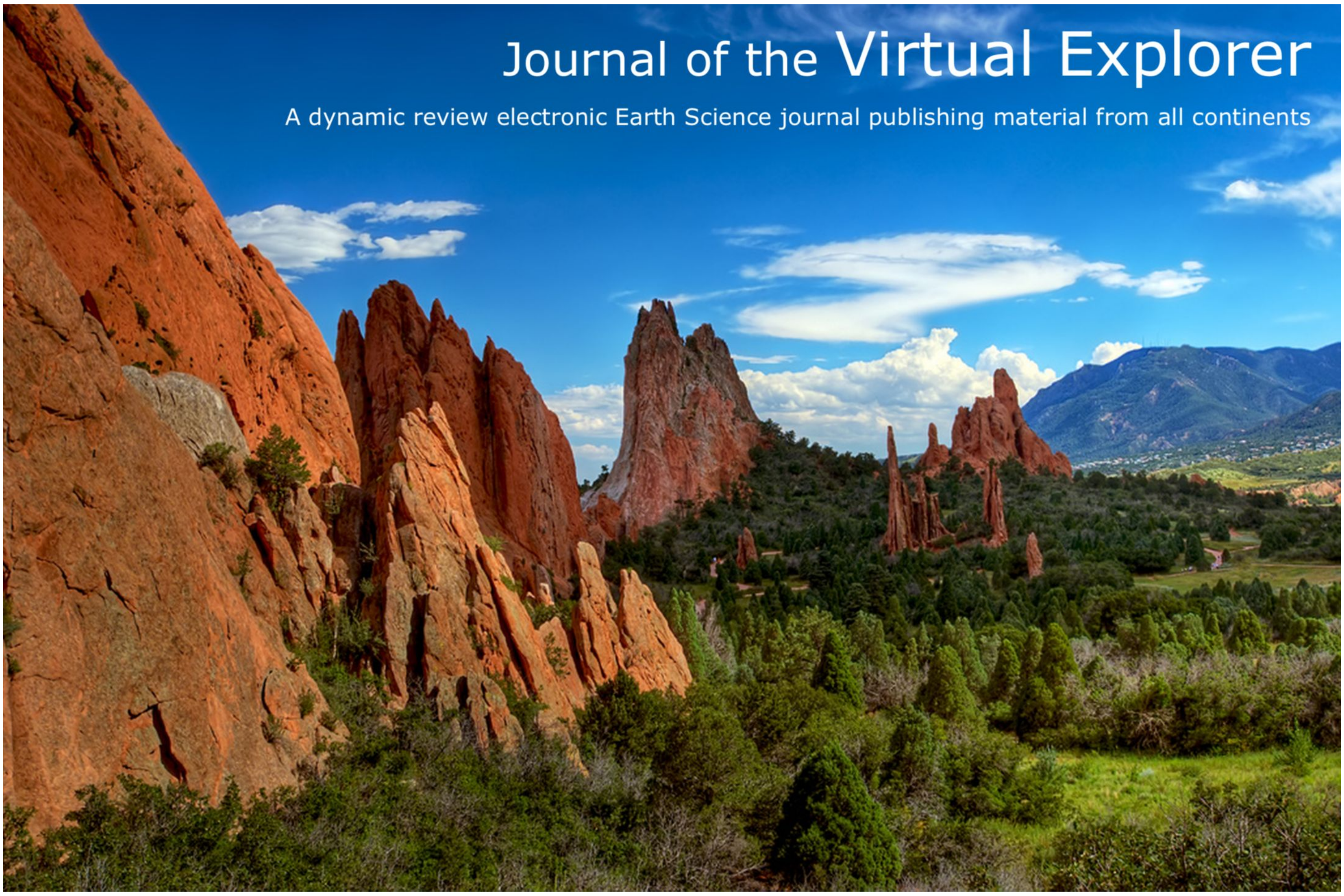

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Abstract: We present the velocity field of Italy derived from the analysis of continuous GPS observations collected during 1998-2009 from 287 sites. The GPS networks analyzed cover the whole country with a mean inter-site distance of about 50 km. The processing is performed using two software programs, BERNESE and GAMIT, adopting in both cases a distributed session approach with more than 10 clusters, sharing common stations, each of them consisting of about 40 stations. Daily loosely constrained solutions (saved as SINEX files) are routinely produced for each cluster by two data analysis centres and the velocity field is obtained by stacking the daily normal equations. The rigorous combination of independent solutions allows the cross-validation of the velocity field.

We have analyzed the time series of the entire area referenced to a common frame (ITRF2005 with respect to Eurasian Plate) and have estimated the velocity field providing an updated detailed picture of the kinematics (velocity map) and deformation pattern (strain rate map) of the Italian area. Additionally, we have combined the two velocity fields obtained from the two software programs obtaining the average velocity field of the Italian area. The two velocity fields agree at the level of 0.2-0.3 mm/yr consistent with their standard deviations. The deformation patterns (strain-rates) do have significant features, showing a distinctive extension along the Apennines on the order of 50-80 10^{-9} yr^{-1} and less pronounced areas of compressive tectonic behaviour at the level of 30-50 10^{-9} yr^{-1}. The GPS kinematic description of the crustal deformation shows a high coherence with the seismotectonic setting of the Italian area.

