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A Combination of Space and Terrestrial Geodetic Techniques to Monitor Land Subsidence: Case Study, the Southeastern Po Plain, Italy

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[1] The southeastern Po Plain is affected by high natural and anthropogenic subsidence. The area is well suited to test the application of an observational strategy which combines different techniques to extract information on the spatial and temporal variability of the subsidence. The simultaneous availability, at a few stations, of several geodetic observation techniques such as Global Positioning System (GPS), gravity, and Interferometric Synthetic Aperture Radar (InSAR) allows for validation of the individual time series. The combination takes advantage of the complementary strengths of each technique by overcoming the limitations inherent in each single technique alone. The combination of velocities derived from the GPS and gravity data, further complemented by the results of the InSAR Permanent Scatterers technique, allows us to monitor continuously, in space and time, vertical crustal movements. This high-density information is of major importance for understanding the processes responsible for the observed deformation. Here long-term trends were derived, enabling us to map the behavior of subsidence (even exceeding 20 mm/yr) with high spatial resolution in the southeastern Po Plain. The uplifting behavior of the Apennines chain bordering the Po Plain is identified together with a narrow zone separating the contrasting vertical crustal movements.

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1. Introduction

[2] Our present knowledge of the surface deformation of the Earth is still discontinuous both in the temporal and spatial domain. A detailed knowledge of the crustal deformation at fine scales is a fundamental issue for achieving an increased understanding of the processes acting at the surface of the Earth as well as in its interior. For example, monitoring the surface deformation before and after earthquakes is essential for providing important insights into the evolution of the strain accumulation phase, transients, and the seismogenic cycle.

[3] Nowadays space geodesy, in conjunction with terrestrial techniques, provides the means to monitor land-surface deformation with high spatial and temporal resolution as referred to a global reference system. The current accuracy of the individual space geodetic techniques is mainly limited by the systematic errors of the individual techniques themselves as well as by our understanding of the geodynamic driving mechanism at the observational timescales. The first step of a methodological approach based on the combined use of several techniques must be a systematic procedure of colocation extended over a certain period of time to allow for the validation and the intercomparison of the individual observations. This enables us to identify problematic data and further lays the basis for exploiting the potential of each single technique.

[4] In this paper, we present a multidisciplinary approach that combines observations derived from continuous Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), and terrestrial gravimetry in combination with times series of local environmental parameters to estimate subsidence in the southeastern Po Plain. By using the Permanent Scatterers (PS) technique of InSAR [*Ferretti et al.*, 2001], we extend our knowledge of the velocity field in space. There is a long history of gravity, GPS, and InSAR observations in this region [*Wegmueller et al.*, 2000; *Zerbini et al.*, 2002].

[5] The length of the height time series is important. In fact, nonlinear variations, mainly driven by environmental forces but also of tectonic origin, might contaminate the comparisons. The modeling of environmental effects has proven to be very important in understanding the long-term height variations [*van Dam et al.*, 2001; *Zerbini et al.*, 2004].

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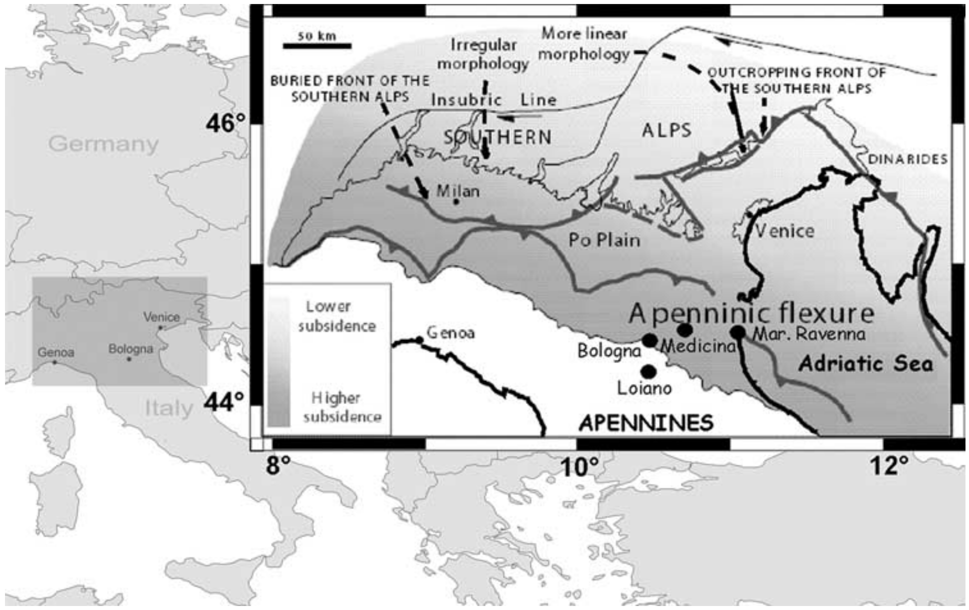

Figure 1. Distribution of natural subsidence rates in northeastern Italy [after *Carminati et al.*, 2003] and location of the permanent GPS stations (black dots). Except for the Loiano site, which is on the uplifting and extensional belt of the Apennines, the other three stations are located in the area of the Po Plain where natural subsidence is highest. Bologna and Medicina are in the southern Po Plain, close to the Pede-Apenninic margin, while Marina di Ravenna lies on the easternmost coastal Plain on the Adriatic Sea at the very front of the Apennines' accretion prism [*Doglioni*, 1993].

[6] The Po Plain and the northern Adriatic Sea is a rapidly subsiding basin surrounded by three uplifting mountain belts, the Alps, the Apennines, and the Dinarides. The geological setting and the locations of the continuously observing GPS stations are given in Figure 1. Although the historical deformation of these regions is well constrained from geological evidence, a measurement of the present-day vertical motions is discontinuous both in space and in time. Natural subsidence affects the entire Po Plain and decreases from the south, where it exceeds 1 mm/yr, to north. According to *Carminati et al.* [2003], the subsidence is related to the northeastward retreat of the Adriatic subduction zone. During the second half of the last century, exploitation of subterranean fluids, primarily water and gas, has significantly increased the natural long-term behavior, in particular in the southeastern part of the plain and along the northern Adriatic coast. At local scales, anthropogenically driven subsidence rates of 10 to 20 mm/yr have superimposed onto the regional tectonic component.

