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Observing the earth at regional and local scale by means of space geodetic techniques

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Abstract Vertical land movements over northern Italy are presented. In this domain, the Po plain is of a particular interest because it is subjected to both natural and anthropic subsidence. Vertical rates derived from two ensembles of leveling measurements performed by IGM during the periods 1877–1903 and 1950–1956 were compared with those obtained from the analysis of the GPS data collected during the last two decades. The GPS network consists of about 130 stations distributed over an area spanning 7° in longitude, from 7° to 14°, and 3° in latitude from 44° to 47°. The vertical deformation relevant to the two investigated periods, and obtained by means of the two different techniques, shows comparable main features: uplift up to a few mm/year in the western sector and subsidence in the central-eastern part. Across the Po plain, subsidence ranges from a few to several mm/year, particularly in urban areas, in the Po river delta and south of it along the Adriatic coast. However, the recent estimates provided by the GPS data indicate a general reduction of subsidence rates with respect to the leveling results. A reduction up to 3 mm/year is found in the Po river delta and along the Adriatic coast. Accurate knowledge of vertical land motion is desirable when studying sea-level variations by means of tide gauge data. We discuss the time series of two tide gauges located in the northern Adriatic, namely, Venice and Marina di Ravenna, and compare the sea level rates obtained from these data corrected for vertical land motions with those deduced from satellite altimetry measurements.

Keywords Po plain · Subsidence · Leveling · GPS · Sea level

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1 Introduction

During the last few decades, observing and studying the planet earth have made considerable and fast progresses, thanks to the availability of high-precision space geodetic techniques and to ever-increasing measurement capabilities. These accurate and global scale observations have allowed advancing from a static knowledge of the geometric and physical parameters describing our planet to the capability of monitoring the dynamics of the system Earth over different spatial and temporal scales.

The knowledge of the vertical land deformation has relied primarily on repeated geometric leveling measurements till the late twentieth century. Precise geodetic leveling is the most accurate method to detect height differences with a mean error ranging from ±0.3 to 1 mm in a line of 1 km long (Torge 1980). However, this traditional geodetic technique is time consuming and costly, considering the instrumental, procedural, and technical manpower requirements. Measurement campaigns are often quite separated in time.

The information on vertical deformation has dramatically increased since the early 1990s, when space technology such as GPS (Global Positioning System) has started providing a wealth of accurate height measurements. Today GNSS (Global Navigation Satellite System), which encompasses all global satellite positioning systems, including GPS, GLONASS, Galileo, and soon Beidou (with BDS anticipated to be global by 2020 http://www.beidou.gov.cn/), enables larger amount of observations to be acquired leading to increased positioning accuracy and reliability. Today the International GNSS Service (IGS) makes available different products of scientific interest for almost 500 worldwide reference stations (http://www.igs.org/products). At regional level, the EUREF permanent GNSS network (Reference Frame Sub-Commission for Europe of the International Association of Geodesy, IAG, http://www.epncb.oma.be/) consists of about 300 permanent stations, the coordinates of which are determined with 1 cm 3-D accuracy (Kenyeres 2010). Santamaria-Gómez et al. (2011), after homogenously processing 275 globally distributed stations, and testing 27 different noise models, estimated a mean vertical velocity uncertainty of ~0.3 mm/year. In addition to the IGS and EUREF products, the data of many other networks of permanent stations are available online providing a rather dense geographic coverage. For example, the Nevada Geodetic Laboratory (2017) (NGL, http://geodesy.unr.edu/index.php) routinely analyzes the GPS data of many archives estimating daily PPP (Precise Point Positioning) station coordinates.

More recently, a satellite-based imaging technique, InSAR (Interferometric Synthetic Aperture Radar), has demonstrated the capability to accurately determine relative vertical deformation over extended areas of up to thousands of square kilometers with spatial resolution of a few tens of meters, thus complementing the point-like GNSS measurements. It shall be pointed out that SAR data are acquired along the satellite line of sight (LOS); therefore, to retrieve the vertical motions, it is necessary to project the original measurements from the LOS to the vertical. If only ascending or descending passes are available, vertical movements can be estimated on the assumption that horizontal motions are absent or negligible. However, if both ascending and descending passes are available, their combination allows properly characterizing the vertical movements (Ferretti 2013). The achievable accuracy of these estimates is of the order of a few millimeters (Ferretti 2013). Integration of the GNSS and InSAR goes far beyond the spatial dimension, by taking advantage of the absolute nature of GNSS positioning versus the relative InSAR approach and of the GNSS observations temporal continuity. The combination of GNSS and InSAR data allows monitoring and studying the spatial distribution and temporal variability of subsidence leading to a thorough understanding of the dynamics of this phenomenon.

