VENEZIA

SUBSIDENCE MONITORING SERVICE

IN THE LAGOON OF VENICE

FOR REGIONAL ADMINISTRATIVE AND WATER AUTHORITIES

DATA USER PROGRAMME (DUP), II PERIOD

Executive Summary

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October 2003

Distribution: F.M. Seifert ESA-ESRIN

Scope: This document is the Executive Summary of the project “VENEZIA - Subsidence monitoring service in the Lagoon of Venice for regional administrative and water authorities” in the framework of ESA Data User Programme (DUP). The Executive Report summarizes the findings of the project in a concise, yet instructive manner, for public access.

Document Status Sheet

Issue	Date	Details	Authors
1.0	28.10.03	Draft	T. Strozzi, L. Tosi, U. Wegmüller, P. Teatini, C. Werner, L. Carbognin and A. Wiesmann

Definitions, acronyms and abbreviations

AOI	Area of Interest
CGPS	Continuous Global Positioning System
CNR	Consiglio Nazionale delle Ricerche
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
EO	Earth Observation
GAMMA	Gamma Remote Sensing and Consulting
GIS	Geographical Information System
GPS	Global Positioning System
INSAR	SAR interferometry
IPTA	Interferometric Point Target Analysis
ISMAR	Istituto di Scienze Marine
SAR	Synthetic Aperture Radar
SLC	Single Look Complex
TBC	To be confirmed
TBD	To be defined
UTM	Universal Transversal Mercator

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1 Introduction

The scope of the project “VENEZIA - Subsidence monitoring service in the Lagoon of Venice for regional administrative and water authorities” was to define and implement a land subsidence monitoring service in the Lagoon of Venice for regional and administrative authorities. In order to provide the best knowledge of the land subsidence process around the Lagoon of Venice, SAR-based monitoring techniques (differential SAR interferometry and interferometric point target analysis) were integrated with levelling and GPS surveys into an overall information system.

Land subsidence due to natural and anthropogenic causes has represented one of the most serious environmental problems for the Lagoon of Venice and its catchment (Tosi et al., 2002, Carbognin and Tosi, 2003, Carbognin et al., in press). Land subsidence has increased the vulnerability and the geological hazard (i.e. river flooding, riverbank stability, intrusion of seawater in the aquifer system, deteriorating of the littoral sectors with a general coastline regression and an increment of the sea bottom slope close to the shoreline) of these areas, a large portion of which lies below the mean sea level. After the regulation of groundwater exploitation from the Venetian aquifer-aquitard system, a remarkable slowing down of the induced subsidence in Marghera (industrial zone), in the historical center of Venice and along the littorals was ascertained in the 1970’s. Recent studies (Carbognin and Tosi, 2003) have shown that land subsidence is still in progress in the southern and northern coastal areas and in the nearby mainland, where groundwater is extracted from artesian wells, thicker and more compressible Holocene sediments are present, and organic soil oxidation takes place in reclaimed areas.

Until 1999, levelling of the Venice region was carried out only along the coast and the lagoon edges and the monitoring network was composed by benchmarks along single levelling lines; a fine grid network was established only in the city of Venice. In recent years, the levelling network has been updated to cover all the southern part of the Lagoon, and plans exist to cover also the northern sector. The same network used for the levelling surveys is also considered for differential GPS measurements. In addition to these ground-based methods, differential SAR interferometry using long series of SAR data (Wegmüller and Strozzi, 1998;

Strozzi et al, 2001) and interferometric point target analysis (IPTA) (Wegmüller et al., 2003, Werner et al., 2003) have emerged as very promising tools for the monitoring of land subsidence at high spatial resolution.

The VENEZIA project was organized along a service definition phase, a service implementation phase and a service quality assessment phase. Important elements of the project were the definition, implementation and validation of the service for interferometric point target analysis and the integration of the SAR-based monitoring techniques with levelling and GPS surveys into an overall information system capable to provide the best knowledge of the subsidence process to the authorities that manage the Po Plain area around the Lagoon of Venice.

2 Current practices and user requirements

Until 2000, levelling surveys, differential GPS (DGPS) and continuous GPS (CGPS) were used for land subsidence monitoring around the Lagoon of the Venice.

The levelling network established around the Venice Lagoon has been updated during the 1999 - 2000 in the eastern part of the coastal plain. The area covered by the present network is shown in Figure 1. The network is about 865 km long and consists of about 1000 benchmarks with average distance of 900 m (Carbognin and Tosi, 2003). The net is connected to the stable areas of Treviso on the Alpine foothills and of Monte Venda on the Eugenean Hills. Since up to now the northern part of the area of interest is not properly covered by a traditional monitoring network and subsidence maps obtained by SAR analyses have evidenced dangerous settling rates (see Section 4 of this document), a new fine net is in planning.

The overall network is composed of a reduced first-class levelling-line group to be monitored every 5 years, and a complete second-class group to be monitored every 10 years.

