Recent Subsidence of the Venice Lagoon from Continuous GPS and Interferometric Synthetic Aperture Radar

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Abstract

Coastal regions are increasingly affected by larger storms and rising sea level predicted by global warming models, aggravating the situation in the city of Venice where tidal-induced seasonal flooding coupled with natural and anthropogenic subsidence have been perennial problems. In light of accelerated efforts to protect Venice from the rise in sea level we assess land subsidence in the Venice Lagoon over the last decade. Through a combined analysis of GPS position time series from 2001.55 to 2011.00 for four stations installed by the Magistrato alle Acque di Venezia and thousands of observations of InSAR permanent scatterers using RADARSAT-1 images from 2003.3 to 2007.85, we determine that the northern lagoon subsides at a rate of 2-3 mm/yr, whereas the southern lagoon subsides at 3-4 mm/yr. The city of Venice continues to subside, at a rate of 1-2 mm/yr, in contrast to geodetic studies in the last decade of the 20th Century suggesting that subsidence has been stabilized. The GPS results indicate a general eastward tilt in subsidence and that the natural subsidence rate related to the retreat of the Adriatic plate subducting beneath the Apennines is at least 0.4-0.6 mm/yr. Our combined GPS and InSAR analysis demonstrates high spatial resolution in the vertical direction with a precision of 0.1-0.2 mm/yr with respect to a global reference frame. Continued efforts to secure the city of Venice from flooding must also take into account the significant local and regional subsidence rates as well as the expected rise in sea level.

1. Introduction

The Venice Lagoon surrounds the city of Venice and protects it from extreme sea and weather conditions coming from the Adriatic Sea (Figure 1). Steady sea level rise and land subsidence have resulted in increased flooding conditions in the lagoon. The Venice tide gauge record at Punta della Salute indicates that the relative sea level rose 0.23 m in the 20th century, in which about half (0.11 m) reflects actual sea level rise in the upper Adriatic; the remainder is attributed to land subsidence induced by natural processes and anthropogenic groundwater extraction in the 1960's [*Gatto and Carbognin*, 1981]. The natural subsidence is thought to be composed of a long-term component (10^6 yr) due to the retreat of the Adriatic plate subducting beneath the Apennines [*Carminati et al*., 2003] and a short-term component (10^3-10^4 yr) controlled by climatic changes through glaciation cycles [*Pirazzoli*, 1996; *Carminati and Di Donato*, 1999].

Relative sea level changes have resulted in increased frequency and severity of flooding (called *acqua alta* – literally high water), which had reached about two events per year greater than 1.2 m after the 1960's [*Camuffo and Sturaro*, 2004]. The last decade has seen an increase in exceptionally high events in the Venice Lagoon (http://www.comune.venezia.it). There were six events; the most recent were 0.156 m on December 1, 2008, 0.144 m on December 23, 2009, 0.145 m on December 25, 2009, and 0.144 m on December 24, 2010 during which more than half of Venice was submerged. Besides the typical devastation resulting from flooding the primary damage to Venice's art and architecture results from seawater impregnating and destroying building materials such as limestone and marble [*Camuffo and Sturaro*, 2004]. Furthermore, one-seventh of the lagoon, approximately 35 km^2, is now covered by salt marsh wetlands. The fragile fresh water ecosystems have been lost at an alarming rate (about 50% over the last century) [*Carbognin et al., 2000*].

Steps have been taken to reverse these trends with marsh restoration projects and cessation of groundwater pumping. In order to save the city, the Italian Government through the local water authority, the Magistrate alle Acque di Venezia (MAV), has completed a number of projects: 60 km of littoral protection with groins and artificial beach nourishments, 100 sites of wetland reconstruction with the re-use of dredged sediments from maintenance dredging of the navigation channels, raising the banks of the city by 0.1-0.2 m in the historical parts and up to one meter along the littorals and the other islands. Furthermore, to mitigate continued damage from increased frequency of flooding in the city of Venice the MAV has nearly completed a long-awaited project [*Gentilomo and Cecconi*, 1997] to install a series of flexible mobile flap-gates built into the inlet canal beds to close the three lagoon inlets of Lido, Malamocco, and Chioggia through which the Adriatic Sea tides enter [*Cecconi*, 2003; *SALVE*, 2011]. The project dubbed MOSE (Modulo Sperimentale Elettromeccanico – Experimental Electromechanical Module) will raise the flood gates when tides reach a pre-determined critical height of 1.1 m to a maximum height of 3 m, expected to occur up to 5 times a year. It is designed to take into account the maximum expected rise in sea level due to global warming.

The Venice Lagoon and its surroundings has a long record of geodetic observations in the 20th Century including tide gauge measurements and spirit levelling and modern methods including GPS and InSAR [e.g., *Tosi et al*., 2002; *Strozzi et al*., 2003; *Carbognin et al*., 2004]. The latest comprehensive study was by *Teatini et al*. [2005], which included complementary data collected with spirit levelling (up to 2004), differential GPS (up to 2003), and ERS-1 and ERS-2 InSAR and Interferometric Point Target Analysis (IPTA) (1992-2000). They also used continuous GPS (CGPS) data (up to 2003) including data collected by the MAV to refer the differential GPS observations. Using an integrated approach they found that the central lagoon, including the city of Venice, is stable, the northern and southern lagoon extremities subside at a rate of 3-5 mm/yr, and the coastland south of the lagoon subsides at a rate of up to 10-15 mm/yr. A study by *Teatini et al.* [2007] that relies on a further IPTA analysis of the same SAR data (1992-2000) confirms that Venice is generally stable, with only the newest sections of the city subsiding at a rate of about 1 mm/yr, and that the Sottomarina at the southern extremity of the lagoon exhibits a significant gradient of land subsidence moving from onshore to the coastline with values of about 4 mm/year. Recent construction work across the lagoon's inlets also produced localized rapid subsidence (ground settlement) with high rates of 40-70 mm/yr [*Strozzi et al.*, 2009]. The subsidence in the past decade (2000-2010) was evaluated by two limited datasets, one using differential GPS data acquired in 2000 and 2004 in the coastal area north of the Venice Lagoon [*Tosi et al.*, 2006], and the second using TerraSAR-X InSAR data with a span of only ten months (March 2008 to January 2009) focused on the effects of the MOSE project construction on the Venice littorals [*Strozzi et al*., 2009].

