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The Earth Expansion Evidence

GPS Positioning and Velocity Field in the Apennines Subduction Zone

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Abstract. A stable geodetic reference frame permits to relate one position to another and to compute a reliable deformation field from geodetic observations. In order to satisfy scientific requirements, the reference frame should be accurate, reliable and internally consistent over time with unambiguously specified datum definition (origin, scale, orientation and their respective time evolution). Current reference frame stability between successive frame realizations suggests that the agreement is at the level of 1 cm and 0.3 mm/yr respectively for absolute and time derivative translation and scale factors. They represent the current stability over time of the reference frame and set the sensitivity for geodetic measurements. Here we will present the results of a GPS deformation field in the Italian region obtained from all the available permanent GPS stations operated in Italy. The complex nature of the ongoing tectonic deformation along the Alpine-Apennines orogenic systems is now evident and GPS data have proven its capability to measure millimetre scale deformations.

Key words. ITRF – Space geodetic techniques – Tie vectors – Co-locations – Local ties

1. Introduction

The possibility of estimating the positions and velocities of GPS stations is firmly connected to the concepts of reference system and reference frame. Defining and using a stable reference frame is of fundamental importance in geodesy, since it permits to relate one position to another and to compute a reliable deformation field from the observations.

The pioneering work by a certain number of geodesists and astronomers is referred in Kovalevsky et al. (1989), it established the foundation of the concept of reference systems and frames currently adopted and used by the international geodetic community as a basis for the International Terrestrial Reference Frame (ITRF) products. The rigorous definition distinguishes between the reference system (RS), as a theoretical inaccessible mathematical model and the reference frame (RF), as the numerical realization of the system.

The RF is accessible to the users and it materializes the conceptual RS through a table of "fiducial" station positions and linear velocities at a given epoch. It is also perfectible, in the sense that its precision and internal consistence may improve, being based on space geodesy observations.

The International Earth Rotation and Reference Systems Service (IERS) dictates the standards and conventions for the RS definition (McCarthy, 1996; McCarthy and Petit, 2004; Petit and Luzum, 2010). The ITRF as a realization of the International Terrestrial Reference System (ITRS) is the standard frame recommended for a variety of applications, from surveying to the very fine studies in Earth Sciences.

The current ITRF release is the ITRF2008 that integrates time series of station positions and daily Earth Orientation Parameters from all the International Services of satellite techniques: the International GNSS Service-IGS (Dow et al., 2005), the International Laser Ranging Service-ILRS (Pearlman et al., 2002), the International DORIS Service-IDS, (Tavernier et al., 2006), and the International VLBI Service-IVS (Schlueter et al., 2002). In order to satisfy science requirements, the ITRF should be accurate, reliable and internally consistent over time with unambiguously specified datum definition (origin, scale, orientation and their respective time evolution). The stability and accuracy of such reference frame datums represent the sensitivity of the GPS tool for studying the geophysical phenomena affecting the surface of the Earth.

We will present the results of a GPS deformation field in the Italian region obtained from all the available permanent GPS stations operated in Italy. The complex nature of the ongoing tectonic deformation along the Alpine-Apennines orogenic systems is now evident and GPS data have proven its capability to measure millimetre scale deformations. The new deformation patterns highlighted in this work will certainly add a new piece of information in the understanding of the subduction process along the Apennines in the context of Africa-Eurasia collision.

2. ITRF2008 Origin and Scale

Realizing and maintaining the ITRF origin at the mean Earth's center of mass is a crucial task for geodetic measurements and its applications in Earth sciences. Although the ITRF is constructed by combining all the space geodesy observations, its origin is currently defined by the single SLR technique, aligning the cumulative ITRF solution to the ILRS-SLR long-term solution. As a consequence it is difficult to independently evaluate the origin accuracy, a rough estimate may be inferred by comparing the translation components between the current and the previous reference frame, respectively ITRF2008 and ITRF2005. However such accuracy reflects only the internal inconsistency of the ITRF and any independent assessment of the stability is difficult to achieve at high level accuracies.