Investigating crustal deformation in northern Italy, in particular vertical movements, is of special interest because a major tectonic feature, such as the Po plain, extends in this region. The Po plain is a rapidly subsiding sedimentary basin surrounded by the Alps and Apennines chains. Additionally, this area is of great importance for Italy's economy, by hosting nearly 40% of the country productive activities. Subsidence in this region can be viewed as the combination of natural and anthropogenic components. In general, natural subsidence can be referred to the dynamics of the lithospheric plates leading to the formation of the Alps and the Apennines, and to loading and compaction of sediments which filled the depression between the two mountain chains. These phenomena evolve over timescales of millions of years and, spatially, over quite wide areas (Bondesan et al. 1997). Climatic variations, such as the one that took place since the last glaciation cycle, also contribute to natural subsidence; in this case, the timescale is in the range of tens of millennia. The anthropogenic contributions to subsidence occur over much shorter timescales, of the order of hundreds years. They have, however, contributed remarkably to the present geomorphology of the Po plain. In particular, during the twentieth century, diverse anthropic activities have locally enhanced natural subsidence inducing soil lowering rates much larger than the one due to natural causes, which is of the order of 2–3 mm/year (Bondesan et al. 1997; Carminati et al. 2003; Teatini et al. 2005). Among the main anthropic activities, we recall groundwater withdrawal for industrial, civil, and agricultural uses, draining of wetlands, and hydrocarbon extraction from deep geological features.

In the Po plain, height measurements have been carried out since more than a century. However, systematic monitoring of subsidence and related studies date back to the last 30 years of the twentieth century, when the detrimental effects of human interventions became increasingly clear and started to raise the level of concern of the public administrations. During last century, repeated geometric leveling was the primary source of data for estimating soil settlement. Aiming at a sustainable land management, different local authorities and private enterprises measured very many leveling lines but, in general, there was lack of overall coordination of these projects. Among these, the Italian first-order leveling network, devised and measured by the IGM (Istituto Geografico Militare), has been of particular importance for at least two reasons. First, it has allowed updating and standardizing the heights of the existing benchmarks and, second, has provided the possibility to quantify ground vertical motions over a wide area (Bondesan et al. 2000).

In the space geodesy era, techniques such as GNSS enable continuous monitoring of crustal deformation. In this work, we will compare, in the Po plain, the vertical crustal movements obtained from geometric leveling data, acquired by the IGM over a period of about 60 years from the end of nineteenth century to 1957 (Salvioni 1957; Arca and Beretta 1985), with those estimated using GPS observations collected during the last 20 years (1996–2016) by a network of about 130 permanent stations. This comparison aims at verifying the existence of the same large-scale spatial behavior of subsidence and the persistence or not of similar subsidence rates over two time periods, namely 1897–1957 and 1996–2016, separated by some 40 years which are characterized by intensive anthropic activities.

2 The data

2.1 Leveling, the Italian fundamental altimetric networks

In Italy, high-precision leveling started during 1876, but it was only during 1878 that the Italian Geodetic Commission assigned the Geodetic Service of the IGM with the task of measuring the national altimetric network. The survey of this network was completed 6 years later, in 1903. Measurements were performed according to the guidelines and complying with the standards recommended by the IAG during its General Assembly held in Berlin in 1864. An updated realization of the national altimetric network was measured by the IGM during the period 1950–1956. The new network was surveyed using modern leveling equipment and advanced data acquisition methods. These were identified by the IAG during the first few decades of 1900 and discussed during general assemblies, including the one held in 1948. Care was taken to remeasure, whenever possible, the same lines and the same benchmarks, although only about 10% of the benchmarks of the old network were found. A first comparison of the geometric leveling data collected during the period 1873–1903 with those acquired during the period 1950–1956 was published by Salvioni in 1957.

The detailed analysis of Salvioni (1957) was first concerned with the homogenization of the two data sets both in terms of computing methods, reference surface, and the measurement epochs. The common reference surface is the Genoa mean sea level of epoch 1957. In a subsequent step, the height values thus obtained were compared over the Po plain, and the mean vertical land motions, occurred between the end of the nineteenth and middle twentieth century, were derived. By considering the mean error per kilometer of the old and the new network, Salvioni (1957) estimated the total error, M, to be associated to a height difference according to the following relationship:

$$M = \pm 1.13\sqrt{S}\ (\text{mm})$$

where S (in km) is the distance from the reference point (Genoa tide gauge). For a distance of 500 km, comparable to the length of the Po plain, and a period of 60 years, which is the time elapsed between the two sets of measurements, the uncertainty turns out to be 0.4 mm/year. This result is quite comparable with the uncertainty of the vertical land movements currently obtainable with GPS data (Santamaria-Gómez et al. 2011).

