The INGV-CNT crustal motion map for the Euro-Mediterranean region

Serpelloni E.*, D'Agostino N., Devoti R., Anzidei M., Avallone A., Cavaliere A., Cecere G., D'Ambrosio C., Esposito A., Falco L., Galvani A., Pietrantonio G., Riguzzi F., Selvaggi G., Sepe E.

*enico.serpelloni@ingv.it

Istituto Nazionale di Geofisica e Vulcanologia
INGV - Centro Nazionale Terremoti

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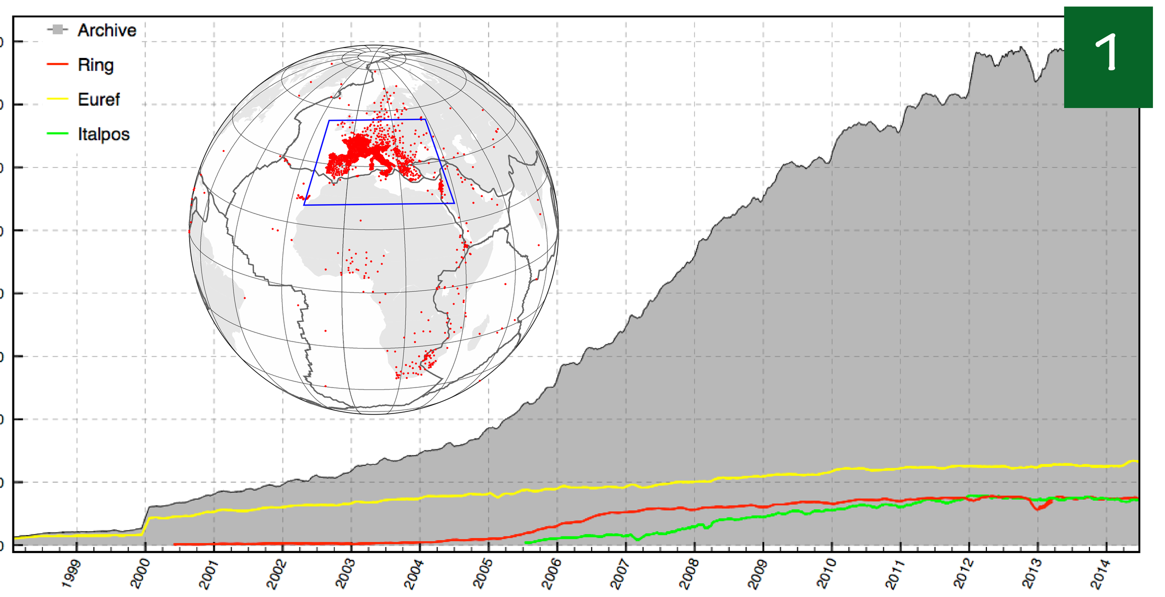
Introduction

Several thousands GPS/GNSS permanent stations, managed by both scientific and cadastral institutions, are now available on the European plate and its boundaries. Data coming from these stations provide unprecedented spatial and temporal coverage of time-dependent deformation signals essential to understand the fundamental physics that govern tectonic deformation and faulting. The National Earthquake Center (Centro Nazionale Terremoti, CNT) of the National Institute of Geophysics and Volcanology (Istituto Nazionale di Geofisica e Vulcanologia, INGV) in Italy, is the Italian leader institution for the collection, management and scientific analysis of Global Positioning Systems (GPS) measurements. Distinct analysis centers independently and routinely process and analyze data using high-quality geodetic software (Bernese, Gamit, Gipsy) to measure the movements of >1000 points spanning the Eurasian plate and its boundaries. The goal of this project is to offer high-quality geodetic products, increase their accessibility to the European scientific community and promote the inter-disciplinary data exchange through a multi-level, user-friendly data gateway. These activities will be performed in strict contact with the GNSS Working Group of the EPOS project (http://www.epos-eu.org) that is proposing to integrate, archive and distribute data, metadata and products for available GNSS stations on the European plate.

GPS/GNSS Networks

The number of continuos GNSS stations operating in the Euro-Mediterranean and African area, and distributing RINEX data, has significantly increased in the last ten years (Fig.1) thanks also to the development of new networks realized for cadastrial and topographic applications both at national and regional scales. The integration of geophysical and non-geophysical networks in the Euro-Mediterranean region provides an almost uniform coverage of continuous stations in southern Europe (Fig.2). Table 1 lists the networks for which we routinely download, archive and analyze raw data. In Italy, all the available non-geophysical networks integrate the INGV RING (http://ring.gm.ingv.it) continuous network, which is the largest GPS network realized for geophysical/tectonic studies in Europe.