In this study we use two complementary datasets collected over the last decade: daily continuous GPS position time series from five stations in the years 2001-2011 and thousands of observations of permanent scatterers (PS) from RADARSAT-1 satellite images in the years 2003-2007 to provide updated estimates of subsidence in the Venice

Lagoon and its surroundings. The GPS stations provide a tie to a global reference frame and excellent temporal resolution at two lagoon sites, one in the city of Venice and two inland stations chosen to provide a stable reference for assessing local subsidence in the Venice Lagoon and the city of Venice. The SAR dataset provides excellent spatial resolution over the entire lagoon and its surroundings. Taken together and with five years of overlap, the two datasets provide an updated picture of subsidence in the Venice Lagoon and its surroundings in the first decade of the 21st Century.

2. Data Analysis

2.1 Continuous GPS Observations

A CGPS network consisting of four stations was installed by the MAV through its concessionary Consorzio Venezia Nuova, two located along the lagoon edge (CAVA in the north at Cavallino and SFEL in the south at Forte San Felice near the Chioggia inlet), and two inland (VOLT at Voltabarozzo near Padua and TREV at Treviso) to serve as reference points outside the region of expected subsidence (Figure 1). CAVA, SFEL, and VOLT were built in September 2001 and TREV in April 2004. All four stations have Dorne Margolin antenna elements with chokerings. VOLT has a deep drilled braced monument (10 m depth; 4 oblique stainless steel rods and one vertical rod) designed by the Southern California Integrated GPS Network (SCIGN) project (http://www.scign.org) for very high stability. The monuments at CAVA and SFEL are stainless steel rods embedded in massive concrete bunkers, and TREV has a building mount. The GPS antennas at CAVA, SFEL, and VOLT are protected by SCIGN antenna covers ("radomes"), while the TREV antenna is covered by a Leica radome. Daily RINEX data from these four stations as well as a fifth station within the city of Venice (VENE) operated by the Agenzia Spatiale Italiana until July 2007 were analyzed by the Scripps Orbit and Permanent Array Center (SOPAC) with respect to ITRF2005 [*Altamimi et al*., 2007] using the GAMIT software [*Herring et al*., 2010], as part of SOPAC's operational analysis of global and regional GPS data [http://sopac.ucsd.edu/processing/gamit].

Independent analysis of the time series in the three coordinate directions is justified since correlations between components are very small [*Zhang*, 1996]. The time series for the MAV stations are uninterruptible and homogeneous in that no equipment changes occurred over the period of study and no seismic events were recorded, both of which could have caused coordinate offsets. Therefore, the time series can be simply fit by weighted linear least squares with a single slope rate and annual and semi-annual terms as described by *Nikolaidis* [2002] in each component. The observed motion of each site in each direction is modeled as

$$y(t_i) = a + bt_i + c\sin(2\pi t_i) + d\cos(2\pi t_i) + e\sin(\pi t_i) + f\cos(\pi t_i) + v(t_i) \quad (1)$$

with offset and rate terms (*a*, *b*) and seasonal term coefficients (annual – *c, d;* semi-annual – *e, f*). To obtain realistic uncertainties for the parameter estimates, the measurement errors, *v*, are assumed to be temporally correlated with a white noise plus flicker noise model [e.g., *Zhang et al.*, 1997] and coefficients for the white noise and flicker noise components are derived by maximum likelihood estimation [*Williams et al*., 2004]. A negative linear change of motion (velocity) in the vertical direction (coefficient *b*) indicates site subsidence, while a positive velocity indicates uplift. The estimated seasonal terms (*c*, *d*, *e*, *f*) are converted using trigonometric relations, to amplitude and phase of annual and semi-annual displacements. The model terms in the ITRF2005 reference frame are shown in Table 1 (velocities) and Table 2 (annual and semi-annual terms). The annual phase terms are very similar with amplitudes varying from about 3-9 mm; the semi-annual phase terms vary more widely (in particular at VOLT) but have negligible (~ 1 mm or less) amplitudes. We, therefore, removed the “common-mode” annual effects from the component time series in a manner similar to the spatial filtering technique described by *Wdowinski et al*. [1997].

The ITRF2005 solution indicates horizontal movements at all stations of 16-18 mm/yr in the north component and 19-21 mm/yr in the east component (Table 1). This motion primarily reflects a rigid motion of the Eurasian plate with respect to ITRF2005 but also includes a small component due to the stations being located on its tertiary Adriatic plate. We defined a local reference frame based on the two reference sites outside of the lagoon, TREV and VOLT, by simply removing the average of their horizontal components (17.1 mm/yr in the North (N) component and 20.5 mm/yr in the East (E) component from all five GPS stations, while the vertical (U) components were untouched. In order to refer the GPS and InSAR motions to the same frame, we projected the three-dimensional GPS vectors in the local reference frame (N,E,U) into the InSAR satellite’s line of sight (LOS) (Figure 2). The LOS time series in the local MAV reference frame clean of seasonal variations were then used in the combined GPS/InSAR analysis. Since we’ve transformed the GPS horizontal motion into a local reference frame, the LOS motion mostly contains the effects of vertical motion, and the actual vertical motion is higher than the LOS motion by a factor of 1.224, which is defined by the incidence angle of the SAR acquisition (1/cos(35.2°)).

An examination of the local N,E,U and LOS velocities in Table 3 indicates significant subsidence at all stations. As expected TREV and VOLT serve as stable reference points for local subsidence within the lagoon, but are themselves subject to a subsidence of 0.3-0.5 mm/yr with respect to the global reference frame. Station CAVA on the northern lagoon is subsiding at a rate of about 3 mm/yr while station SFEL on the southern lagoon is subsiding at a higher rate of about 4-5 mm/yr. However, we notice that SFEL is also subjected to residual horizontal motion of 2-3 mm/yr and that it exhibits changes of rate in 2003 (E component) and 2005 (N component), suggesting possible instability of the SFEL monument. The vertical velocities for each of the 4 MAV stations are within 0.5 mm/yr over their entire observation span compared to their values over the period of overlap with the SAR analysis. Station VENE in the city of Venice also shows some (but less than SFEL) horizontal instability and overall non-linear behavior. Furthermore, the subsidence rate at VENE for the longer period is 1.04±0.06 mm/yr, compared to 2.62 ±0.07 for the overlap period.

