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GEODESY AND GEOMATICS TO THE EDGE

Satellite positioning and geophysics studies in Italy

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Abstract A brief historical overview of the Italian geophysical studies using satellite positioning observations.

Keywords Satellite positioning · Satellite geodesy · Geophysics · Italy

1 The rise of satellite positioning

Precise positioning refers to the determination of geometrical quantities that enables to locate any arbitrary event in space. On a global scale, it requires the establishment of the terrestrial and celestial reference frames, and the transformation between the two or, in other words, the monitoring of the Earth's rotation. In the past, the art of precisely locating a target, to range over the oceans or to plan a new commercial route, was a critical issue for many societies. The early Greeks were especially fascinated by different theories and conceptual representations of the Earth. In the 6th century BC Anaximander of Mileto was probably the first "scientist" who realized that the Earth is freely floating in space founding his theory on simple observations and logical reasoning, a pleasant review of these early achievements is given by Rovelli (2011). Since then, many scientists developed a manifold of innovative solutions to determine the position on the Earth's surface, using basically ground-based and astronomical (optical) techniques. Only more recently, after the beginning of the space age in 1957, the use of artificial satellites became a tool for geodetic measurements allowing the achievement of unprecedented positioning accuracies. The artificial satellite Sputnik-1, launched on 4 October 1957 by the former Soviet Union, carried only a small radio beacon that beeped at regular intervals; nevertheless, it was the circumstance that triggered the outbreak of satellite positioning systems. In fact, shortly after Sputnik's launch, William Guier and George Weiffenbach at the John Hopkin's applied physics laboratory (APL), exploiting their skills and great enthusiasm in solving math and physics problems, were the first pioneering researchers to successfully recover the Sputnik's orbital parameters. Soon after their first experiments, a fruitful interaction with the chairman of APL, F. McClure, allowed them to solve the "inverse" problem, i.e. recovering the station position while assuming the orbit as known. These first enthusiastic achievements at APL were certainly motivated and strongly influenced by the cold war, namely positioning was strongly driven by the problem of locating the Navy ballistic missile submarines, but in fact they marked the rise of modern satellite navigation techniques and, more broadly, led to the development of satellite geodesy. A fascinating account of their experiences and efforts at APL at those times is given by the authors themselves in Guier and Weiffenbach (1998). These pioneering efforts yielded soon a new satellite system, the TRANSIT, also known as Navy Navigation Satellite System (NAVSAT) sponsored by the US Navy that was successfully tested in 1960. It was widely used as a navigation system by military and civilian watercraft, as well as for

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hydrographic and geodetic surveying. The TRANSIT system became obsolete only after the establishment of the actual US navigation system, the global positioning system (GPS) and ceased the service in 1996.

In 1964, a laser-based technique was developed, in which short energetic light pulses, sent out by an astronomical telescope, are reflected by special corner cubes mounted on satellites (Satellite Laser Ranging, SLR) or on the Moon (Lunar Laser Ranging, LLR) and detected back by the telescope. The measured distances between the target and the station enable the estimation of precise positions as well as Earth's variable gravity field parameters (gravity coefficients and geocenter).

During the same epoch, an essential development in geodesy was the very long baseline interferometry (VLBI), a non-satellite positioning technique based on astronomical radio source observations. Its fundamental contribution to geodesy and astronomy, even today, is the realization of the celestial reference system, and the long-term and short-term monitoring of the transformation between the celestial and terrestrial reference frames. Today, satellite positioning systems and VLBI are jointly referred to as space geodetic techniques.

Space geodetic techniques are now primary tools to study the size, figure and deformation of the Earth. They still have a great impact in many scientific disciplines, especially in geodesy, geodetic astronomy and geodynamics. The current generation of navigation systems, the so-called global navigation satellite system (GNSS), in which the GPS represents the best known system, has also an important impact on the society as a whole: it revolutionized surveying, timing, and pedestrian, car, marine and aircraft navigation. A comprehensive and interesting review of this revolution is outlined by Beutler (2004).

