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***Brief Communication***

# Co-seismic displacement on October 26 and 30, 2016 ($M_w$ 5.9 and 6.5) - earthquakes in central Italy from the analysis of discrete GNSS network

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**1 - Abstract**

On October 26th 2016, immediately north of the epicentral area affected by the $M_W$ 6.0, August 24th earthquake, a strong earthquake ($\boldsymbol{M}_w$ = 5.9), with a focal mechanism showing *W*-dipping normal faulting, occurred at the boundary between Marche and Umbria regions (central Apennines, Italy). Four days later (on October 30th), the main-shock ($\boldsymbol{M}_w$ = 6.5) of the whole seismic sequence occurred in the same area. The central Apennines are characterized by northeast-verging thrust-propagation folds, involving Mesozoic-Tertiary sedimentary successions. During the 2016 sequence, coseismic deformation has been recorded at the rear of the Sibillini Thrust which separates the main mountain chain from the Marche-Abruzzi foothills (Fig. 1). This contractional structure has been partly dissected and/or inverted by NNW-SSE trending Quaternary normal and oblique-slip faults. The major event (October 30) induced extensive geological effects at the surface and structural damages in the broader epicentral area up to a distance of 30 km. According to the report of the Istituto Nazionale di Geofisica e Vulcanologia (SUMMARY REPORT ON THE 30 OCTOBER, 2016 EARTHQUAKE IN CENTRAL ITALY Mw 6.5, Gruppo di Lavoro INGV sul Terremoto in centro Italia 10 November 2016), the hypocenter of major event was located at 42.8322°N, 13.1107°E at a depth of 9.2 km (Figs. 1 and 2). Following the August seismic events, we installed five new geodetic points located on both sides of the principal fracture zone and carried out two campaigns of GNSS measurements, the first one at the end of September (30-09/02-10, 2016), the second one early November (11/13-11, 2016) that covered the period of the October events.

In this brief communication, we provide the results of our geodetic campaigns that registered the co-seismic displacement occurred in the period between doy (day of year) 2016/274 and doy 2016/318, therefore documenting the two latter major shocks. We also compare our results with the available surface deformation field of the broader area obtained on the basis of the DInSAR technique and particularly the elaboration realized by CNR-IREA of Sentinel-1 radar imaging of Copernicus European Program of 26/10 - 1/11 (http://www.irea.cnr.it/index.php?option=com_k2&view=item&id=761:nuovi-risultati-sul-terremoto-del-30-ottobre-2016-ottenuti-dai-radar-dei-satelliti-sentinel-1). The comparison shows an overall good fit. It's worth to note that these earthquakes occurred in a sector of the Central Apennines characterized by high geodetic strain-rates (e.g., D'Agostino 2014), where several continuous GNSS stations are operating.