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Introduction

The Italian peninsula is a rather interesting natural laboratory for geophysical investigations. Its tectonic evolution is driven by the interplay of two major plates, the African and Eurasian plates, and possibly by smaller intervening micro plates. The entire area is characterized by a complex tectonic setting where two very different orogens, the Alps and the Apennines, interfere and cause vast areas to deform in a complex way. Compressional regimes are contiguous to extensional regimes along the whole Apennine belt; and to the North, a double vergent thrust belt characterizes the Alpine belt. The whole area is subjected to slow crustal deformations (at the few mm/yr level) (Serpelloni *et al.*, 2005; Devoti *et al.*, 2008; Jenny *et al.*, 2006) originated by the African-Eurasian convergence and modulated by the double subduction of Europe underneath the Adriatic plate and the westward Adriatic plate subduction beneath the Tyrrhenian Sea. The crustal velocity gradients (strain-rates) have been demonstrated to be strongly correlated to the actual seismic activity (Kremer *et al.*, 2002; Bird *et al.*, 2010). The magnitude and kinematics of the strain-rate and consequent stress accumulation on seismogenic structures in Italy is not well known and only recently, thanks to the relatively low cost of GPS surveys, fault-scale mapping of crustal strain-rates have been made available to the scientific discussion and can be tentatively correlated with geological and seismological deformation in an attempt to provide valuable data to help investigating earthquake recurrence and seismic hazard (Caporali *et al.*, 2003, Serpelloni *et al.* 2005, D'Agostino *et al.*, 2009).

The first attempt to build a nation-wide continuous GPS network was undertaken by the Italian Space Agency (ASI) in the late 1990's. Since then, it delivers continuous GPS data from about 30 sites and maintains the regional reference frame in strict cooperation with the European reference frame consortium (EUREF). In 2001, the Istituto Nazionale di Oceanografia e Geofisica Sperimentale (INOGS) started installing a local GPS network in the Friuli region (northeastern Italy) to study the deformation pattern of the peri-Alpine thrust. In 2004, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) started the construction of the first national GPS network (RING) dedicated to geodynamic investigation of a wide area (Avallone *et al.* 2010). At present, the network consists of about 130 stations whose data are continuously transmitted to an archiving center *(http://ring.gm.ingv.it)* that performs quality checking and data storage. Currently, the data from only 36 of the sites are freely provided on the web site, but there is a strong demand for access to the full archive on a public domain to stimulate the research on this interesting area. Finally, in past years an increasing number of permanent GPS sites were installed by regional administrations and private companies, dedicated mainly to topographic applications and commercial services. These networks, although not conceived to measure long term ground deformations, proved useful in augmenting the backbone RING geodynamic network and are currently archiving their data, making it available for the scientific community. These GPS datasets are currently archived at different INGV archiving centers providing over 400 RINEX files per day for a mean geometric interdistance of about 20 km over the whole country.

The processing of the entire GPS dataset has been carried out by two different analysis centers at INGV (CNT-Bologna and CNT-Roma) using different GPS analysis software (Gamit and Bernese, respectively) and slightly different procedures and models. A rigorous combination of different independent solutions is fundamental in order to cross-validate them, and to produce a final combined velocity field representing the most reliable kinematic representation of the region.

In this work, we perform our analysis following a three-step procedure. In the first step, the GPS raw observations are processed independently using the two software programs following a distributed session approach (Dong *et al.*, 1998), obtaining daily loosely constrained site positions of the different networks. In the second step, the daily solutions are transformed into a common reference frame (ITR2005) to form the position-time series, and then two independent velocity fields are estimated. In the third step, the two velocity fields are rigorously combined in a least-squares sense, thus obtaining the best unbiased estimate of the surface velocity field. All the analysis and combination procedures are performed using the full covariance matrix and following the basic procedures commonly used for the space geodesy reference frame realization and combination (Altamimi *et al.*, 2007).

Because the three steps propagate the full covariance matrix from the original daily solutions, the final combined velocity retains the full information content derived from the observations and from the reference frame datum. Often this type of solution is termed as a 'rigorous' geodetic solution or a 'rigorously' derived solution (IERS Technical Note 30). As a consequence of the covariance propagation, each site is re-weighted against the entire network so that the final velocity field contains, indeed, the complete covariance matrix.

GPS data analysis

Estimating the precise coordinates of a GPS network requires an accurate definition of the reference frame, otherwise the geodetic problem cannot be solved. The normal matrix usually has a rank deficiency equal to the number of parameters needed to define the reference frame datum. The GPS processing scheme subdivides the observations in daily batches and estimates a series of model parameters (troposphere delays, phase ambiguities, Earth Orientation Parameters (EOP) and satellite state vectors (SV)) at convenient frequencies and site positions once a day. Stated in this way, the observation equation is invariant for rigid rotations of the Earth-Satellite system; the normal matrices of the observation equation show a distinct rank deficiency with the same degree of freedom. The rank deficiency is fixed once the orientation of the Earth-Satellite system has been defined or, alternatively, if a number of selected sites and satellites has been forced to the *a priori* values (ITRF sites and orbits) and the transformation between the reference systems is defined through the EOPs. The classic approach is to fix a number of reference frame parameters in the processing phase or to apply tight constraints to the normal matrix in order to remove the singularity (Biagi and Sansò. 2003, 2004a, 2004b). In the late 1990s and early 2000, a slightly different approach was proposed (Dong *et al.*, 1998; Davies and Blewitt, 2000). The philosophy is to loosely constrain the parameters defining the reference frame (site positions, EOP and SV) leaving all the observations to contribute to the reference frame definition in a consistent way. By not tightly constraining any of the geodetic parameters, we allow the reference frame to be defined in a further step, but on the other hand, some constraints are necessary to prevent the normal matrix from becoming singular. The loose constraints should be chosen weak enough so as not to affect the parameter estimates, but not so weak as to cause significant rounding errors. The main advantage is that no *a priori* information affects the GPS data processing, thus reducing the risk of possible deformations induced by wrong *a priori* information.

Both the processing software programs used in this work are able to produce daily loosely constrained solutions that, in principle, are free from any *a priori* reference frame datum. This means that, since the observations define the reference frame, every daily position is expressed in an unknown reference system, but each reference frame differs day to day in a systematic way dictated by the rank deficiency of the normal equations.

