon margins, and the littorals over the time period between 1992 and 2007. The establishment in 2006-2007 of a network of ad-hoc reflectors will allow in the near future to detect movement information also in the inner lagoon. The methodology provides important results both for the environmental point of view in relation to land subsidence and for engineering purposes by checking the movement of the structures that are under construction to protect the lagoon from high tides. The application of IPTA within the INLET Project has also shown the importance of maintaining traditional levelling and GPS monitoring networks that are necessary for the calibration of the SAR-based technique.

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