2 Paths towards a global and integrated monitoring network

2.1 CDP: 1979–1990

The first scientific project that promoted the development of satellite positioning on a global scale, was the Crustal Dynamics Project (CDP) supported by NASA in the late 1970s. The international partners involved in the CDP have made measurements of crustal motion between numerous sites around the world and retrieved the rotational dynamics of the Earth with unprecedented accuracy. The objectives of CDP required the development of a global geodetic system that could measure distances with high accuracy. As a consequence, in the 1980s, SLR and VLBI techniques were developed and improved to accuracy levels that would enable the scientific problems to be addressed. Several Italian researchers took part to the CDP topics and the first SLR station in Italy was installed by the Agenzia Spaziale Italiana (ASI) in strict cooperation with NASA and the Smithsonian Astrophysical Observatory, near the city of Matera in southern Italy (http://geodaf.mt.asi.it/).

2.2 DOSE: 1991–2001

A major emphasis in Dynamics of the Solid Earth (DOSE) was granted by NASA in the 1990s, a key contribution to the implementation and operation of an international geophysical network. This network incorporates VLBI, SLR, and GPS systems which are operated on a permanent, continuous basis, and which will provide the backbone network for the establishment of a global terrestrial reference frame. It is in these years that the international community organized cooperative services responsible for data and product delivery. The International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), the International GNSS Service (IGS) were established and conventional procedures and standards were recognized and put in operation. In Italy, fundamental geodetic stations became operative at Matera, Medicina (Bologna), Noto (Sicily) and Cagliari (Sardinia) and later on, many other GPS stations operated by ASI took part in the construction of a global monitoring network coordinated by the International Earth Rotation and Reference Systems Service (IERS) and regionally by the EUREF consortium.

2.3 GGOS: 2003–present

The Global Geodetic Observing System (GGOS) is the current observing system supported by the International Association of Geodesy (IAG). It was established by IAG in July 2003 and it represents IAG's contribution to the Global Earth Observation System of Systems (GEOSS). GGOS integrates different geodetic techniques, different models, and different approaches to ensure a long-term, precise monitoring of the geodetic observables. The Italian scientific community, since the very beginning, participates in several international consortia and activities, contributing with observing networks, archiving facilities, and analysis centers, contributing to the technological and scientific achievements in satellite positioning techniques. Over 20 permanent GPS stations in Italy are now active and operated in the framework of the EUREF Permanent Network (EPN), 3 Radio Telescopes (Matera, Medicina and Noto) participate to the VLBI measurement campaigns and the Matera Space Geodesy Centre has been recognized as a "fundamental station" in the GGOS core network, see Fig. 1.

Fig. 1 The fundamental geodetic station "G. Colombo" at Matera, Italy. The three main space geodetic observing techniques are highlighted by labels next to their respective sensors

3 First steps for precise position measurements in Italy

Geodesy techniques in the pre-space age, were essentially based on astronomical methods or on ground observations that are intrinsically relative measurements. In most cases, the estimated positions were solved in one or two dimensions, which were adequate for most cartographic applications. During the 19th and first half of 20th century, spirit leveling and triangulation surveys were mainly used to realize the Italian reference frame and to monitor the deformation processes of the ground.

The possibility of establishing a single geodetic reference frame at national scale, was taken into account only after the Italian unification (1861). The Istituto Geografico Militare (IGM) was appointed to initiate a first-order triangulation network, aggregating old and isolated geodetic benchmarks with the aim to provide the first topographic map at national scale. It so happened that after the 1908 Messina earthquake ($M\ \sim 7.1$), that terribly struck the Sicilian and Calabrian coasts, it was possible to reconstruct the height variations caused by the earthquake along the borders of the Messina Straits thanks to a leveling campaign carried out on both sides of the Straits shortly before the seismic event. The repetition of this survey (Loperfido 1909; De Stefani 1910) showed therefore a considerable coseismic subsidence, up to −70 cm in Sicily and −50 cm along the Calabrian coast, giving for the first time the description of the surface deformation due to a high magnitude earthquake in Italy.