Bernese processing

The GPS data processing is performed by the Bernese software package (Version 5.0; Beutler *et al.*, 2007) forming the double difference of the L1 and L2 phase observations. The GPS orbits and the Earth's orientation parameters are fixed to the combined IGS (International GNSS Service) products and an *a priori* error of 10 m is assigned to all site coordinates. The pre-processing phase, used to clean up the raw observations, is carried out in a baseline-by-baseline mode. Independent baselines are defined by the criterion of maximum common observations. The elimination of gross errors, cycle slips and the determination of new ambiguities are computed automatically using the triple-difference combination. The *a posteriori* normalized residuals of the observations are checked for outliers, too. These observations are marked for the final parameter adjustment. The elevation-dependent phase centre corrections are applied including in the processing the IGS phase centre calibrations (absolute calibrations); moreover, the ocean-loading model FES2004 is adopted *(http://www.oso.chalmers.se/~loading/)*. The troposphere modeling consists of an *a priori* dry-Niell model improved by the estimation of zenith delay corrections at 1-hour intervals at each site using the wet-Niell mapping function. The ionosphere is not modeled *a priori*, but removed by applying the ionosphere-free linear combination of L1 and L2. The ambiguity resolution is based on the QIF baseline-wise analysis. The final network solution is solved with back-substituted ambiguities, if integer; otherwise ambiguities are considered as real valued measurement biases.

Gamit processing

To analyze code and phase data with GAMIT software (Version 10.33; Herring *et al.*, 2006), we adopt standard procedures for the analysis of regional networks (e.g., McClusky *et al.*, 2000, Serpelloni *et al.*, 2006) applying loose constraints to the geodetic parameters. We followed a distributed session approach, subdividing the whole dataset into several smaller sub-networks, sharing some common sites. The analysis is performed on a 20-node CPU cluster that makes an efficient use of the distributed session approach.

GAMIT software uses double-differenced phase observations (ionosphere-free linear combinations of the L1 and L2) to generate weighted least-squares solutions for each daily session (Schaffrin and Bock, 1988; Dong and Bock, 1989). An automatic cleaning algorithm (Herring *et al.*, 2006) is applied to post-fit residuals in order to repair cycle slips and to remove outliers. The observation weights vary with elevation angle and are derived individually for each site from the scatter of post-fit residuals obtained in a preliminary GAMIT solution. The effect of solid-earth tides, polar motion and oceanic loading are taken into account according to the IERS/IGS standard 2003 model (McCarthy and Petit, 2004). We apply the ocean-loading model FES2004 and use the IGS absolute antenna phase center table for modeling the effective phase center of the receiver and satellites antennas. We use orbits provided (as g-files) by the Scripps Orbit Permanent Array Center (SOPAC).

Estimated parameters for each daily solution include the 3D Cartesian coordinates for each site, the 6 orbital elements for each satellite, Earth Orientation Parameters (pole position and rate and UT1 rate) and integer phase ambiguities. We also estimate hourly piecewise-linear atmospheric zenith delays at each station to correct the poorly modeled troposphere, and 3 east-west and north-south atmospheric gradients per day to account for azimuth asymmetry; the associated error covariance matrix is also computed and saved in SINEX (Solution Independent EXchange) format.

Imposing the reference frame constraints

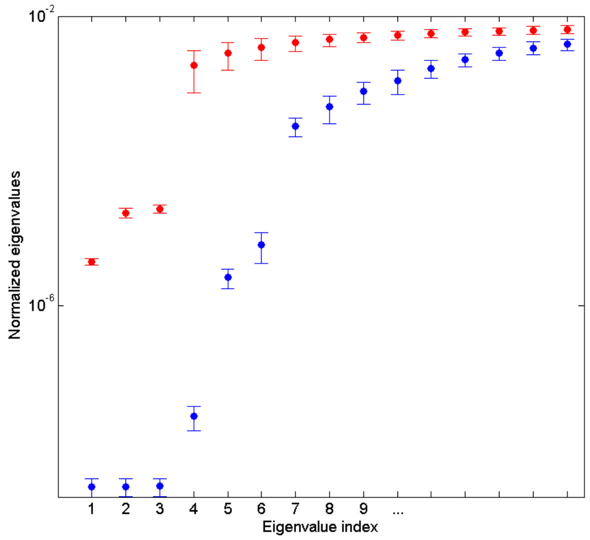
The daily GPS solutions are not estimated in a given reference frame since they are computed in a loosely constrained reference frame. Therefore, their coordinates are systematically translated or rotated from day-to-day and their covariance matrices have large errors as a consequence of the loose constraints applied to the *a priori* parameters (on the order of meters). To express the coordinate-time series in a unique reference frame, associated to their consistent covariances, we have to perform two main transformations. First the loose covariance has to be projected into a well-defined reference frame imposing tight internal constraints (at mm level), and then the coordinates have to be transformed into a given external reference frame - the ITRF2005 catalogue of GPS coordinates and velocities.

In general geodetic problems, the observation equation is invariant for a given symmetry transformation (e.g. the simultaneous translation of the geocentre and the satellite orbits); as a consequence of this invariance, the normal matrix (inverse of the covariance matrix) is singular, and there exist eigenvectors associated with null eigenvalues.

On the contrary, GPS observables (phase double differences) don’t show exact translational symmetry since the satellite orbits are sensitive to the position of the Earth’s center of mass; and weak tracking network and/or poor orbital dynamics require a translational constraint in order to stabilize the solution. Additionally, the GPS observables are not degenerate for scale transformations, but they have errors that may encourage us to constrain the scale. Modeling antenna phase center variations, atmospheric delays and satellite orbits may cause instabilities in the coordinate solutions that can be solved by estimating explicitly translation and scale parameters that can absorb the effects of modeling errors on the estimates. In global GPS networks, the symmetry transformations may have a six-fold degeneracy corresponding to translational and rotational symmetries. Transforming the loosely constrained solution into a well-defined reference frame means fixing the degeneracies (symmetry transformations) and computing the corresponding Helmert transformation (rigid translation, rotation and scaling) to transform the geodetic solution in the given ITRF reference frame.