Data from the RING network are currently distributed through its web site. Within this ongoing project, the RING web portal will be the gateway for the dissemination of high quality data and geodetic products obtained from the analysis of all available networks in the Euro-Mediterranean area.



Geodetic Networks			
AGROS	Serbia	National	http://agros.rgz.gov.rs/
BASILICATA	Italy	Regional	http://geodaf.mt.asi.it/
CANARY	Global	Continental	http://www.canarygnsscenter.org/
EUREF	Europe	Continental	http://www.epncb.oma.be
GEODAF	Italy	National	http ://geodaf.mt.asi.it
GREF	Germany	National	http://www.bkg.bund.de
HARTRAO	Africa	Continental	http://www.hartrao.ac.za/
IGNE	Iberia	National	http://www.ign.es/
IGS	Global	Global	http://igscb.jpl.nasa.gov
NIGNET	Africa	National	http://www.nignet.net/
RENEP	Portugal	National	http://www.dgterritorio.pt/cartografia_e_geodesia/geodesia/redes_geodesicas/renep/
RGP	France	National	http://rgp.ign.fr/
SEGAL	Africa	Continental	http://segal.ubi.pt/
SIGNAL	Slovenia	National	http://www.gu -signal.si
SOI	Israel	National	http://www.soi.gov.il
TRIGNET	Africa	National	http://www.trignet.co.za/
Geophysical networks			
ALBANIA	Albania	National	https://gpscope.dt.insu.cnrs.fr/chantiers/albanie/
ALGERIA	Algeria	Local	https://gpscope.dt.insu.cnrs.fr/chantiers/algerie/
CORINTH	Iberia	Local	https://gpscope.dt.insu.cnrs.fr/chantiers/corinthe/
FREDNET	Italy	Regional	http://www.crs.inogs.it/frednet
HEMUSNET	Bulgaria/Greece	National	http://www.hemus -net.org
NOA	Greece	National	http://www.gein.noa.gr/services/GPS/noa_gps.ht ml
OLGGPS	Austria	National	http://gps.iwf.oeaw.ac.at
RENAG	France	Regional	http://webrenag.unice.fr
RING	Italy	National	http://ring.gm.ingv.it
SONEL	Europe	Continental	http://www.sonel.org/
UNAVCO	Global	Global	http://www.unavco.org/
Topographic networks			
ABRUZZO	Italy	Regional	http://gnssnet.regione.abruzzo.it/
ARAGEA	Iberia	Regional	http://gnss.aragon.es/
ASSOGEO	Italy	Regional	http://www.gps -assogeo.it
CALABRIA	Italy	Regional	http://gpscalabria.protezionecivilecalabria.it/
CAMPANIA	Italy	Regional	http://gps.sit.regione.campania.it
CANTABRIA	Iberia	Regional	http://www.gnss.unican.es/
CARM	Iberia	Regional	http://gps.medioambiente.carm.es/
CATNET	Iberia	Regional	http://www.icc.cat/cat/Home -ICC/Geodesia/Estacions-GNSS
CVEN	Italy	Local	http://ww w.consorziovenezianuova.com/
EMILIA	Italy	Regional	http://www.gpsemiliaromagna.it
ERVA	Iberia	Regional	http://icverva.icv.gva.es:8080/
EUSKADI	Iberia	Regional	http://www.gps2.euskadi.net/
FRIULI VENEZIA G.	Italy	Regional	http://gnss.regione.fvg.it /dati-GPS/
GALNET	Iberia	Regional	http://www.cartogalicia.com/?page_id=861
GIPUZKOA	Iberia	Regional	http://b5m.gipuzkoa.net/web5000/es/geodesia/red -gnss/
GNSSPIEMONTE	Italy	Regional	http://gnss.regione.piemonte.it
ICM	Iberia	Regional	http://www.madrid. org/cartografia/planea/cartografia/html/web/VisorGps.htm
IREALP	Italy	Regional	http://www.gpslombardia.it
ITACYL	Iberia	Regional	http://gnss.itacyl.es
ITALPOS	Italy	National	http://www.italpos.it
LARIOJA	Iberia	Regional	http://www.iderioja.larioja.org/ index.php?id=20&lang=es
LAZIO	Italy	Regional	http://gnss -regionelazio.no-ip.org/
LIGURIA	Italy	Regional	http://www.gnssliguria.it
METRICA	Greece	National	http://www.metricanet.gr/
NETGEO	Italy	National	http://www.netgeo.it/
ORPHEON	France	National	htt p://reseau-orpheon.fr/
PIEMONTE	Italy	Regional	http://webgis.arpa.piemonte.it/gpsquakenet/GPSQuakeNET.php
PUGLIA	Italy	Regional	http://gps.sit.puglia.it
RAP	Iberia	Regional	http://rap.uca.es/
REGAM	Iberia	Regional	http://cartomur.imida.es/regam/
REP	Iberia	Regional	http://rep -gnss.es/
RGAN	Iberia	Regional	http://www.navarra.es/AppsExt/RGAN/
SARDEGNA	Italy	Regional	http://www.sarnet.it/
STPOS	Italy	Regional	http://www.provincia.bz.it/catasto -librofondiario/libero-professionista/geodetico.asp#anc684
TPOS	Italy	Regional	http://www.catasto.provincia.tn.it/TPOS/
UMBRIA	Italy	Regional	http://labtopo.ing.unipg.it/labtopo
VENETO	Italy	Regional	http://147.162.229.63

