ERS AND ENVISAT SAR INTERFEROMETRY TO MEASURE LAND SUBSIDENCE IN THE VENICE LAGOON ON NATURAL AND ARTIFICIAL POINT TARGETS

P. Teatini (1), T. Strozzi (2), L. Tosi (3), U. Wegmüller (2), C. Werner (2), L. Carbognin (3), R. Rosselli (4), G. Cecconi (5), M. Giada(6)

(1) Dept. of Mathematical Methods and Models for Scientific Applications, University of Padova, Via Trieste 63, 35121 Padova, Italy, Email: teatini@dmsa.unipd.it
(2) Gamma Remote Sensing Worbstrasse 225, 3073 Gümligen, Switzerland, Email: strozzi@gamma-rs.ch; wegmuller@gamma-rs.ch; cw@gamma-rs.ch
(3) Institute of Marine Sciences, National Research Council, National Research Council, San Polo 1364, 30125 Venice, Italy, Email: luigi.tosi@ismar.cnr.it; laura.carbognin@ismar.cnr.it
(4) Sistema Informativo, Venice Water Authority, Campo S. Stefano 2949, 30124 Venice, Italy, Email: roberto.rosselli@magisacque.it
(5) Consorzio Venezia Nuova, Servizio Ingegneria, S. Croce 505, 30135 Venice, Italy, Email: giovanni.cecconi@consorziovenezianuova.com
(6) Morgan S.r.l., Via dell'Elettricità 5/D, 30175 Venice, Italy, Email: marco.giada@morganrilievi.com

ABSTRACT

The Venice Lagoon, Italy, is a unique worldwide environment which is presently vulnerable due to loss in surface elevation as a result of land subsidence referred to the mean sea level. Land displacements in the Venice coastland have been determined over time by traditional monitoring techniques (i.e., spirit leveling and GPS). Recently, SAR-based analyses have been used to complement the ground-based methods. Interferometric analysis on persistent point targets has been proved to be very effective in detecting land displacement in the coastal environment. ERS SAR and ENVISAT ASAR images spanning the time period 1992-2005 and 2003-2006, respectively, have been processed at regional and local scale and on “natural” as well as “artificial” reflectors.

1. INTRODUCTION

Similar to many other coastal lowlands and deltaic plains, the Eastern Po Plain, in general, and the Venice coastland, in particular (Fig. 1), have been characterized throughout the centuries by land subsidence of both natural and, lately, anthropogenic origin, with variable rates depending on geological events and human activities. The assessment of the displacements has been performed with different procedures according to the period of investigation.

An integrated magneto-bio-cyclostratigraphy of lithofacies and palynofloral analyses have been used by [1] to characterize the long-term subsidence rate at Venice over Pleistocene, i.e. from 1.8 year BP. The results show an average subsidence rate less than 0.5 mm/year which reflects mainly (about 70%) tectonic processes. C^{14} radiocarbon measurements have been used to date the late Pleistocene and Holocene organic remains, mainly shells and peats, collected from boreholes scattered all over the lagoon area [2]. An average subsidence rate of 1.2-1.3 mm/year has been found over the last 40,000 years by relating their depth and date. References [3,4] have obtained a reliable estimate of the Venice submersion over the last three centuries by using Canaletto's paintings. The comparison of the present position and that in 1750 of the green front left by the algae on the building walls shows that the city sunk on the order of 1.2 mm/year from the beginning of the 18th century.

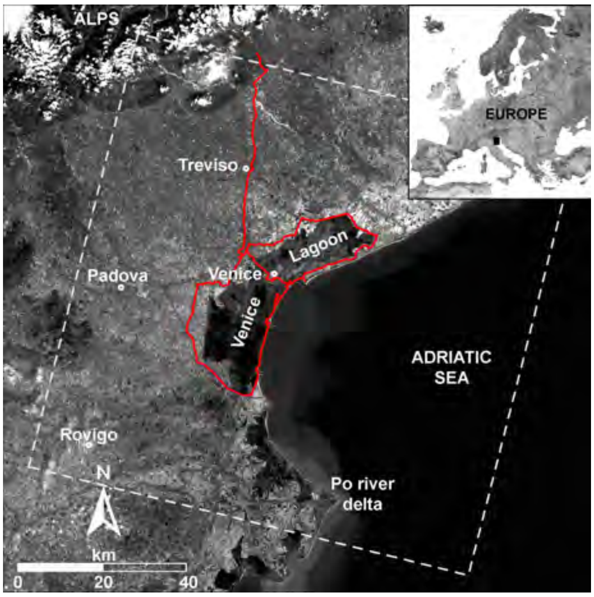

Figure 1. Landsat image of the Venice region. The red lines around the lagoon and connecting the city to the Alpine foothills represent the leveling network used since the beginning of the. The dashed box indicates the trace of the ERS – ENVISAT SAR images (track (2)122, frame 2691, descending mode, VV polarization) used to map land displacements