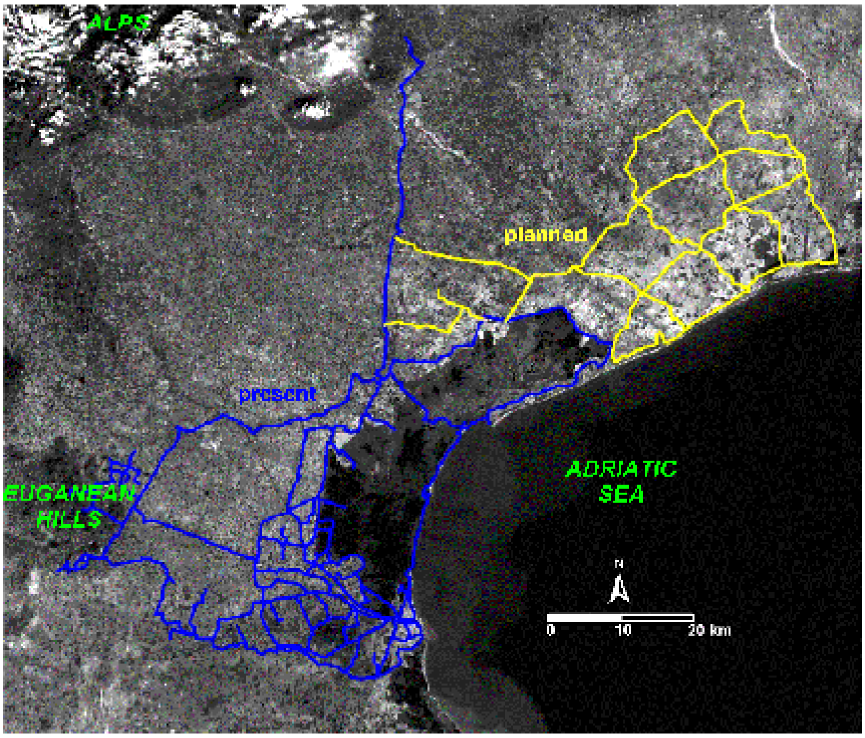

Figure 1. Overall levelling network around the Lagoon of Venice with an indication of the network planned to be established in the near future.

The present distribution of continuous GPS (CGPS) is scarce (see Figure 2). Two permanent stations in Venice and in Padova have been established in 1995. Three new stations were established in Voltabarozzo (Padova), Chioggia and Cavallino-Jesolo in 2000 with the scope of monitoring local subsidence associated with the rise in sea level in Venice (Carbognin et al., in press).

The differential GPS (DGPS) network is composed of 119 benchmarks (Figure 2) with an optimal ratio of 1/5 between the DGPS and geometric measurement points. All the nodal benchmarks of the levelling net have been used as GPS stations, and a number of benchmarks have been located on the stable Euganean Hills, Treviso and Rua di Feletto. The first DGPS measurements have been performed in 1999-2000 (Carbognin and Tosi, 2003). The next DGPS measurements, to perform the first monitoring, are planned for this year.

The monitoring by DGPS of the overall network is recommended every 2-3 years.

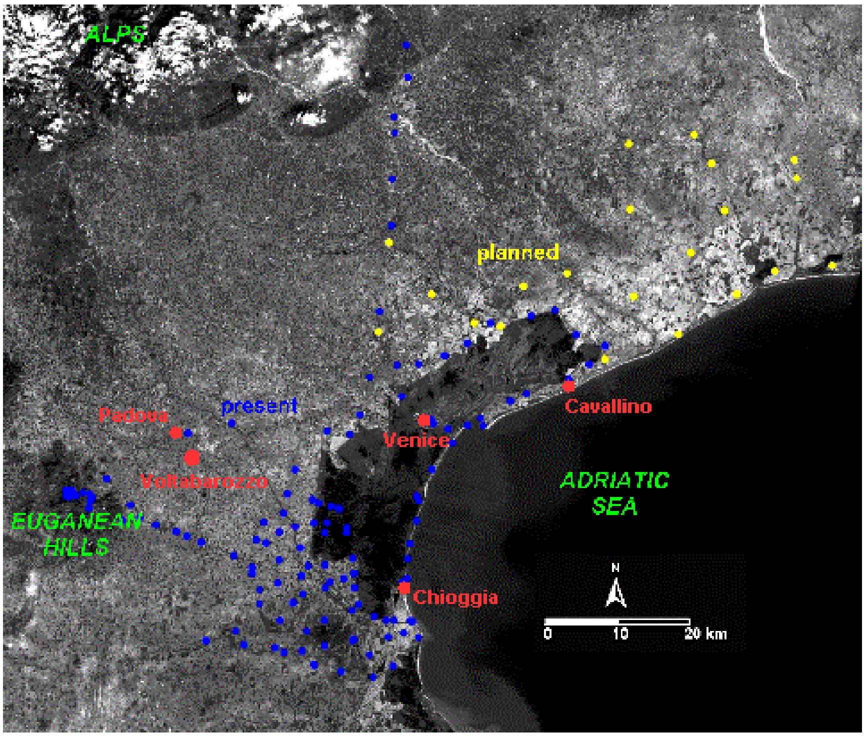

Figure 2. Location of the CGPS stations and distribution of the GPS benchmarks.

