The coseismic ground deformations of the 1997 Umbria-Marche earthquakes: a lesson for the development of new GPS networks

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Abstract

After the occurrence of the two main shocks Mw=5.7 (00.33 GMT) and Mw=6.0 (09.40 GMT) on September 26, 1997, which caused severe damages and ground cracks in a wide area of the Umbria Marche region, the Istituto Nazionale di Geofisica in cooperation with the Istituto Geografico Militare Italiano set out to detect the coseismic ground deformation and reoccupied the available geodetic monuments placed across the epicentral area, belonging to the first order Italian GPS network IGM95 and to the Tyrogeonet network.

The comparison between the pre and post-earthquakes coordinate set, the latter obtained from the surveys performed in the early days of October 1997 in the Umbria Marche earthquake area, showed maximum displacements values at the closest stations to the epicentres, up to 14.0±1.8 and 24.0±3.0 cm in the horizontal and vertical components, respectively. The availability of the IGM95 stations allowed geodetic data to be translated into relevant geophysical results. For the first time in Italy, the evaluation of post-earthquake coordinates at 13 vertices provided the estimation of a significant deformation field associated with a seismic sequence.

Unfortunately, the same actions could not be applied to the October 14, 1997, Mw=5.6 Sellano earthquake, whose epicentre was located a few tens of km south of the previous ones, due to a lack of available geodetic vertices of Tyrogeonet and IGM95 networks in the surroundings of the epicentral zone. This fact, which prevented the estimation of coseismic deformation and seismic source modelling for this earthquake, clarified the need to set up tailor made GPS networks devoted to geophysical applications, able to capture a possible coseismic signal, but also interseismic and post-seismic signals, at the surface of the Earth’s crust at the scale of the expected magnitudes and fault length. Here we show and discuss the development of the Discrete GPS and Continuous GPS (CGPS) networks in the Italian region started since the early 1990s, which greatly increased after the 1997 Umbria Marche earthquakes, and the insights gained from this action which can be also integrated as Global Observing Strategy to monitor our Environment from Earth and Space.

Key words GPS – IGM95 – Umbria-Marche earthquakes

1. Introduction

The Italian peninsula is among the most active seismic areas of the Mediterranean basin and its tectonic setting results from the collision between the African/Arabian and Eurasian plates (Dewey et al., 1989; Faccenna et al. 2004). The kinematics of this region has been predicted since 1994 with a NW-SE converging motion at about 7 mm/yr, from the NUVEL-1A plate motion model (De Mets et al., 1994). Recent analysis of GPS and seismic data (D’Agostino and Selvaggi, 2004; Serpelloni et al., 2005; Battaglia et al., 2004; Serpelloni et al., 2007 and references therein) estimated new converging velocities and complex deformation patterns along the Africa-Eurasia plate boundary. The distribution of in-
instrumental seismicity depicts the high crustal fragmentation of the area and provides a picture of the plate boundary mosaic with tectonic units developed during the subduction and collision of the Alpine and Apennine belts (Dercourt et al., 1993; Malinverno and Ryan, 1986; Patacca et al., 1990; Chiarabba et al., 2005). From seismic tomography it appears that the initially continuous Apennines subduction has been segmented into different arcs, due to the nature of the lithospheric subducting material (Piromallo and Morelli, 2003).

The Apennines suffer from the complex Mediterranean framework and are largely affected by extension oriented perpendicular to the chain axis (Anderson and Jackson, 1987; Westaway, 1990; Pondrelli et al., 1995; Selvaggi, 1998; Vannucci et al., 2004), in agreement with the distribution of historical seismicity and other geological/geophysical observations (Valensise and Pantosti, 2001a), which suggest the presence of active normal faults striking about parallel to the Apenninic chain (Valensise and Pantosti, 2001b). Seismological data and recent geodetic studies reveal that the Apennines are undergoing a NE-trending extension, with seismic deformation rates higher in the southern Apennines (Anderson and Jackson, 1987; Westaway, 1990; Pondrelli et al., 2002; Hunstad et al., 2003; Serpelloni et al., 2005; Anzidei et al., 2005).

The extensional behaviour of the area, which was estimated only from seismic data at the time of the Umbria-Marche earthquakes (Selvaggi, 1998 and reference therein), has been revealed through the analysis of repeated GPS data obtained from the reoccupation of the discrete networks or through the available CGPS stations only in recent times. As a consequence, geodetic estimates of rates of crustal extension across the Apennines were still unknown in September 1997 (D’Agostino et al., 2001; Serpelloni et al., 2001; Hunstad et al., 2003; Anzidei et al., 2005; Serpelloni et al., 2005; Serpelloni et al., 2007). In the northern Apennines, earthquake focal mechanisms show that compression is active in the external sector of the arc (Montone and Mariucci, 1999), where the few deep earthquakes have been interpreted as due to remnant subduction processes (Selvaggi and Amato, 1992).