2. The Techniques

[7] The Department of Physics of the University of Bologna (UNIBO), Italy, in 1996, initiated a program to install a network of permanent GPS stations in the southeastern Po Plain (Italy), with the aim of monitoring and studying land subsidence in the region. The stations considered for this study are Medicina, Marina di Ravenna, Bologna, and Loiano (see Figure 1). The first two GPS receivers were installed in July 1996 at Medicina, close to Bologna, and Marina di Ravenna on the Adriatic coast. Both stations have been operational since the installation. The GPS station at Medicina has recently become an European Permanent Network (EPN) site (MSEL). Since the early 1990s, the station has been equipped with a 32-m Very Long Baseline Interferometry (VLBI) antenna. In October 1996, the Bundesamt fuer Kartographie und Geodaesie (BKG, Frankfurt, Germany) installed the GWR Superconducting Gravimeter, (SG) C023. The SG has been operative since then. Its behavior is periodically checked by means of absolute gravity (AG) measurements. Several environmental data series, such as water table heights, hydrological balance time series, meteorological data, and radio-sonde profiles, are being collected at the station to provide additional data sets for modeling the seasonal effects (e.g., surface mass loading, soil compaction, change in the center of mass of the atmosphere, etc.) in the crustal displacements and gravity variations.

[8] The Marina di Ravenna area is characterized primarily by anthropogenic-driven subsidence. The GPS receiver there was installed in the harbor in close proximity to the tide gauge, which is also being used for sea-level variation studies [*Zerbini et al.*, 1996; *Becker et al.*, 2002]. Because of the large subsidence rates, which affected the area until about 1980 when groundwater control policies were initiated, leveling data have also been collected in this region since 1950.

[9] The GPS station in Bologna (BOLG) has operated continuously since 1999, and the station is now part of the EPN. Since 2002, absolute gravity measurements have been performed biannually with the FG5 gravimeter. The measurements are taken in the same building to which the BOLG GPS antenna is attached.

[10] The GPS station at Loiano only became operational in 2003. The time series is rather short; however, we feel there is value in considering these data because the station is located outside the subsiding Po Plain. These data should be tectonically independent from the other GPS solutions and should show the uplifting behavior of the Apennines.

[11] For the geographical area of interest to this study, InSAR images are available.

2.1. GPS

[12] With the advent and continued evolution of the routine operation of the International GPS Service for Geodynamics (IGS) since 1992, now the International Global Navigation Satellite System (GNSS) Service, GPS has been used in an efficient way for geodynamics studies, varying in spatial scale from tens of kilometers to global-scale studies. The current accuracy of the IGS products is 3, 3, and 6 mm for weekly mean values of the north, east, and up coordinates, respectively, and 2, 2, and 3 mm/yr for the associated linear velocities [see http://igscb.jpl.nasa.gov/components/prods.html, *Altamimi et al.*, 2001]. GPS is, at present, the only time-continuous geometric geodetic observation, and it provides absolute coordinates with respect to a global well-defined geocentric reference system. However, spatially, the information is limited to the station location. Though the potential for unlimited spatial densification exists, a GPS network will never deliver spatially continuous information on surface deformation.

2.2. InSAR and the PS Approach

[13] InSAR is a relative technique with proven capability to provide spatially continuous information, which, however, is limited in temporal coverage due to the satellite repeat cycle. To provide absolute information at the submillimeter-per-year level, the vertical motion of the reference point must be known to sufficiently high accuracy.

[14] The application of the PS methodology (*Ferretti et al.*, 2001; *Colesanti et al.*, 2003; *Hilley et al.*, 2004; *Dixon et al.*, 2006) allows us to overcome the problems of the traditional interferometric approach and of the optical systems in general. This methodology is based on a few basic observations. Atmospheric artifacts show a strong spatial correlation within every single synthetic aperture radar (SAR) acquisition; however, they are uncorrelated in time. Conversely, target motion is usually strongly correlated in time and can exhibit different degrees of spatial correlation depending on the phenomenon at hand (e.g., subsidence due to water pumping, fault displacements, localized sliding areas, collapsing buildings, etc.). Based on these findings, atmospheric effects can be estimated and removed by combining data from long series of SAR images (>than 20). In order to best exploit the available images and to improve the accuracy of the estimation, only scatterers slightly affected by both temporal and geometrical decorrelation are selected. This group of radar targets composed of PS (actually PS candidates) shows ideal characteristics for interferometric observations. Phase-stable pointwise targets called PS are then selected from this group on the basis of a statistical analysis of the amplitudes of their electromagnetic returns. A PS preserves the phase information with time and with varying acquisition geometries. PSs are, for example, parts of buildings, metallic structures, exposed rocks, in any case elements already present on the ground whose electromagnetic characteristics do not vary from acquisition to acquisition. PSs constitute a sort of "natural geodetic network", a monitoring tool with a very high spatial density of measurements. The stability of these targets allows the removal of the spatially uniform atmospheric phase screen (APS) and the estimate of their relative motion with a precision in the order of 1 mm/yr for each scatterer. The quality of the removal of the APS decreases with the distance from the reference point, also due to the fractal character of the APS power spectrum, rapidly increasing at lower frequencies. Therefore, the quality of the relative motion retrieval of each point is reduced to 4 to 5 mm/yr at relative distances in the order of 20 km. These results, however, are strictly dependent on the quality of the satellite orbital measurements and are in progressive improvement, as the orbits themselves are estimated from the PS data rather than from the ephemerides (*Kohlhase et al.*, 2003).

[15] The PS technique yields the component of the PS's ground motion, relative to a reference point, along the satellite Line of Sight (LOS). To derive absolute velocities, one needs information about the vertical velocity of the reference point and the horizontal direction of the motion. This can be obtained from the analysis of GPS data. In this paper, referring to the PS analyses, we will always suppose the ground motion to be only up-down, and its amplitude will be obtained from the one along the LOS by simple geometrical considerations. Further, the motion can be linear with time or sinusoidal, as in the case of seasonal fluctuations (*Colesanti et al.*, 2003; *Rocca*, 2003). The approximate orthogonality of sinusoids and linear trends, even with a rather irregular sampling of the time axis, allows the independent estimate of the sinusoidal and of the progressive motion. However, in this work, they have been jointly estimated.

2.3. Terrestrial Gravimetry

[16] Among the terrestrial observation techniques used for estimating vertical land movements, gravimetry is a completely independent method with respect to space geodetic techniques. Over the last five decades, gravimetry has made impressive progress. The precision of both absolute and relative measurements has improved by almost three orders of magnitude to presently 10^{-9}. The instrumental accuracy of the absolute gravimeter FG5 is about $1-2\ \mu$Gal at good stations for a 24-hour observation period [*Niebauer et al.*, 1995]. Continuous measurements are not feasible because of the wear and tear of the mechanical system. *Van Camp et al.* [2005] demonstrated that gravity trends with uncertainties of 0.1 μGal/yr can be achieved over a time span of 7 years with annual observations. A technology to measure the temporal variations of the gravity field continuously at a given site by means of SGs exists. The SGs are relative instruments but very stable in time. Absolute gravimeter observations taken at the location of a SG allows the identification of outliers and the correction for long-period, mostly environmental, signals. In this way, the accuracy mentioned above can be achieved in a much shorter time span [*Zerbini et al.*, 2002; *Richter et al.*, 2004]. Continuous monitoring of height and gravity changes allows the separation of the gravity potential signal due to mass redistribution from the geometric signal due to

height changes and the sound interpretation of crustal deformation processes.