2.2 InSAR Permanent Scatterers

Using the PSInSAR^{TM} method [e.g., *Ferretti et al.* 2001, *Colesanti et al.* 2003] we analysed 61 SAR scenes acquired over the Venice Lagoon by the Canadian RADARSAT-1 satellite between April 2003 and October 2007 (Figure 1). This approach is based on the identification of a set of targets in the area of interest exhibiting stable radar response over time, named permanent scatterers (PS), which can be used to estimate and remove the atmospheric disturbances affecting the radar images. Once atmospheric contributions are removed, a very precise estimation of the line of sight (LOS) motion component of each PS as a function of time, together with the target elevation, can be obtained [*Colesanti et al.* 2003]. For this study, more than 600,000 PS were identified in the region of interest corresponding to a density of about 230 PS/km^2. This approach has been already applied to monitor surface motion in many different applications including landslide monitoring [*Hilley et al,* 2004], volcano monitoring [*Salvi et al.,* 2005], and subsidence analysis [*Vasco and Ferretti,* 2005; *Dixon et al.,* 2006].

3. Combined GPS/InSAR Analysis

The combination of the GPS and PS observations seems straightforward, but actually requires a careful analysis because the PS targets do not necessarily coincide with the CGPS station locations and PS observations are differential. We initially chose an arbitrary reference benchmark in the middle of the Venice Lagoon near the city of Venice for the InSAR analysis. However, we noticed that the GPS vertical results displayed a significant tilt across the region of interest of several mm/yr. Therefore, we selected for each CGPS station a subset of PS located nearest to the CGPS station to test for the stability of the GPS monument with respect to its surroundings (Figure 3). This step was motivated by the non-linear motion of SFEL (Figure 2) but also to account for possible spatial heterogeneities in the site motion. The PS selection radius was chosen to guarantee a sufficient number of homogeneous PS (with low velocity dispersion) as close as possible to the GPS avoiding a large radius where possible. The actual PS velocity value for each GPS station was derived by averaging using a covariance matrix accounting for the PS coherence values (Table 4).

In order to tie the PS observations to the GPS reference frame, we fit a plane to the differences between PS and GPS LOS velocities of the 4 MAV GPS stations. Because the plane fitting consists of three parameters (N-gradient, E-gradient, and vertical offset) and there are four independent observations, the fit has only one degree of freedom. We then applied the predicted tilt by the plane as a correction to the PS observations and, thus, tied the velocity field to an absolute reference frame defined through GPS analysis in ITRF2005 (Figure 4). The comparison between CGPS and PS LOS velocities and the results of the GPS/PS calibration are shown in Table 4. We excluded GPS station VENE from the calibration process because of its shorter overall time span, its non-linear behavior, the large discrepancy in subsidence between the entire period and the period of overlap, and its location on a building in an urban environment.

4. Discussion

Our joint GPS/InSAR analysis allows us to accurately monitor subsidence of the land surrounding the Venice Lagoon and in the city of Venice by exploiting the strengths and minimizing the weaknesses of each technique. The accurate low-spatial-resolution GPS point vertical velocities are used to correct the precise high-spatial-resolution PS velocities for a tilt across the area of interest and reference the vertical motions with respect to an absolute reference frame (ITRF2005). A closer look at the PS distribution around the station SFEL (Figure 3) shows that the structure holding the SFEL station indeed moves independently of the nearby structures. The monument at SFEL is a stainless steel rod embedded in a massive concrete bunker, which we assumed to be stable at the time of installation. Thus, using the PS information around each station we have being able to still use SFEL in the calibration after isolating its local instability relative to its surroundings. In Table 4, the calibrated LOS velocity values at the stable reference stations TREV and VOLT are -0.37 ± 0.28 and -0.47 ± 0.13 mm/yr, respectively. At CAVA on the northern lagoon the LOS velocity is -2.34 ± 0.16 mm/yr and at SFEL in the southern lagoon it is -4.53 ± 0.17 mm/yr. Note again that the GPS point velocity at VENE was not used in the plane fitting and that after calibration the LOS velocity of VENE is -1.23 ± 0.29 mm/yr, which corresponds to a subsidence rate of about 1.5 mm/yr.

The results of the combined GPS/PS analysis are presented in Figure 4a as the annual average displacement rate along the LOS. The precision of the estimated motion varies as a function of the distance from the reference benchmark, as shown in Figure 4b where the *a posteriori* standard deviation of the annual average velocity along the Venice Lagoon is in the range of 0-1 mm/yr. Thus, the PS analysis provides a highly precise measurement of deformation with high spatial resolution. This is further demonstrated in Figure 5 where the GPS and InSAR results are overlain for the four MAV GPS station locations. The scatter in the InSAR point scatterers is clearly less than the GPS. Considering also that the GPS-derived vertical velocities uncertainties are based on a noise model that takes into account the temporal correlations in the daily time series [*Williams et al*., 2004], it is clear that the combined GPS/InSAR result provides both a highly accurate and precise absolute measurement with high spatial resolution at an uncertainty of 0.1-0.2 mm/yr.

The analysis clearly shows up to 4 mm/yr of subsidence along the Cavallino Littoral in the northern lagoon and south of Chioggia/Forte S. Felice in the Sottomarina area.

There is about 1-2 mm/yr of subsidence along the Lido Littoral, the Marghera Industrial Area, and in the City of Venice. There is no apparent subsidence along the Pellestrina Littoral, indicating that littoral protection efforts by the MAV have been effective in the southern lagoon.

Our combined analysis indicates continued subsidence of 1-2 mm/yr in the city of Venice, as seen in Figure 4a in the vicinity of GPS station VENE (with a subsidence rate of 1.5 ± 0.3 mm/yr), and in Figure 6 for the entire city (dominated by yellow PS dots). There appear to be a few localized effects (isolated orange dots in Figure 6) indicating slightly higher rates of subsidence. Our results differ from the results of *Teatini et al.*, 2005 and 2007 who indicated a more stable situation in the city. This could be due to an actual change in subsidence rate over the last decade, or to a possible bias (tilt) in their IPTA analysis, similar to the one that we have corrected for in our analysis. It is more likely that the subsidence rate has been steady over the last two decades, and that total subsidence in Venice over this period has been 20 to 40 mm.