2. The Umbria Marche seismic sequence of September-October 1997

The 1997 Umbria-Marche seismic sequence, which caused severe damage and ground cracks in a wide area of the Umbria Marche region (Tosi et al., 1999), started on September 3 with a ML 4.7 foreshock followed by a large and diffuse microseismicity, in an area of the Apennines which was previously struck by a long seismic sequence during year 1703 (Boschi et al., 1995). On September 26, two moderate magnitude earthquakes occurred at 00:33 (Mw = 5.7) and 09:40 GMT (Mw = 6.0) near the village of Colfiorito and on October 14 a third mainshock (Mw = 5.6) took place 15 km to the SE, close to Sellano village. The whole seismic sequence consisted of six main earthquakes with magnitudes >5.0 that occurred in the following months on normal faults oriented NW-SE (Amato et al., 1998; Ekström et al., 1998). The spatial distribution of aftershocks (Amato et al., 1998; Cattaneo et al., 2000, and Deschamps et al., 2000) stretched ~50 km along the Apennines seismogenic belt. Focal mechanisms resulting from CMT solutions show normal faulting on shallow low-angle faults (Ekström et al., 1998; Pino and Mazzu, 2000). The three largest earthquakes ruptured normal faults dipping 40°–45° to the SW, with geometries well constrained by seismological data (Amato et al., 1998; Deschamps et al., 2000; Cattaneo et al., 2000; Ekström et al., 1998; Capuano et al., 2000). Moreover, three additional earthquakes of magnitude larger than 5.0 occurred close to the three largest shocks and showed similar fault plane solutions.

3. The GPS networks in Italy at 1997: limits during the Umbria-Marche earthquakes

During the occurrence of the Umbria-Marche earthquakes, two GPS national networks were available in Italy: the Tyrrhenian Geodetic Network (TyrGeoNet) (fig.1a) and the IGM95 (fig.1b). Both these networks consist of benchmarks established on reinforced concrete pillars, anchored in the bedrock or on stable
buildings, planned to be measured during repeated geodetic campaigns. The former was established in 1990-1992 in the Mediterranean region by the Istituto Nazionale di Geofisica and the University of Bologna in cooperation with a group of Italian and foreign Institutions, with the aim of measuring the current deformation of the Earth’s crust in the central Mediterranean area (Anzidei et al., 1995). The network consists of 50 benchmarks, 34 of which located in

Fig. 1a. The Tyrrhenian Geodetic Network (52 benchmarks) (from Anzidei et al., 1995, modified).
Italy and 16 in the surrounding countries, partially belonging to the first order IGM network. It includes some local networks, placed in seismic (across the Messina Straits fault, Forlivese, Gargano, etc.) and volcanic areas (Aeolian Islands, Colli Albani, etc.), and it has been measured since 1990 by single and dual frequency GPS receivers.

A densification of TYRGEONET was established in the frame of the GEOdynamic MODeling of the APennines project, funded by the E.C. in the Central-Southern Apennines, with the aim to increase the resolution of the current crustal motion of this seismic region. The GeoModAp network was repeatedly surveyed between 1994 and 2001 and velocity and strain rate fields were estimated for this region (Anzidei et al., 2001; Serpelloni et al., 2002).

Most of the benchmarks of these networks are geodetic pillars often equipped with a force centering plate to permit unambiguous placement of the GPS antenna. Measurements were annually repeated during week-long surveys, with daily sessions of 8-24 hours duration each.

Results from these measurements, published in several papers during the last decade (Anzidei et al., 1996, 1997, 2001; Serpelloni et al., 2005), began delineating the kinematics of the Italian peninsula and the central Mediterranean region (Anzidei et al., 1996).

The IGM95 network, whose measurements were completed in 1995, was planned and set up by the Italian Istituto Geografico Militare to determine a new fundamental network covering the whole country. Since the beginning, the network consisted in more than 1200 benchmarks, partially shared with the Tyrgeonet network, which were occupied during single or repeated measurements sessions of a few hours duration. The aim of this network was to provide a new set of reference coordinates computed into the WGS84 reference system and mainly devoted to cartographic and topographic applications (Surace, 1993; 1997). For this reason, most of the IGM95 sites did not follow restrictive geodetic requirements for geophysical applications in terms of monument quality and particularly, due to the short duration of the data acquisition windows, especially for crustal strain estimation, even if the scientific community gained benefits from this network (D’Agostino et al., 2001).

The final adjustment in one block of the entire network, provided 3-dimensional coordinates with a mean accuracy of 22 mm and 35 mm in the horizontal and vertical components, respectively (95% confidence level) (Surace, 1997).

In 1997 CGPS stations were not yet available in the earthquake area, and the only operational one, was located in peninsular Italy at the Geodetic Space Center of the Italian Space Agency in Matera. Nineteen stations of the IGM95 network were available around the epicentral area of the three main shocks of the Umbria-Marche seismic sequence and were first measured by IGM in March-April 1995 (Anzidei et al., 1998b; 1999; 2000).