A first guess to establish the proper constraints to be applied is to study the rank deficiency (first eigenvalues) of the normal matrices. Figure 1 shows the first 15 eigenvalues of the daily solutions obtained from the two different analyses. The values represent the average eigenvalues over the entire period and the errorbar represents the scatter from day to day of the corresponding eigenvalue. The main difference arises from the different realizations of loose constraints; namely, in the Bernese approach we fix the EOP and SV to the IGS standard products and apply loosely constraints (10 m) only on coordinates; whereas in the Gamit approach, we loosely constrained the whole reference frame parameters (EOP, SV and coordinates). This reflects directly on the rank deficiency of the normal matrices and, therefore, on the eigenvalues of the daily solutions. The Bernese solutions show three low eigenvalues and often a fourth intermediate eigenvalue. On the other hand, the Gamit solutions show six lower eigenvalues and occasionally a seventh. Therefore, we chose to impose the reference frame through a four-parameter Helmert transformation for the Bernese solutions and a seven-parameter transformation for the Gamit solutions, applying the corresponding constraints to the loose-constrained covariance matrices (see Appendix C of Dong *et al.*, 1998).

Figure 1. First eigenvalues of the Bernese and Gamit normal matrices.



Lowest 15 eigenvalues (average values) of the daily covariance matrices obtained for the Bernese (red) and Gamit (blue) solutions. Each null eigenvalue corresponds to an invariant symmetry (reference frame degeneracy) of the solution. The Bernese and Gamit solutions provide different types of degeneracies.

Velocity field estimation

We have estimated the velocity fields consistently for the two time series using a self designed MATLAB toolbox (NEVE). We estimate the velocity of the GPS sites together with seasonal variations and offsets (due to possible changes in the stations equipment) in the position time series using the full covariance matrix of the input coordinates. The coordinates are provided as daily SINEX files, each one containing the ITRF daily coordinates with the complete covariance matrix.

The normal equations are built according to the following functional model

$$x_i(t) = x_i^0 + r_i \cdot t + \alpha_i \cdot \sin(\omega t + \psi_i) + \Delta x_i \cdot H(t_j) \equiv A \cdot y$$

where x_i are the Cartesian coordinates of each site (i=1,2,3), x_i^0 is the constant r_i and the rate of the fitting straight line, α and φ are, respectively, the amplitude and phase of the annual, semi-annual signal and H is the Heaviside step-function used to define a coordinate offsets (Δx_i) at a given time t_j.

The unknown parameters of the least squares problem are the components of the vector

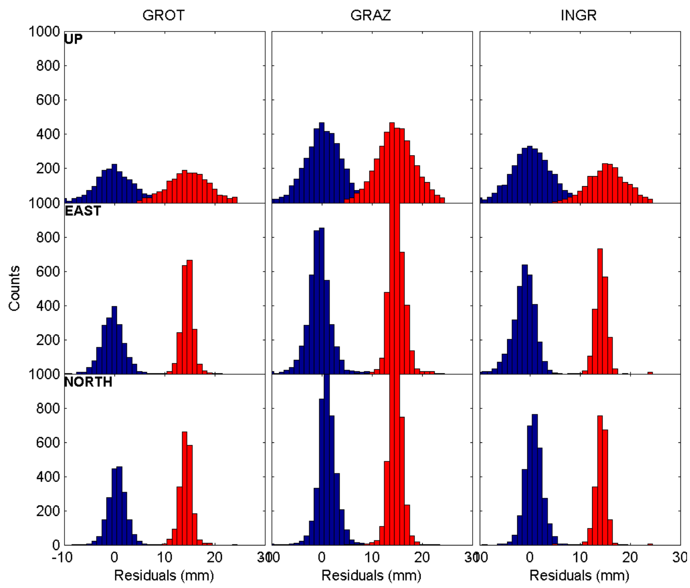
$$y = (x_0, r, \alpha, \psi, \Delta x)^T$$

and its estimation reads

$$\hat{y} = (A^T C_x^{-1} A)^{-1} A^T C_x^{-1} x$$

where A is the design matrix, x the observation vector and C_x is the covariance matrix of the observations. Figure 2 shows some examples of site coordinate residuals with respect to the fitted model (1) in the vertical (up) and horizontal (east, north) components.

Figure 2. Coordinate residuals.



Coordinate residuals in the topocentric reference frame (up, east, north) with respect to the linear model: in blue the Gamit and in red the Bernese residuals.

Note: Supplementary information

The authors have arranged an ftp link (anonymous) where the SINEX file can be downloaded. Click *ftp.ingv.it/pro/s1ur104/GeodeticSolutions/combinedGPS_Italy_Bern_Gamit.snx* to go to the site. (Warning: large (38MB) file.)

Combination procedure

The strategy adopted in this work foresees the combination of the velocity solutions at the normal equation level. Each individual solution is inverted and the two normal matrices are compounded to form the global normal equation matrix, treating each site's velocity and position as an independent observation. The combined normal matrix is then inverted again in order to estimate the unified velocity field and positions of the entire network and saved in the standard SINEX format.

Denoting with S_i (i=1,2) the arrays of the site coordinate-velocity vectors of the i-th solution, the combined field (S_c) is estimated by solving in a least squares sense the following design equation where the design matrix, P_i (i=1,2) is simply the reordered matrix (reordering the i-th solution parameters into the combined parameters order) and η is the noise array.

$$S_c = P_i S_i + \eta$$

Since usually the covariance matrix is known, apart from a solution-dependent variance factor, a scale factor is also estimated together with the combined solution. This assures that each solution's contribution to the total χ^2 is equally balanced, and individual solutions do not prevail in the combination because of differences in the uncertainties caused by unknown covariance matrix scaling factors. The estimated solution scaling factors f_i fulfil the following condition between each *i* and *j* contributing solution:

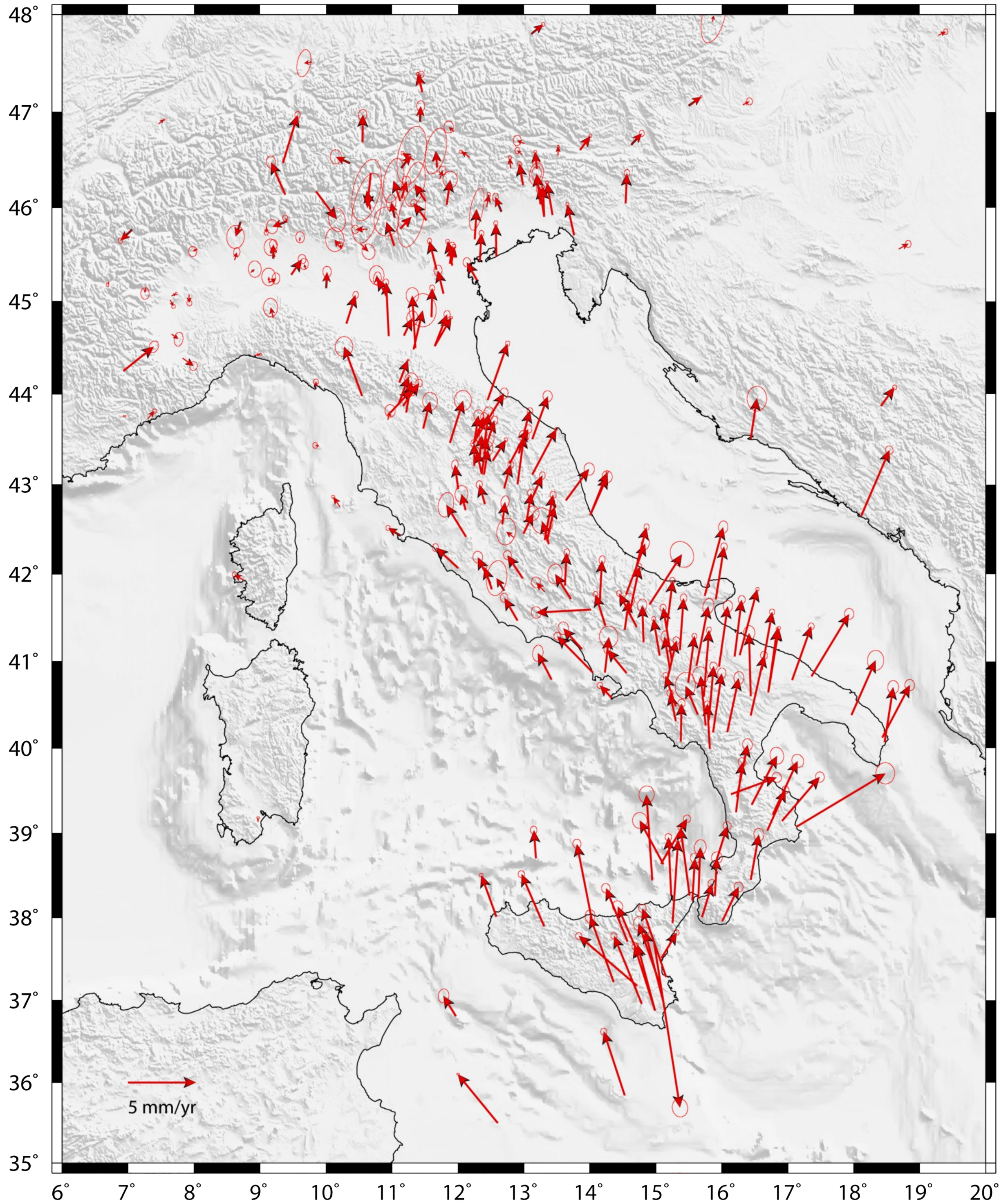
$$R_i^T (f_i C_i)^{-1} R_i = R_j^T (f_j C_j)^{-1} R_j$$

where $R_i = S_i - S_c$ are the coordinate-velocity residuals. The Bernese solution incorporates 433 sites whereas the Gamit solution 378 and the final combined solution hold 481 site coordinates and velocities (481 x 6 parameters). The estimated covariance scale factors are 23.9 and 57.9, respectively, for the Bernese and Gamit solutions, while the reduced chi squared of the combination (variance factor) is 0.8.