With regard to land subsidence problems and monitoring, requirements were assessed for a number of regional and administrative authorities, including the Servizio Informativo of the Magistrato alle Acque di Venezia - Consorzio Venezia Nuova, the Consorzio di Bonifica Adige-Bacchiglione, the provinces of Padova and Venezia, INSULA, Agip and other local authorities (communes). The end users requirements are summarized in Table 1 as function of the area of interest. An accurate and cost effective solution is requested by all users.

Table 1. Summary of the End User requirements.

Area	Problems	Accuracy (mm/year)	Frequency (years)	Current practices	Output format
Venezia and other inhabited islands	high water, urban fragility	1-3	2-3	Leveling, DGCP, CGPS	Raster maps, ASCII files, logs for selected points
Lagoon	erosion, changes in the lagoon habitat	1-3	3-7	Leveling, DGCP	Raster maps, ASCII files
Littorals	Erosion of the coastline, deterioration of the jetties	1-2	2-3	Leveling, DGCP, CGPS	Raster maps, ASCII files, logs for selected points
Catchment	hydrogeological hazard	1-3	2-3	Leveling, DGCP	Raster maps, ASCII files, logs for selected points

3 Service definition

Differential SAR interferometry has demonstrated a good potential to derive land subsidence information for urban areas at sub-cm vertical accuracy and relatively low cost (Bamler and Hartl, 1998, Strozzi et al., 2001). In addition, SAR interferometry exhibits complementary characteristics to the levelling surveys, because it has the capability to map large urban areas (i.e. where stable structures permit the formation of a coherent phase signal over time) at high spatial resolution, whereas the high precision levelling surveys can be used outside of the cities and to set up a reference point for the SAR subsidence values. In the case of the Venetian area, where high precision levelling surveys were available only around the Lagoon margin and along two lines from Venezia to Treviso and from Mestre to Padova, SAR interferometry has the capability to monitor the vertical displacements of all the built-up areas not fully covered with levelling results. For all these reasons, an INSAR-based service for the area around the Lagoon of Venice was purchased by one of the users and integrated in the current project.

An important limitation of INSAR, though, is the incomplete spatial coverage. Decorrelation does not permit a reliable analysis of the interferometric phase for parts of the area. Techniques to interpret the phases of stable reflectors have been also proposed (Ferretti et al, 2001, Werner et al., 2003). These reflectors must satisfy two conditions. The first one is that their scattering behavior corresponds to that of a point target so that there is no geometric decorrelation. This permits phase interpretation even for baselines above the critical one with the advantage that more acquisitions may be included in the analysis. The second condition is that the same reflector remains present over the time period of interest to permit analysis of its phase history. For its potential to improve the spatial coverage and reduce the main error source through the use of many images over the same area, Interferometric Point Target Analysis (IPTA) was implemented and results around the Lagoon of Venice derived.

For the definition of a land subsidence monitoring service in the Lagoon of Venice the major characteristics of the various monitoring techniques were summarized (see Table 2). The integration of the various monitoring techniques to complete the limitations of each one of them from both the temporal and the spatial points of view is expected to improve the knowledge of the phenomenon. Guidelines for the integration and management of the various monitoring techniques, including costs, were defined. In addition, integrated products for regional and local use were also delineated and problems connected to result distribution and accessibility addressed.

Table 2. Comparison of the major characteristics of levelling surveys, CGPS, DGPS, ERS differential SAR interferometry, and ERS ITPA.

	Levelling	**CGPS**	**DGPS**	**INSAR**	**IPTA**
Spatial resolution	~ 900 m	few permanent stations	> 1 km	30 m	5m x 25m
Spatial characteristics	levelling lines	few significant points	levelling lines	built-up areas	point targets
Other characteristics	benchmarks may be used on exposed structures	necessary few years of data acquisition	benchmarks may be used on exposed structures		possible use of artificial point targets
Reference	Treviso	WGS84	Treviso	Treviso	Treviso
Temporal sampling	’52/‘61/‘69/‘73/‘93/‘00	hourly-daily	2-3 years	~ 7 years	~ 2 years
Vertical accuracy	~ 1-2 mm/year	~ 1-2 mm/year	~ 1 mm/km (8-10 hours)	~ 1-2 mm/year	~ 1-2 mm/year