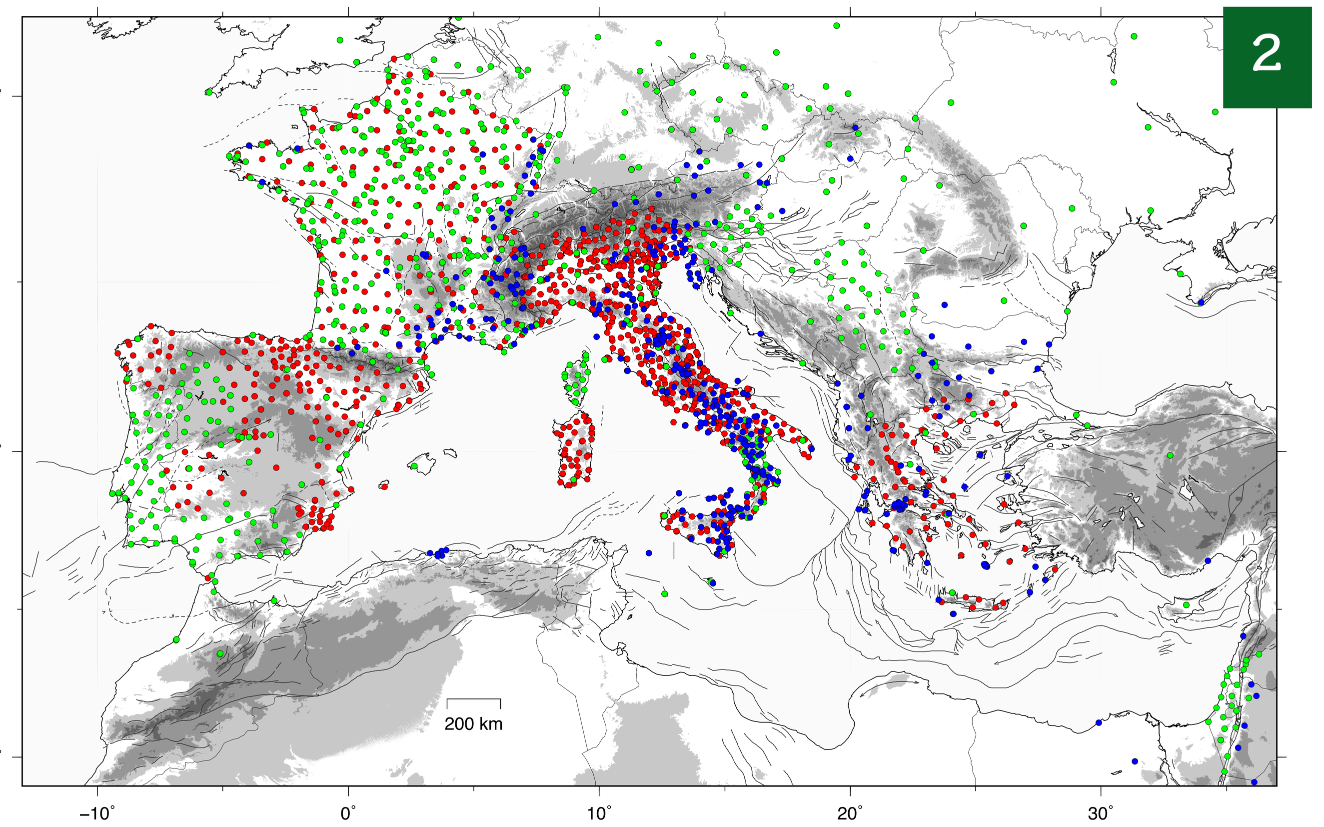
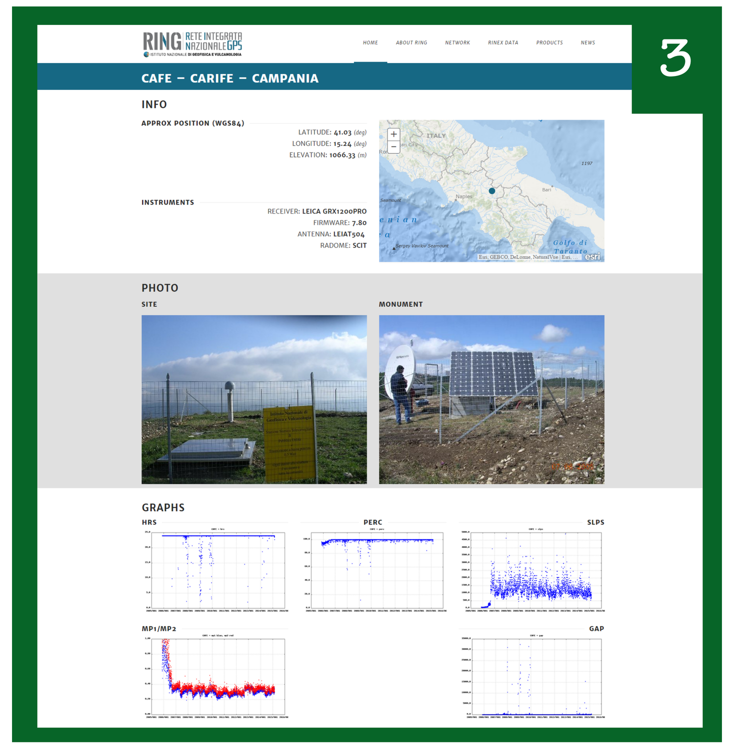