Proc. ‘Envisat Symposium 2007’, Montreux, Switzerland
23–27 April 2007 (ESA SP-636, July 2007)

Ground elevation at Venice and its surroundings has been accurately measured over the last 50 years by repeating traditional high precision leveling of a benchmark network (Fig. 1) established in the city, extended into a broader regional network around the lagoon boundaries, and connected to the stable area of Treviso, a major city close to the Alpine foothills [5]. The last surveys have been carried out in 1993 and 2000. A portion of the leveling net has also been used in 2000 and 2003 for differential GPS measurements in quasi-static mode. Results have shown that the city of Venice and its nearby mainland were almost stable whereas land subsidence was active at the lagoon extremities with rates that progressively increase south- and northward up to 5 mm/year [6].
Since 2000, interferometric SAR-based techniques have also been used to improve the qualitative and quantitative analysis of the vertical displacements in the Venice region. Within ESA Data User Progamme (DUP) funded Project "VENEZIA", differential SAR interferometry (InSAR) and Interferometric Point Target Analysis (IPTA) were employed on a time series of 11 and 59 ERS-1/2 SAR images (track 122, frame 2691), respectively, acquired between 1992 and 2000. About 380'000 coherent pixels have been detected by InSAR on urban centers with an areal extent larger than 1 km^2 [7], and some 120'000 Pint Targets (PTs) with valuable subsidence information were found over cities, suburban areas, and isolated structures in the farmland.
InSAR and IPTA have been integrated with leveling and GPS into a Subsidence Integrated Monitoring System (SIMS) to overcome the limits characterizing each technique and infer therefore an accurate and reliable figure of regional land displacements [8,9]. The SIMS results have shown that the central lagoon, including the city of Venice, shows a general stability while the northern and southern lagoon extremities and their related catchment sectors sink with rates ranging from 3 to 15 mm/year. Relatively small uplifts (on the order of 1 mm/year) are observed at the Alpine foothills and in a wide area comprised between the Euganean Hills and the lagoon (Fig. 2).
Following the successful results obtained within the VENEZIA Project, the End Users directly managing the Venice lagoon and the coastland funded a new research and monitoring study with the following main goals:

- to investigate at a greater resolution and a better accuracy the IPTA capability to detect land displacement in the lagoon and littoral environment; this is accomplished by reducing the area of investigation to the coastland with respect to the whole frame 2691 analyzed in the VENEZIA Project;
- to update the displacement measurement up to 2007 by using ENVISAT;
- to establish an optimal network of artificial reflectors within the lagoon and in extreme rural zones where IPTA has failed to retrieve subsidence information;
- to accurately analyze the subsidence rate in some site of particular interest.

The paper provides preliminary results obtained within this new project.

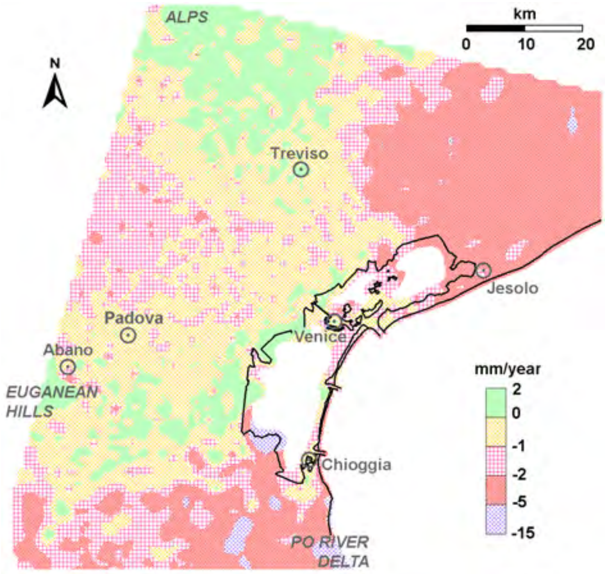

Figure 2. Vertical displacements in the Venice region over the period 1992-2002 obtained by SIMS (modified after [9])