A few years later in 1915, another catastrophic earthquake struck central Italy, near Avezzano ($M\ \sim 7$), and once again Antonio Loperfido lead a leveling survey to evaluate the vertical deformation induced by the seismic event. The field operations and the works were concluded successfully in the following years (Loperfido 1919). Thereon the IGM post-event survey became a standard procedure after major earthquakes in Italy (Talamo et al. 1978; Arca and Marchioni 1983; Arca et al. 1985).

In the first half of the 20th century, the vertical deformation velocity in the Po plain was also depicted by Salvioni (1957) and Boaga (1957). The results of these studies pointed out a dominant subsidence in the eastern Po Valley and a prevalent uplift in the western part. In many areas of the Po Valley, the natural and tectonic processes were modified by a rapid anthropogenic subsidence induced by underground extraction from aquifer systems and gas fields. The economic impact of man-induced subsidence was extremely high; for this reason this phenomenon has been systematically monitored during the last century (Caputo et al. 1970, 1972; Arca and Beretta 1985; Bondesan et al. 1997; Zerbini et al. 2007), providing the groundwork for a drastic reduction of water withdrawal in that area (Baldi et al. 2009, and references therein).

Since the early 1970s the Italian scientific community started to fully exploit geodetic techniques to investigate more general geophysical phenomena. At the very early stage, classical measurement techniques were extensively practiced (triangulation, electronic distance and geometric leveling) and more recently, the use of space geodetic observables (SLR, VLBI and GPS) has been widely explored, allowing figuring out a fully three-dimensional picture of the ongoing deformation processes. These positioning observations allow to study and to comprehend a large spectrum of active geophysical phenomena with exceptionally high time resolution, addressing complex tectonic processes, volcanic activity, natural and anthropogenic-induced subsidence, and gravitational instabilities.

4 Positioning and Geophysical investigations in Italy

The first satellite navigation system TRANSIT, based on Doppler observations, became available to civilian users in 1967. These data provided a substantial contribution to the operational definition of conventional terrestrial reference systems, giving the possibility to establish geodetic networks on regional, continental or global scale with accuracies of a fraction of meter. In Italy, a few measurement campaigns were performed to determine the coordinates of several control points. The data collected during the IDOC (Italy Doppler Observation Campaign) in 1982, have been used to strengthen the Italian terrestrial network (Baldi et al. 1984, 1985).

Around 1970, the Messina Straits area was the location of an important engineering project devoted to the construction of a single-span bridge to connect Sicily to the mainland. The scientific community was involved in studying the details of the tectonic processes. In this context, a geodetic network was set up across the Straits and was first repeatedly measured using principally theodolites and laser geodimeters (Caputo et al. 1974, 1981; Bencini 1975; Baldi et al. 1983) and since 1987, with the use of GPS receivers. In 1994, the network was upgraded and widened and the GPS surveys were systematically repeated in subsequent years. At that time, the tectonic deformations across the Straits turned out to be not significant and probably below the centimeter level (Achilli et al. 1988; Anzidei et al. 1998). Nowadays, the Straits area is monitored by a large number of permanent and periodic surveyed GPS stations showing a rather complex tectonic deformation pattern at the few mm/yr level (D'Agostino and Selvaggi 2004; Mattia et al. 2006; Serpelloni et al. 2010; Palano et al. 2012). Figure 2 outlines the recent past, and present knowledge of the ongoing deformations in that area.

As the GPS receivers became more reliable and their use in the field was economically sustainable, the scientific community started a pilot project aimed to study the ongoing crustal strain rates in the whole Mediterranean area. The TYRGEONET project started in 1989, thanks to the cooperation between the University of Bologna, the Istituto Nazionale di Geofisica (ING) and other Italian and European research institutions. The project was soon recognized as an important contribution to constrain the geodynamical models. The first GPS campaign was performed in 1990, using alternatively dual- and single-frequency GPS receivers, and measuring 33 geodetic benchmarks distributed in Italy, France and Tunisia. In 1991, the network was extended to the Ionian and Adriatic area including stations in Greece and Yugoslavia, moreover, the number of vertices in the Central Apennines was increased to achieve a better coverage of that peculiar seismogenetic area (Achilli et al. 1993; Anzidei et al. 2001).