The estimated translation and translation rate parameters between the two frames suggest that the origin agreement is at the level of 1 cm over the time span (1983-2009) of the SLR observations (Altamimi et al., 2011) and it may be adopted as the stability threshold of the current ITRF origin. Fig. 1 represents the history of translation and scale parameters and their rates from ITRF2008 to previous ITRF versions (Petit and Luzum, 2010). The ITRF origin has been adopted historically on SLR solution only, until the transition from ITRF2005 to ITRF2008 so the translation parameters show significant shifts as SLR results have evolved. The scale parameter instead has been tight to the VLBI and SLR solutions, that have proven to provide an accuracy not better than 1 ppb.

The scale of ITRF2008 is realized by averaging the scales provided by VLBI and SLR and its accuracy may be assessed by propagating the discrepancy between the two techniques at the limits of the observation time span, leading to a maximum discrepancy of 1.2 ppb, or 8 mm at the equator (Altamimi et al., 2011). The scale and scale rate agreement between SLR and VLBI is at the level of 7 mm and 0.3 mm/yr respectively and represent the current stability over time of the reference frame scale.

The scale rate agreement represents currently the detection threshold of space geodesy techniques for any geophysical phenomenon that deforms the Earth's surface. The ability of discerning between competing geophysical processes that affect the observations at the order of magnitude of the RF stability, will be a difficult task that imply a large number of

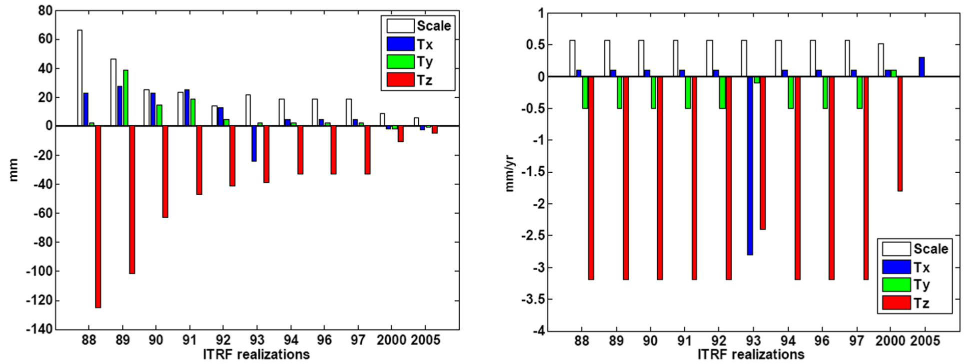

Fig. 1. Translation and scale parameters (left panel) and rates (right panel) of previous ITRF realizations with respect to current ITRF2008.

uncertain assumptions. The glacial isostatic adjustment (GIA), a global rise of land masses that react to the unloading of large ice masses during interglacial times and other significant changes induced by the land/ocean water distribution that occur at present are among the most probable causes of unmodelled residuals. Also whether the solid Earth is expanding or not has attracted persistent attention (McElhinny et al., 1978; Burša, 1993; Williams, 2000; Wu et al., 2011) and the possibility to measure it with current space geodetic techniques is limited by the ITRF origin and scale stability.

Another geodetic measurement bias comes from the uneven distribution of the geodetic networks. Any geophysical effect that in principle do not contribute to degree-0 or net expansion components, could be severely contaminated by the inhomogeneous distribution of the geodetic network. The network effect may well explain differences in the radial expansion rates reported in the literature (Gerasimenko, 1993; Sun et al., 2006; Shen et al., 2011). Recently Wu et al. (2011) tried to unravel the possibility of a varying solid Earth radius considering ITRF2008 3-d positions and velocities, GRACE and ocean bottom pressure observations and inverting for a varying Earth radius, their conclusion is that the mean radius of the Earth is not changing to within an uncertainty of 0.2 mm/yr. A result, that is not far from the findings of Shen et al. (2011) based on a completely different approach, claims that the Earth is expanding at a rate of 0.2 mm/yr!

3. GPS Data Analysis in the Italian Area

We analyzed an overall GPS network consisting of more than 600 permanent stations operated by different research institutions, regional governmental offices and private companies. (see Devoti et al., 2011 for references and links to the data archives). The analysis includes all the permanent GPS data acquired in the Italian region in the period 1998-2009.