2. INTERFEROMETRIC POINT TARGET ANALYSIS

In SAR interferometry (InSAR), a pair of SAR images acquired from slightly different orbit configurations and at different times is combined to exploit the phase difference of the signals [10]. The interferometric phase is sensitive to both surface topography and coherent displacement along the look vector occurring between the acquisitions of the interferometric image pair, with inhomogeneous propagation delay and phase noise introducing the main error sources. The basic idea of SAR interferometry for land surface displacement mapping is to subtract the topography related phase from the interferogram and to moderate the effects of the error sources.
SAR interferometry is mainly limited by phase decorrelation [11]. Temporal decorrelation occurs from changes in time of the scatterer characteristics within the resolution cell. Spatial decorrelation precludes interpretation of interferometric phases for extended targets in pairs with long baselines.
In IPTA [12,13] differential SAR interferometry is applied only to selected pixels with a point target scattering behavior and persistent over long time scale. If the dimension of these points is much smaller than the resolution cell, almost no spatial decorrelation occurs, permitting interpretation of the interferometric phase of

pairs with long baselines. Consequently, more observations are available allowing reduction of errors resulting from the atmospheric path delay and leading to better temporal coverage and accuracy. In particular, interferometric phase analysis is feasible even outside cities and villages on single structures, like electrical transmission towers, threshing-floors, and farmsteads.
The IPTA results consist of the height, linear deformation rate, atmospheric phase, quality information related to height and deformation rate, and nonlinear displacement history for each selected PT. The stable area of Treviso has been used as reference (Fig. 1). Since the Venice coastland is very flat, the DEM of the Italian Geological Service, characterized by a regular grid of 10'' in latitude and 7'' in longitude and a vertical resolution of 1 m, is assumed detailed enough for the IPTA purposes and has been used as the topographic reference.

3. IPTA IN THE VENICE LAGOON ON ERS IMAGES

The IPTA carried out in the VENEZIA Project on the ERS data has been continued on the frame portion covering the lagoon area. An IKONOS image of the study area made available by the Sistema Informativo of the Venice Water Authority (SI-MAV) has been used for visualization of the results.
Three aspects have been specifically addressed:

- the improvement and update of the analysis performed during the VENEZIA Project [8,9] at the lagoon-scale;
- the development for a number of selected PTs of a sort of “benchmark sheet” similar to that usually developed for the geodetic benches;
- local scale investigations aimed at understanding the physical process responsible for the displacement history detected on some PTs of particular interest.

3.1. Lagoon-scale studies

A stack of 68 ERS SAR images from 1992/05/10 to 2005/08/24, commercially acquired by SI-MAV, has been processed by IPTA on the whole lagoon area.
Improved co-registration possible at a smaller scale of investigation, more efficient computational techniques, and an advanced experience have allowed the detection of a number of PTs larger than that found at the regional scale within the VENEZIA Project [8,9] (Fig. 3). The PT density is mainly increased along the inland lagoon margins and on the littoral strips, and remains practically unchanged in the urban areas. However, in spite of the significant covering improvement, IPTA misses to infer displacement information on "natural" targets in the inner lagoon and in some limited portions of the farmland at the southern and, secondarily, northern lagoon extremities (Fig. 3). It is finally to point out that the Doppler centroid instability characterizing the ERS-2 SAR data of the zero gyroscope operation mode after June 2001 has reduced the availability of scenes useful for the interferometric processing, yielding also some problems of phase unwrapping. While the PT displacement histories have been elaborated until 2005, the linear subsidence rates have been computed for the time period 1992-2000 only.
The preliminary results in term of displacement rates (Fig. 3) confirm the knowledge acquires in the last few years [6,9,14]. The central part of the Venice coastland, including the major cities of Venice and Mestre, is substantially stable. Conversely, land settlement appears as a widespread phenomenon in the northern and southern coastlands of the lagoon extremities, with rates up to 5 mm/year. Uplifts on the order of 1 mm/year, probably related to tectonics, have been measured in the farmland bounding the central lagoon margin.

3.2. Local scale studies

IPTA application at a few kilometre scale has revealed that a deep knowledge of the geology, geomorphology, hydrology, and anthropogenic development of the coastland is required to provide an accurate interpretation the SAR-derived displacements on persistent targets.