At the same time, also the IGM set up and measured a new national geodetic network (the IGM95) based on a wide GPS survey including 1,260 benchmarks. The primary scope of this activity was to provide a set of 3D coordinates useful for cartography and civilian users (the average accuracy of the horizontal and vertical coordinates was estimated to be respectively, 2.2 and 3.5 cm (Surace 1997).

All these activities disclosed the possibility to monitor continuously the regional tectonic motion to understand and model the Eurasia–Africa convergence, in a peculiar region where continental collision, slab rollback and back-arc basin formation are coeval. The Italian Space Agency (ASI) was the first agency that fosters a nation-wide network of permanent GPS stations in the early 1990s. The GPS data were centrally collected and made available to the public, and ASI's network, after 20 years of continuous operation, is still contributing actively to the European reference frame definition, serving as regional archive center and analysis center of the EUREF consortium. Afterwards a series of geophysical monitoring projects promoted the development of GPS networks with carefully designed geodetic monumentation. The OGS built a regional monitoring network in NE Italy (FREDNET). Moreover, a follow-on of the CAT/SCAN project (http://www.ldeo.columbia.edu/res/pi/catscan) managed a transect of nine stations in the Calabria region and recently INGV (Istituto Nazionale di Geofisica e Vulcanologia) established a dense national network of permanent GPS stations, RING (Avallone et al. 2010). After these research efforts, in the second half of 2000, many regional authorities and private companies built proprietary GPS networks for cartographic and commercial purposes. Today many researchers are using all such GNSS data to study and model the geodynamics of the plate boundaries and their associated orogens (D'Agostino et al. 2005; Serpelloni et al. 2005; Devoti et al. 2011; Palano et al. 2012; Caporali et al. 2013; Serpelloni et al. 2013; Cheloni et al. 2014a), to constrain the Adria sub-plate kinematics (Battaglia et al. 2004; D'Agostino et al. 2008; Devoti et al. 2008; Cuffaro et al. 2010) and to correlate surface deformations (strain-