Immediately after the Colfiorito earthquakes of September 26, 1997 and the Sellano earthquake of October 14, 1997, two different GPS campaigns were performed, using six GPS TRIMBLE 4000 SSE/SSI dual frequency receivers. The geodetic monuments occupied during these survey consisted of concrete pillars or markers fixed on the ground or on small and sta-
ble concrete buildings undamaged by the ground shaking (Anzidei et al., 1998a,b). During both campaigns, three receivers were kept fixed at Castiglione del Lago (CAST), Foligno (FOLI), and Colfiorito (COLF), and data were continuously recorded at a 30 second sampling rate. Five roving receivers measured the other sixteen sites during a 4–6 hours time window each day, for at least two survey sessions. The 1997 data were processed by means of the Bernese software (version 4.0) using the precise satellite ephemerides computed at the Centre of Orbit Determination in Europe (CODE), and adopting the standard procedures described by Rothacher et al. (1996), estimating the tropospheric delay and fixing the ambiguities by rounding their real value to the nearest integer one. The 3-dimensional coordinates obtained show a mean accuracy of 10 mm in the horizontal component (mean value of the semi-axes of the error ellipses) and 20 mm in the vertical one (both at 95% confidence level). Site displacements were computed by minimizing the residuals at the GPS stations located at distance greater than 15 km from the epicenters, assuming that for earthquakes of moment magnitude less than 6.0, coseismic ground deformation is negligible at such distances (Anzidei et al., 1999; Hunstad et al., 1999). The maximum displacement of the stations closest to the epicentral zone, were mainly distributed across and around the earthquake faults, up to 14.0±1.8 cm and 24.0±3.0 cm along the horizontal and vertical components, respectively (Anzidei et al., 1999; Hunstad et al., 1999; Anzidei et al., 1999; Anzidei et al., 2000). Geodetic data were successfully used to identify and model the faults responsible for the main shocks for Colfiorito area and to understand the seismic source mechanisms (Hunstad et al., 1999). Moreover, the combination of GPS results with ERS-SAR differential interferograms as well as seismological parameters, allowed the estimation of the geometry and slip distribution on the fault planes (Stramondo et al., 1999; Salvi et al., 2000; Belardinelli et al., 2003) (fig. 2a).

4. A lesson for the development of new GPS networks

The inhomogeneous coverage of the IGM95 and Tyrgeonet networks, the quality or type of the benchmarks, the on average short time-window of available observations and the lack of CGPS stations in the earthquake region, prevented us benefitting from optimal geodetic constraints for the geophysical modelling of the causative faults of the Umbria Marche earthquakes, especially in the surroundings of the epicentre of October, 14, 1997, near Sellano, where there was a lack of available GPS benchmarks.

Despite the clear limits of the available GPS data, the location of the geodetic monuments and the re-analysis of the old field data, allowed the geophysical community to benefit from a GPS reference network for the estimation of ground coseismic displacements during the 1997 Umbria Marche earthquakes (Anzidei et al., 1997; 1998b; 1999; 2000; Hunstad et al., 1999; Stramondo et al., 1999; Salvi et al., 2000; Crippa et al., 2006; Dalla Via et al., 2007) (as well as also recently occurred for the 2003 Molise earthquake, as reported in Giuliani et al., 2006).

This fact clarified to the entire Italian geophysics community the need to dispose of new GPS and CGPS networks devoted to geophysical purposes, widely distributed throughout the Italian region, with the goal to obtain detailed knowledge of the ongoing crustal strain rates, in order to better constrain the kinematics of the Italian peninsula. At the same time, denser GPS networks were required across known active faults and tectonic structures, equipped with high quality monuments, to have the opportunity to model the deformation processes induced by strong earthquakes at major decoupling zones (Johnson and Wyatt, 1994; Wells and Coppersmith, 1994).

Specifically, the CGPS stations should be able to collect and transmit data in real time, suitable to be processed rapidly (hourly or daily) by data analysis centres. Unfortunately, in 1997 the present technologies applied to GPS receivers were not yet available, especially those concerning continuous data retrieval from
remote stations. Only since 2000 the rapid development of GPS space geodesy technique provided a new type of receivers at lower costs, especially planned to be used as CGPS stations, which could be more easily managed and powered through small batteries or solar panels due to a major reduction of their power consumption. These new receivers were also suitable to be used successfully during longer episodic geodetic campaigns. Moreover, they can be controlled by conventional or cellular telephone lines, as well as satellite or internet connections for data retrieval, increasing their range of use dramatically.

The construction of new geodetic networks provided a new source of 3-D geodetic data which began to introduce new constraints on the measurements of the active geological processes occurring in the Mediterranean area (e.g., Battaglia et al., 2004; D’Agostino and Selvaggi, 2004; Goes et al., 2004; D’Agostino et al., 2005; Serpelloni et al., 2005; Serpelloni et al., 2007), focusing on the large scale tectonic aspects (i.e., the motion of major tectonic plates, intra-plate rigidity), but also in more specific areas, through dense and small aperture networks, focusing on local tectonic processes, such as deformation along particular segments of fault zones (e.g., Anzidei et al., 1998a; Anzidei et al., 2005).