On the basis of Salvioni's geodetic results, Arca and Beretta (1985) discussed a geologic interpretation of the observed vertical motions and mapped a series of isokinetic contours (Fig. 1). Both manuscripts (Salvioni 1957; Arca and Beretta 1985) highlighted the different behavior of the central-western (CW) with respect to the central-eastern (CE) sector of the Po plain. The CW part was characterized by uplifting, with rates up to 4 mm/year, while the CE sector showed subsidence, with rates up to −7 mm/year in the area of the Po delta. The separation between the uplifting and the subsiding sector was identified along an imaginary null velocity line, roughly extending from the city of Genoa to that of Brescia.

2.2 The GPS data

In northern Italy, many permanent GPS stations are operative; unfortunately, they are not coordinated by a unique entity. However, diverse regional authorities, universities, and institutions running these systems make their data openly and timely available online. These archives contribute to the global network of many thousands of GPS stations routinely processed by the NGL at the University of Nevada, Reno, USA (http://geodesy.unr.edu/) in the framework of the Plug and Play GPS Project (http://geodesy.unr.edu/PlugNPlayPortal.php). Details on the data processing strategy can be found at http://geodesy.unr.edu/gps/ngl.acn.txt.

Within the area described by the isokinetics (Fig. 1), we have selected 122 permanent GPS sites (Fig. 2), characterized by continuous coordinate time series over a minimum period of 3 years. However, most station time series are about 10 years long and some even reach a 20 years' time period. It is well known that the length of the time series has an impact on the quality of the estimated coordinates and velocities (Blewitt and Lavallee 2002; Kenyeres 2006). The PPP daily estimates of the ellipsoidal heights of these stations were downloaded from the online service of the NGL (http://geodesy.unr.edu/NGLStationPages/GlobalStationList). We analyzed the series: first, outliers were removed, then discontinuities were corrected on the basis of the STARS method (Bruni et al. 2014), and, finally, the linear vertical velocities were estimated.

3 Comparison between leveling and GPS vertical velocities

Figure 3 presents the vertical velocities derived from the comparison of the "old" and "new" leveling networks