3. Observed Height Variations

[17] Long-term trends can be interpreted as driven by tectonic and/or environmental effects (e.g., surface mass loading, expansion or contraction of soils, etc.). For example, *Carminati et al.* [2003] point out that the natural component of subsidence can be due to a long-term component controlled by tectonics and geodynamics, active on time spans of about 10^6 years, and by a "shorter"-term component, likely controlled by climatic changes (glaciation cycles), acting on periods of 10^3-10^4 years.

[18] Depending on the tectonic regime, the analysis of GPS height time series shows the presence of long-term trends upon which are superimposed seasonal oscillations. A similar behavior is observed in the gravity time series of the SG at Medicina.

[19] Seasonal variations of the amount of the solar radiation cause redistributions of fluids such as atmosphere, oceans, and hydrology on the surface of the Earth. While variations in the atmosphere and in the ocean deform the Earth's surface only by loading [*Blewitt et al.*, 2001; *van Dam et al.*, 2001; *Zerbini et al.*, 2004], hydrology can generate a signal from loading as well as by soil-mechanism processes [*Terzaghi and Peck*, 1974].

[20] Large seasonal oscillations, if not accounted for and removed, can corrupt the estimate of the long-term trends [*Blewitt and Lavallée*, 2002] particularly in the case of time series with less than 3 years of observations. To account for this problem, in general, the approach adopted is to fit a linear trend and an annual sinusoidal component to the observations. This purely mathematical approach, however, does not explain the physical processes driving the seasonal variations. For example, seasonal variations are characterized by interannual and decadal variability and cannot be described with a pure sinusoid. In this paper, we have chosen to instead model the seasonal variations using environmental mass models (air pressure and ocean bottom pressure) and local hydrological information.

3.1. GPS

[21] The GPS observations at the Medicina, Marina di Ravenna, and Bologna stations were analyzed using the Bernese software package version 4.2 [*Beutler et al.*, 2001]. In the data processing, we incorporate high-accuracy International GNSS Service (IGS) products including the ionospheric files, the satellite orbits, and the Earth-rotation parameters. The International Terrestrial Reference Frame, ITRF2000, coordinates and velocity field [*Altamimi et al.*, 2001] were specified for five IGS stations in Europe, Zimmerwald (ZIMM), Graz (GRAZ), Medicina (MEDI), Matera (MATE), and Cagliari (CAGL) and used as fiducial sites in the network adjustment procedure.

[22] In addition to the seasonal oscillations in the time series of the Medicina (8.5 years), Marina di Ravenna (8.5 years), and Bologna (5.5 years) stations, long-term signals with periods in the order of 10 years having amplitudes even exceeding those of the seasonal oscillations are observed (see Figure 2a). At the present time, the origin of these signals is not completely understood. Potential contributors are effects due to the transformations applied to account for successive upgrades of the ITRF starting from version 94 till 2000 as well as effects of changes associated with upgrading of the Bernese software from version 4.0 to 4.2 [*Hatanaka et al.*, 2003]. Also, systematic biases deriving from the daily alignment of the regional reference frame to the ITRF, complicated by the presence of seasonal oscillations, cannot be ruled out a priori. These concerns do not apply to the analysis of the InSAR and gravity data. Moreover, it shall be pointed out that long-term variations in height have been observed even in time series analyzed using the same ITRF [*Freymueller*, 2006].

[23] Nonetheless, these features have been empirically modeled by fitting a fifth-order polynomial to the Medicina and Marina di Ravenna height data and a third-order polynomial to the Bologna data. Subtracting these polynomials from the time series changes the linear trends up to a few tenths of millimeter per year. These changes are comparable to the realistic estimates of the errors that will be associated with the GPS height linear trends (see section 4). Because we feel that this is an artifact of the GPS data processing, we do not remove this signal from the InSAR PS and gravity data series.

[24] As discussed above, to obtain reliable estimates of the long-term trends, we have chosen to remove the seasonal oscillations from the GPS time series using environmental models. The height variations due to atmospheric pressure [*van Dam and Wahr*, 1987] and to nontidal oceanic effects [*van Dam and Francis*, 1998] were computed by convolving the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis surface pressure and the Estimating the Circulation and Climate of the Ocean (ECCO) http://www.ecco-group.org) ocean bottom pressure data, respectively, with *Farrell*'s [1972] mass-loading Green's functions. The nontidal oceanic effect has been multiplied by a factor 2.6 for Medicina and Bologna and 2.7 for Marina di Ravenna according to the findings of *Zerbini et al.* [2004].

[25] The predicted vertical crustal motions due to variations in the local hydrology have been derived by computing, for each station, the admittance between the GPS height series, where the atmospheric and nontidal ocean-loading effects were removed, and the respective hydrological balance data. We speak, in this case, of vertical displacements due to the local hydrology rather than of a loading effect because the estimate was obtained by means of a simple regression and not by using a physical model involving the Green's functions. While the Green's function approach allows us to model the physical process of loading, the use of a transfer function does allow us to account for the loading as well as for the height changes due to soil compaction and expansion. The daily hydrological balance data series are provided by Agenzia Regionale per la Prevenzione e l'Ambiente (ARPA) (E. Romagna, personal communication, 2004). The data, an estimate of water in the unsaturated layer, is derived by taking the difference between precipitation and evapotranspiration [*Zerbini et al.*, 2002].

[26] Figure 2b shows, as an example for the Medicina station, the model of the height seasonal oscillation as a function of time. The model, which tracks the observations extremely well, is the sum of the atmospheric, nontidal