With this aim the number of continuous monitoring stations strongly increased in Italy, under national or international research programs and monitoring projects funded by the Italian Space Agency, INGV (under contracts of MIUR and Dipartimento della Protezione Civile) and other institutions (mainly Universities and Regions), following the examples of USA (Zhang et al., 1997) and Japan (Miyazaki et al., 1994) which had been establishing networks consisting of hundreds of stations since 1990 to measure the crustal dynamics and the

Fig. 2a,b. The distribution of GPS stations and the GPS and SAR modelling from the IGM 95 benchmarks during the 1997 Umbria-Marche earthquakes for the epicentres of September 26, 1997 Colfiorito a) and b) the epicentre of October 14, 1997, Sellano earthquake. The lack of the GPS benchmarks around the epicentre at Sellano is evident and the fortunate positions of the GPS benchmarks across the fault between Colle Croce and Monte Pennino (from Salvi et al., 2000).
coseismic displacements of their highly seismic regions (Bock et al., 1993; Tsuji et al., 1995 and references therein). Increasingly denser GPS networks, both regional or local, are the mainstay of deformation monitoring, especially over large areas and offer high accuracy and continuous observation, as experimented for the case of the 2004 Sumatra earthquake (Boschi et al., 2006). Dense regional networks, such as the SCIGN network in Southern California (USA) demonstrated the value of such systems. In the meantime, in Italy GPS networks were also developing under specific projects, through the establishment of a large number of additional geodetic vertices in selected areas, such as Southeastern Sicily (Achilli et al., 1995; Bonforte et al., 2002), or the central and southern Apennines (Anzidei et al., 1995; Anzidei et al., 2005).

During the last 10 years, the IGS and other computational centres provided a more precise determination of satellite orbital parameters, through the enlargement of the GPS satellite constellation, and the improvement of the global Continuous CGPS tracking station coverage, resulting in the increasing accuracy of GPS measurements. Moreover, the establishment of regional networks of CGPS stations (e.g., EPN-EUREF, ASI, Regal, FredNet networks) increased the number of stations available to tie observations together interferometrically. All these technological developments significantly increased the precision of station position determinations, reducing the noise spectra of the solutions, and allowing for a better resolution of the coordinate changes detection, even in the vertical component. This is fundamental in areas characterized by low deformation rates, where an accurate estimate of crustal deformation parameters mainly requires the use of CGPS stations.

In Italy, several CGPS stations began to operate after 1997, and especially after 2000, were managed by different agencies, private companies and national scientific institutions (Sansò and De Lacy, 2000). Unfortunately, a significant number of these stations do not follow the minimum requirements needed for geophysical applications (antenna/receiver features and geodetic monument quality). For this reason, new CGPS and GPS stations have been planned by INGV, with the specific goal to provide a geodetic infrastructure able to provide high quality GPS data. In recent years the number of CGPS and GPS stations suitable for geophysical applications has rapidly increased, particularly in the frame of INGV activities, mainly supported by the Dipartimento della Protezione Civile, MIUR and ASI. From this perspective, automatic facilities to handle the CGPS data archiving and data processing have been developed and applied (Serpelloni et al., 2006b).

4.1. The new GPS networks

The development and the accuracy of the GPS technique, imposed to project and realize new GPS monuments following restrictive requirements needed for geophysical purposes (benchmarks placed in stable outcrops, concrete pillars or stable buildings, planned to improve antenna position repeatability during surveys). Besides the IGM95 network, more than 300 benchmarks are currently available belonging to sub-regional or local INGV GPS networks, distributed in selected seismic areas of the Italian region, mainly across the Apennines and the Messina Straits (fig. 3a).

In the following, besides the large development of the IGM95 network (fig. 3b) mainly devoted to topographic applications, three major new GPS networks, CAGeoNet, RETREAT and Capo Vaticano, together with the INGV Rete INtegrata GPS (RING) CGPS network, are briefly described as follows. These new GPS networks, designed after the experience gained during the 1997 Umbria-Marche seismic crisis, are located across some of the most seismic areas of Italy and they have been repeatedly measured during recent years. These networks which provided valuable data for the ongoing geodynamic and seismotectonic studies, have driven a new road to plan and build GPS networks in seismically active faulted areas. The reduced distance between the vertices and the average grid at a few km, can increase the resolution of the geodetic strain and velocity fields as well as its temporal and spatial variability (Anzidei et al., 2005) across faults and seismogenic structures known from historical
sources and geological constraints (Valensise and Pantosti, 2001b).

CAGeoNet - The Central Apennines Geodetic Network (CA-GeoNet), was established in the time span 1999-2001, under the umbrella of the ASI projects. It consists of 125 GPS stations equipped with 3-D monuments, distributed with an average grid at 3-5 km (Anzidei et al., 2005) across the main seismogenic structures of the central Apennines (fig. 3a). Siting was performed taking into account the geological and structural features of the region. Most of the GPS stations are located across the Plioquaternary basins and the main active faults, inferred from geological and seismological data (Valensise and Pantosti, 2001).