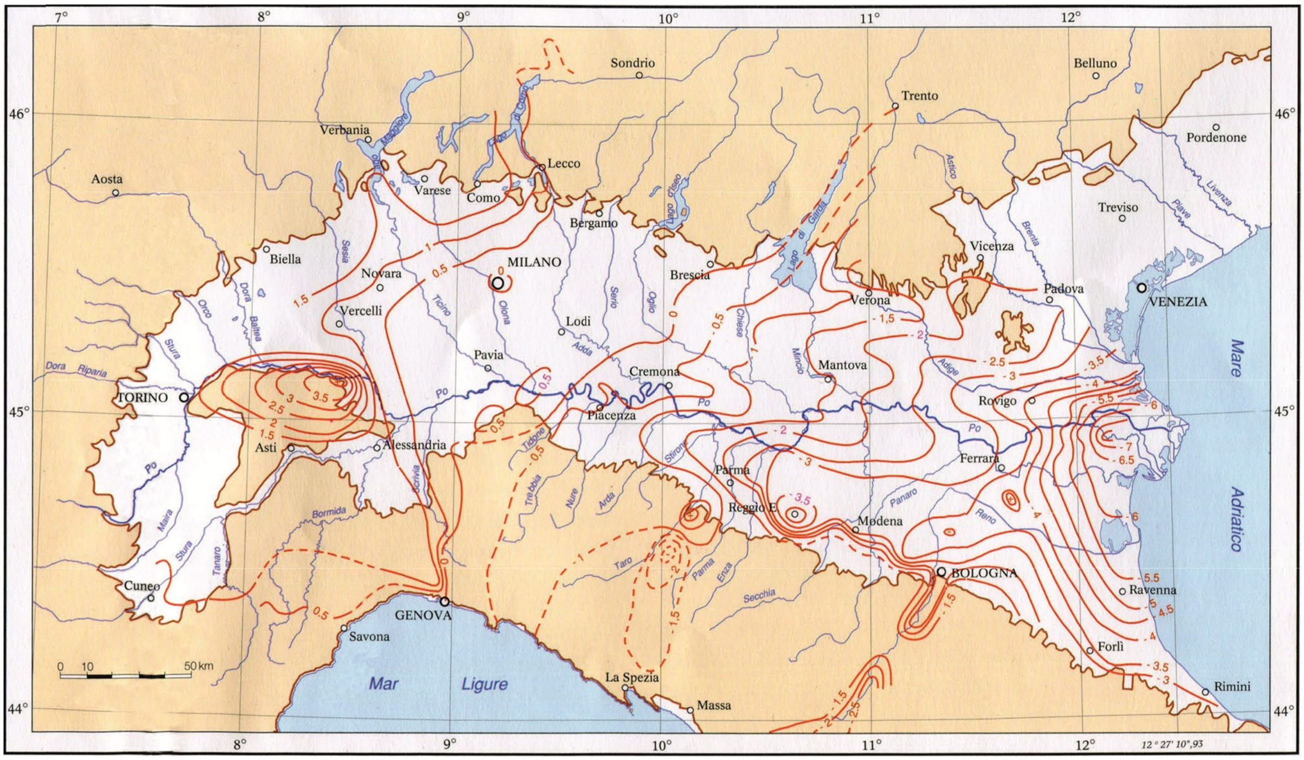


Fig. 1 Map of the vertical movements over the Po plain from repeated levelings. Isokinetic contours from Arca and Beretta (1985) reproduced by permission of S.EL.CA. Srl, Firenze

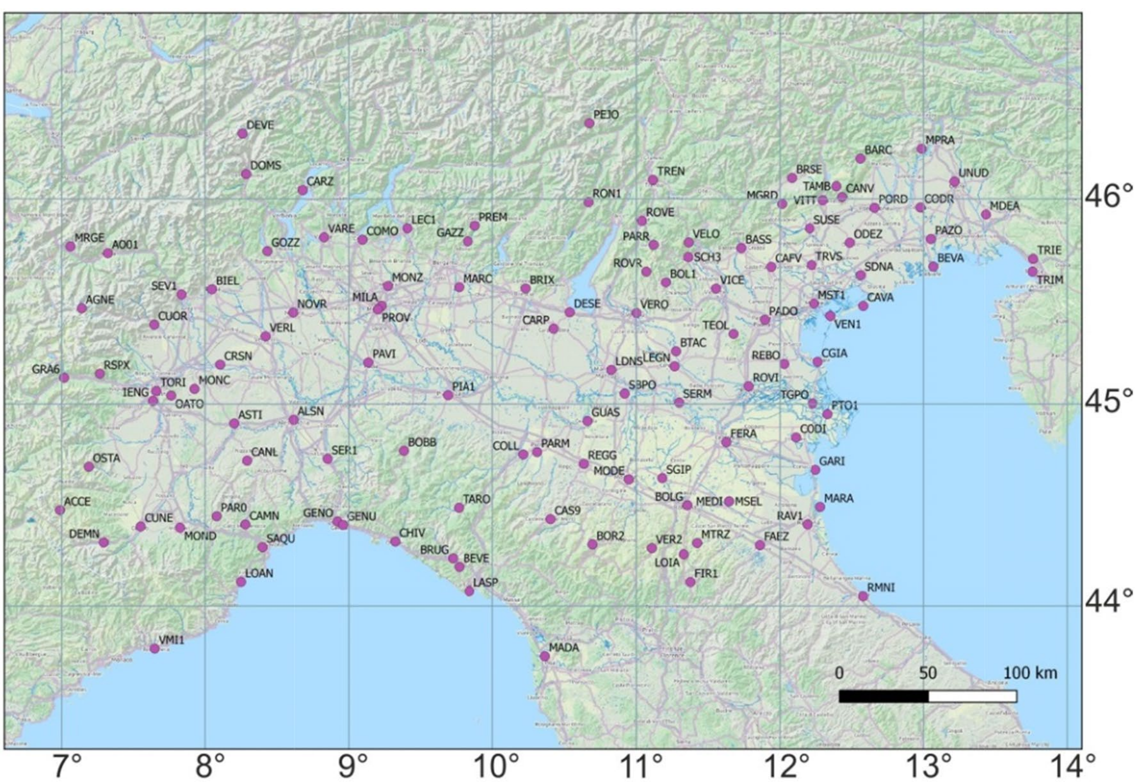


Fig. 2 Permanent GPS stations in northern Italy contributing data to the "Plug and Play GPS project" of the Nevada Geodetic Laboratory, University of Reno, Nevada, USA

(Salvioni 1957; Arca and Beretta 1985) and those estimated using the GPS data. The isokinetic contour map describes the motions occurred over the 60 years period 1897–1957, while the color map plot refers to the past 20 years, 1996–2016. The color mapping results from a linear interpolation of the vertical velocities of the GPS stations presented in Fig. 2. There are a few clear cases of overfitting (localized blue spots), where the GPS stations are isolated. However, in general, the relatively dense spatial distribution of the stations results in a smooth color transition.

The velocity fields were derived from data acquired over two quite different and faraway periods of time and from different sets of measured points. However, a qualitative comparison shows consistency between the main spatial features. A different behavior is found between the CW and the CE part of the plain. The CW sector, in fact, presents a general tendency to uplift, of the order of a few mm/year, while in the CE part subsidence prevails. Stronger values are found in urbanized areas of the Via Aemilia which runs along the plain, in the coastal zone and in the Po river delta, where rates exceeding 5 mm/year are present.