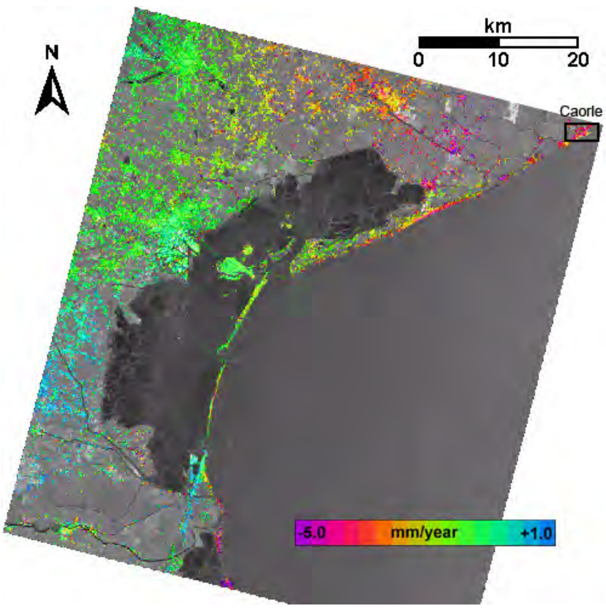

Figure 3. Average land subsidence for the Venice Lagoon during the 1992-2000 period from the IPTA on 59 ERS-1/2 SAR scenes. The black box on the right-top corner highlights the area of Caorle where results at the local scale are presented. Background is an average SAR backscattering intensity image

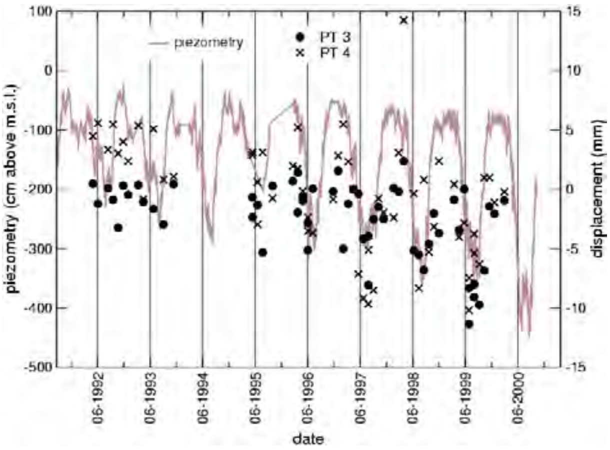

Figure 4. Displacement history for a couple of PTs in Venice showing a significant correlation with the piezometric head in the aquifer system underlying the city (after [16])

In agreement with previous results from other researchers [e.g., 15], we have found that the target movement is the superposition of a short-time, generally seasonal, reversible component and a long-time linear/nonlinear irreversible trend [16]. The first contribution is connected in Venice to meteorological conditions, tidal regime, and seasonal fluctuation of the piezometric head in the aquifer systems (Fig. 4). Several factors contribute to the irreversible displacements, such as natural consolidation of the Quaternary deposits, surface loads, tectonics, oxidation of recently reclaimed marshes, and fluid removal from the subsurface.

4. IPTA IN THE VENICE LAGOON ON ENVISAT IMAGES

In order to continue in the years to come the land subsidence monitoring service by SAR-based technology integrated to ground-based methods, the End Users managing the Venice territory commercially purchased ENVISAT ASAR images for the track and frame corresponding to the ERS SAR. Orders were put to program ASAR acquisitions on Venice at each pass since January 2003 when the commissioning phase of the satellite terminated. After some initial difficulties (only the images on 2003/04/02, 2003/09/24, and 2003/10/29 are available during 2003), ENVISAT scenes started to be regularly acquired on the study area from the beginning of 2004. Since then only the 2006/09/13 acquisition was missed due to satellite orbit correction.
It is finally to be noted that, contrarily to the ERS acquisitions, ENVISAT scenes are roughly cut along the orbit so that there is a 10 km wide strip on the northern and southern frame boundaries where information are only seldom available.