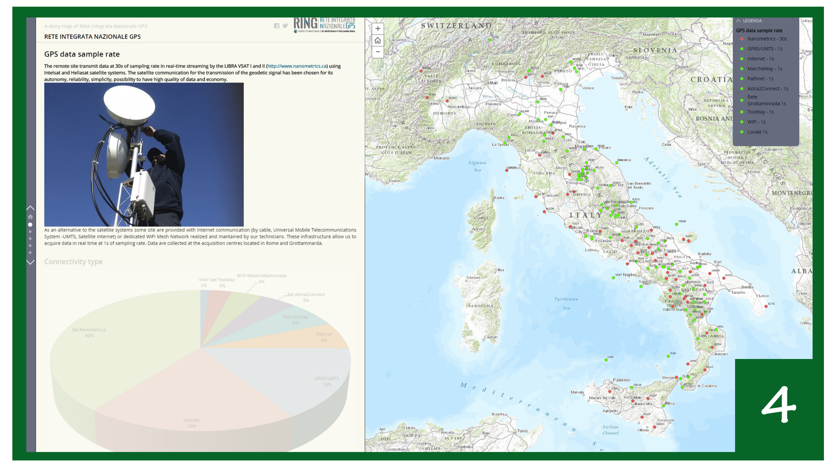