To provide a more detailed comparison, we estimated the differences between the GPS vertical velocities and those obtained from the isokinetics. The differences were computed for those GPS sites located in the area encompassed by the isokinetic contour map. Obviously, the GPS station points do not coincide with the leveling benchmarks. Therefore, a general criterion was adopted to determine, at the GPS locations, the vertical velocity values as provided by the isokinetics. We choose the value corresponding to the isokinetic when the GPS station is located on a contour line, or within 1/4 of the distance between two consecutive contours. The mean value of two consecutive isokinetics was, instead, selected when the GPS station is located approximately midway between two adjacent isokinetic contours. The errors associated with these extrapolated velocities are in the order of 0.25 mm/year, which is half of the interval between two successive isokinetics. A more sophisticated analysis could have been performed by interpolating the isokinetic values; however, within the stated limits of precision, the differences would be negligible.

Figure 4 presents the differences between the two velocity fields. In particular, Fig. 4a displays the differences for those stations showing absolute positive velocities (uplift in Fig. 3), while Fig. 4b shows the differences for the stations located in subsiding areas (red areas in Fig. 3). In both cases, differences were estimated with respect to the velocities determined by means of the leveling information. In Fig. 4a, the four sites identified by shades of beige color are characterized by GPS vertical velocities which are, on average, 1 mm/year lower than those provided by the isokinetics. Incidentally, these four sites are located at the edge of the area covered by the isokinetic contours. The five white triangles indicate sites where no significant differences between the GPS and the leveling vertical velocities were found. The remaining stations, identified by triangles of different shades of green color, indicate that the GPS vertical velocities are about 1 mm/year higher than those derived by the leveling measurements during the first 60 years of the twentieth century. These findings are in agreement with the GPS vertical velocity field estimated for this area by Devoti et al. (2011).

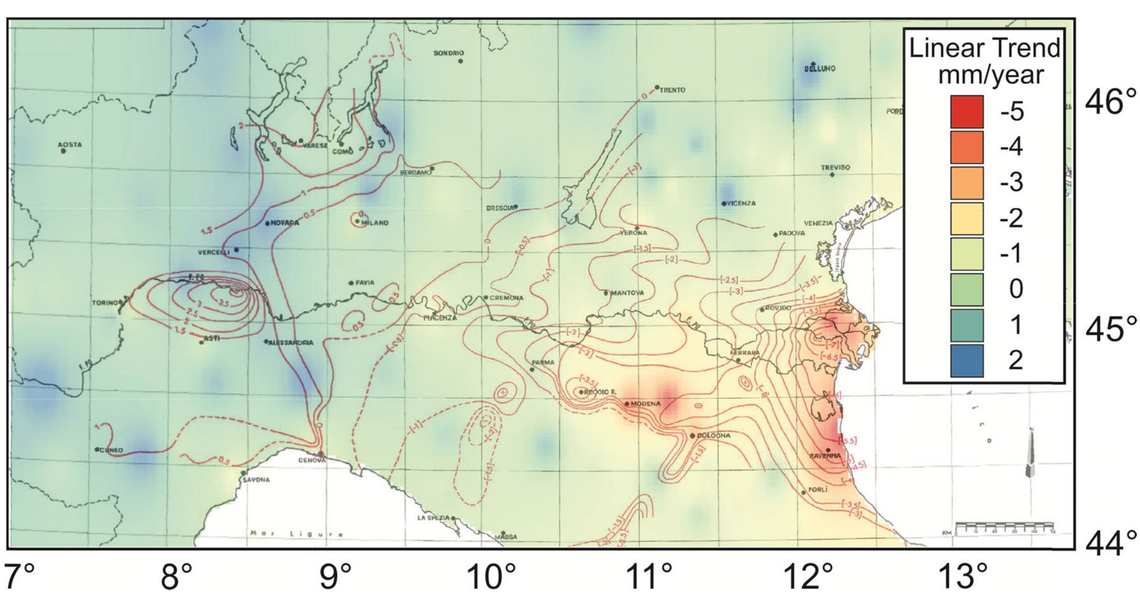


Fig. 3 Comparison between the vertical velocities obtained from leveling measurements and those estimated using the GPS data (*color map plot*). Isokinetic contours, *red color*, modified from Arca and Beretta (1985)