4 Service implementation

INSAR was employed with a time series of six interferometric radar images of the ERS-1 and ERS-2 satellites from 1993 to 2000. In order to generate a single subsidence map with reduced errors, the interferometric radar images were combined (Strozzi et al., 2001). The land subsidence map was transformed to the Italian cartographic system with a spatial resolution of 30 m and Treviso was considered the stable reference. The land subsidence map of the Lagoon of Venice for the time period 1993-2000 is shown in Figure 3 with superimposed the levelling lines used for validation. As it can be observed in Figure 5 for a specific area around the Lagoon of Venice, SAR interferometry exhibits complementary characteristics to the levelling surveys, because it has the capability to map urban areas at high spatial resolution. In particular, SAR interferometry is very useful to perform detailed investigations in coastal areas: in Chioggia a significant seaward gradient in land subsidence, practically impossible to be detected by the other traditional monitoring techniques, is visible. The high precision levelling surveys, on the other hand, are used outside of the cities, as to the east of Chioggia. The high accuracy of the two surveying techniques is confirmed by their cross-validation along the levelling lines.

For IPTA (Werner et al., 2003), we considered all the available ERS SAR images between 1992 and the end of 2000. The IPTA subsidence map of the Lagoon of Venice is presented in the Italian cartographic system Gauss-Boaga, zone 2, datum Roma 1940, at a spatial resolution of 30 m. The area around the benchmark Nodale 63 (ex 24’) in Treviso was considered the stable reference. The IPTA-derived subsidence map of the Lagoon of Venice for the time period 1992-2000 is shown in Figure 4. The vertical displacement rates of the built-up areas are represented in a saturated color scale between +1.0 and -5.0 mm/year. An interpolation of the point targets was computed to improve the visibility of the map. The potential of the IPTA to improve the spatial coverage of SAR-derived subsidence maps is shown in Figure 6. Significant information is retrieved also outside Chioggia.

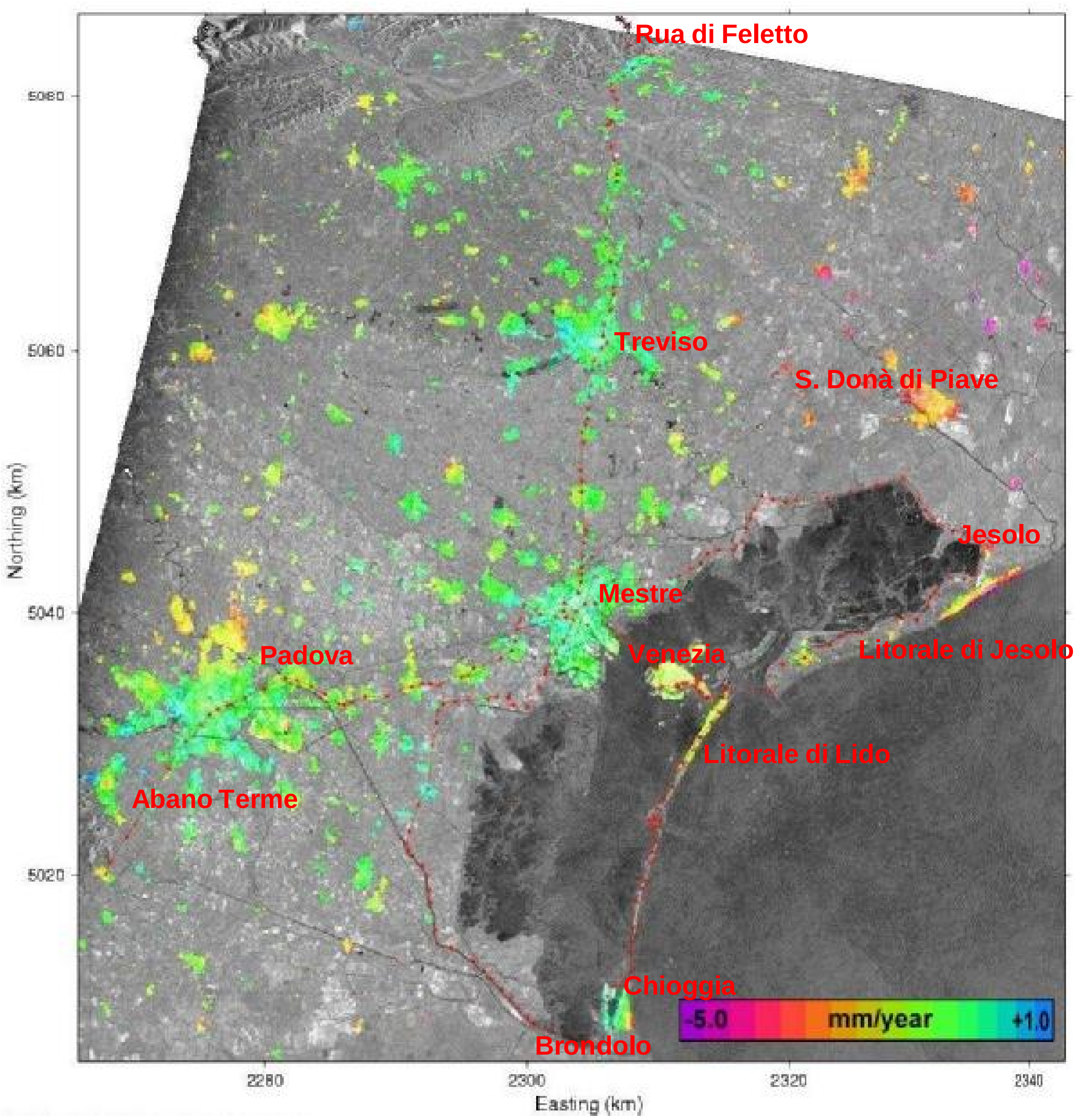

Figure 3. *INSAR land subsidence map (in mm/year) of the Lagoon of Venice for the time period 1993 - 2000 with superimposed the levelling lines used for comparison*