Discussion

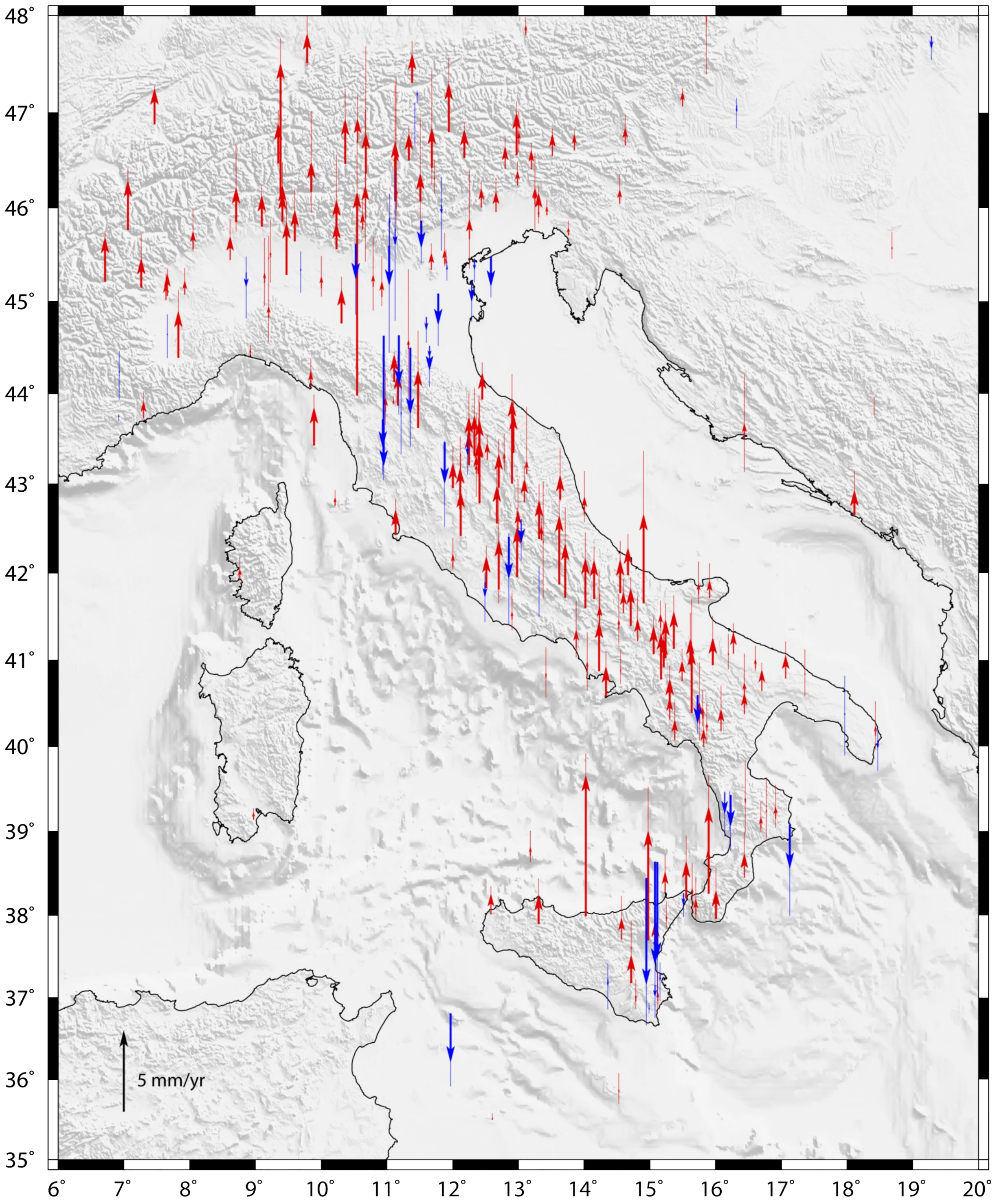
Figure 3 shows the horizontal velocity field of the combined solution w.r.t. Eurasia (Devoti *et al.*, 2008), the error ellipses being the formal 1-sigma confidence regions (68% confidence region), whereas Figure 4 shows the combined vertical velocity field. The GPS network has been selected based on a data persistence criteria - only sites with more than 2.5 years of continuous position determinations has been considered, thus minimizing biases due to seasonal signals (Blewitt and Lavallée, 2002), a total of 287 sites satisfy this criterion. Despite the rigorous selection, the vertical velocity field should be taken with care because the vertical component can be largely affected by a number of systematic effects, including: tropospheric mismodeling, change in environmental noise (multipath), monument instability, etc. Moreover, the scatter of the vertical rates are a factor of 2-4 higher than the horizontal components.

Figure 3. GPS horizontal velocities with respect to Eurasia.



GPS combined horizontal velocities with respect to Eurasia fixed reference frame. Only sites with more than 2.5 years of observations are shown.

Figure 4. GPS vertical velocities.