Retreat - The RETREAT GPS Network has been realized in the framework of the REtreating TRench Extension and Accretion Tectonics (RE-TREAT) project, funded by the National Science Foundation (USA) in the frame of the Continental Dynamics Program, in cooperation with several American and European Universities and research centres (http://earth.geology.yale.edu/RE-TREAT). The aim of the project is to understand the evolution of the convergence and rapid uplift of the northern Apennines, studying the relationships between the surface geological processes and the deep dynamics of the Earth’s mantle, to obtain new constraints on the kinematics and seismotectonics of the northern Italian region. The new network consists in 22 stations often equipped with 3-D monuments (fig. 3a). Three of them have become continuous since 2004.

Capo Vaticano - The Capo Vaticano GPS network was established in 2002 in the framework of a INGV multidisciplinary project funded by CNR-Agenzia 2000, carried out in cooperation with other Italian universities and institutions (Anzidei et al., 2006). The goal of the network is to provide the current horizontal and vertical deformation rates across the main seismogenic faults in the area of the September 8, 1905, Ms= 7.0 earthquake (Boschi et al., 1995), and give new data on the relative sea level
changes along the coast of the Capo Vaticano promontory. The network, which consists in 13 monuments 3-D type distributed with an average grid at 3-5 km, has been measured since 2002 (fig. 3a). Recently, it has been extended with another 20 additional benchmarks partially overlapping with a previous terrestrial geodetic network (Pingue and Guerra, 1989), recently reoccupied and extended.

4.2. The new CGPS networks

In the last decade the number of CGPS sites operating in the Italian region and in the Central Mediterranean region, has significantly increased. This action was led by EUREF initiative as a partner of IGS for the European region, while in Italy the largest developments have mainly been produced since 1995 by ASI and after 2000 by INGV, under the umbrella of the Italian Department of Civil Protection. Densifications exist in some specific areas of geophysical interest, as for example in Friuli Venezia Giulia, where the Frednet (FRiuli REgional Deformation NETwork, http://www.crs.inogs.it/frednet/) is maintained by the OGS or in Tuscany where the Universities of Bologna and Siena, supported by Regione Toscana, have set up a network of 9 permanent GPS stations around the principal tectonic troughs in Tuscany, which have been the sites of the most intense earthquakes in the region (Cenni et al., 2008). Some additional currently operating stations are maintained by university departments, administrative agencies, or by professional companies. Besides these geophysical networks, some Regional administrations have also developed their own CGPS networks, mainly designed for topographic or navigation applications.

RING network - In 1999, the INGV, began to set up a permanent GPS network in Italy with the goal to detect the crustal deformation for geodynamics (Anzidei et al., 2004). The RING (Rete Integrata Nazionale GPS) network started at the beginning with 6 stations (Anzidei et al., 2004) and grew up rapidly all over the Italian region, thanks to specific funding provided by the Department of Civil Protection and the Ministry for Universities and Research (MIUR) (Selvaggi et al., 2006) (figs. 4 and 5). Most of the stations are co-located with seismic stations. The GPS antenna is connected to the pillar by means of two different devices: the INGV-3D antenna mount (Anzidei and Esposito, 2003) and the SCIGN antenna mount (http://jacinto.ucsd.edu/gpsmon/adaptor_design/intro.html). Raw data are transferred daily to a local server and archived. The Observatory of Grottaminarda currently maintains the RING as well as the data archiving, quality check and distribution (www.gm.ingv.it).

The RING network is still increasing and nowadays consists in about 120 continuously monitoring stations remotely controlled mainly by satellite systems, with an average grid at about 50 km or less (Selvaggi et al., 2006). It is the most powerful CGPS geophysical network active in Italy and is partially densified by the networks managed by the Italian Space Agency (Vespe et al., 2000), and the Universities of Bologna and Siena in Tuscany region (Cenni et al., 2008).

Together with increasing in the GPS networks, new development of the GPS data analysis software and procedures was performed to fit the new large amount of data coming from the CGPS stations and GPS networks. New powerful processors were used together with suitable data storage systems to archive the resulting daily, weekly, monthly and annual solutions of the GPS networks. Currently data from hundreds of stations belonging to RING and to other national or European regional CGPS networks are collected and processed to produce position time-series (Serpelloni et al., 2006b).

5. Recent results

After the first pioneering geodetic results at global and regional scale for the Mediterranean region (Smith et al., 1994) or in Italy (Anzidei et al., 1996; 1998a), in recent years new results have been published (Anzidei et al., 2001; Anzidei et al., 2005; Oldow et al., 2002; Hellenstein et al., 2003; Caporali et al., 2003, Serpelloni et al., 2002; 2005; 2006; 2007; D’Agostino and Selvaggi, 2004; D’Agostino et al., 2005 among others), providing new con-
strains on the active deformation of the Italian peninsula in the frame of the Mediterranean geodynamics. The complex kinematics and tectonic pattern due to the collision of the Eurasia-Africa plates and the interaction of several minor crustal blocks (i.e., ADRIA) began to be partially revealed thanks to the high number of available GPS and CGPS stations and in some cases to the high density of the networks.