Figure 2 - Distribution of geophysical (blue symbols), geodetic (green symbols) and topographic (red symbols) GPS/GNSS networks in the Euro-Mediterranean area.





Figures 3 and 4 show two screenshots of the new INGV RING network web page (http://ring.gm.ingv.it). In particular Fig.3 shows a typical description of site realization and data quality monitoring, while Fig.4 shows a section of the RING story-map, reporting the description of several network characteristics (e.g., monumet types, telemetry type, sampling rates, etc.). The RING web page will host tools for visualizing and download high quality geodetic products (time-series, velocities, etc).

Multi-software Processing

Raw data from GPS sites shown in Fig. 2 are routinely analyzed by three different analysis centers, using different software and methods to estimate 3D velocities.

BERNESE - The Bernese software ver. 5.0 is used following the Guidelines for EUREF Analysis Centres (http://www.epncb.oma.be). Daily solutions of different sub-networks are obtained by means of Ionosphere Free linear combinations and solving for the troposphere biases and phase ambiguities using the Quasi Ionosphere Free approach. The GPS orbits and the Earth's orientation parameters are fixed to the combined IGS products and an apriori loose constraint of 10 m is assigned to all site coordinates. The estimated daily coordinates are thus estimated in a loosely constrained reference frame. In order to express the GPS time series in a unique reference frame, the daily solutions are first projected imposing tight internal constraints (at millimeter level), and then the coordinates are transformed into the ITRF2008 reference frame by a 4-parameter Helmert transformation (translations and scale factor). The regional reference frame transformation uses 45 anchor sites located in central Europe. To get rid of common translations of the entire network, the time series are readjusted through a common mode filtering procedure similar to that proposed by Wdowinski et al. (JGR, 1997). Velocities at GPS stations are estimated fitting simultaneously a linear drift, episodic offsets and annual sinusoids to the network coordinate time series.

GAMIT - The GAMIT/GLOBK (10.5) software is used to estimate site position, adjustments to satellite orbital parameters and time-variable piecewise linear zenith and horizontal gradient tropospheric delay parameters, applying loose constraints to geodetic parameters. Each GPS network (as in Table1) is processed independently, with larger networks (n. site > 50) discretized into smaller sub-networks, sharing some high quality tie-sites. Phase data are weighted according to an elevation-angle-dependent error model. The ocean loading and pole-tide correction model FES2004 is used, toghether with the Global Mapping Function (GMF) for both hydrostatic and nonhydrostatic components of the tropospheric delay model and the global pressure and temperature model. The IGS absolute antenna phase center model for both satellite and ground-based antennas is used. Loosely constrained solutions, in the form of ASCII GAMIT H-files and SINEX files, are later combined, using the ST_FILTER program of the QOCA software with IGS solutions from SOPAC (http://sopac.ucsd.edu), while simultaneously realizing a global reference frame by minimizing coordinates and velocities of the IGS global core stations, estimating a 7-parameter Helmert transformation with respect to the IGS realization of the ITRF2008 NNR frame (i.e., IGb08). GPS velocities are obtained by fitting a linear trend, annual and semi-annual terms and site specific offsets, assuming a white+flicker (powe-rlaw) noise model. The Common Mode Error in the time-series is estimated using a PCA methods, as described in Serpelloni et al. (JGR, 2013).

GIPSY - The JPL GIPSY-OASIS II software (ver. 6.2) is used in a Precise Point Positioning mode applied to ionospheric-free carrier phase and pseudorange data and using JPL's final fiducial-free GPS orbit products (Bertiger et al., J. Geod, 2010). We apply the Global Mapping Function with tropospheric wet zenith delay and horizontal gradients estimated as stochastic random-walk parameters every 5 min. Ocean loading is computed using the FES2004 tidal model coefficients given by the Ocean Tide Loading provider (http://holt.oso.chalmers.se/loading) and applied as a station motion model. Ambiguity resolution is applied using the wide lane and phase bias method (Bertiger et al., J. Geod., 2010). Station coordinates obtained in the loose frame of JPL fiducial-free GPS orbits are transformed into the IGS08 reference frame using daily 7-parameter transformations delivered by JPL. In order to analyse and interpret station velocities relative to the Eurasia plate and reduce the common mode signal, we have specifically developed a terrestrial reference frame (called EU14) suitable for crustal deformation studies in and around that plate following the approach of Blewitt et al. (J. Geod., 2013). This frame is defined by 6 Cartesian coordinates and velocities of each of 174 stations selected by specific quality criteria. Our eurasian frame is aligned in origin and scale with IGS08. It is implemented to have no-net rotation with respect to the stable interior of the Eurasian plate, realized by a 69-station core subset. GPS velocities are obtained by fitting a linear trend plus annual and semi-annuals terms and site specific offsets at position time-series, assuming a whte+flicker noise stochastic model.