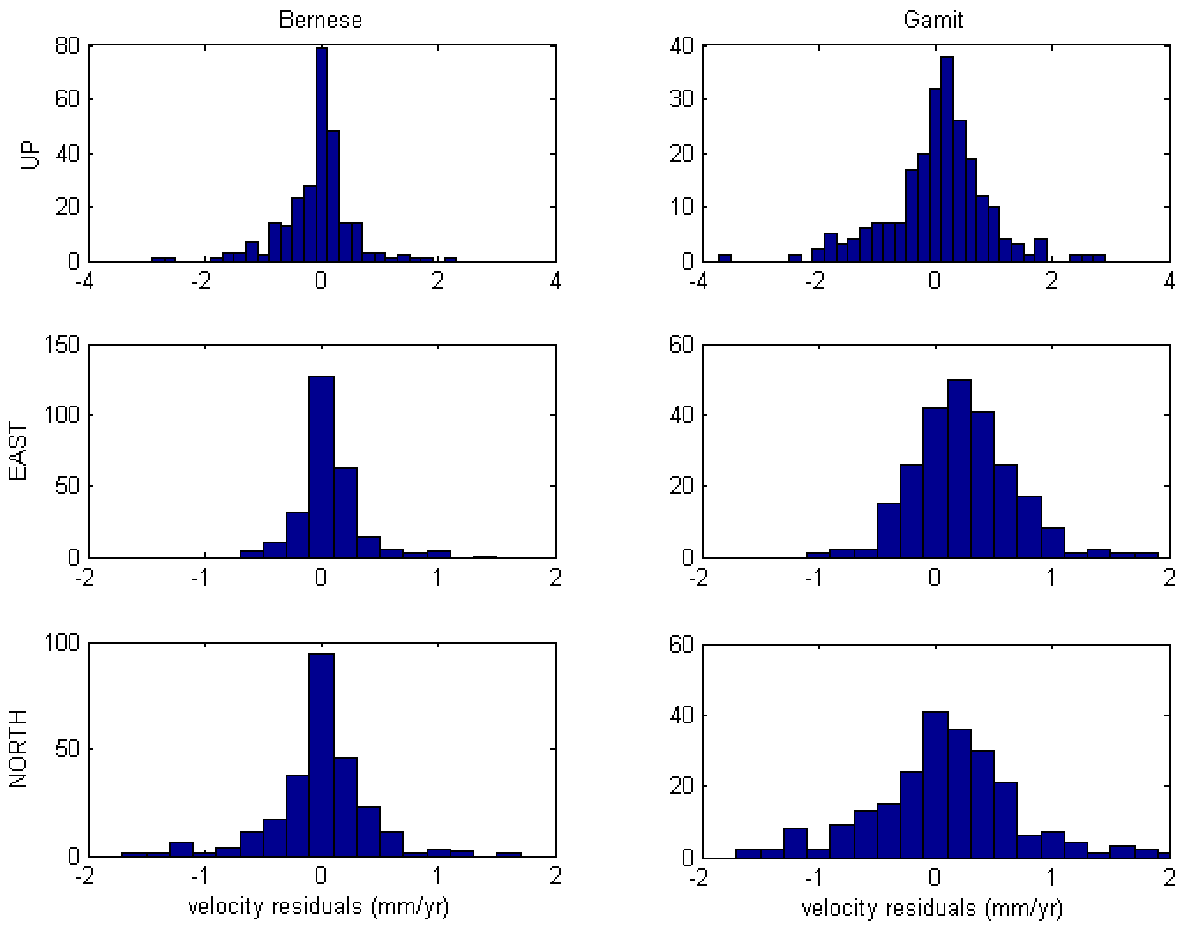


GPS combined vertical velocities with respect to the reference ellipsoid. Sites with more than 2.5 years of observations are shown.

The velocity values are reported in *Table 1* (subscribers can download from http://virtualexplorer.com.au/

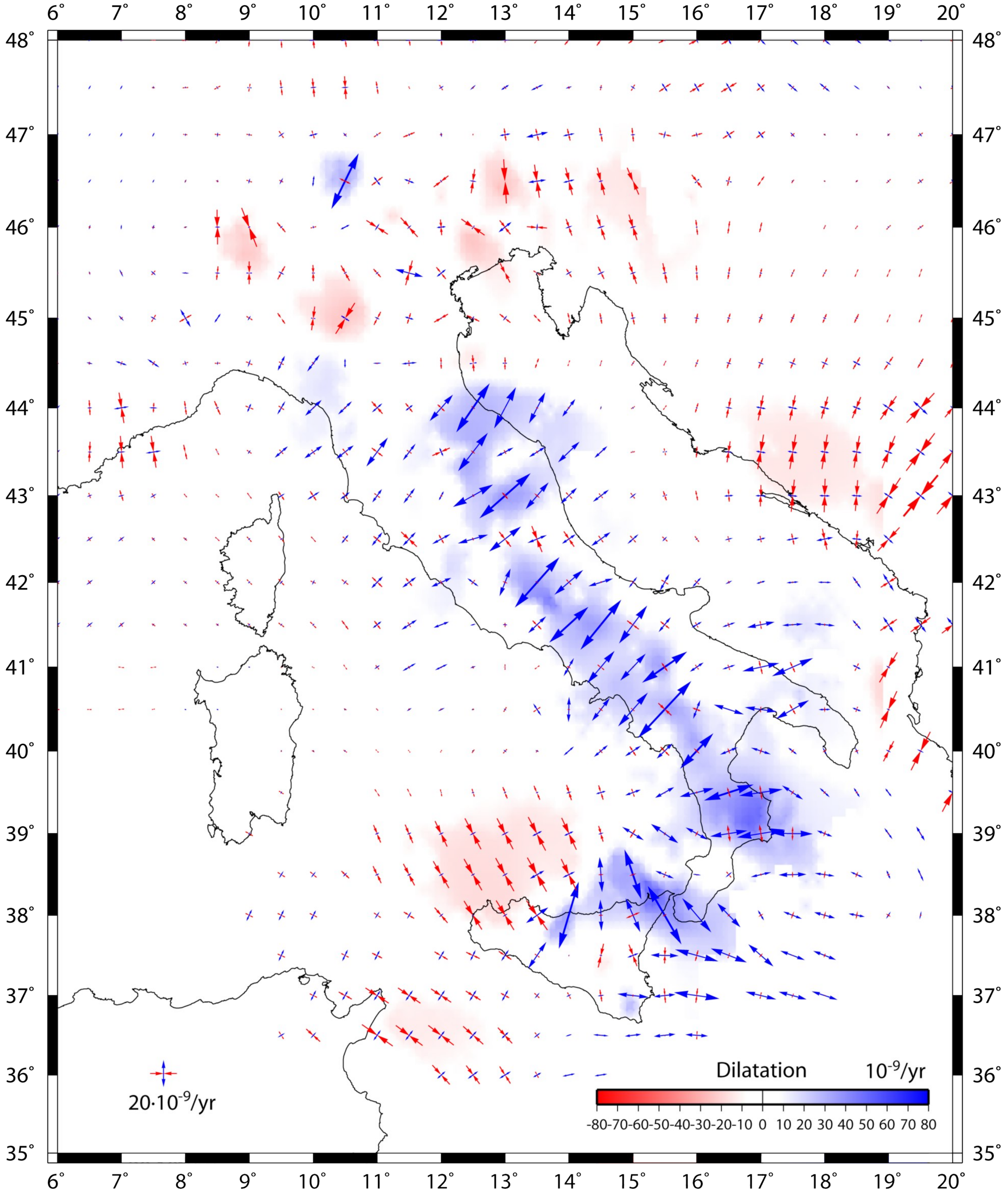
article/2010/237/kinematics-of-italy/pdf/table1.pdf), associated with the Bernese and Gamit time-series repeatability (WRMS of residuals with respect to the linear trend). It is worthwhile to note that not all sites have similar noise content; the WRMS in the horizontal components for long-lasting sites is typically around 1-3 mm, whereas the vertical components are on the order of 4-6 mm. In particular, a few sites (ESLN, LATT) that demonstrated an anomalous high scatter should be treated with care when studying tectonic motion, since periodic variations may be attributed either to instrumental malfunctions, anomalous multipath noise or mismodeled residuals. Subtle variations of site positions may arise also from local geophysical processes (water table variations, landslides, etc.) or site effects (soil compaction, monument type or foundation effects). All these effects may produce aliasing in the estimated secular trends and could explain a few 'anomalous' velocities from a tectonic perspective. Figure 5 shows the velocity residuals of the single solutions with respect to the combined velocity field in the vertical and horizontal planes. The Gamit velocity residuals show a slightly broader distribution than the Bernese residuals, which reflects the difference in the relative weights that have been estimated in the combination process.