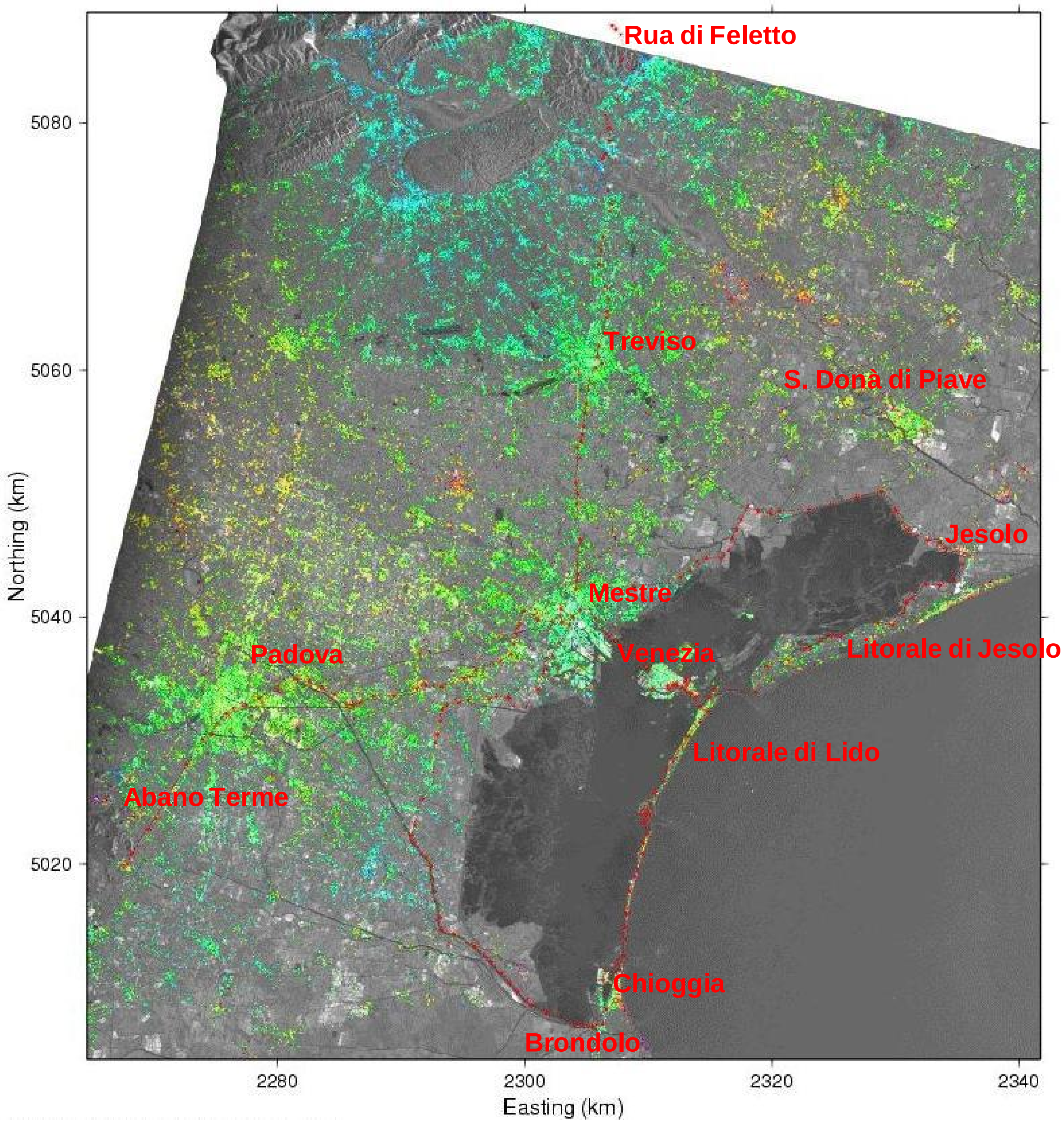

Figure 4. *IPTA land subsidence map (in mm/year) of the Lagoon of Venice for the time period 1992 - 2000 with superimposed the levelling lines used for comparison.*