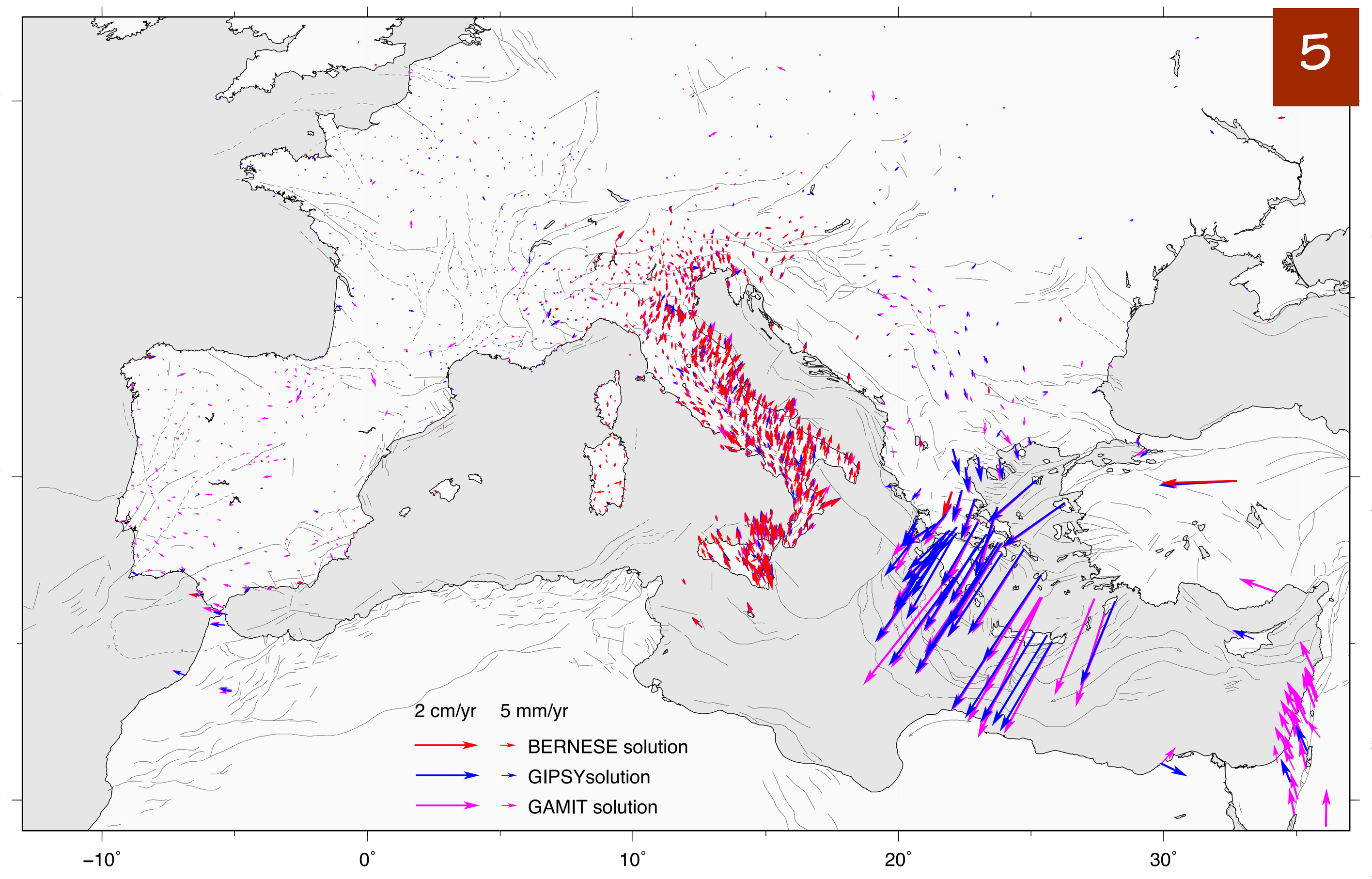


Figure 5 - Individual velocity fields given with rescpet to a common Eurasian-fixed frame. For clarity error ellipses are not shown.