Figure 5. Velocity residuals.



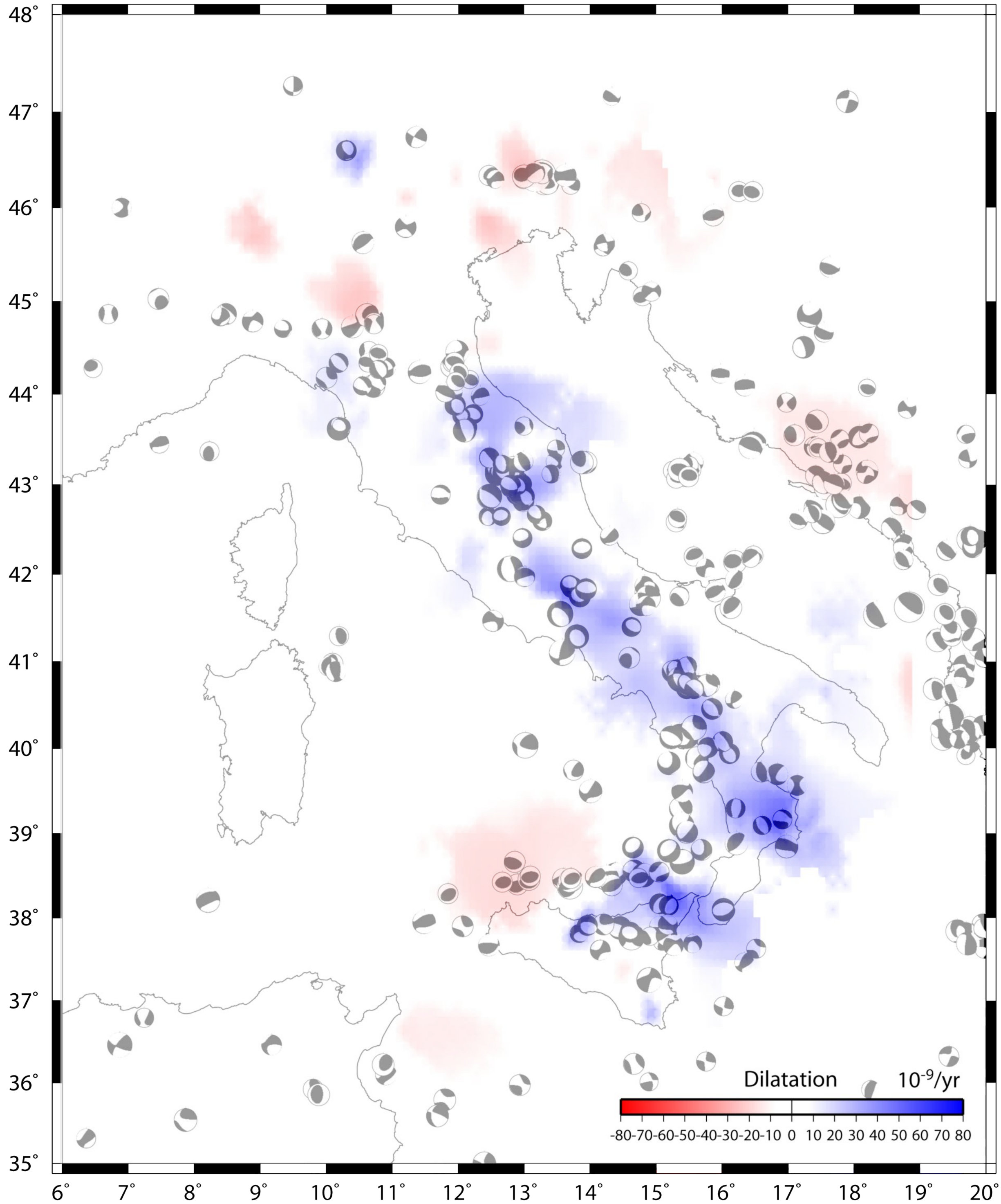
Velocity residuals with respect to the combined solution in the topocentric reference frame (up, east, north).

Figure 6. Strain rate map of Italy.



Principal strain-rate axes interpolated on a 0.5°x0.5° grid and two-dimensional dilatation rates obtained from a selected set of site velocities.

Figure 7. Dilatation rates and seismicity of Italy.



Two-dimensional dilatation rates and focal mechanisms from 1976 to 2010 (RCMT catalogue, Pondrelli *et al.*, 2010).

In figure 6 we present the principal axes of the strain-rates interpolated on a 0.5°x0.5° grid derived from the combined velocity field, superimposed on the 2-D dilatation field (red compressional and blue extensional dilatation) using the algorithm described by Shen *et al.*, 1996. To obtain a smoother map of the dilatation rate, we have interpolated the velocity field on a 0.1°x0.1° grid. A variable smoothing factor (from 20 to 150 km) is applied to the velocity data. In addition, to avoid fake strain-rate features, isolated velocity vectors that differ significantly from their neighbours have been edited from this computation. All the non-significant strain-rate values on the maps are plotted as zero strain-rates.

The extensional belt along the Apennine chain is the most relevant feature recorded by our combined GPS velocity solution, and it represents the most distinct deformation observed in the Italian area. Typical values range between $20\text{-}60 \cdot 10^{-9}$ yr^{-1}, with a variable magnitude along the chain. Significant shortening associated with pure compressional dilatation is noticeable in the Dinaric Arc, the eastern Alps and offshore north-west of Sicily. Figure 7 shows the dilatation field associated with the seismotectonics of the region. The focal mechanisms are extracted from the RCMT catalogue (Pondrelli *et al.*, 2006), relevant to the seismicity recorded in the period 1976-2010. The geodetic deformation is clearly associated with the seismic deformation styles in large domains, thus emphasizing a correlation between crustal deformation and the occurrence of earthquakes in this area.

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