We reiterate that although point scatterer methods are highly precise, they do not provide an accurate estimate of subsidence rates since they are differential by nature. Continuous GPS stations within the SAR images as shown in this paper provide observations of absolute vertical deformation with high temporal resolution at a precision of 0.1-0.2 mm/yr with respect to the global reference frame. They can be used to correct for systematic errors in InSAR analysis due to troposphere refraction and orbital errors, which can manifest themselves as tilts. On the other hand care must be taken that the GPS monuments are stable; this can be verified by precise point scatterer observations as shown in this paper near one of the GPS stations. Therefore, it is good practice to include a sufficient number of continuous GPS stations within the project area. In any case, it is not sufficient for large regional analyses of subsidence with point scatterer methods (e.g., *Teatini et al.* 2011) to use a single reference point.

The increase in eustasy due to global warming in the last decade as exhibited by the increase in exceptionally high acqua alta events in Venice (http://www.comune.venezia.it) and the here documented continued subsidence over the last decade of 1-2 mm/yr continue to stress the city and its surroundings. Based on the GPS results at the two inland stations, we infer that subsidence due to natural processes at work in the Venice Lagoon, specifically the larger geodynamic system manifested by the retreat of the Adriatic plate subducting beneath the Apennines are at least 0.5 mm/yr, as compared to 0.7-1.0 mm/yr estimated from the thickness of Pleistocene sediments recorded in industrial wells [*Carminati et al*., 2003]. The difference is probably due to shorter term uplift due to post glacial rebound in the late Pleistocene [*Carminati and Di Donato*, 1999], rather than uplift from thrust faulting [*Carminati et al.*, 2003, Figure 4]. If indeed it is the former there could be a small discrepancy due to our reference frame being ITRF2005 which is related to the ellipsoid rather than the geoid used as a reference in post glacial rebound studies. However, there is no reason to assume a tilt of the geoid relative to the ellipsoid in this region (e.g., *Caporali*, 1993). The remaining natural subsidence within Venice and its surroundings is most likely due to Holocene sediment compaction and consolidation due to surface loads [*Carminati and Di Donato*, 1999; *Teatini et al.*, 2011] rather than anthropogenic causes such as fluid (water and hydrocarbon) extraction from the subsurface, which has been minimized through regulation.

4. Conclusions

We have estimated through combined analysis of continuous GPS and InSAR point scatterers in the first decade of the 21st Century that the city of Venice and its surroundings are still subsiding. The extremities of the northern and southern lagoons are subsiding at a rate of 3-4 mm/yr, while subsidence of the littorals appears to have been stabilized. The city of Venice is subsiding at a rate of 1-2 mm/yr from natural processes, stressing the importance of efforts to secure the city from flooding, in particular the MOSE project to raise the flood gates during high tides in the Adriatic Sea. Efforts to secure the city, therefore, need to take into account the natural subsidence in addition to the maximum expected rise in sea level due to global warming.

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Figure Captions

Figure 1. Map of study area showing locations and photos of the MAV CGPS stations and the coverage of the processed RADARSAT-1 data (track 154).

Figure 2. GPS time series in the MAV reference frame. The red lines show the best fit curve using linear and seasonal (annual and semi-annual) terms. The Line of Sight (LOS) time series was computed according to the Radarsat-1 parameters after removing the modeled seasonal terms. The green data points in the LOS plots show the unfiltered time series containing seasonal changes, which is masked by the filtered series (blue). The slopes are in mm/yr.

Figure 3. LOS surface changes at the GPS stations (white circles) and the surrounding PS targets. The red circles include the PS targets used in the GPS/InSAR calibration.

Figure 4. (a) Annual average rate of LOS surface displacement in mm/yr estimated for all the PS identified in the area. CGPS stations are denoted by circles and labeled with their four-character codes. (b) *Posteriori* standard deviation of the PS annual average rate in mm/yr.

Figure 5. PSInSAR and CGPS time series projected along the satellite line of sight.

Figure 6. Annual average rate of LOS surface displacement in mm/yr estimated for the PS identified in the city of Venice.

Table 1. CGPS site velocities in the ITRF2005 reference frame

Site/Data Span	**Geodetic Latitude [a] (N)**	**Geodetic Longitude (E)**	**North (mm/yr)**	**East (mm/yr)**	**Up (mm/yr)**
CAVA - Cavallino					
2001.554 - 2011.0014[b]	45° 28′ 45.7″	12° 34′ 57.6″	17.51 ± 0.03[d]	20.71 ± 0.03	-3.28 ± 0.06
2003.3-2007.85 [c]			17.54 ± 0.03	20.72 ± 0.03	-3.07 ± 0.15
SFEL - Chioggia Inlet					
2001.547 - 2011.0014	45° 13′ 48.1″	12° 17′ 28.9″	15.17 ± 0.03	18.10 ± 0.03	-4.81 ± 0.09
2003.3-2007.85			15.63 ± 0.06	17.92 ± 0.06	-3.97 ± 0.15
TREV - Treviso					
2004.335 - 2011.0014	45° 39′ 50.2″	12° 15′ 23.5″	17.06 ± 0.03	20.31 ± 0.03	-0.36 ± 0.09
2004.335-2007.85			17.00 ± 0.06	20.41 ± 0.06	-0.38 ± 0.27
VENE - Venice					
2001.552 - 2007.563	45° 26′ 13.1″	12° 19′ 55.2″	17.16 ± 0.06	19.92 ± 0.09	-0.87 ± 0.21
2003.3-2007.563			17.57 ± 0.12	19.20 ± 0.12	-2.25 ± 0.24
VOLT - Paduva					
2001.600 - 2011.0014	45° 23′′ 4.5″	11° 54′ 39.3″	17.08 ± 0.03	20.60 ± 0.03	-0.42 ± 0.06
2003.3-2007.85			17.12 ± 0.03	20.56 ± 0.03	-0.66 ± 0.12

[a] With respect to WGS84 ellipsoid

[b] The first velocity is for the entire period analyzed in this study.