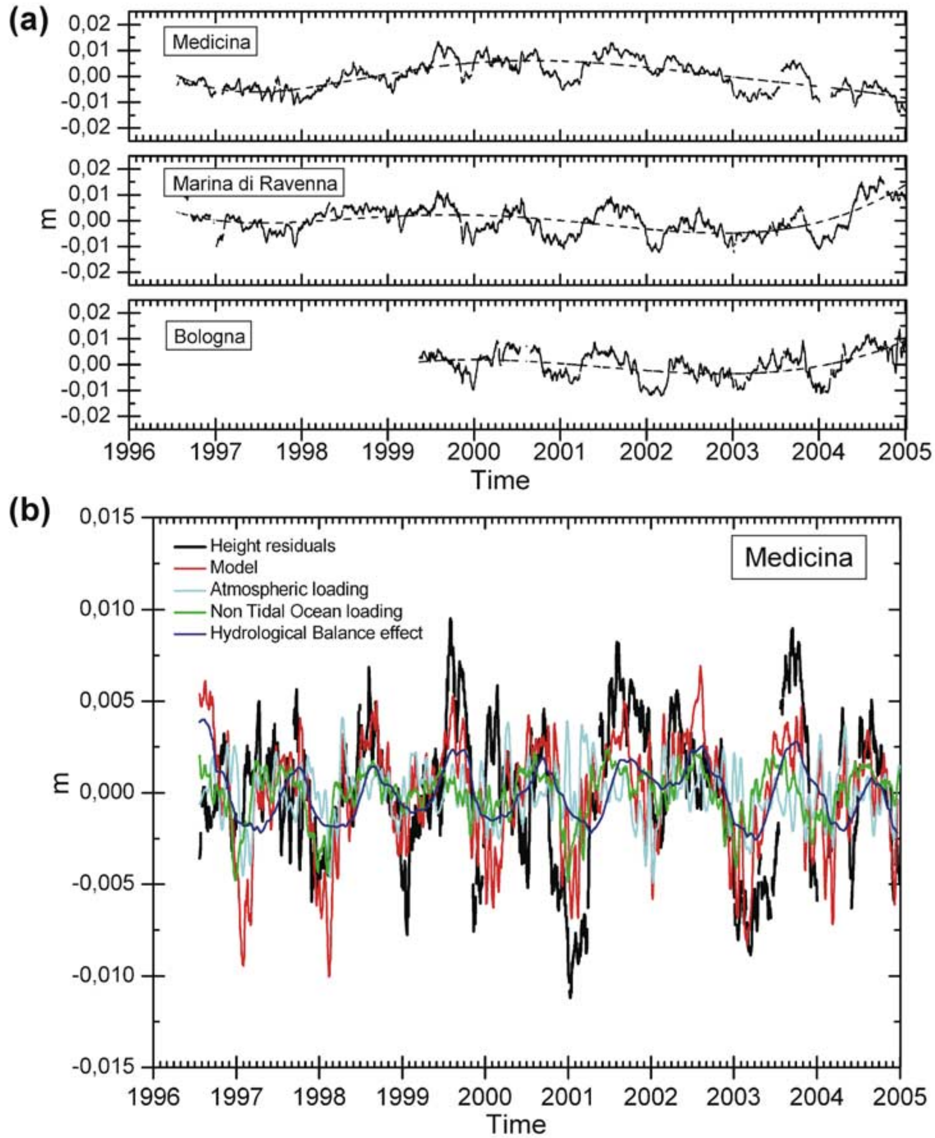

Figure 2. (a) GPS seasonal and long-term oscillations (continuous black line); linear trends have been subtracted. The nonlinear long-term signal present in the Medicina and Marina di Ravenna series has been approximated by fitting a fifth-order polynomial, while for Bologna, a third-order polynomial was used (dashed lines). (b) Observed GPS height seasonal oscillations (black line) at the Medicina station together with the seasonal model (red line) obtained by summing the air pressure (light blue line) and nontidal ocean loading (green line) as well as the effect of hydrology (blue line). The nonlinear long-term signal and the linear trend have been subtracted.

ocean, and hydrological loadings. The model components are also shown in the same figure. Removal of the modeled daily values reduces the variance of the observed height seasonal oscillation by 13% for Medicina, 22% for Marina di Ravenna, 46% for Bologna, and 33% for Loiano.

[27] Figure 3 shows the GPS height time series after removal of both the long-term signals and the modeled environmental effects and the estimates of the long-term linear trends. In the case of the Loiano station, we did not remove the modeled seasonal oscillation, since the time series is only 15 months long, and it does not include at least two complete seasonal cycles.

[28] The three stations in the Po Plain show clear subsidence rates which are quite large, -10.23 ± 0.03 and -16.69 ± 0.05 mm/yr in Marina di Ravenna and Bologna, respectively, but are somewhat smaller in Medicina, -3.31 ± 0.03 mm/yr. The precision quoted for the trends are formal errors. As we will see in the following section, these rates are in good agreement with those derived from the InSAR and gravity techniques. At Medicina, a VLBI antenna is also available; rates provided by *Bitelli et al.* [2005] and D. McMillan (personal communication, 2004) are -3.42 ± 0.23 and -3.29 ± 0.14 mm/yr, respectively. The agreement between the GPS vertical rate and those derived by means of the VLBI data analysis is excellent.

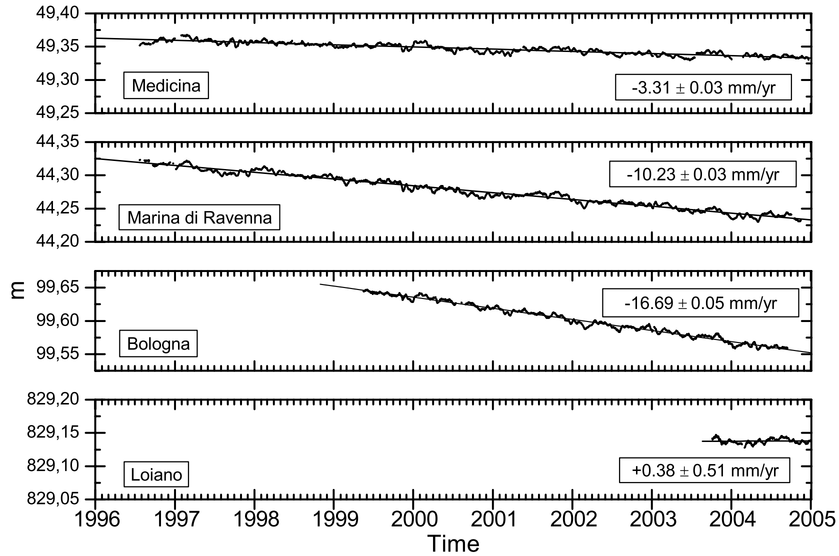

Figure 3. GPS long-term trends. They have been estimated by removing the long-term signal and the modeled seasonal oscillations from the daily height time series for the Medicina, Marina di Ravenna, and Bologna stations.

[29] As pointed out in the introduction, the Loiano GPS station is the only one of the four stations analyzed which is outside the subsiding Po Plain. It is located on the Apennines belt, a region characterized by uplifting and extension. At present, the available time series is still too short to derive a reliable vertical rate, and the error associated to the estimate is large. Nonetheless, we believe that it is interesting to note the positive trend, which supports the geologically claimed uplift. We will use this information to make a tentative comparison with the InSAR results.

3.2. InSAR

[30] Figure 4 illustrates the location of the InSAR PSs in the Medicina and Bologna region and their vertical velocity with respect to the reference point (the magenta dot in the figure). For this analysis, 73 images from the European Remote-Sensing (ERS) 1 and 2 satellites were used. Please note the remarkable number of PSs which are used to estimate the spatial variability of the vertical crustal rates in the region. The reference point, which is located close to the Medicina station, is in an area that is characterized by a velocity in the order of a few millimeters per year, as demonstrated by the GPS and the VLBI results. Figure 4 shows the considerable spatial variability in subsidence rates in the region, with large values even exceeding −20 mm/yr in and around the city of Bologna. South of Bologna, it is possible to observe a clear demarcation line where the Apennines chain begins.