The data processing has been carried out with the Bernese software (Beutler et al., 2007), dividing the whole GPS network into 11 clusters, each containing up to 80 sites and sharing 11 common anchor stations.

The tropospheric delay is partially modelled with the a priori dry-Niell model and corrected by estimating 1-hour interval zenith delay corrections. The ambiguity resolution is based on a baseline-wise approach in which the unknown integer number of wavelengths is estimated for each pair of stations using the Quasi-Ionosphere-Free (QIF) strategy (Mervart, 1995).

All GPS data observed in a cluster and over a day are processed simultaneously,

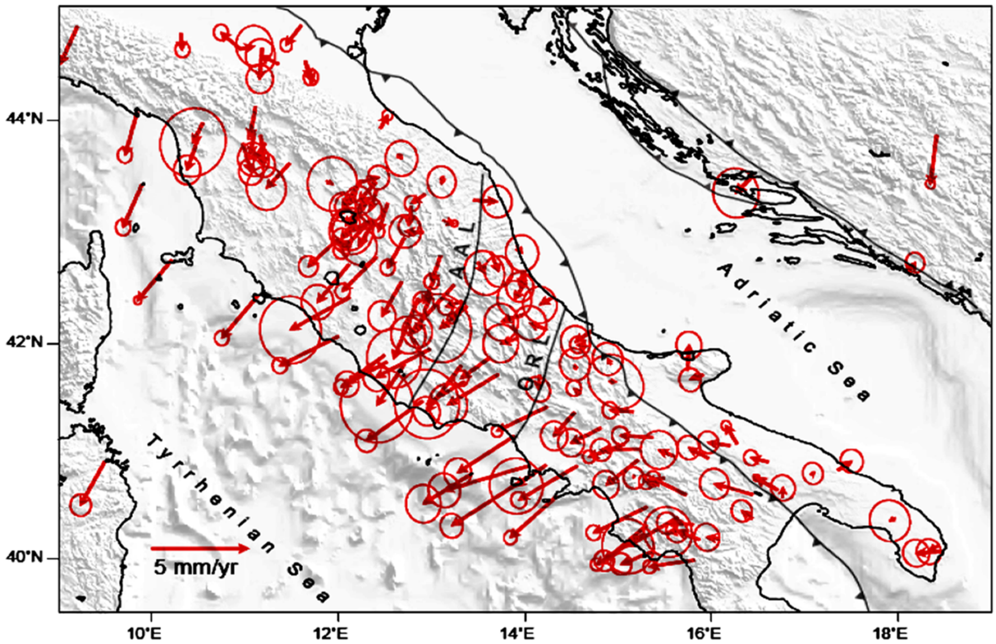

Fig. 2. Horizontal velocity field in central and southern Apennines with respect to a non-moving Adriatic coast, ellipses represent 1-σ confidence regions.

daily global solutions are formed by combining all the cluster solutions in a least squares sense. The reference frame datum is established projecting the daily network solution on the IGS05 frame, more details on the processing scheme may be found in Devoti et al. (2011).

A linear velocity model is fitted to all station positions simultaneously in a least-squares inversion of all the GPS time series. The 3-D velocity components, seasonal variations (mostly annual) and static offsets (i.e. changes in the stations equipment, earthquakes, etc.) are estimated at once for all sites having more than 2.5 years of position determinations.

The final velocity field show a mean horizontal uncertainty of 0.5 mm/yr and a mean vertical uncertainty of 1.3 mm/yr, reflecting the intrinsic weakness of GPS in measuring the vertical component. It is well known that the vertical drift can be largely affected by a number of systematic effects that are difficult to identify: tropospheric and ionospheric higher order mismodeling, variable environmental noise and multiple reflections of the observed signal (multipath), the monument instability, reference frame instability, etc. all of them are highly correlated in the vertical direction. All these effects are responsible for the relatively high uncertainty (few millimetres) of the vertical component. It is therefore important to underline that any geophysical interpretation based on the behaviour of a single station or baseline is intrinsically wrong and should be avoided. Here we will highlight only deformation patterns measured by groups of stations that share a common regional signal. The spatial coherence of the deformation patterns may be therefore a strong ev-