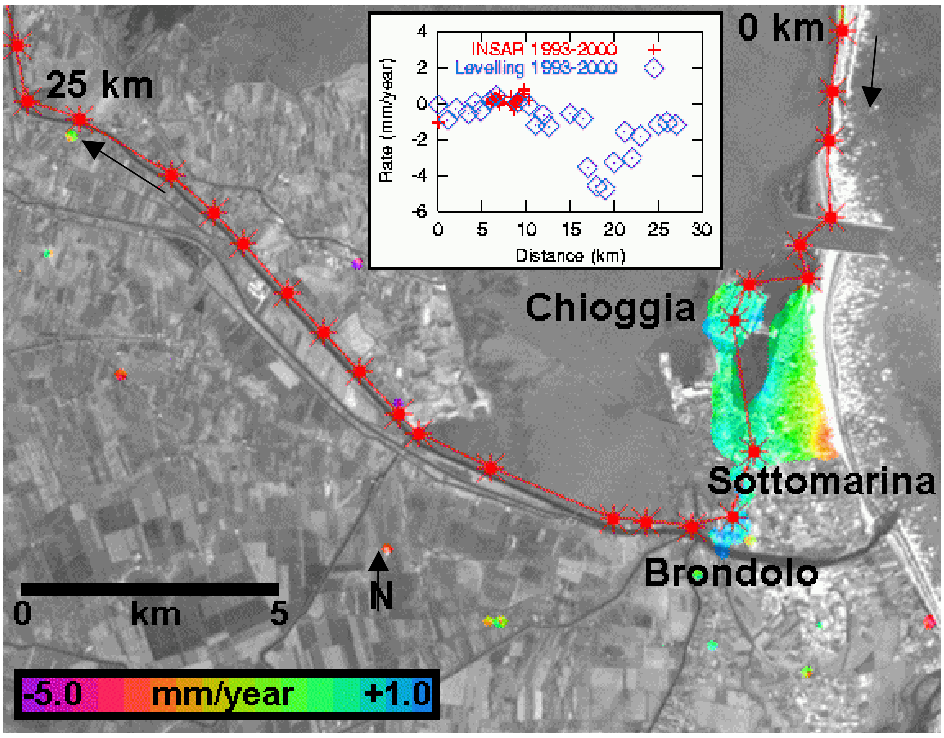

Figure 5. Land subsidence map (in mm/year) for the area of Chioggia during the time period 1993 - 2000 from INSAR with superimposed the levelling line used for comparison. Background image is an ASTER data from USGS.

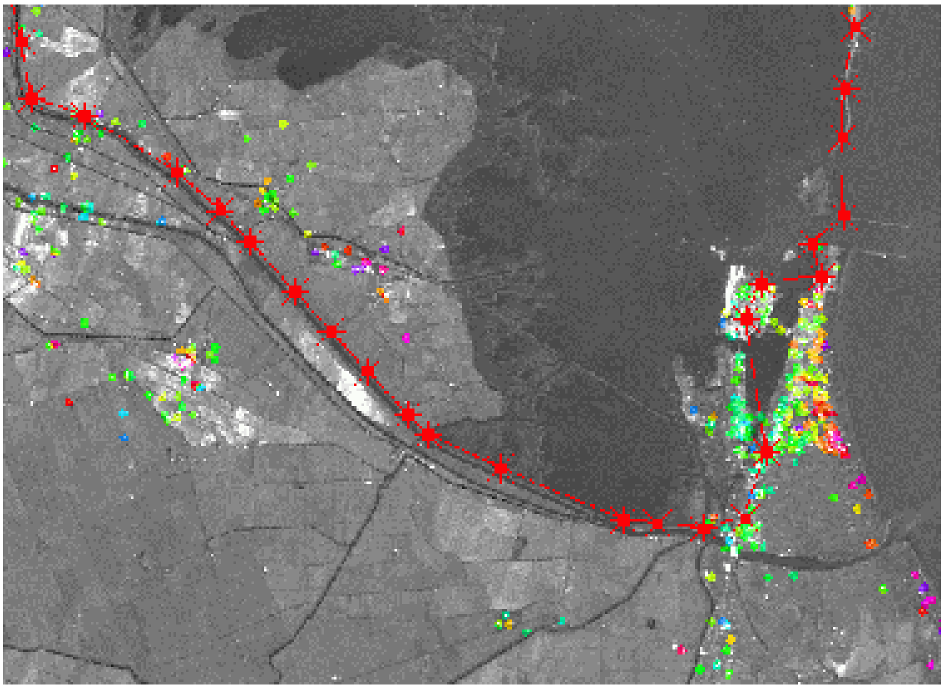

Figure 6. Land subsidence map (in mm/year) for the area of Chioggia during the time period 1991 - 2000 from the IPTA. Color scale as in Figure 5.