3.2.1. Medicina

[31] Figure 5 shows the Medicina station and its immediate surroundings. It is a rural area; therefore the amount of PSs available is quite limited. However, fixed metallic structures belonging to the Northern Cross radio telescope, to the VLBI antenna, and to the station buildings can be clearly identified. The relative vertical velocities obtained from the InSAR data analysis for the PSs identified in the station area are all close to zero. In particular, the PS closest to the GPS antenna has a relative vertical rate equal to +0.2 ± 0.5 mm/yr. The reference point for the InSAR analysis, shown in Figure 4, is outside this map, only a few km to the north, and the area is characterized by the same moderate subsidence. We can reasonably assume that the reference point for the InSAR analysis has the same vertical velocity as that observed by the GPS as well as by the VLBI technique at the Medicina station, −3.3 and −3.4 mm/yr, respectively. Thus the total InSAR rate for this PS would be only slightly smaller, between −3.1 and −3.2 mm/yr, according to which vertical rate is assumed for the reference point.

3.2.2. Bologna

[32] Figure 6 presents a sector of the city of Bologna where the GPS station is located and where a program of absolute

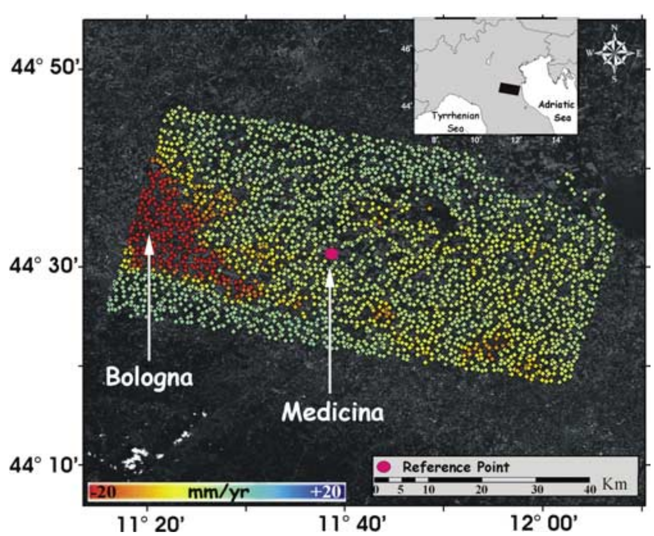

Figure 4. The ensemble of PSs available in the Bologna and Medicina area and the relevant vertical rates. The magenta dot identifies the location of the reference point for the InSAR data analysis. The location of the SAR images is shown in the right upper corner.

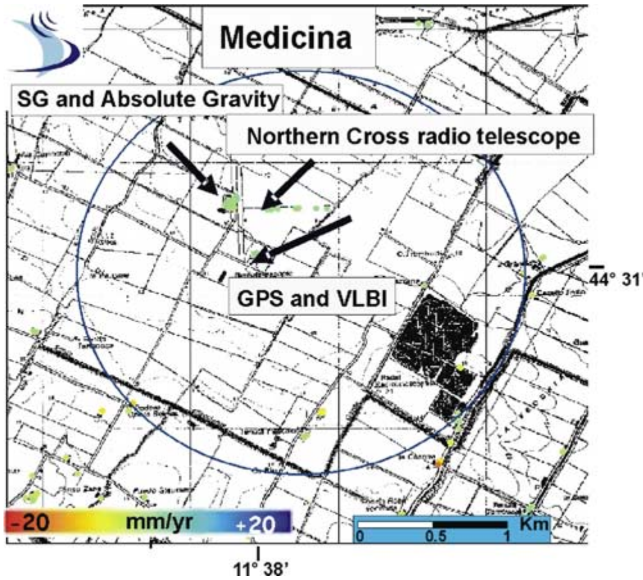

Figure 5. The Medicina station area. The image shows a limited number of PSs because this is a rural environment.

gravity measurements has recently started. The image clearly shows the abundance of PSs and the large subsidence rate, mostly of anthropogenic nature which affects the city and its surroundings. The PS closest to this GPS station is characterized by a linear vertical velocity relative to the reference point in the vicinity of Medicina equal to −16.0 ± 0.5 mm/yr over the time period 1992–2001. By adding the vertical rate of the reference point, the absolute subsidence rate of this PS is thus −19.3/−19.4 mm/yr, which is consistent with the estimate −16.7 ± 0.1 mm/yr provided by the GPS in the 1999–2004 period. However, please note that the GPS rate is derived using a different time period compared to that of the InSAR data.

[33] PSs ''elements'' are characterized only by their ability to reflect the electromagnetic signal emitted by the SAR satellite. Therefore, in most cases, they are not attached to geodetically recommended monumentation. This means that for any individual PS, unknown trends in the order of 1–2 mm/yr might corrupt the absolute comparison with GPS. However, the spatial coherence of the InSAR PS results provides confidence that the observed subsidence is not due to anomalies at the GPS monument.

3.2.3. Marina di Ravenna

[34] The InSAR vertical rate estimated for the PS closest to the GPS site at Marina di Ravenna, −2 mm/yr (Figure 7), was obtained from the analysis of 64 images of the ERS 1 and 2 satellites. It is relative to the InSAR reference point located south of Marina di Ravenna in the city of Cesenatico. The Cesenatico reference point is subsiding at a rate of −7 to −8 mm/yr, as illustrated in Figure 8. This subsidence rate has been determined by high-precision leveling measurements performed during the period 1990–1999 along a north-south line from Ferrara to Rimini [*Benedetti et al.*, 2000]. The absolute subsidence is therefore in the order of −10 mm/yr. Recall that the GPS determined rate is −10.2 mm/yr, which means that the InSAR determined rate is again consistent with the GPS rate in this region.