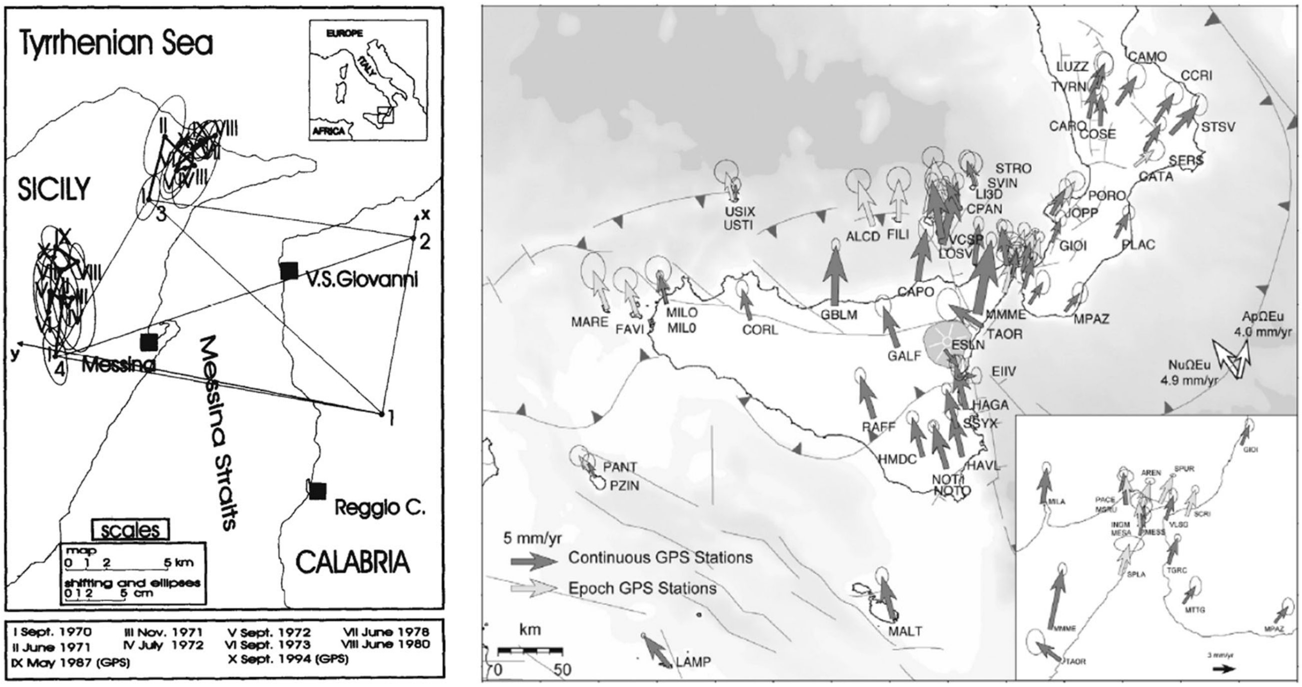

Fig. 2 On the left panel the Messina Straits deformation pattern as measured by leveling and the very first GPS surveys (Anzidei et al. 1998). On the *right panel*, a slightly wider area showing the GPS inferred surface deformation after more than a decade (Serpelloni et al. 2010)

rate) with earthquake occurrences (Riguzzi et al. 2012; D'Agostino 2014). In particular, Fig. 3 shows the crustal deformations projected in the horizontal and vertical directions, with respect to Eurasia fixed plate. The general northeastern motion of the Italian peninsula identifies the Adriatic microplate moving towards the Dinarides, while Corse and Sardinia represent the stable Eurasia. The southernmost velocities reveal the details of the Africa–Eurasia collision zone. The Alps show little horizontal deformations and a clear uplift signal, active extension and coeval uplift (at the mm/yr level) is instead evident along the Apennine chain. Areas subject to subsidence at different rates has been detected in the Po plain, mostly toward the Po estuary, in the Eolian back-arc area and in the Sicily channel.

Geodetic monuments located in relevant tectonic areas, such as the Italian peninsula, provide the geophysical community with invaluable information on ground displacements in case of occurrence of moderate and large earthquakes. During the three main shocks of the Umbria–Marche seismic sequence (M 5.7, 6.0, 5.6) in September–October 1997, nineteen stations of the IGM95 network were available around the epicentral area. A GPS surveying campaign, performed by INGV in October that year, allowed to measure for the first time in Italy the coseismic horizontal displacement and to use the data to constrain the source model of the earthquake (Anzidei et al. 1999; Stramondo et al. 1999; Hunstad et al. 1999). The same approach was followed in 2002 after the Molise seismic sequence (main shock M 5.7): the coseismic displacements obtained from the difference between pre- and post-event coordinates allowed defining the source fault (Giuliani et al. 2007). However, the total lack of knowledge of the interseismic motion, hampered the correct reconstruction of the coseismic displacements for both the Umbria–Marche and the Molise events. For this reason INGV promoted an intensive GPS measuring campaign in the first decade of 2000. Later in 2009, after the L'Aquila earthquake (M 6.3), the surveyed network allowed the reconstruction of a very detailed coseismic deformation field reported in Fig. 4 (Devoti et al. 2012). At the same time, it was then possible to study the post-seismic response of the crust in the neighborhood of the epicenter (Cheloni et al. 2014b). In this occasion, two receivers were also acquiring high rate GPS observations, and for the first time in Italy the earthquake ground shaking was registered at 10 Hz in two different places very close to the epicenter. These high-rate GPS observations has proven to be useful in seismological studies, to solve the kinematics of the fault rupture (Avallone et al. 2011) and also stimulated an Italian research team of La Sapienza University to develop a novel approach for precise, real-time displacement estimations from a single standalone GPS receiver (Colosimo et al. 2011). Figure 4 shows the two fundamental GPS signals observed during L'Aquila earthquake. In May 2012, two earthquakes (M 5.9, 5.8) occurred in the Emilia–Romagna