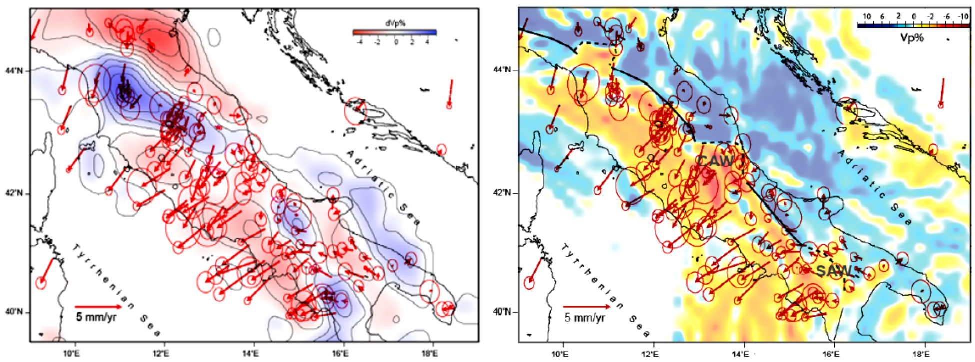

Fig. 3. Comparison between the GPS velocities (Adria fixed) with other tomographic data. The left panel shows the V_p model at 70 km depth inferred from teleseismic data (Giacomuzzi et al., 2011) blue is high and red low V_p; the right panel reports the V_p anomalies at 52 km depth computed from regional seismicity (red high, blue low V_p) showing the central Apennines window (CAW) and the southern Apennines window (SAW) locations (Di Stefano et al., 2009), figure adapted from Devoti et al. (2011).

idence for a common physical mechanism that needs a general explanation. We investigate a few of them that become visible along the Italian peninsula once the rigid plate movement has been cleaned out.

4. Horizontal Deformation Patterns in Central and Southern Apennines

Fig. 2 shows the horizontal velocity field represented with respect to a non-moving Adriatic coast, which can be considered close to but not necessarily coincident with the Adriatic plate. The residual velocities, free from any regional translational or rotational motion, evidence lateral variations along the Adriatic foreland and wide regions exhibit non-stationary behaviour in this representation. We recognize a first pattern in between the main structural discontinuities of the central Apennines, the Ancona-Anzio Line (AAL) and the Ortona-Roccamonfina Line (ORL), a funnel like pattern oriented from east to west, moving towards the Apennines. A second pattern visible in southern Italy, originates on the Apulian foreland initially directed along the Apennine axis and subsequently turning to the west orthogonally.

Both kinematic patterns move coherently at a rate of approximately 1 mm/yr and the geographical extent is on the order of ~100 km. The broad feature of the deformations suggests that the driving mechanism is deeply rooted in the lithosphere and possibly modulated by a variable crustal thickness.

The deformation patterns show a remarkable correlation with tomographic Vp models (Di Stefano et al., 2009; Giacomuzzi et al., 2011) and are located in tomographic transition zones i.e. transitions between high and low V_p beneath the Apennine chain. The left panel of Fig. 3 show the tomographic image of the Italian peninsula at 70 km depth inferred from teleseismic data (adapted from Giacomuzzi et al., 2011) whereas the right panel reports the V_p anomalies at 52 km depth computed from regional seismicity. The surface deformation patterns are located in the proximity of the central Apennines window (CAW) and the southern Apennines window (SAW) (adapted from Di Stefano et al., 2009).

Many authors support the existence of a detached deeper slab in those zones that allow the connection of Tyrrhenian and Adriatic domains in Central-Southern