4.1. Natural point targets

IPTA has been performed on the first 31 ENVISAT scenes acquired on the Venice coastland (i.e. from 2003/04/02 to 2006/08/09).
Very consistent results have been so far obtained with local scale investigations. At the lagoon scale, on the other hand, a certain difficult remains for the precise analysis of the large-scale settlement of few mm/year that affect the lagoon southern and northern edges. More consolidated results are expected with a stack of more images covering a longer time period.
Fig. 5 shows an example of the outcome for the urban area of Caorle, a tourist village located a few tens of kilometres north of Venice (see the black box in Fig. 3). The figure provides a comparison between the average

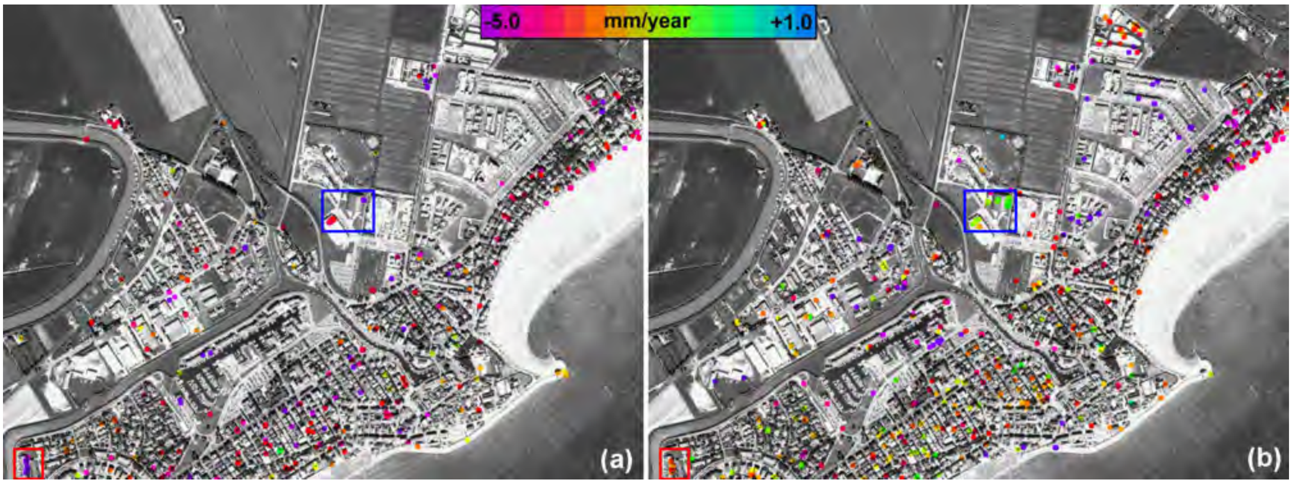

Figure 5: Displacement rates from IPTA at Caorle, northern Venice coastland: (a) from ESR scenes averaged over the 1992-2000 period; (b) from ENVSAT scenes over 2003-2006. The displacement history for one of the PTs in the red box is shown in Fig. 6. The blue box highlights a portion of the village sport centre where the PT subsidence rate changes significantly over time. Background is an IKONOS image of 2006

displacement rates obtained by IPTA on ERS and ENVISAT images over the 1992-2000 and 2003-2006 periods, respectively. In the old portion of the village along the seashore the whole PTs are not exactly the same because of the slightly different frequencies of the two sensors. The area where ENVISAT interferometric phase analysis is feasible is enlarged due to the recent transformation of agricultural environments in new urbanized zones (e.g., the industrial and commercial zone in the upper-right corner of Fig. 5).
Another important result is that the subsidence rates and the displacement history for the PTs identified with both satellites are coherent (Fig. 6). A general small reduction of the sinking rates (of the order of 1 mm/year) can be observed and it is likely to be related to a residual consolidation process still ongoing. For certain buildings, e.g. those within the blue box in Fig. 5, s remarkable decrease of the mean settlement rate from more than 5 mm/year to 1-2 mm/year has been observed passing from ERS to ENVISAT due to a faster consolidation process.

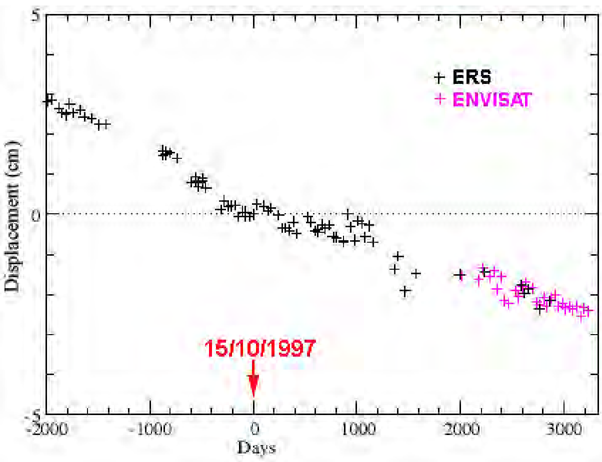

Figure 6. Displacement history detected by IPTA on ESA and ENVISAT acquisitions during the period 1992-2005 and 2003-2006, respectively, for a PT on the red bottom left corner in Figure 5