After the Umbria-Marche earthquakes of 1997, the increase in geodetic monitoring through GPS and CGPS networks, at local and regional scale, yielded new insights on the kinematics of the Italian peninsula as well as new constraints to the geological and seismological evolution of this seismically active region (Serpelloni et al., 2005; Serpelloni et al., 2007; D’Agostino and Selvaggi, 2004; D’Agostino et al., 2006; Anzidei et al., 2005; Hunstad et al., 2003; Battaglia et al., 2004). Figure 6 shows the last velocity field obtained by the combination of GPS and CGPS stations in the time span 1991-2007. GPS data show that the lineament of seismogenic faults, which are striking about parallel to the chain axis, appears to play a fundamental role for the major kinematics boundaries, in separating two different velocity domains: an Adriatic one, with NE- to NNE-ward motion trends, and a Tyrrhenian one, with NW- to NNW-ward motion trends.

The regional ~NE-SW extension of the Apennines was detected through GPS data, in agreement with seismological and geological evidence (fig. 7). The rates of extension along the southern and central sectors of the chain are estimated at ~1.8 and ~2.5 mm/yr, respectively, and deformation appears to be mainly confined to a relatively narrow belt, within which the largest part of the seismic moment release is observed and most of the seismogenic faults are located. In the Southern Apennines, across the Irpinia region, NE-SW extension is occurring at
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A rate of about 2.3 mm/yr. The area of transition between the Southern and Central Apennine arcs (i.e., Southern Latium and Molise regions), instead, displays a more complicated deformation pattern, where right-lateral strike-slip motion active along E-W trending faults, at a rate up to 2.8 mm/yr, could explain the high local strains observed. In this area, between Latium, Umbria, Marche and Abrutii regions, the densifications provided by the GPS CAGeoNet network, with a grid at 3-5 km, disclosed an active aseismic NE-SW prevailing extension normal to the chain, even if this region experienced destructive earthquakes in the past (Anzidei et al., 2005). Moreover, local complexities have been evidenced, likely related to deep gravitational movements or faults, still under investigation. So far this interseismic deformation describes the regional and purely elastic deformation field of this area while its extensional behaviour is in agreement with the distribution and trend of the main seismogenic sources reported in Valensise and Pantosti (2001b). The latter could play a major role in the observed deformations and in the kinematics of Italian peninsula.

In the Northern Apennines, regional extension at ~3.3 mm/yr appears to be mainly confined to its inner sector, while small SW-NE to N-S shortening is present in its outer sector. The two velocity profiles across the Northern Apennines show that most of the regional extension observed is currently taking up its northern-western sector (Northern Tuscany), while moving toward the Umbria-Marche region, extension is more localized in a narrow band. They also show that the outer sector of the chain displays smaller deformation rates, and indications of active shortening (at rates below the 1 mm/yr level) are observed only in the outer Northern Apennines, and mainly in the Emilia-Romagna Region.

While there is no evidence of active NW-SE back-arc spreading currently active in the Tyrrenian Basin, a NW-SE extension at more than 2 mm/yr is active in Calabria; nevertheless, this value must be considered preliminary, given the still poor geometry of the available geodetic network. The deformation rates observed in the rest of the peri-Adriatic region (i.e., Southern Alps and Dinarides) are related to the counter-clockwise rotation of the Adriatic microplate with respect to Eurasia, displaying values of SW-NE shortening along the Dinaric front ranging between 2 and 3.3 mm/yr, and rates of N-S to SW-NE shortening in the Eastern Alpine between 1 and 2 mm/yr.

In the Central Mediterranean, D’Agostino and Selvaggi (2004) from GPS and CGPS data, focused on the crustal deformation along the Eurasia-Nubia plate boundary in Calabria and Sicily, disclosing two distinct crustal domains, characterized by different motions and styles of deformation. Significant Eurasia (~3 mm/yr to NNE) and Nubia-fixed (~5 mm/yr to ESE) residual velocities in Calabria were found, suggesting the presence of an intermediate crustal block which can be interpreted as a forearc sliver or as an independent Ionian block. The first hypothesis indicates a still active subduction in the Ionian wedge, although no evidence was found for active back arc spreading in the Tyrrenian Sea. It is relevant that up to 3 mm/yr

Fig. 5. The Ring Network at 2007 (in green ASI stations) (courtesy of Dr. G. Selvaggi, modified).
(~80%) of this estimated relative motion between Sicily and the Calabrian Arc may be taken up in the Messina Straits, locus of the great 1908, $M_W=7.1$ earthquake.