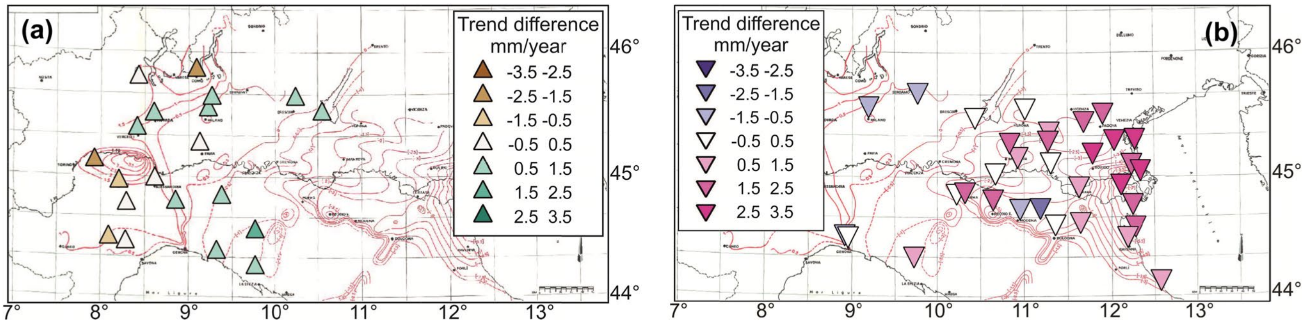


Fig. 4 Differences between the GPS vertical velocities (1996–2016) and those obtained by means of leveling (1897–1957). The differences are represented by *colored triangles* at GPS locations. **a** The results for stations characterized by absolute positive velocities (*uplift* in Fig. 3); **b** the results for stations characterized by absolute negative velocities (subsidence in Fig. 3)

In Fig. 4b, the magenta and pink triangles show that subsidence during the past two decades has, in general, diminished with respect to the first half of the twentieth century. In particular, in the Po river delta, the decrease is significant, up to 3 mm/year. Similarly to panel (a), the white triangles indicate those sites where no significant differences of the vertical velocities were identified. Instead, blue and dark blue triangles represent those sites where the GPS subsidence rates turned out to be larger than those provided by the isokinetic contours. It is clear the persistent problem of subsidence, however, mainly restricted to the north-western area in and around the city of Bologna. Here, rates still range from a minimum of a few mm/year (about 5) to a maximum of 3–4 cm/year (Bitelli et al. 2008; Bonsignore 2008; Bonsignore et al. 2011, 2012). These large subsidence values are due to groundwater withdrawal for civil and industrial purposes. Along the Adriatic coast and in the area of the Po river delta, the GPS height time series show an average reduction of subsidence of the order of 3 mm/year with respect to the values derived from leveling.

It shall be pointed out that since the end of the nineteenth century anthropogenic activities have enhanced the natural subsidence which, in the Po plain, along the Adriatic coast, and in the Po river delta, had locally reached very large rates up to several cm/year. Only recently, since the last two decades of the twentieth century, the adoption of environmental protection policies has started to provide a significant contribution towards reducing the size of this phenomenon. It is well understood, however, that subsidence cannot be represented, in general, both in time and space, by a simple linear approximation. This concept was already introduced by Caputo et al. (1970) in a study devoted to subsidence in the Po delta. The present availability of different space geodetic techniques, such as GNSS and InSAR, makes it possible to monitor very accurately temporal and spatial subsidence variations, thus providing detailed and timely information on the evolution of the phenomenon.

4 Sea-level variations and vertical movements

Precise knowledge of the vertical motion of the Earth's crust is desirable when tide gauge data are analyzed. Tide gauges, in fact, measure the sea level elevation with respect to a geodetic reference benchmark located in close proximity of the recording gauge. Therefore, vertical land motions, being embodied in the tide gauge records, need to be removed from the sea-level data before estimating sea-level trends. Today, this task can be accomplished accurately and continuously by co-locating a GNSS system at tide gauge stations or by exploiting the combination of GNSS and InSAR data.

Sea level can be measured from space with high accuracy by means of radar altimeters, which provide the height of the sea surface relative to the Earth's center of mass. These data are not affected by vertical crustal motions. Precise satellite radar altimetry was borne in August 1992, when the Topex/Poseidon satellite was launched. More than 20 years of highly accurate sea-level height time series are now available, which can be compared, at coastal sites, with the tide gauge measurements.

In this study, we provide an estimate of the northern Adriatic sea-level variation, for the period 1993–2014, as derived from the analysis of both tide gauge and satellite altimetry data. We have selected the tide gauge stations of Marina di Ravenna and Venice (Fig. 5), because both sites were and are affected by subsidence, which was particularly severe in the past few decades in the Ravenna area (Zerbini et al. 2017).

Figure 6 illustrates the monthly sea-level means of the Marina di Ravenna (panel a) and Venice Punta della Salute (panel b) tide gauges, after having applied the inverted barometer and seasonal corrections.