[c] The second set is for the overlap period with the InSAR processing.

[d] The "one-sigma" velocity uncertainties are based on a white noise plus flicker noise model.

Table 2. CGPS site velocities in the local MAV reference frame and satellite line of sight.

Site/Data Span	North (mm/yr)	East (mm/yr)	Up (mm/yr)	Line of Sight (mm/yr)
CAVA - Cavallino				
2001.554 - 2011.0014[a]	0.41 ± 0.03 [c]	0.21 ± 0.03	-3.28 ± 0.06	-2.61 ± 0.07
2003.3-2007.85 [b]	0.44 ± 0.03	0.22 ± 0.03	-3.07 ± 0.15	-2.44 ± 0.16
SFEL - Chioggia Inlet				
2001.547 - 2011.0014	-1.93 ± 0.03	-2.40 ± 0.03	-4.81 ± 0.09	-5.04 ± 0.10
2003.3-2007.85	-1.47 ± 0.06	-2.58 ± 0.06	-3.97 ± 0.15	-4.51 ± 0.17
TREV - Treviso				
2004.335 - 2011.0014	-0.04 ± 0.03	-0.19 ± 0.03	-0.36 ± 0.09	-0.40 ± 0.10
2004.335-2007.85	-0.10 ± 0.06	-0.09 ± 0.06	-0.38 ± 0.27	-0.35 ± 0.28
VENE - Venice				
2001.552 - 2007.563	0.06 ± 0.06	-0.58 ± 0.09	-0.87 ± 0.21	-1.04 ± 0.24
2003.3-2007.563	0.47 ± 0.12	-1.30 ± 0.12	-2.25 ± 0.24	-2.62 ± 0.29
VOLT - Paduva				
2001.600 - 2011.0014	-0.02 ± 0.03	0.10 ± 0.03	-0.42 ± 0.06	-0.28 ± 0.07
2003.3-2007.85	0.02 ± 0.03	0.06 ± 0.03	-0.66 ± 0.12	-0.51 ± 0.13

[a] The first velocity is for the entire period analyzed in this study.

[b] The second set is for the overlap period with the InSAR processing.

[c] The "one-sigma" velocity uncertainties are based on a white noise plus flicker noise model.

Table 3. Periodic terms for GPS vertical components.

Site	Annual		Semi-annual	
	Amplitude (mm)	Phase (radian)	Amplitude (mm)	Phase (radian)
CAVA	4.43	-1.95	0.54	0.48
SFEL	4.10	-2.13	0.90	0.13
TREV	6.64	-1.94	1.40	0.42
VENE	8.68	-1.80	1.53	0.62
VOLT	3.31	-2.15	0.28	2.61

Table 4. A comparison between CGPS and PS average rate of LOS motion.

GPS Station	V_{CGPS}[a] (mm/yr)	$V_{CGPS-PS}$[b] (mm/yr)	V_{PS}[c] (mm/yr)	$V_{PS-nocorr}$[d] (mm/yr)	#PS[e]	D_m[f] (m)	σ_{PS}[g] (mm/yr)
CAVA	-2.61 ± 0.07	-2.44 ± 0.16	**-2.34 ± 0.16**	-1.82	6	36	0.80
SFEL	-5.04 ± 0.10	-4.51 ± 0.17	**-4.53 ± 0.17**	-3.71	2	13	0.21
TREV	-0.40 ± 0.10	-0.35 ± 0.28	**-0.37 ± 0.28**	-1.84	4	35	0.97
VENE[h]	-1.04 ± 0.24	-2.62 ± 0.29	**-1.23 ± 0.29**	-1.33	16	33	0.47
VOLT	-0.28 ± 0.07	-0.51 ± 0.13	**-0.47 ± 0.13**	-1.61	12	64	0.95

[a] CGPS LOS velocity over the entire length of the GPS time series (e.g., 2001.554 - 2011.0014 for CAVA) as shown in Table 3.

[b] CGPS LOS velocity over the PS database time period (2003.3-2007.8), as shown in Table 3.

[c] PS velocity after fitting a plane through the differences between the GPS and PS velocity values.

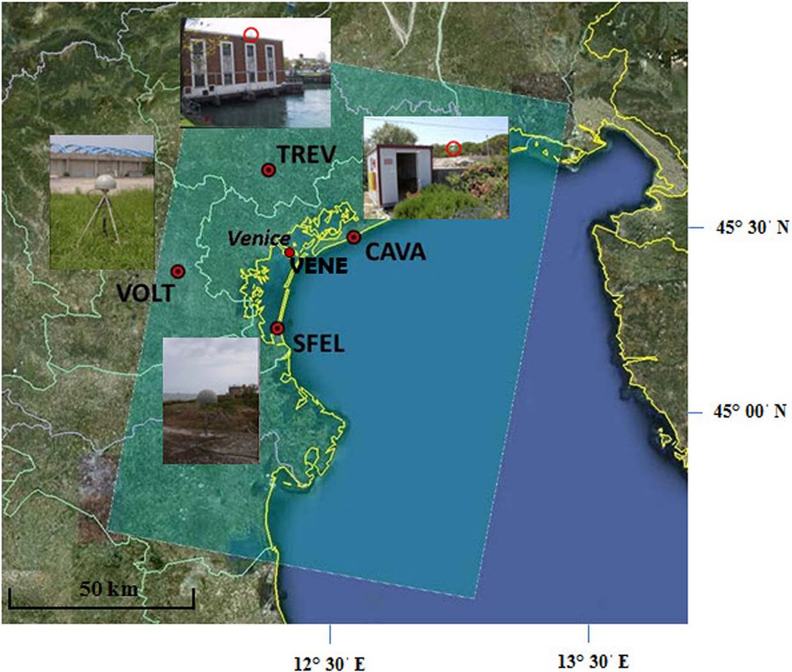
[d] PS velocity without GPS calibration.