A comparison of the INSAR and IPTA performances for the generation of land subsidence maps around the Lagoon of Venice led to the following conclusions:

- the spatial coverage with subsidence information on urban areas is, on a regional point of view, generally similar between INSAR and IPTA;
- IPTA was however able to better identify subsidence of isolated structures;
- whereas INSAR, with the use of short baselines, and therefore the absence of spatial decorrelation, and the strong filtering, permitted to better identify small patterns of land subsidence;
- the spatial coverage with subsidence information in less urbanized environments is much better with IPTA than with INSAR;
- for suburban areas between the large cities IPTA permitted the retrieval of many points with valuable subsidence information;
- for very rural zones, however, also IPTA failed to retrieve subsidence information;
- the accuracies of INSAR and IPTA averaged subsidence rates are, in comparison with levelling data, on the order of 1 to 2 mm/year and they generally agree to each other;
- for the area in the northeast of the Lagoon, however, differences on the order of 2 to 3 mm/year were found between INSAR and IPTA, even if similar local subsidence effects were identified with both SAR-based analysis;
- only a comparison with an independent method will help us in better clarifying the error budgets of the two methods in these areas where phase unwrapping difficulties were faced because few built-up areas are present and large distances separate them.

An example of a map of vertical movement rates during the period 1993-2000 obtained through the interpolation of the INSAR and levelling measurements using the Kriging stochastic method is shown in Figure 7. Such an integration is useful for a regional overview of land subsidence and to extract profiles along any direction, e.g. the coast or a river.

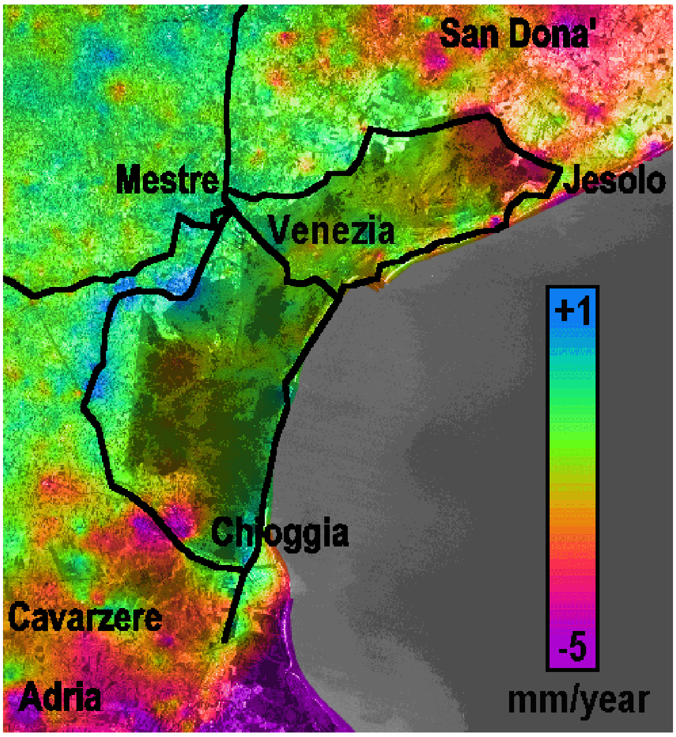

Figure 7. Map of vertical movement rates during the period 1993-2000 obtained through the interpolation of the INSAR and levelling measurements using the Kriging stochastic method.

5 Service quality assessment

The VENEZIA information service, designed to provide the best knowledge of the land subsidence process in the Po Plain area around the Venice Lagoon to the regional, administrative and water authorities that manage that area, consists of an integration of five land subsidence monitoring techniques: leveling surveys, continuous GPS (CGPS), differential GPS (DGPS), SAR interferometry (INSAR), and Interferometric Point Target Analysis (IPTA).

Product validation has been performed by the spatial validation of the geocoded SAR data and the comparison of the INSAR and IPTA results with in situ measures on specific points, along leveling lines and at aerial scale.

The estimate of the present INSAR and IPTA geocoding have shown that the SAR data can be considered adequately referenced for regional investigation at a scale less than 1:25,000. For more detailed investigation, INSAR analysis is intrinsically not applicable while IPTA should be very useful, also for monitoring single structures. Unfortunately, the geocoding of IPTA, at present, has been proven to be not sufficiently accurate and presents a variable error, depending on the location coordinates, on the order of 50-100 m.

The validation of INSAR and IPTA displacement rates have been performed by the use of in situ data from 255 leveling benchmarks and 4 CGPS. At present, DGPS results are not yet available. Different validation approaches have been applied to the calibrated INSAR and IPTA results because of the intrinsic smoothness of the INSAR results in opposition to the very high scattered distribution of the IPTA values. The validation of the INSAR data has provided a positive result. The difference between leveling and INSAR is within the accuracy of the leveling surveys (± 1 mm/year). The results of the IPTA validation showed that the method is not affected by systematic errors and that the settlement rates, although generally quite scattered, are in good agreement with results from the other EO techniques in the lagoon area, with a few local zones where the discrepancies increase. Higher differences, up to 3-4 mm/year, have been detected in a wide territory locate in the north-eastern part of the monitoring region. Validation of isolated points with subsidence rate and of logs derived from IPTA is still ongoing.