Serpelloni et al. (2007), studying the kinematics Western Mediterranean, revealed a more complex fragmentation of the Nubian and Eurasian plate boundaries than previously proposed. The analysis suggests that the Sicilian-Pelagian domain is moving independently from Nubia, according to the presence of a right-lateral and extensional decoupling zone corresponding to the Tunisia-Libya and Strait of Sicily deformation zone. Despite the space variability of active tectonic regimes, plate convergence still governs most of the seismotectonic and kinematic setting up to the central Aeolian region. Along Calabria and the Apennines the contribution of the subducted Ionian oceanic lithosphere and the occurrence of microplates (i.e. Adria) appear to substantially modify both tectonics and kinematics. Across the Gibraltar Arc and the Trrhenian-Calabria domain data induce the hypothesis that slab rollback in these regions is mostly slowed down or stopped.

5. Conclusions

The Umbria-Marche earthquakes marked a
change in the evolution of the GPS networks in Italy. On the one hand, new GPS networks have been installed in selected areas using high accuracy 3-D geodetic benchmarks distributed with average grid up to 3-5 km. On the other, the CGPS network developed thanks to the new technologies provided by the GPS manufacturers as well as the fast data transmission by satellite or internet together with the new powerful computer processors and hardware used to analyse and archive data (Serpelloni et al., 2006). The gap with respect to other countries characterized by high seismic hazard, has now been filled and nowadays continuous and not permanent GPS networks useful for geophysics studies are active in the Italian region following the examples of the USA (Zhang et al., 1997) and Japan (Miyazaki et al., 1994), which have established hundreds of stations since 1990 to measure the crustal dynamics and the coseismic displacements of their highly seismic regions (Bock et al., 1993; Tsuji et al., 1995 and references therein).

These new GPS networks are continuously adding new constraints on the kinematics and current deformation of the Italian peninsula, as well as allowing more detailed studies of the seismogenic structures during different phases of the seismic cycle. Moreover, the combination of GPS and seismic observations together with DiSAR data (Massonnet et al., 1993; Massonnet and Feigl, 1998), will help to determine the size, location and extent of co-seismic deformations, better than the case of the 1997

Fig. 7. Current geodetic strain field of the Italian region from GPS and CGPS data (from Serpelloni et al., 2006a).
Umbria- Marche earthquakes (Hunstad et al., 1998; Anzidei et al., 1999; Stramondo et al., 1999; Salvi et al., 2000).

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REFERENCES


The coseismic ground deformations of the 1997 Umbria-Marche earthquakes: a lesson for the development of new GPS networks


MIYAZAKI, S., H. TSUI, Y. HATANAKA, Y. ABE, A. YOSHIMURA, K. KAMADA, K. KOBAYASHI, H. MORISHITA and Y.
IMURA (1994): Establishment of the nationwide GPS array (Grapes) and its initial results on the crustal de-
formation of Japan, *Bulletin of the Geographical Sur-
vey Inst.*, 42.

MONTONE, P. and M.T. MARIUCCI (1999): Active stress along the NE external margin of the Apennines: the 
Ferrara arc, northern Italy, *J. Geodyn.*, 28, 251-265.

IGOS-geo hazard Theme Report 2003 (2003): IGOS an 
Integrated Global Observing Strategy for the moni-
toring of our Environment from Earth and Space, 
http://dup.esrin.esa.it/igos-geo hazards, pp. 56.

OLDOW, J.S., L. FERRANTI, D.S. LEWIS, J.K. CAMPBELL, B.
D’ARGENIO, R. CATALANO, G. PAPPONE, L. CARMIGNANI, 
P. CONTI and L.V. AIKEN (2002): Active fragmentation of 
Adria based on Global Positioning System velocities 

PATARCA E., R. SARTORI and P. SCANDONE (1990): Tyrrhen-
ian basin and Apenninic areas. Kinematic relations since 

PINGUE, F. and I. GUERRA (1989): Geodetic monitoring of 
crustal deformations in the Catanzaro trough, Calabria, 

PIROMALLO, C. and A. MORELLI (2003): P-wave tomography of 

PINO, N.A. and S. MAZZA (2000): The Umbria-Marche (Central 
Italy) earthquakes: relation between rupture directivity and sequence evolution for the Mw > 5 

deformation in the Mediterranean area estimated by mo-

PONDRELLI, S., A. MORELLI, G. EKSTROM, S. MAZZA, E. 
BOSCHI and A.M. DZIEWONSKI (2002): European-
Mediterranean regional Centroid Moment Tensors Cat-

ROTHACHER, M. and L. MERVART (1996): Bernese GPS Soft-
ware Version 4.0, (Astronomical Institute University of 
Berne).

ware Version 4.0, (University of Berne, Switzerland).