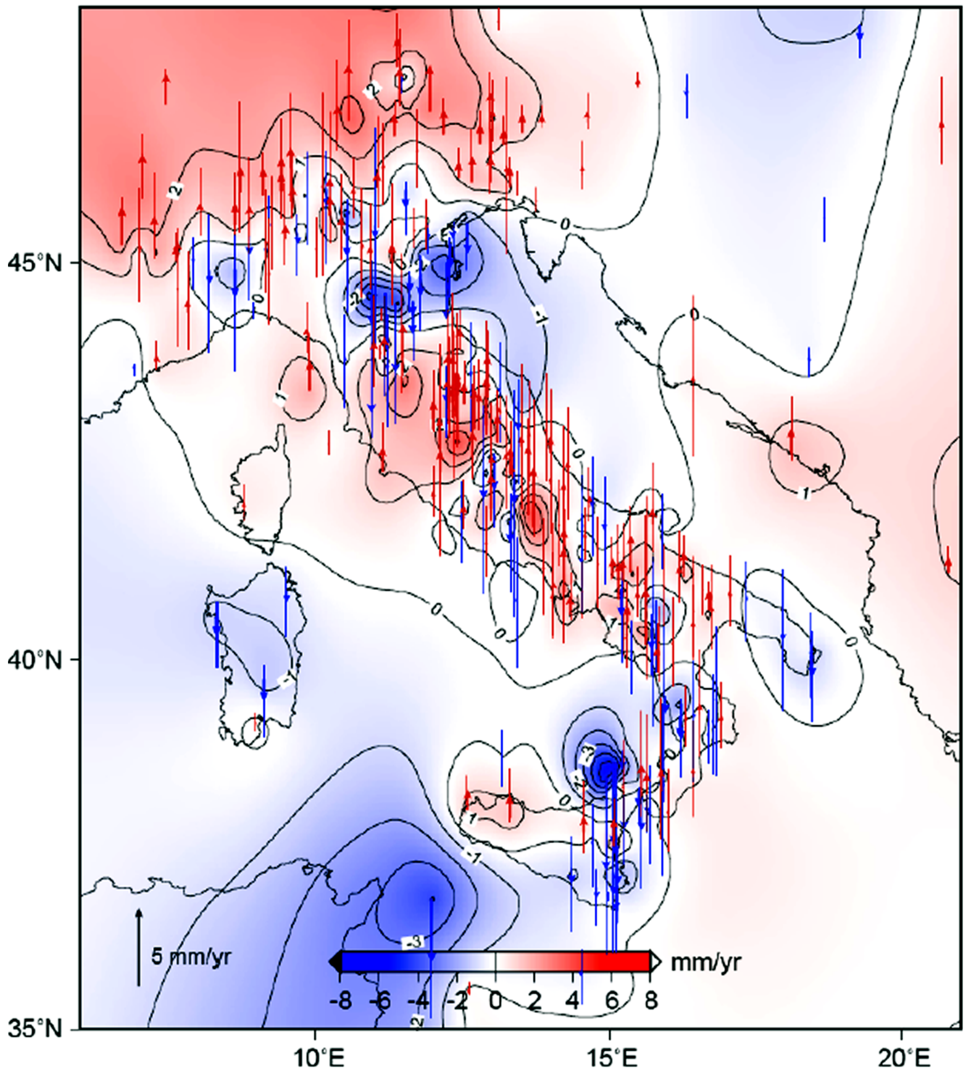

Fig. 4. Vertical GPS velocities, red represents uplift and blue subsidence. Contours show the interpolated velocity field obtained with a continuous curvature surface gridding algorithm and a tension factor of T = 0.25 (published in Devoti et al., 2011).

Apennines (Amato et al., 1993; Piromallo and Morelli, 2003; Di Stefano et al, 2009). This concept fits well with the anomalous anorogenic magmatism of Mt. Vulture (Southern Apennines) discussed in Bianchini et al., 2008 and De Astis et al., 2006 where the authors support the existence of a slab window that could allow the inflow of sub-Adriatic asthenosphere into the Tyrrhenian mantle wedge. We therefore conclude that the complex lithospheric structure beneath the Apennines subduction zone, in particular the presence of slab windows (detached slabs and slab tears) may induce possible upwelling of asthenospheric flows and causes the surface to deform in a complex way evidenced by lateral variations of the surface defor-

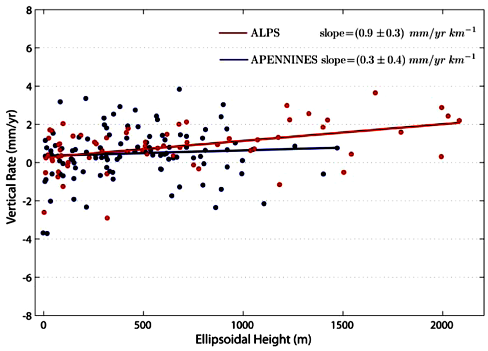

Fig. 5. Vertical rates plotted as a function of smoothed site elevation. Red dots indicate the alpine sites whereas blue dots indicate the Apennines sites, the slopes of straight lines represent the gradients of the vertical rates (published in Devoti et al., 2011).

mation field along the Apennines belt on the order of about 1 mm/yr.