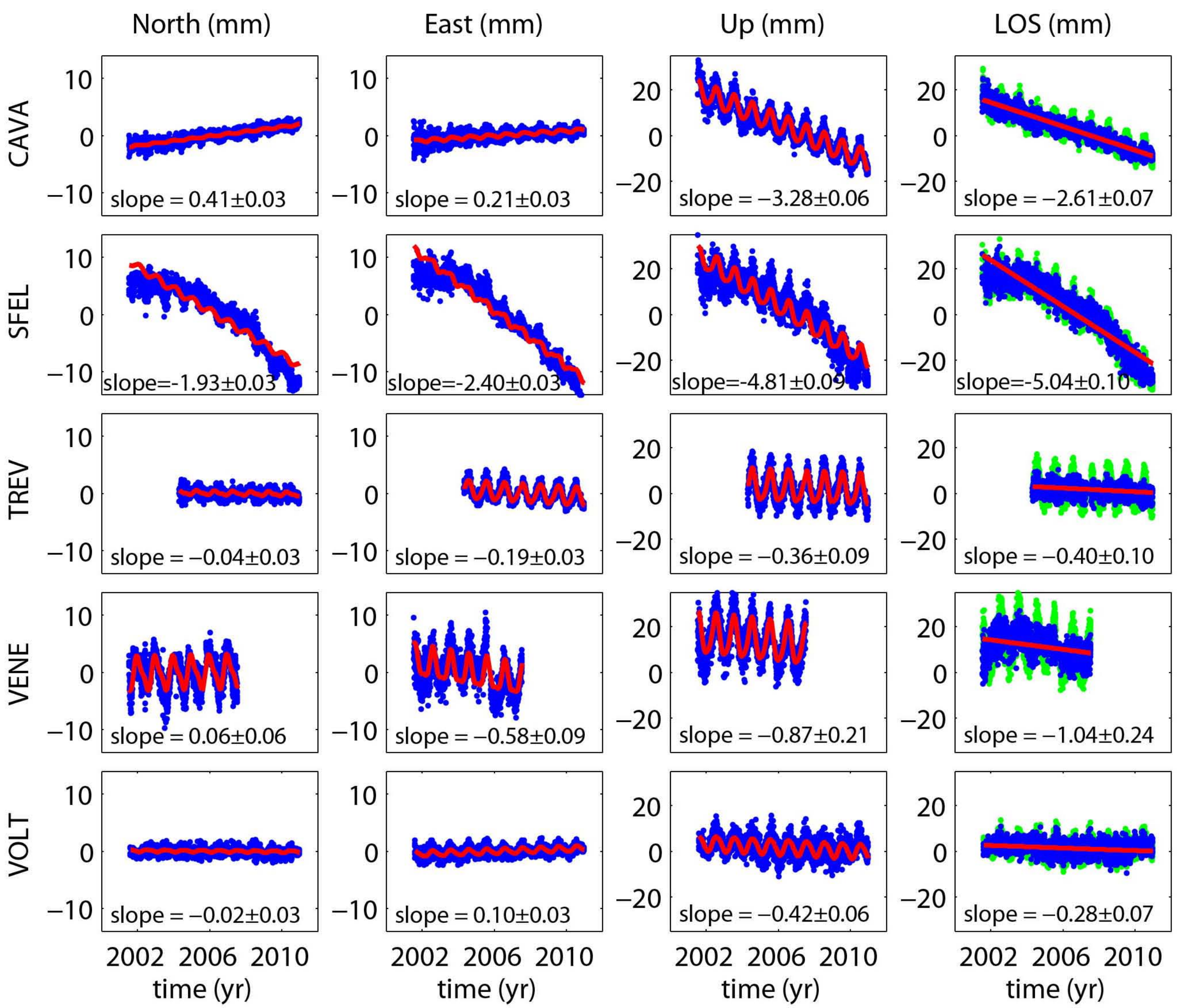
[e] Number of PS averaged for each CGPS station (see Figure 3).

[f] Average distance of the selected PS from the station.

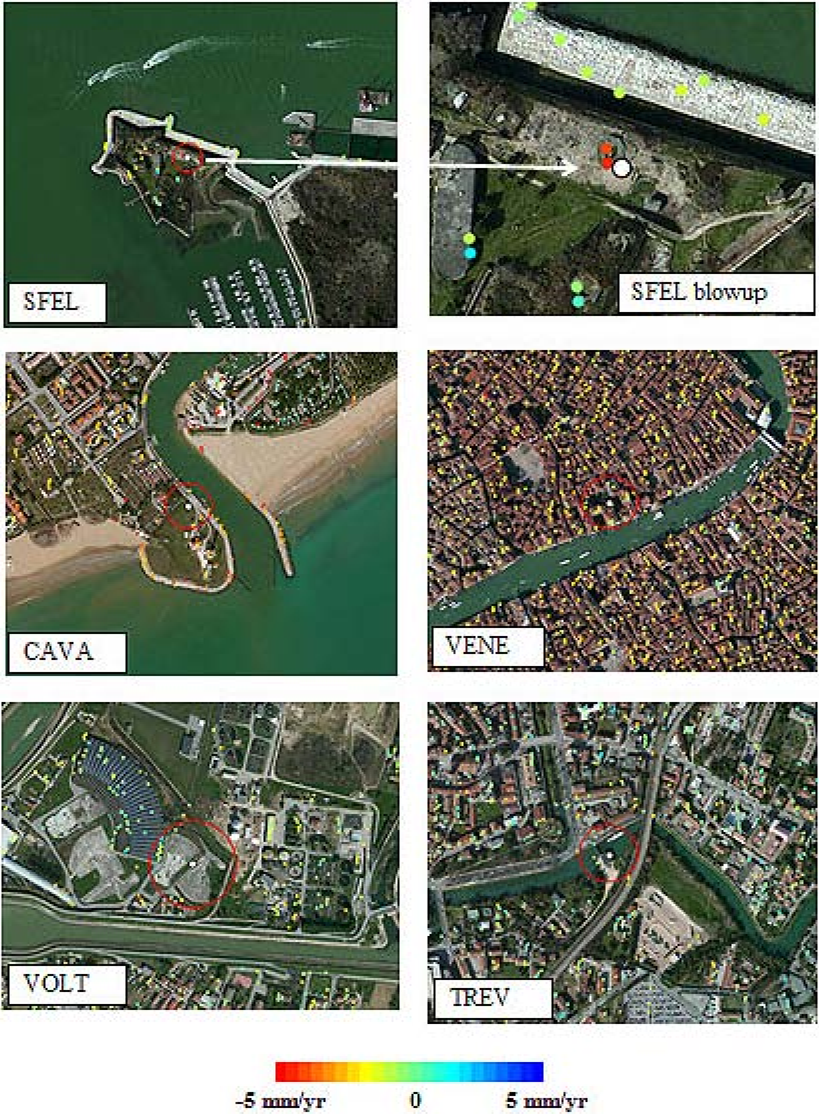
[g] standard deviation of the velocity of the selected PS.