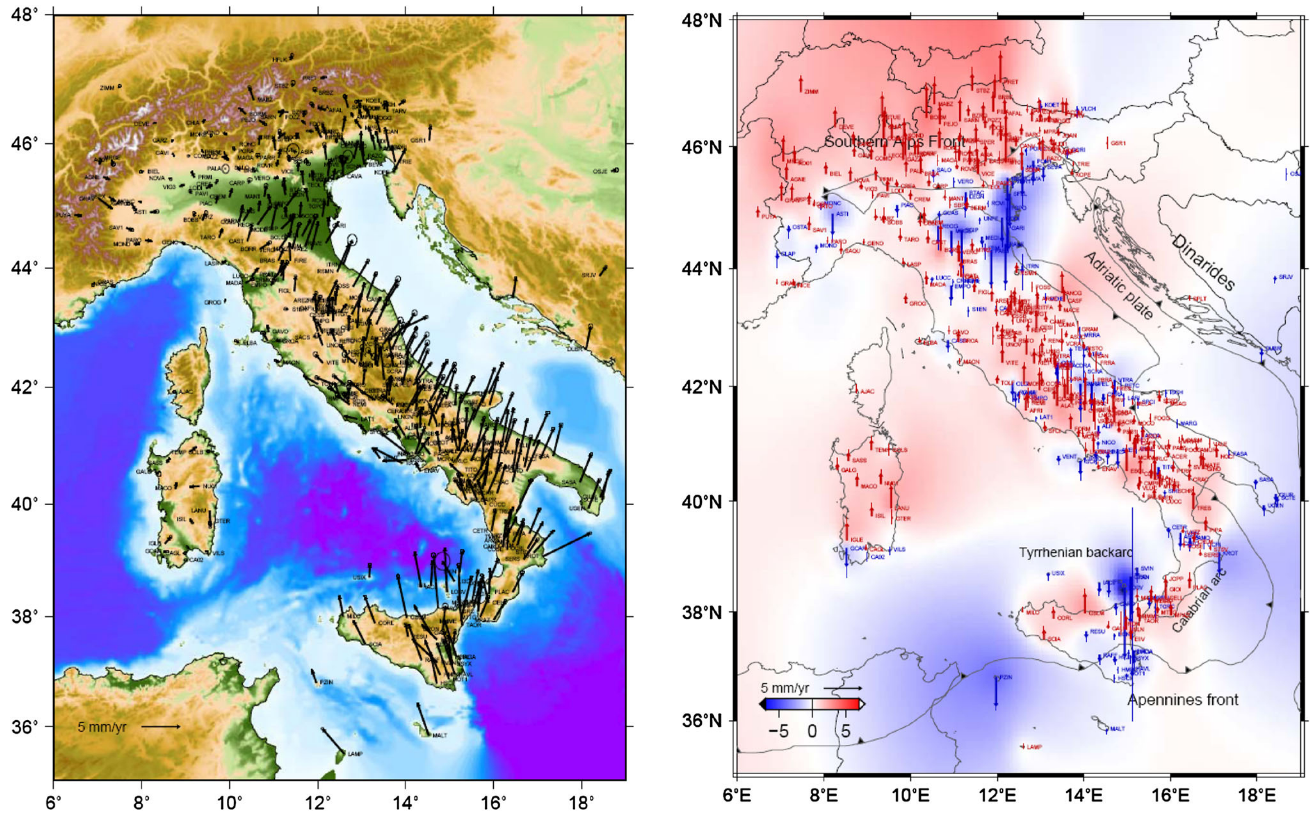

Fig. 3 A typical GPS velocity solution (horizontal with respect to Eurasia and vertical components, respectively on the *left* and *right panels*) obtained from the combined analysis of all existing permanent networks in Italy. The reference Eurasian plate has been realized by minimizing the rigid motion of 15 selected EUREF stations located in central Europe (Devoti et al. 2014)