3.2.4. Loiano

[35] Figure 9 presents the InSAR results for the Bologna and Loiano area. The magenta dot identifies the location of the reference point for the InSAR data analysis. The results clearly show the completely different tectonic behavior of the two areas, namely the subsidence in the Po valley and the uplift of the Apennines with a clear demarcation line between the two. According to *Doglioni* [1993], the subsidence in the area is due to the ongoing slab retreat of the Apennines subduction zone. The retreat generates subsidence and accretion of the prism buried beneath the southern Po Basin. The southern border of the basin shows

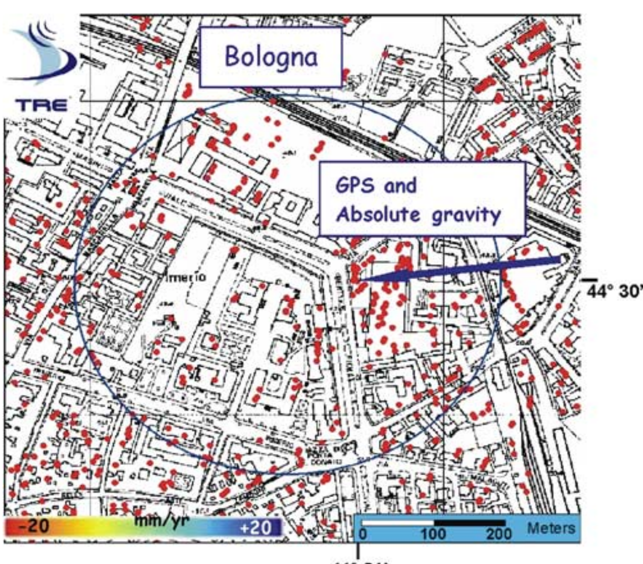

Figure 6. Sector of the city of Bologna showing the large amount of PSs available, the remarkable subsidence rate, and the location of the GPS and absolute gravity station.

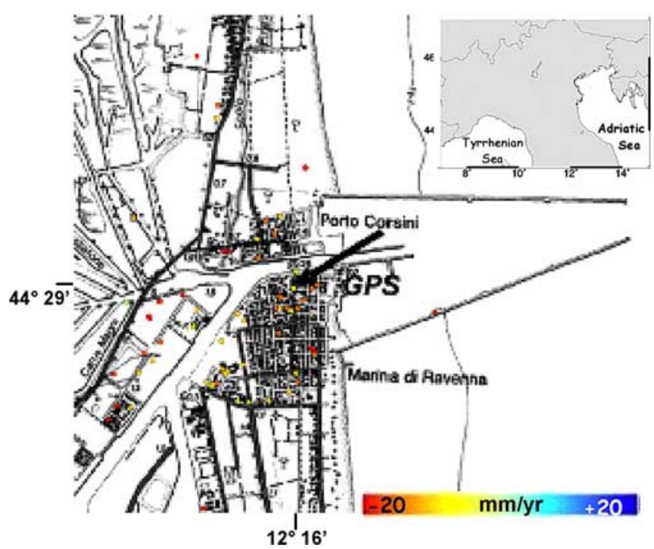

Figure 7. Distribution of PSs in the Marina di Ravenna area, relevant subsidence rates, and location of the GPS station. The location of the SAR images is shown in the right upper corner.

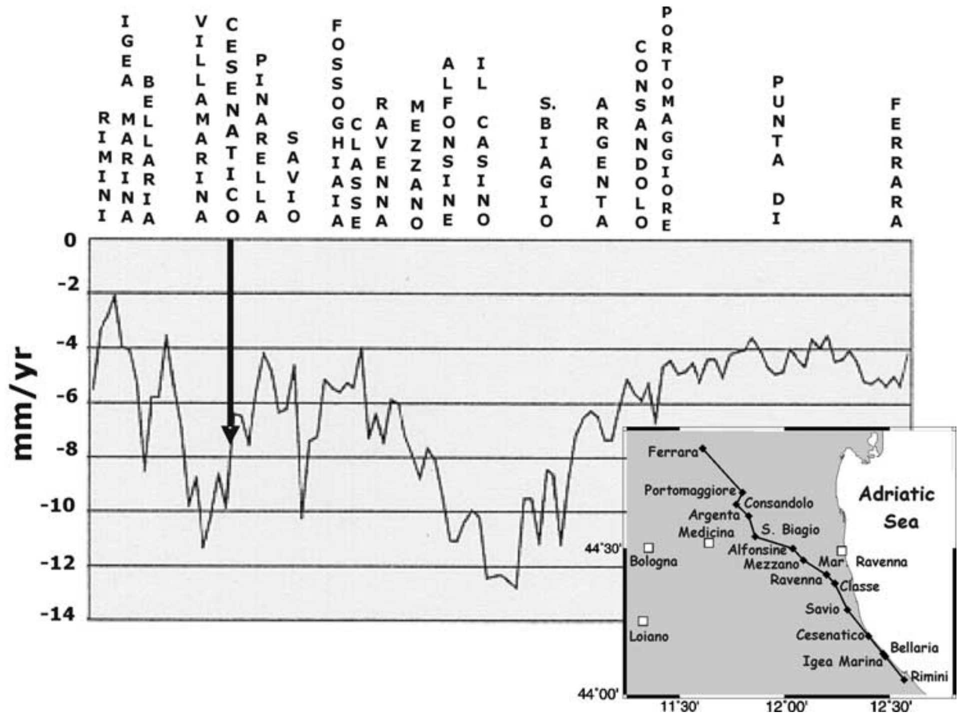

Figure 8. Estimate of subsidence rates along a line from Rimini to Ferrara from high-precision leveling data acquired in the period 1990–1999 [after *Benedetti et al.*, 2000]. The location of the leveling line is shown in the lower right corner.

active thrusting limiting the area of uplift of the Apennines' belt where extension dominates.

[36] The GPS height time series at the Loiano station is still too short to provide a reliable estimate of the vertical uplift rate; however, from both the GPS and InSAR observations, a very preliminary estimate of the uplift rate could be in the order of 1 mm/yr.

3.3. Gravity

3.3.1. Medicina

[37] In this study, we use continuous SG data recorded at Medicina from the beginning of 1998 till the end of 2004. In the case of the SG measurements, the instrumental linear drift was estimated by comparison with a series of AG observations performed by FG5 instruments [*Niebauer et al.*, 1995]. The gravitational effects due to earth and ocean tides were analyzed with the Eterna software package [*Wenzel*, 1998] for the tidal period up to solar semiannual constituent (SSA). The 18.6-year tide, the effects introduced by polar motion, and the annual tide solar annual constituent (SA) have been scaled by 1.16 to take into account the elastic behavior of the Earth. All these tidal and long-term effects have been removed.

[38] Local air-pressure variations (-0.3 μGal/hPa) and the vertical air mass effect [*Simon*, 2003] have also been taken into account and removed. This latter contribution was estimated by using 12-h radio-sonde data regularly acquired nearby the Medicina station.

[39] Figure 10a shows the seasonal oscillations in the SG time series. As for the GPS analysis, we have modeled the observed seasonal gravity oscillations present in the SG data series. In the case of gravity, however, a geometrical component (the height variations), the Newtonian attraction, and a change in gravitational potential have to be taken into consideration for each load.