Quality assessment of VENEZIA information system consisted of a brief, concise, and straightforward presentation of user requirements versus achieved information.

The ***area*** covered by the SAR images includes all the areas of interest of the various users. Levelling and DGPS lines will, after implementation of the new lines, also cover all the areas of interest. Few continuous GPS stations were installed in particular locations of interest.

The ***spatial coverage*** achieved with land subsidence information is sufficient for a regional analysis of the land subsidence. In urban areas, through INSAR and IPTA, there is great information on land subsidence, surely meeting users requirements. For rural areas, few points are available which are nevertheless, with the integration of levelling surveys, DGPS, INSAR and IPTA, sufficient for a regional analysis. Only particular areas inside of the Lagoon and in large agricultural zones are not properly covered with land subsidence information.

Accuracies of 1 to 2 mm/years were reported for the SAR based methodologies over urban areas and are meeting user requirements. Discrepancies of 2 to 3 mm/year were reported between INSAR and IPTA for the rural areas in the south and in the northeast of the Lagoon. Cross-validation with other methods is necessary to precisely assess the ongoing sinking phenomenon of these areas.

Updated ***frequencies*** of less than one year up to 3 years are often required by the users. Logs of land subsidence available through IPTA do not usually show such short-term variability of the land subsidence rate. With IPTA it is realistic to consider that when land subsidence rate is less than few mm/year a SAR series of at least 2 years is required in order to be able to identify possible changes of subsidence rate.

The ***output data format*** was not a problem, also because interpretation of the measurements is often performed by ISMAR-CNR. Only maps, profiles and logs are delivered to the users.

Considering that INSAR and IPTA represent the most innovative elements of the service, the assessment of their processing chains was also assessed in detail. In general, we recognized that the production of land subsidence maps with INSAR and IPTA is operational at GAMMA. The modular end-to-end information service system implemented in WP 6000 may be easily adapted also to other cases. Difficulties were found in the phase unwrapping of rural zones with few built-up areas separated by large distances and for the estimation of the baselines. The interpretation of the IPTA results is still ongoing, especially for isolated subsiding points and the logs. A general error estimate was derived only for the regional averaged subsidence rate. More experience is required for the interpretation of the other two types of information, which raised, nevertheless, a certain interest by the users.

6 Service sustainability assessment

The sustainability of the VENEZIA information service was investigated in terms of costs and data availability.

Although the final objective is the management of an overall network, including all different monitoring techniques and in accordance with the guidelines of Table 3, we have to face at present difficulties that prevent us to achieve this ambitious goal. In particular, the segmentation of the users in interregional, regional and local entities, their limited budgets, and the consideration that some of the service elements (in particular CGPS but also DGPS and levelling) are managed by other organizations, are pushing us in the direction of proposing only smaller projects focused on certain parts of the overall service. For ISMAR-CNR it is then essential to have access to the results of all these projects in order to maintain them in the position of scientific advisers for the users.

In accordance with the considerations for other projects, we worked out at the end of this project a proposal for the continuation of the SAR-based service elements to be submitted to local and regional authorities. The proposal is focused on the analysis of ENVISAT ASAR data for the time period 2003-2006. After careful investigations, ERS-2 SAR data were discarded, because of the current instability of the ERS-2 platform regarding Doppler centroid and of the uncertainty regarding future acquisitions. Point target analysis in particular areas of the territory will be supported by corner reflectors and local levelling and DGPS surveys.

The cost analysis of this proposal was positively assessed by the users in an initial evaluation. However, the problem with ENVISAT ASAR data availability, in spite of a related commercial data order, is currently compromising our efforts.

Table 3. Optimal temporal plan for the integrated monitoring service within a decade.

Technique	Leveling		CGPS	DGPS	InSAR	IPTA
Time (year)	1-class	2-class				
0						
0.5						
1						
1.5						
2						
2.5						
3						
3.5						
4						
4.5						
5						
5.5						
6						
6.5						
7						
7.5						
8						
8.5						
9						
9.5						
10						

Taking into consideration that a land subsidence monitoring service integrating various techniques was a very difficult product to commercialize on an international basis, global service sustainability is assessed for the SAR based services only. This was achieved by combining elements of a business plan.

7 Service promotion

Service promotion was done both locally in the area around the Lagoon of Venice, for the future continuation of the service, and internationally for the SAR-based products and services. Regarding the SAR-based products and services, GAMMA offers, along the lines of its business activities, land subsidence maps as off-the-shell products and licenses for its processing software. Service promotion activities covered both GAMMA's business activities.

Service promotion included preparation and dissemination of application demonstration material in form of papers, brochures, and online over the Internet. Discussion on the quality, usefulness, potential, applicability, cost and limits of the products were included. Considering that the user community for the presented services is expected to include research institutes or institutes related to research, the application demonstration material included also concise scientific discussion of the technical approach used to generate the value added products.

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