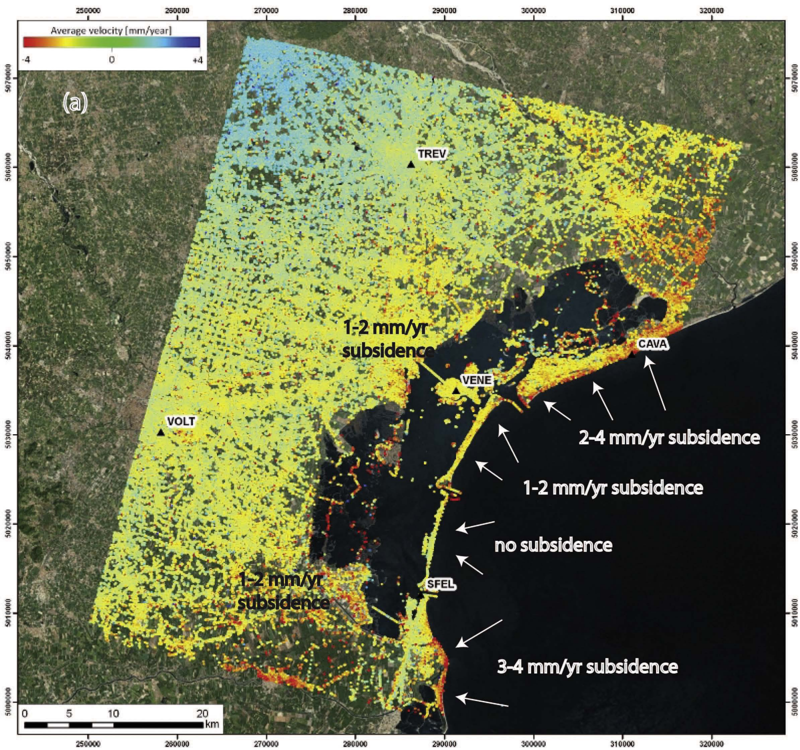
[h] Station VENE was not used in the estimation of the planar surface.