[40] The gravity variations due to nontidal oceanic effects were estimated by convolving the 12-hourly ECCO ocean

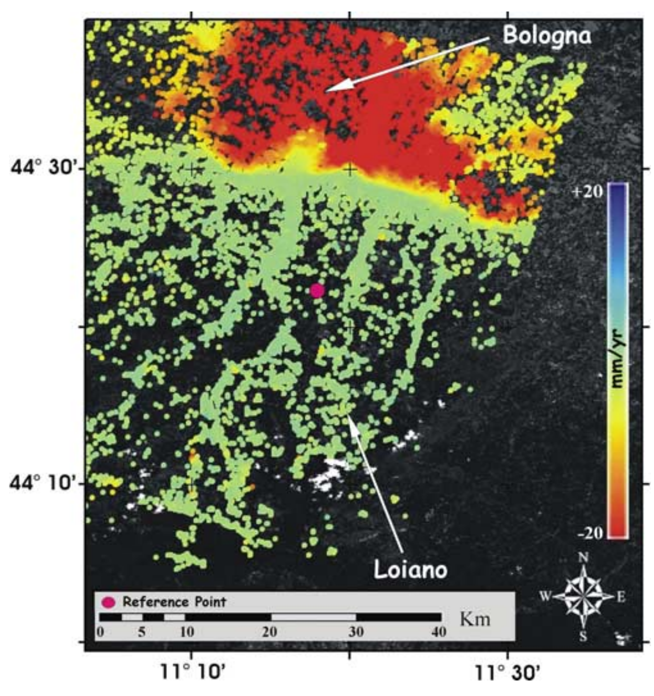

Figure 9. The Bologna and Loiano areas. The image shows the large amount of PSs available and the relevant vertical rates. The magenta dot identifies the location of the reference point for the InSAR data analysis.

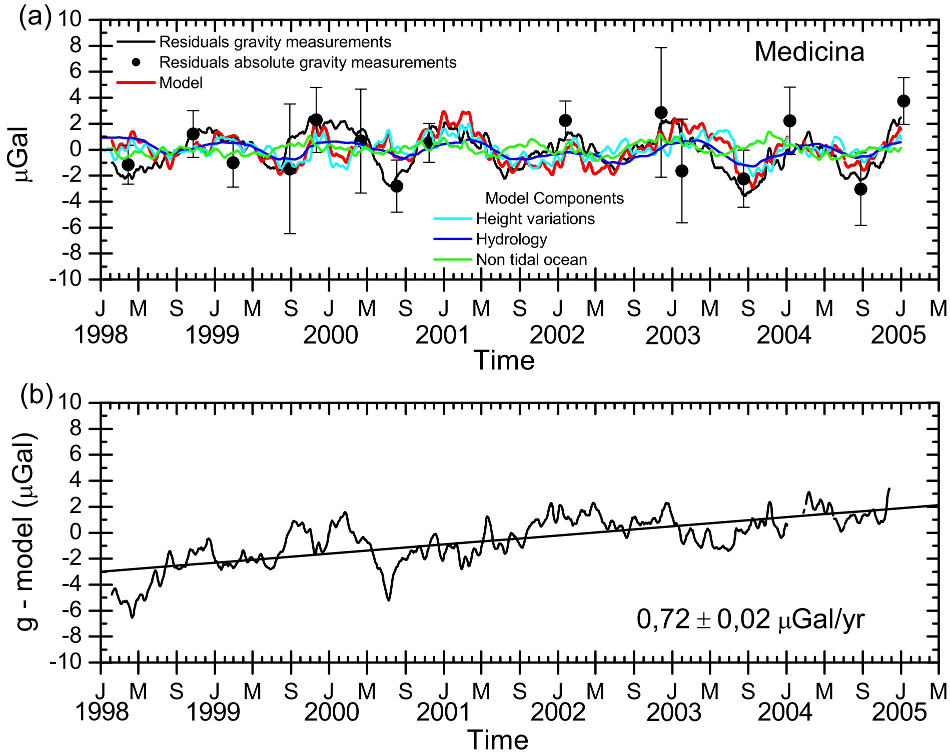

Figure 10. (a) Observed gravity seasonal oscillations (black line) and absolute gravity FG5 measurements (black dots), both detrended. The seasonal model is represented by the red line. The model is the sum of the gravimetrical contributions due to height variations (light blue line), nontidal oceanic effect (green line), and local hydrology (blue line). (b) Estimate of the long-term trend. The seasonal model has been removed from the time series before estimating the long-term trend.

bottom pressure data with *Farrell*'s [1972] Green's functions. This procedure accounts for the change in gravity due to the surface displacement and the Newtonian attraction [*van Dam and Wahr*, 1987]. The results presented in *Zerbini et al.* [2004] demonstrated that the modeled nontidal ocean loading (NTOL) effect using ECCO data as input was a factor of two smaller than the observations. As a result, we have multiplied the ECCO NTOL effect by a factor of two. To estimate the gravimetric effect due to local hydrology, a regression between the gravity residuals and the hydrological balance series has been calculated. All seasonal effects as described above, as well as the geometrical part observed with GPS, were removed beforehand. The admittance factor is 3.20 ± 0.14 in units of μGal over meters of hydrological balance. The hydrological balance is used because in Medicina, the water-table record has a gap of 1 year in the 2000/2001 period [*Zerbini et al.*, 2002].

[41] The model, which is the sum of the individual seasonal signals affecting gravity (nontidal oceanic, hydrological mass, and deformation components), is shown in Figure 10a together with the model components.

[42] The seasonal gravity signal, modeled using the local and global environmental data, has been removed from the daily gravity observations. The residuals are shown in Figure 10b. A long-term trend of +0.72 ± 0.02 μGal/yr for the 1998–2004 time period is also shown.

[43] To transform the gravity displacements from units of micro-Gals into units of millimeters, we have used a conversion factor of −207 μGal/m (1 μGal equal to about −4.8 mm) obtained at Medicina from the ratio of the observed seasonal gravity and GPS changes. This finding is well within the range of values between −150 and −350 μGal/m mostly observed for the differential gravity-height change ratio [*Torge*, 1989]. We recall that −300 μGal/m is the free-air relation while −200 μGal/m represents the Bouguer relation, which indicates mass variations in addition to vertical surface movements. The admittance we found is closer to −200 μGal/m, the Bouguer height change/gravity change relation, rather than to the free-air relation.

[44] Based on this, the secular height change determined from the gravity data is −3.48 ± 0.10 mm/yr. This rate is in very good agreement with the vertical rate estimated from the analysis of the GPS data over the same period, −3.31 ± 0.04 mm/yr.