SALVI S., S. STRAMONDO, M. Cocco, E. SANSOTTI, I. HUN-
STAD, M. ANZIDEI, P. BRIOLE, P. BALDI, M. TESAURO, E. 
LANARI, F. DOUMAZ, A. GALVANI and A. PESCI (2000): 
Modelling coseismic displacement resulting from sar 
interferometry and gps measurements during the 1997 
Umbria-Marche seismic sequence, *Journal of Seismol-
ogy*, 4, 479-499.

SANSO, F. and M.C. DE LACY (2000): Uno studio sulle diverse 
applicazioni del GPS e sul futuro sviluppo della rete di 
stazioni permanenti GPS sul territorio italiano orientato 
alla creazione di un servizio geodetico nazionale (avail-
able on line at http://geomatica.como.polimi.it/gps/arti-
coli/sai.pdf).

SELVAGGI, G. (1998): Spatial distribution of horizontal seis-
mic strai in the Apennines from historical earth-

SELVAGGI, G. and A. AMATO (1992): Subcru tal earthquakes in 
the Northern Apennines from historical earthquakes, 

SELVAGGI, G., M. MATTIA, A. AVALLONE, N. D’AGOSTINO, L. 
ABRUZZESE, M. ANZIDEI, M. CANTARERO, V. CARDI-
NALE, A. CASTAGNOZZI, G. CASULA, G. CECERE, R.

COGLIANO, F. CRISCUOLI, C. D’AMBROSIO, E. D’ANAS-
tASIO, P. DE MARTINO, S. DEL MESE, G. DE LUCA, R.
DEVIOTI, L. FALCO, V. FLAMMA, A. GALVANI, L. GIO-
VANE, I. HUNSTAD, A. MASSUCCI, F. MINICHELLO, A. 
MEMMOLI, F. MIGLIARI, R. MOSCHILLO, F. ORIZZO, M.
PALANO, G. PIETRANTONIO, M. PIGNONE, M. PULVIREN-
ti, M. ROSSI, F. RIGUZZI, E. SERPELLONI, U. TAMMARO 
and L. ZARRILLI (2006): La Rete Integrata Nazionale 
GPS (RING) dell’ INGV: una infrastruttura aperta per 
la ricerca scientifica, *Atti della X Conferenza Nazionale 
Dell’ASITA* (Bolzano 14-17 novembre 2006).

SERPELLONI E., M. ANZIDEI, P. BALDI, G. CASULA, A. GAL-
VANI, A. PESCI and F. RIGUZZI (2002): Combination of 
permanent and non-permanent GPS networks for the 
evaluation of the strain-rate field in the central Mediter-

SERPELLONI E., M. ANZIDEI, P. BALDI, G. CASULA and A. 
BALDI (2005): Crustal velocity and strain-rate fields in 
Italy and surrounding regions: new results from the 
analysis of permanent and non-permanent GPS net-
works, *Geophysical Journal International*, 161 (3), 

SERPELLONI, E., M. ANZIDEI, P. BALDI, G. CASULA and A. 
BA SMOLI (2006a): GPS measurements of active strains 

SERPELLONI, E., G. CASULA, A. GALVANI, M. ANZIDEI and 
P. BALDI (2006b): Data analysis of Permanent GPS net-
works in Italy and surrounding region: application of a 
distributed processing approach, *Ann. Geophys.*, 49 (4-
5), 897-928.

SERPELLONI, E., G. VANNUCCI, S. PONDRELLI, A. ARGIANI, G.
CASULA, M. ANZIDEI, P. BALDI and P. GASPERINI (2007): 
Kinematics of the Western Africa - Eurasia Plate Bounda-
ry From Focal Mechanisms and GPS Data., *Geophys. 

SMITH, D.E., R. KOENKIEWICZ, R.S. NEREM, P.J. DUNN, 
M.H. TORRENCE, J.W. ROBBINS, S.M. KLOSKO, R.G. 
WILLIAMSON and E.C. PAVLIS (1994): Contemporary global 
horizontal motion, *Geophys. Jou. Int.*, 119, 511-
520.

STRAMONDO, S., M. TESAuro, P. BRIOLE, E. SANSOTTI, S. 
SALVI, R. LANARI, M. ANZIDEI, P. BALDI, G. FORNARO, 
A. AVALLONE M.F. BUONGIORNO, G. FRANCESCHETTI 
and E. BOSCHI (1999): The September 26, 1997 Central 
Italy earthquakes: coseismic surface displacement de-
tected by sar interferometry and GPS, and fault model-


SURACE, L. (1997): La nuova rete geodetica nazionale 
IGM95: risultati e prospettive di utilizzazione, *Boll. 

TOSI, P., A. TERTULLIANI, V. DE RUBEIS and C. GASPARINI 
(1999): Preliminary results of a macroseismic survey of 
the Coltiorito sequence (Central Italy), *Phys. Chem. 
Earth.*, 24, 477-481.

TSUI, H., Y. HATANAKA, T. SAGIVA and M. HASHIMOTO 
Hokkaido-Toho-Oki earthquake monitored by a nation-
22 (13), 1669-1672.

VALENSE, G. and D. PANTOSTI (2001a): The investigation