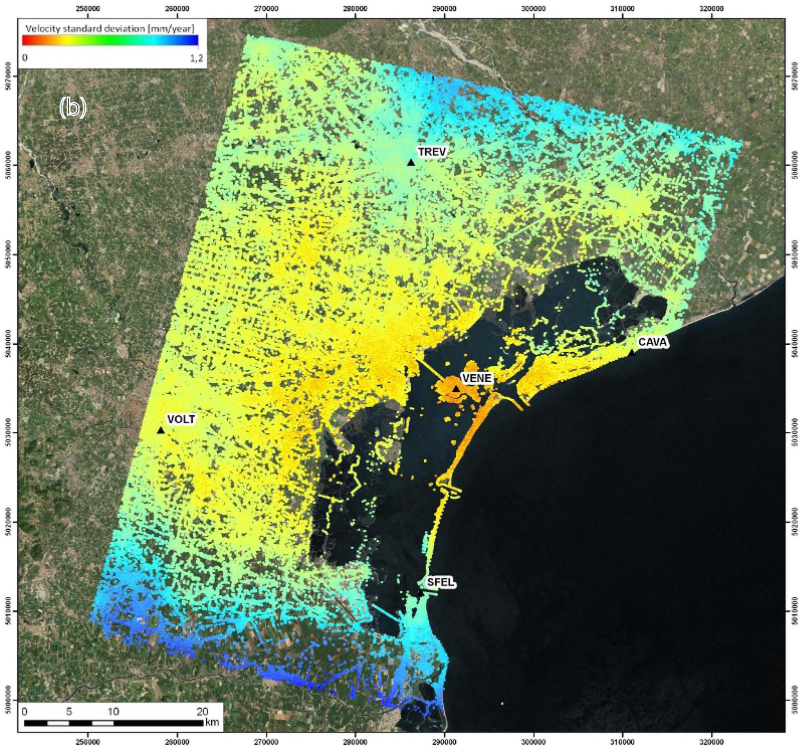

TREV
Venice
CAVA
VENE
VOLT
SFEL
45° 30′ N
45° 00′ N
50 km
12° 30′ E
13° 30′ E

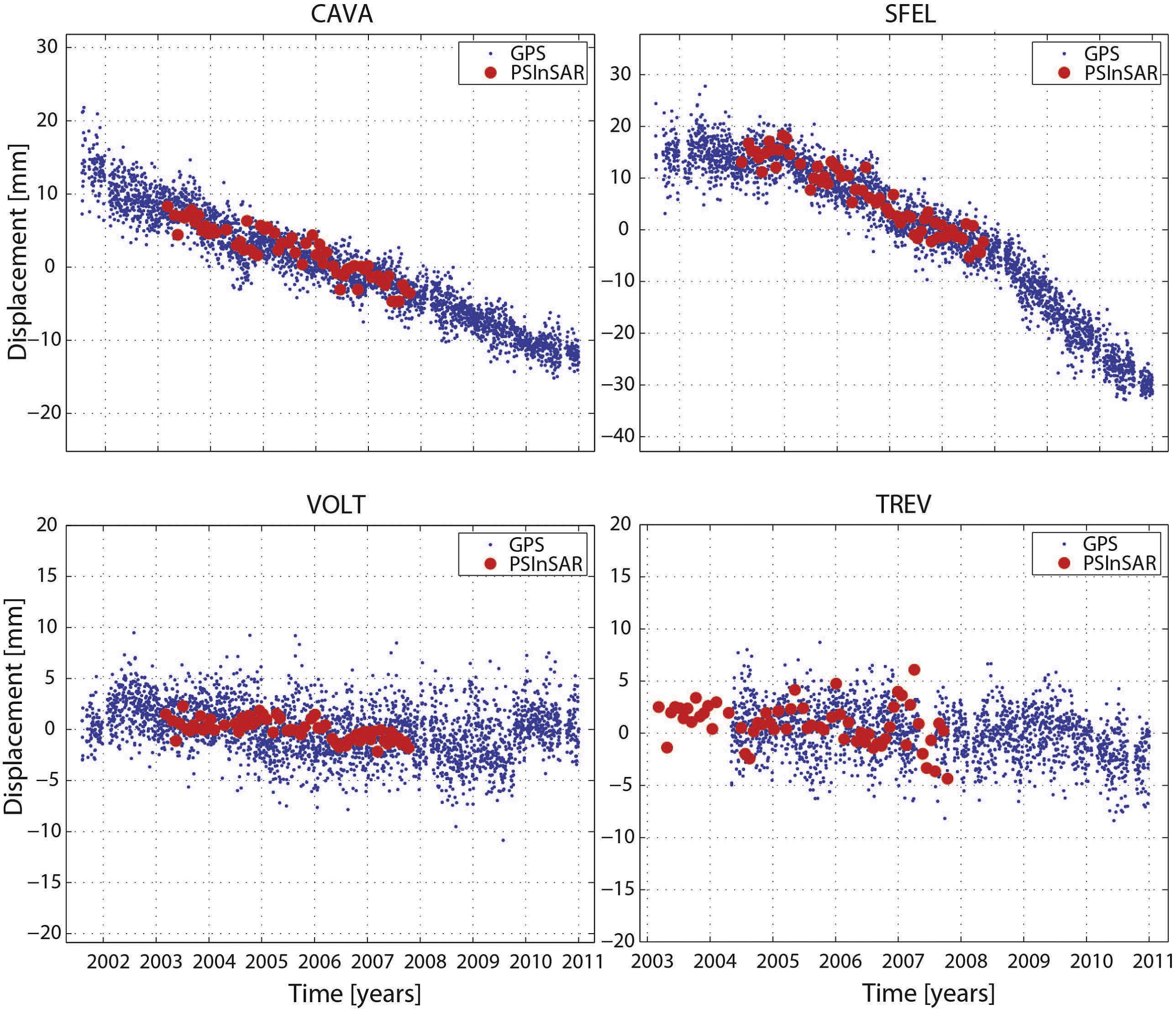


North (mm)
East (mm)
Up (mm)
LOS (mm)
CAVA
SFEL
TREV
VENE
VOLT
slope = 0.41±0.03
slope = 0.21±0.03
slope = −3.28±0.06
slope = −2.61±0.07
slope=-1.93±0.03
slope=-2.40±0.03
slope=-4.81±0.09
slope=-5.04±0.10
slope = −0.04±0.03
slope = −0.19±0.03
slope = −0.36±0.09
slope = −0.40±0.10
slope = 0.06±0.06
slope = −0.58±0.09
slope = −0.87±0.21
slope = −1.04±0.24
slope = −0.02±0.03
slope = 0.10±0.03
slope = −0.42±0.06
slope = −0.28±0.07
time (yr)
time (yr)
time (yr)
time (yr)

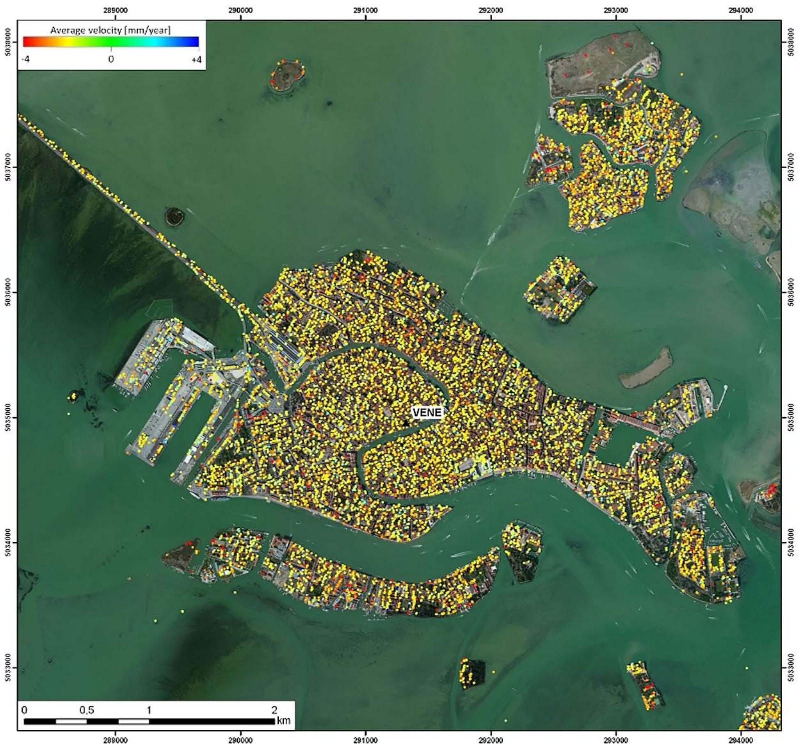

SFEL
SFEL blowup
CAVA
VENE
VOLT
TREV
-5 mm/yr
0
5 mm/yr


Average velocity [mm/year]
-4
0
+4
(a)
TREV
VOLT
VENE
CAVA
SFEL
1-2 mm/yr subsidence
2-4 mm/yr subsidence
1-2 mm/yr subsidence
no subsidence
1-2 mm/yr subsidence
3-4 mm/yr subsidence
0
5
10
20
km
250000
260000
270000
280000
290000
300000
310000
320000
5070000
5060000
5050000
5040000
5030000
5020000
5010000
5000000


Velocity standard deviation [mm/year]
0
1,2
(b)
TREV
VOLT
VENE
CAVA
SFEL
0
5
10
20
km
250000
260000
270000
280000
290000
300000
310000
320000
5070000
5060000
5050000
5040000
5030000
5020000
5010000
5000000



CAVA
SFEL
VOLT
TREV
GPS
PSInSAR
Displacement [mm]
Time [years]
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011



Average velocity [mm/year]
-4
0
+4
VENE
0
0,5
1
2
km
289000
290000
291000
292000
293000
294000
5038000
5037000
5036000
5035000
5034000
5033000