3.3.2. Bologna

[45] Since the data are still quite limited in number, it is not possible at the moment to properly identify a seasonal component. Therefore, no attempt was made to remove a seasonal effect before estimating the linear trend (Figure 11). The linear trend computed from the six absolute gravity measurements, +6.39 ± 0.92 μGal/yr, would result in about −23.3 ± 3.4 mm/yr, if assuming, as a first guess, the gravity-to-height relation determined in Medicina. This trend would be larger than the height variation observed by GPS over the same time period 2002–2004 (−15.6 ± 0.2 mm/yr). The

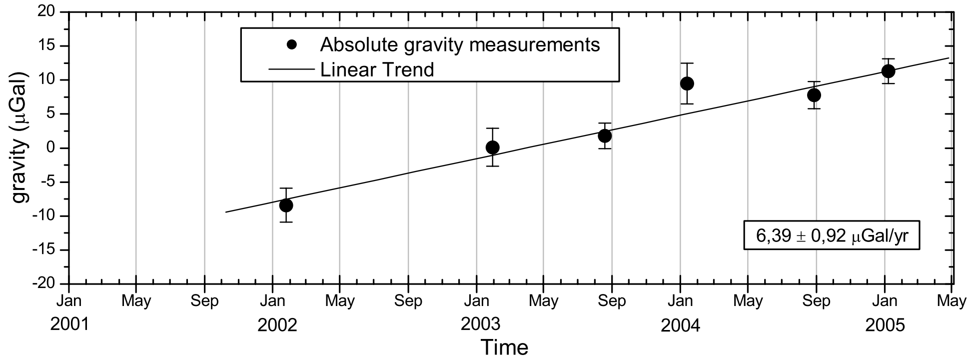

Figure 11. Bologna station. Series of six absolute gravity measurements (dots) and linear trend.

limited number of measurements presently available is certainly a factor.

4. Combined Interpretation of the Results

[46] The comparison of the secular vertical motion in the Po Plain using observations from the GPS, InSAR, and gravity demonstrates the agreement between all techniques and provides a solid basis for establishing a program to integrate the different techniques at a larger scale. In this work, we have first considered the need for a thorough comparison among the results of the different techniques. As a first approach to the problem of the integration, we have adopted the simple option, which is the combination of the results. This shall provide a product (vertical rates) which is more reliable and of higher quality with respect to that obtained by a single technique alone. For the Medicina station, Figure 12 presents the different solutions determined using the GPS, InSAR, gravity, and VLBI data as well as their weighted mean, -3.33 ± 0.09 mm/yr (the mean represents the combined solution over the period 1996–2004). In the case of the GPS and gravity results, to provide a conservative estimate of the error associated with the vertical rate, we have multiplied those formal errors by an arbitrary factor of 5. It is well known, in fact, that unrealistically small formal errors are associated with large populations of data. Concerning VLBI, a mean value of the two solutions relevant to the 1996–2004 time period has been computed (see section 3.1).

5. Conclusions and Outlook

[47] The study shows the value of cross-validation of the different and compatible techniques to provide reliable vertical crustal motion determinations in space and time. The combination takes advantage of the techniques' complementary aspects, proving to be a powerful means to observe and study vertical deformation with reliable spatial and temporal continuity. The long-term linear trends estimated by using the data of the different techniques show a very good agreement.

[48] By combining GPS, InSAR, and gravity, subsidence in the southeastern Po Plain has been mapped, revealing a noticeable spatial variability. Large vertical rates, mostly of anthropogenic nature, in the order of 20 mm/yr have been observed in and around the city of Bologna. The transition between a subsiding region and the uplift of the adjacent Apennines occurs over a narrow zone as evidenced by the analysis of the InSAR PS results. This is in agreement with a preliminary result provided by the GPS height data from the Loiano station located in the Apennines. The Loiano series, however, is still too short to provide a reliable estimate for the vertical linear trend. These results identify clearly the separation line between the different geodynamic characters of the two zones: the subsiding foredeep, where the sediments allow ground-fluids withdrawal to significantly enhance the natural tendency, and the uprising Apennines belt.

[49] With this study, we provide a means to reliably identify, monitor, and model, in a timely manner, the space and time distribution of vertical surface deformation. Subsidence is the potential cause of environmental degradation on basic societal infrastructures such as buildings, pipes, roads, railroads, bridges, etc. Focusing only on the geographic area of interest to this study, this knowledge is of major importance for the presence of natural lowlands and coastal lowlands such as the northeastern Adriatic coast, including the Po river Basin, which are exposed to the risks of flooding events due to river overflow or to the occurrence of extreme storm events.

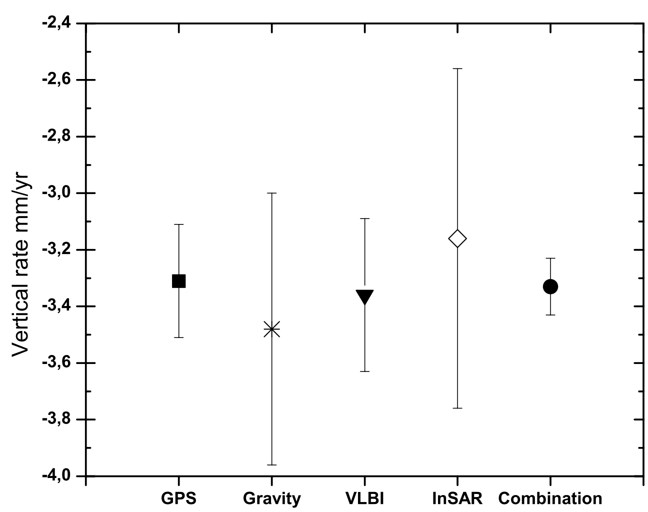

Figure 12. Different vertical rates estimated at Medicina from the various techniques. The combined solution (dot) is also presented.

[50] Through this geodetic study, the actual integration of the GPS and InSAR results revealed the importance of knowing to a high degree of accuracy the absolute vertical velocity of the InSAR image reference point in a well-defined reference frame. This can be achieved by colocating a GPS antenna with InSAR corner cubes at the image reference point. On the other hand, the spatial information provided by the InSAR images will be invaluable for determining the appropriate colocation point within the region of study. Another issue concerning the technique combination is the choice of the optimal spatial distribution of the GPS sites in a region which would be required to support the InSAR analysis. Such a realization will be a key element for systematically understanding local phenomena such as, for example, slope instabilities and surface deformation associated to earthquakes.

[51] As for the gravity data, the measurement of mass and height variations rather than height alone introduces an additional parameter beyond geometry to be assessed. The gravity measurements, combined with the geometrical information, allow us to distinguish between the different sources and mechanisms driving the observed height changes. At Medicina, the comparison of the secular gravity trend and the long-term linear height variations seems to indicate that there are no significant mass redistribution processes involved in this region.

[52] The remarkable consistency found between the time series derived from the GPS, InSAR, and gravity observations in this study provides significant confidence in our interpretation of the geodynamical processes at this region. This study indicates that a systematic and synergetic combination of these technologies appears to be a valuable approach for monitoring and understanding surface deformation.

[53] As a final remark, we feel that this combination of techniques is important because it provides a contribution to the realization of a local vertical reference frame, and it adheres to the principles of the Global Geodetic Observing System (GGOS) presently being developed by the International Association of Geodesy (IAG). Moreover, the combination of positioning and environmental data is a basic element of Global Monitoring for Environment and Security (GMES) and of the forthcoming Global Earth Observing System of Systems (GEOSS).

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