Figure 7 presents an ensemble of data characterizing the vertical land motion over the study period. For Marina di Ravenna (Fig. 7a), the data are the leveling measurements of a benchmark close to the tide gauge, GPS and PS-InSAR (Ferretti et al. 2001) heights which were all normalized to the sea-level difference Genoa–Marina di Ravenna. Since

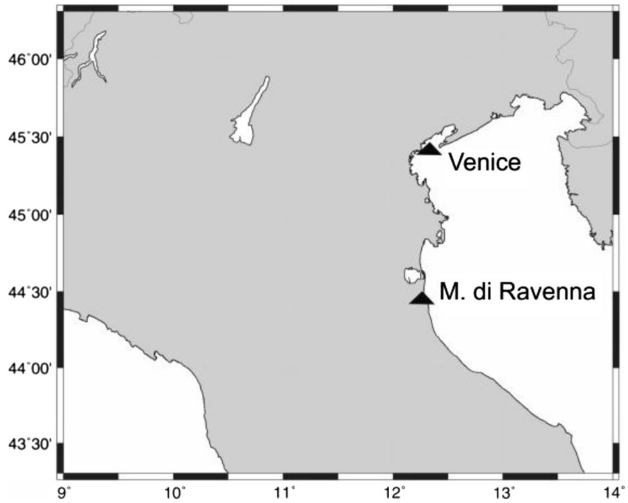


Fig. 5 Location of the Marina di Ravenna and Venice tide gauges

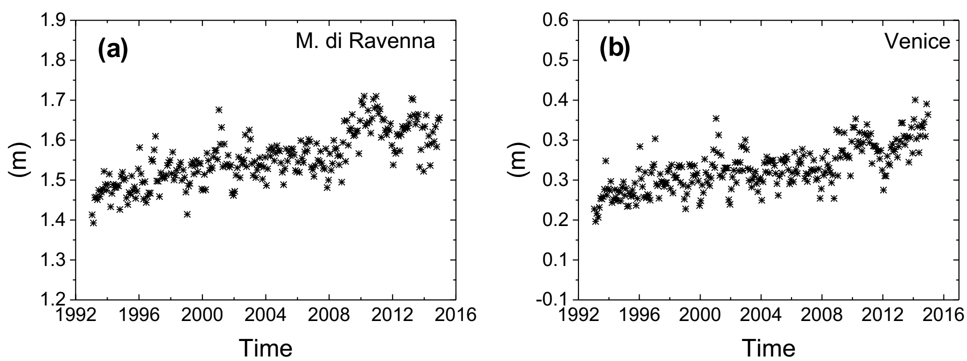
Genoa is considered to be tectonically stable, these differences shall be representative of the vertical land motion at Marina di Ravenna. The black line is a linear model of the available height measurements describing the subsidence behavior over the period 1993–2014. The model well represents the subsidence behavior at the Marina di Ravenna tide gauge for the two decades under consideration. However, it has been shown (Caputo 1973; Zerbini et al. 2017) that, when considering a much longer period of time, including the observations from the end of the nineteenth century, a simple linear model cannot satisfactorily approximate the data.

In the case of Venice (Fig. 7b), a third-order polynomial fit to five leveling benchmarks, GPS and InSAR heights was used to represent the vertical land behavior. All height data were normalized to the sea-level difference Genoa–Venice.

The subsidence models presented in Fig. 7 (panels a and b) were subtracted from the relevant monthly sea-level values. Linear trends were computed from the series thus obtained. Over the period 1993–2014, the sea-level trend turns out to be 4.01 ± 1.01 and 4.39 ± 0.93 mm/year for Marina di Ravenna and Venice, respectively. The associated standard errors were estimated by accounting for serial autocorrelation (Zervas 2001).

In the case of satellite altimetry, we downloaded the data from the AVISO web site (Archiving, Validation and Interpretation of Satellite Oceanographic data, http://www.aviso.

Fig. 6 Monthly sea-level means of the Marina di Ravenna (**a**) and Venice (**b**) tide gauges. The inverted barometer and the mean seasonal cycle corrections have been applied