5. Vertical Motion of the Alps and Apennines

The vertical velocity field of the Alps (Fig. 4) shows a broad and continuous uplift on the order of 1-2 mm/yr following the arcuated shape of the belt. Maximum values are located in the northern portion towards the front of the chain. Along the southern piedmont belt of the Alps we recognize the transition to the wide E-W oriented area of the Po plain, characterized by an average subsidence of about 1.5 mm/yr, the highest value being located in correspondence of the Po estuary (3.7±2.0 mm/yr). Along the Apennines we estimate a general uplift of 1-2 mm/yr, following the topographic ridge of the chain. This uplift is interrupted by occasional subsiding areas (~1 mm/yr) due to GPS stations placed in intramountain basins (Tiber basin, Rieti basin, Leonessa basin and L'Aquila basin) filled by Plio-Quaternary continental sediments and bounded by NNW-trend Quaternary active normal faults (Galadini & Galli, 2000 and references therein).

Consolidation of sedimentary lithotypes and groundwater withdrawal could be the main driving factor of subsidence in these areas. Because of the straightforward correlation with the mountain belts, it is worthwhile to detail the regional property expressing the vertical deformation field as a function of its elevation. In mountain regions the short wavelength topographic relief is essentially uncompensated and supported by the elastic strength of the lithosphere, we therefore apply a low-pass filter to the topography averaging on a 0.1°×0.1° geographic cell (Wessel & Smith, 1991). Fig. 5 represents the vertical rates as a function of the smoothed ellipsoidal elevation.

The Alpine domain is separated from the Apennines domain by selecting stations located on or adjacent to the mountain belts. The two domains reflect rather different uplift behaviour, the Alps show a higher correlation with a vertical gradient of (0.9±0.3) mm/yr over 1000 m elevation, whereas the Apennines don't reveal any significant variation with altitude (0.3±0.4) mm/yr but show an almost constant uplift of about 1 mm/yr. These results, despite their intrinsic weakness (partial coverage, high uncertainties, unknown systematic errors), are consistent with the proposed scenarios in the literature that explains the observed uplifts. The elevation dependent gradient shown in the Alpine domain may be consistent with noticeable ongoing isostatic rebound or crustal thickening processes (Champagnac et al., 2009; Barletta et al., 2006). Whereas the meaningless elevation gradient in the Apennines is compatible with the models suggested by D'Agostino et al. (2001) and Shaw & Pysklywec (2007), that propose a dynamically supported uplift of the Apennines by mantle convection processes.

6. Conclusions

GPS technique has proven to be an invaluable tool for measuring the ongoing deformations of the Earth's surface. In the last decades the technique has improved dramatically in terms of receiver technology, data processing strategies and modelling of main error sources. The reference frame used to express the time variable station position is currently limiting the accuracy of the geodetic solutions. The stability of the reference frame is presently on the order of 1 cm over a 30 year period or 0.3 mm/yr changes of the scale factor. These values represent the detection threshold for any geophysical phenomenon that actively deforms the Earth's surface.

The processing of a dense GPS network in the Italian area revealed unknown patterns in the horizontal and vertical deformation fields. Coherent deformation patterns on the order of 1 mm/yr in central and southern Apennines could be related with asthenospheric flows in detached slab windows and vertical rates in Italy could also be associated to deep mantle convection processes.

The complex nature of the deformations uncovered by recent GPS networks especially in orogenic and active deforming regions poses many issues that should be addressed in the next future. In any case space geodesy measures the sum of all phenomena, from particular to general, in a space-time domain.

The uneven distribution of GPS stations, the effects of locally driven processes such as the Alps and Apennines uplift or the Po plain subsidence, the isostatic adjustment caused by large ice masses and land/ocean water re-distribution, may represent an insurmountable obstacle to unravel any possible varying solid Earth radius, especially if the effect is on the order of the reference frame stability.

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