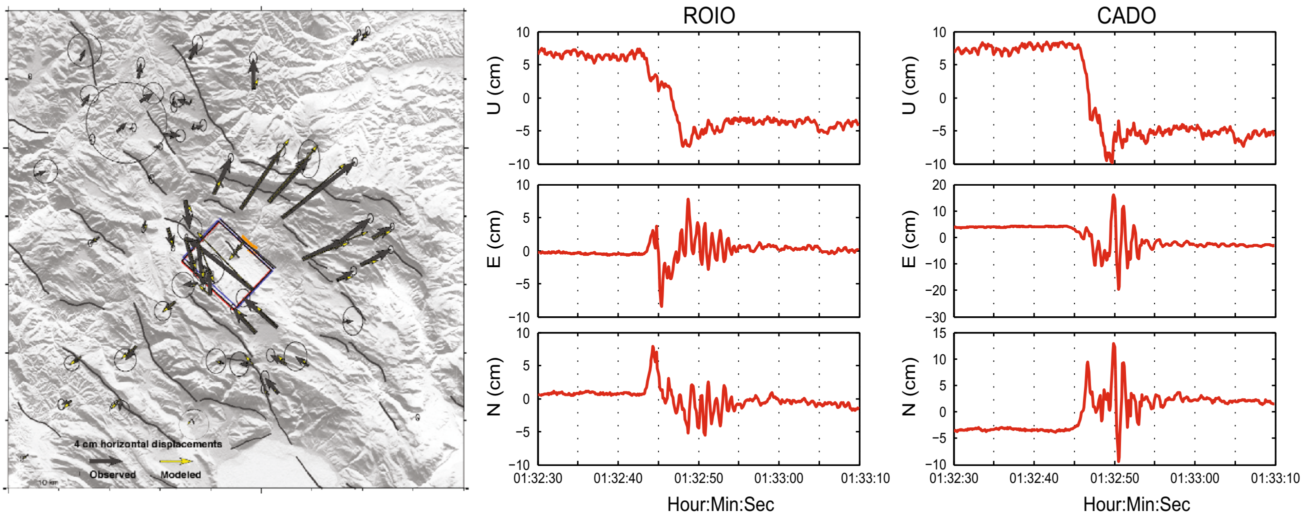

Fig. 4 The M 6.3 earthquake of L'Aquila on April 6, 2009. The *left panel* shows the coseismic displacement as observed by analysing long-lasting GPS surveys before and after the event (Devoti et al. 2012). On the *right*, the 10 Hz ground shakings in the three components (*vertical-top*, *east-middle*, *north-bottom*) as measured by two GPS stations

region, Northern Italy. For this event the Department of Civil Protection (DPC) activated an emergency procedure to produce a geodetic data set (mainly from the COSMO-SkyMed satellite constellation) and a prompt source model was produced using coseismic displacements from both GPS and SAR observations (Pezzo et al. 2013).

Satellite positioning provides also an important data source for monitoring volcanic-induced deformations in different areas of the Italian peninsula: Campi Flegrei, Ischia, Somma–Vesuvio, Etna and Eolian islands are the most investigated areas (Puglisi et al. 2001; Mattia et al. 2008; Palano et al. 2010; Del Gaudio et al. 2011; De Martino et al. 2011, 2014; Tammaro et al. 2013; Amoruso et al. 2014).

All these monitoring networks constitute now valuable and important research tools for many geophysical investigations, and current GNSS systems are able to deliver precise absolute positions for a wide range of frequencies, from secular variations down to periods of seconds, spanning many applications in geodesy, geodynamics and seismology. GNSS revolutionized our perception of space and permitted so far significant advances in scientific knowledge, but its real-time capabilities and its sensitivity to different natural processes (lithosphere, troposphere, ionosphere, cryosphere and hydrosphere) will certainly assure further important developments in the fields of real-time monitoring and natural risk surveillance.

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