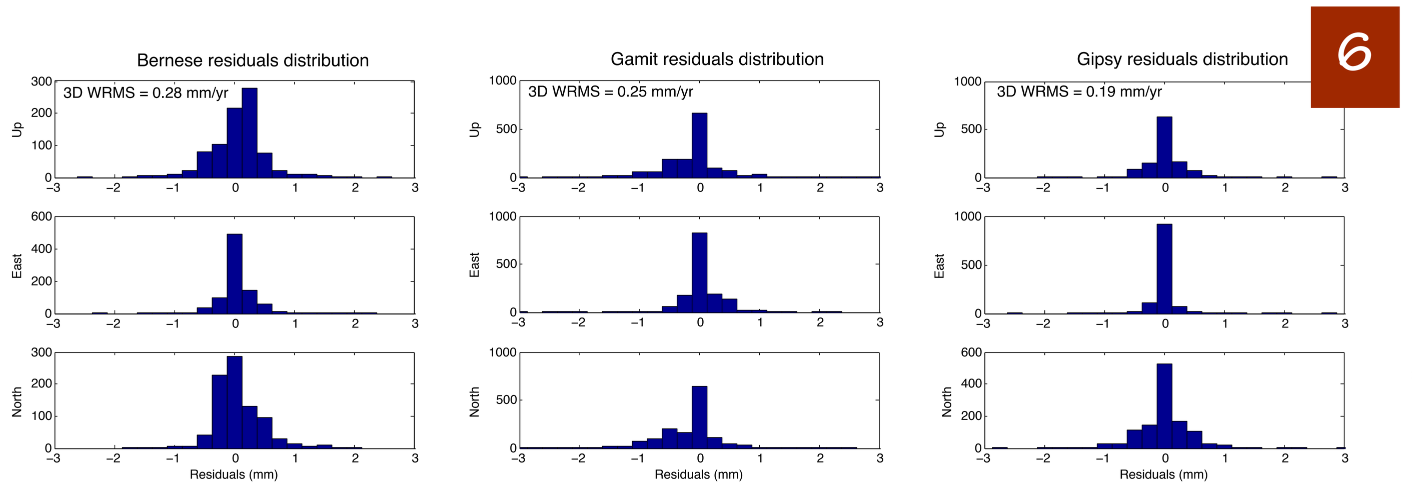
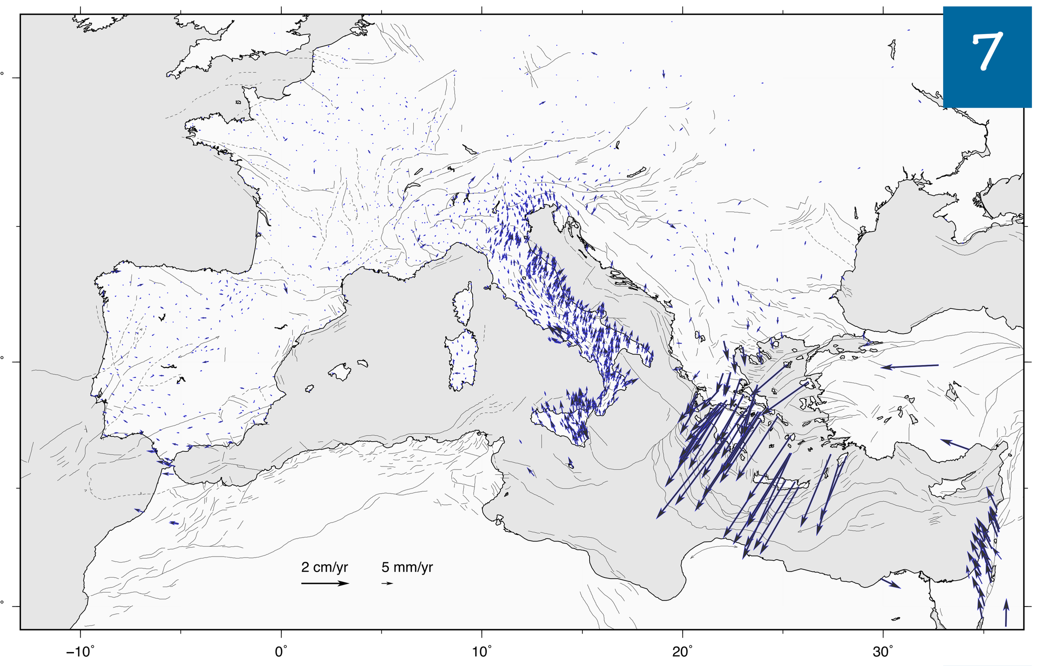


Figure 6 - Histograms of residuals of single velocity solutions with respect to the combined velocity solution.