4.2. Artificial point targets

As previously highlighted, there are some parts of the study area where anthropogenic structures completely lack (e.g., in the inner lagoon) or few constructions are scattered in the farmland at a distance from one to each other too large to resolve the radar phase ambiguity.
In order to fill this gap of IPTA application, a few tens of artificial square trihedral corner reflector (TCR) are planned to be established before summer 2007 (Fig. 7). The TCR are characterized by a 30 to 60 cm long edge and made of aluminium to reduce their weight. Different types of foundation from deep to shallow are planned to be experimented in order to evaluate various components of the displacement, e.g. the consolidation of marshes recently rebuilt within the lagoon rather than long-time subsidence rate due to the residual consolidation of the Quaternary column. Moreover, we are also evaluating the possibility to use drilled plates or wire nettings to reduce the TCR resistance to wind that blows particularly strong during winter in the lagoon.
An optimal TCR network has been planned taking into account the location of the "natural" PTs and keeping to a value of about 1km the maximum distance between them or between an "artificial" and the adjacent "natural" reflector. Fig. 8 shows a preliminary result on a lagoon portion where 3 TCRs have been established on 2006/12/21. The comparison between the average ENVISAT ASAR backscattering intensity image before and after September 2006 confirms the very good visibility of the installed reflectors.

Figure 7. Establishment of a TCR on a marsh in the southern Venice Lagoon

5. CONCLUSIONS

The natural processes and the human interventions in the Venice Lagoon may induce in the near future time-dependent land movements at the local and lagoon scales which will require a highly accurate monitoring.
SAR interferometry on persistent targets appears to be a consolidated tool to map land subsidence in the Venice coastal environment, even more so if the establishment of artificial reflectors will allow to detect displacement information in areas of particular interest, e.g. the inner lagoon, where man-made structures lack.
On the other hand, it is to be pointed out that the PT displacements cannot be straightforwardly translated to regional/local land subsidence/uplift and a detailed knowledge of the natural features and anthropogenic development of the coastland is required to provide an accurate interpretation the SAR-derived displacements.
The continuity of the ENVISAT functioning is of paramount importance to supply a future reliable land subsidence monitoring service in the Venice coastland. The End Users managing the lagoon and its catchment have already ordered the acquisitions till to 2008/01/16 and are willing to extend image ordering at least till the end of 2008.

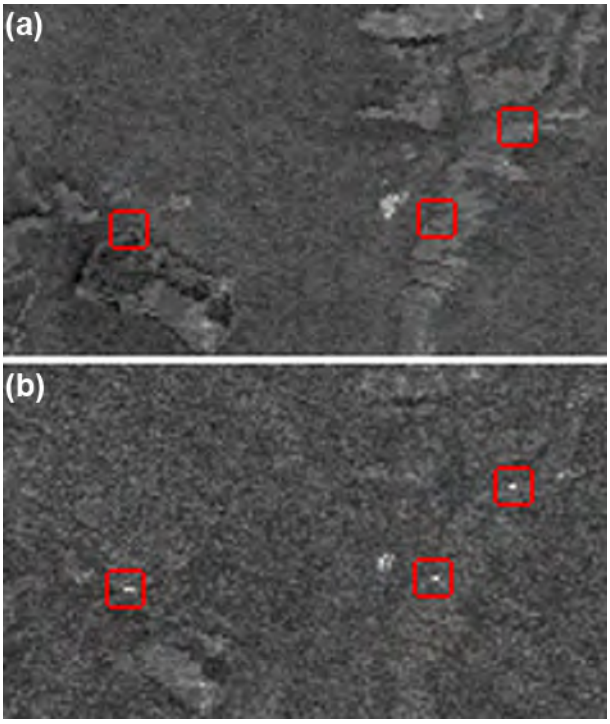

Figure 8. Northern Venice Lagoon: ENVISAT ASAR backscattering intensity image obtained by averaging the scenes acquired (a) before and (b) after September 2006. The locations of the TCR are highlighted by the red boxes