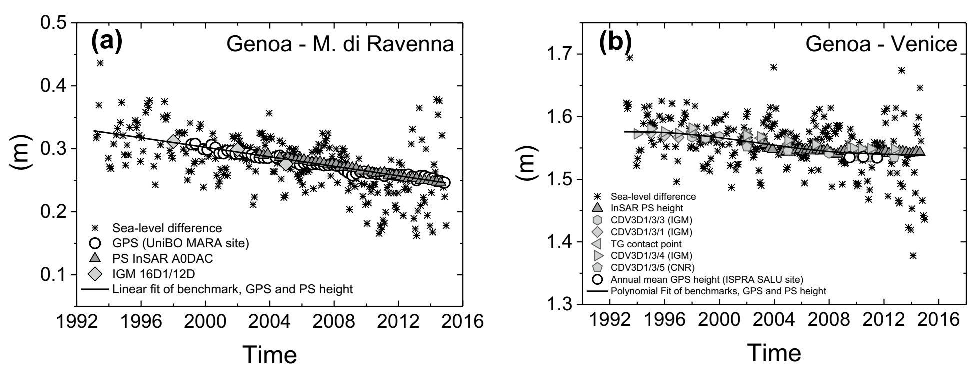


Fig. 7 Vertical land motion at Marina di Ravenna (**a**) and Venice (**b**) tide gauges during the period 1993–2014. The *black stars* are the monthly mean sea-level differences with respect to the Genoa tide gauge. The *open circles* are GPS heights, *dark gray triangles* represent InSAR PS heights while the other symbols refer to different series of benchmark levelings. The different data sets have been normalized to the relevant sea-level difference. The *black curve* is a fit of the normalized heights

Table 1 Sea-level trends at Venice and Marina di Ravenna over the period 1993–2014

Tide gauge 1993–2014	TG trend corrected for VLM (mm/year)	Satellite altimetry (AVISO) trend (mm/year)	Trend difference altimetry–TG VLM corrected (mm/year)
Venice	4.39 ± 0.93	4.18 ± 0.92	−0.21 ± 1.31
M. di Ravenna	4.01 ± 1.01	4.28 ± 0.90	+0.27 ± 1.35

Estimates were obtained using tide gauge data corrected for vertical land motion (column 2) and satellite altimetry data for the nearest grid point to the respective tide gauge (column 3). The difference of the two estimates is listed in column 4

oceanobs.com/en/altimetry/index.html). In particular, the data were the SSALTO/DUACS Mediterranean Sea multi-mission daily gridded sea-level anomalies (SLA) based on observations of 10 satellites. DUACS (Data Unification Altimeter Combination System) is the SSALTO (Segment Sol multi-missions d'ALTimétrie, d'Orbitographie et de localization précise) multi-mission altimeter data processing system. To compare the altimetry and the tide gauge results, the nearest grid point to the Marina di Ravenna and Venice tide gauge stations was selected among the available SLAs. Monthly averages were computed from the daily values and the resulting time series were de-seasoned. Finally, linear trends were estimated with associated standard errors accounting for serial autocorrelation.

The results are summarized in Table 1. The estimates listed in the table show that the tide gauge data, corrected for vertical land motions, lead to sea-level trends which are in good agreement with those obtained by means of the satellite altimetry data.

5 Conclusions

Across the Po plain, vertical land movements were examined. We compared the values of the isokinetic lines provided by Salvioni (1957) and Arca and Beretta (1985) over the interval 1897–1957 with the trends estimated from series of GPS observations acquired during the 1996–2016 time frame. The two periods are rather far away and also differ in time length; the isokinetics cover about 50 years, from the end of the nineteenth till middle twentieth century, while the GPS data refer to the last 20 years.

Over the whole Po plain, the comparison shows coherent spatial patterns. The CW sector is characterized by uplift, while subsidence is the dominant feature in the CE part. This is in line with the geologic context describing the Po plain as a sedimentary subsiding basin surrounded by the uplifting Alps and Apennines chains (Bondesan et al. 1997). The natural, or otherwise known, structural subsidence was locally aggravated during the twentieth century, mainly because of withdrawal of fluids from the underground. The adoption of environmental protection policies during the second half of the twentieth century contributed reducing alarming subsidence rates. Along the coastal area and in the Po river delta, the comparison between the isokinetic values and the GPS vertical velocities shows a reduction of the rate of subsidence of about 3 mm/year. However, still today, there are critical areas where anthropic activities are responsible for a significant increase of the subsidence rate. A clear example is a sector north-west of the city of Bologna. In this area, our results show an increase of only a few mm/year, but this is due to the fact that the GPS site is located at the very border of the fastest subsiding crater which is lowering at rates even exceeding 3 cm/year (Bonsignore et al. 2011; Pignone et al. 2008).

The importance of carefully modeling vertical land motions when estimating sea-level trends by means of tide gauge time series was highlighted by two examples: Venice and Marina di Ravenna. Both sites are known to be subjected to subsidence. The data analyzed refer to the past 20 years (1993–2014) because GPS, InSAR, and satellite radar altimetry data became available in this time frame.

Modeling of the vertical land motion was achieved by using the available leveled benchmarks as well as GPS and InSAR heights. At Ravenna, a linear fit was adopted, while for Venice a non-linear model fit the data. At both sites, sea-level trends estimated from satellite altimetry data and from tide gauge measurements corrected for subsidence well agree within the errors.

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