Combined Velocity and Strain-Rate Fields



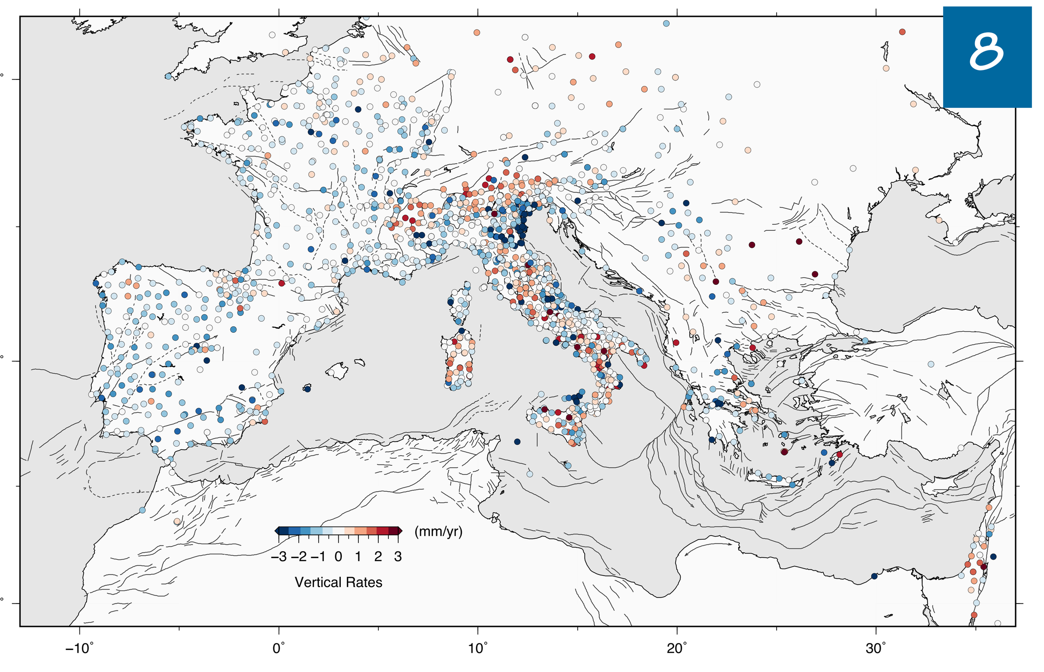


Figure 7 - Combined horizontal velocities in the Eurasian fixed frame (error ellipses are not shown for clarity).
Figure 8 - Combined vertical velocities (in blue sites going down and in red sites going up).

The ITRF cartesian velocities are combined in a least squares sense, treating reference frame differences (rotations and scale) as stochastic biases, generalizing the loosely constraints approach proposed by Heflin et al., (GRL, 1992) and Davies & Blewitt (JGR, 2000). In principle loosely constrained solutions can be combined regardless of the datum definition of each contributing solution, since large errors associated to reference frame transformations allow to treat the systematic errors as stochastic variables without the need to explicitly estimate the scale and rotation parameters. The combination process foresees three main steps: 1) covariance loosening of the input solutions, rotations and scale are "loosely constrained", 2) least squares estimation of the velocities only, each solution is weighted according to its own chi-square in order to balance the relative weighting factor (see e.g. Devoti et al., VII Hotine-Marussi Symposium, 2012), 3) reference frame alignment and minimal inner constraints of the covariance matrix to get the final solution.

Pros: 1) No need to estimate solution-dependent parameters, all parameters needed to build velocities are solved consistently by each analysis center; 2) no need to combine day-by-day coordinate solutions, taking into account eccentricities at each station; 3) computationally efficient, large velocity fields can be rapidly updated, 4) velocity covariances are fully propagated.

Cons: 1) no time series available, 2) no check on the hidden parameters used to estimate velocities (steps, annual terms, etc.

Figure 9 - Continuous horizontal velocity (a) and strain rate fields (b and c) obtained adopting a multiscale approach (Tape et al., GJI, 2009) for the area where the 3 different geodetic solutions (see Fig. 5) are present. The area characterized by the highest deformation rates are: a) the Apennines belt, b) the Flegrean Fields Vulcanic Area, c) the Etna Vulcano and d) the Aeolian Island.