6. REFERENCES

1. Kent, V.D., Rio, D., Massari, F., Kukla, G.& Lanci, L. (2002). Emergence of Venice during the Pleistocene. *Quaternary Sci. Rev.*, **21**, 1719-1727.
2. Bortolami, G., Carbognin, L. & Gatto, P. (1984). The Natural Subsidence in the Lagoon of Venice, Italy. In 'Land Subsidence' (Eds. A.I. Johnson et al.), IAHS Publ. no. 151, pp 777-785.
3. Carbognin, L., Gatto, P. & Marabini, F. (1984). The city and the lagoon of Venice: A guidebook on the environment and land subsidence. Pamphlet published on the occasion of the Third International Symposium on Land Subsidence, Venice, CNR, 36 pp.
4. Camuffo, D. & Sturaro, G. (2003), Sixty-cm Submersion of Venice Discovered Thanks to Canaletto's Pintings, *Climatic Change*, **58**, 333-43.
5. Carbognin, L., Gatto, P., Mozzi, G., Gambolati, G. & Ricceri, G. (1984). Case history no.9.3 Venice, Italy. In 'Guidebook to Studies of Land Subsidence Due to Ground-Water Withdrawal' (Ed. J.F. Poland), UNESCO, Paris, pp 161-174.
6. Carbognin, L., Teatini., P. & Tosi, L. (2004). Relative Land Subsidence in the Lagoon of Venice, Italy, at the beginning of the new millennium, *J. Marine Syst*., **51**(1-4), 345-353.
7. Strozzi, T., Carbognin, L., Rosselli, R., Teatini, P., Tosi, L. & Wegmüller, U. (2003). Ground Vertical Movements in Urban Areas of the Veneto Region (Italy) Detected by DInSAR. In '4th European Congress on Regional Geoscientific Cartography and Information Systems' (Eds. A. Angelelli et al.), Vol.1, Bologna (Italy), Regione Emilia-Romagna, pp 190-194.
8. Strozzi, T., Tosi, L., Wegmüller, U., Werner, C., Teatini, P. & Carbognin, L. (2003). Land Subsidence Monitoring Service in the Lagoon of Venice. In 'IGARSS 2003', Vol. I, pp 212-214.
9. Teatini, P., Tosi, L., Strozzi, T., Carbognin, L., Wegmüller, U. & Rizzetto, F. (2005). Mapping Regional Land Displacements in the Venice Coastland by an Integrated Monitoring System, *Remote Sens. Environ*., **98**(4), 403-413.
10. Bamler, R. & Hartl, P. (1998). Synthetic Aperture Radar Interferometry, *Inverse Probl*., **14**, R1-R54.
11. Zebker, H. A. & Villasenor, J. (1992). Decorrelation in Interferometric Radar Echoes, *IEEE TGARS*, **30**, 950-959.
12. Werner, C., Wegmüller, U., Strozzi, T. & Weismann, A. (2003). Interferometric Point Target Analysis for Deformation Mapping. In 'IGARSS 2003', Vol. VII, pp 4362-4364.
13. Wegmüller, U., Werner, C., Strozzi, T. & Wiesmann, A. (2004). Multi-temporal Interferometric Point Target Analysis. In 'Analysis of Multi-Temporal Remote Sensing Images' (Eds. P. Smits & L. Bruzzone), World Scientific, Series in Remote Sensing, Vol. 3, pp 136-144.
14. Tosi, L., Carbognin, L., Teatini, P., Strozzi, T. & Wegmüller, U. (2002). Evidence of the Present Relative Land Stability of Venice, Italy, from Land, Sea, and Space Observations, *Geophys. Res. Lett.*, **29**(12), doi:10.1029/2001GL013211.
15. Schmidt, D. A. & Bürgmann, R. (2003). Time-dependent Land Uplift and Subsidence in the Santa Clara Valley, California, from a Large Interferometric Synthetic Aperture Radar, *J. Geophys. Res.*, **108**(B9), doi: 10.1029/2002JB002267.
16. Teatini, P., Strozzi, T., Tosi, L., Wegmüller, U., Werner, C. & Carbognin, L. (2007). Assessing Short- and Long-time Displacements in the Venice Coastland by Synthetic Aperture Radar Interferometric Point Target Analysis, *J. Geophys. Res.*, **112**, F01012, doi:10.1029/2006JF000656.