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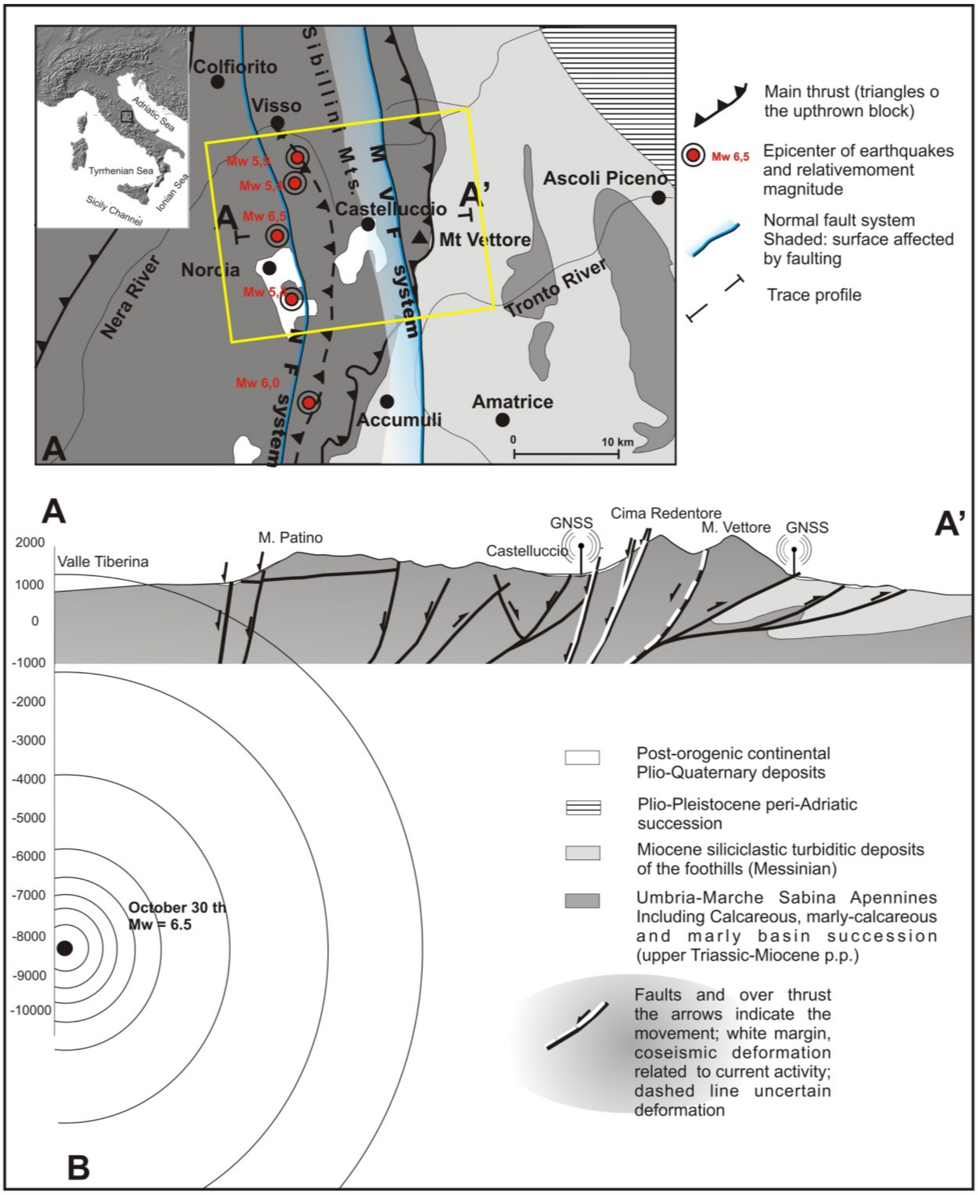


*Fig. 1 A) Simplified seismotectonic map of central Apennines; B) east-west geological profile; for the trace see the A map. The main geostructural features are reported (Pierantoni et al., 2013, modified)*

**Active faults**

According to many authors in the area affected by the recent earthquakes, the main thrust-related anticlines and associated reverse faults characterizing have been dissected and/or inverted by NNW-SSE trending Quaternary normal and oblique-slip faults (Figs. 1 and 2), in particular by the Norcia Fault system (NF) (Calamita and Pizzi, 1992; Calamita et al., 1982; 1995; 1999; 2000; Blumetti et al., 1990; Blumetti,

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1995; Brozzetti and Lavecchia, 1994; Cello et al., 1998; Galadini and Galli, 2000; Pizzi and Scisciani, 2000; Pizzi et al., 2002; Galadini, 2006; Gori et al., 2007) and by the Mt. Vettore Fault system (MVF) (Calamita and Pizzi, 1991; Coltorti and Farabollini, 1995; Cello et al., 1997; Pizzi et al., 2002; Galadini and Galli, 2003; Pizzi and Galadini, 2009) (Figs. 1 and 2). Conversely, Pierantoni et al. (2013) suggest that the major Mt. Sibillini Thrust has not yet been dissected by Quaternary normal faulting though some fresh morphological scarps with free faces in the carbonate bedrock and/or affecting recent slope deposits have been observed and attributed to the local  seismic activity.

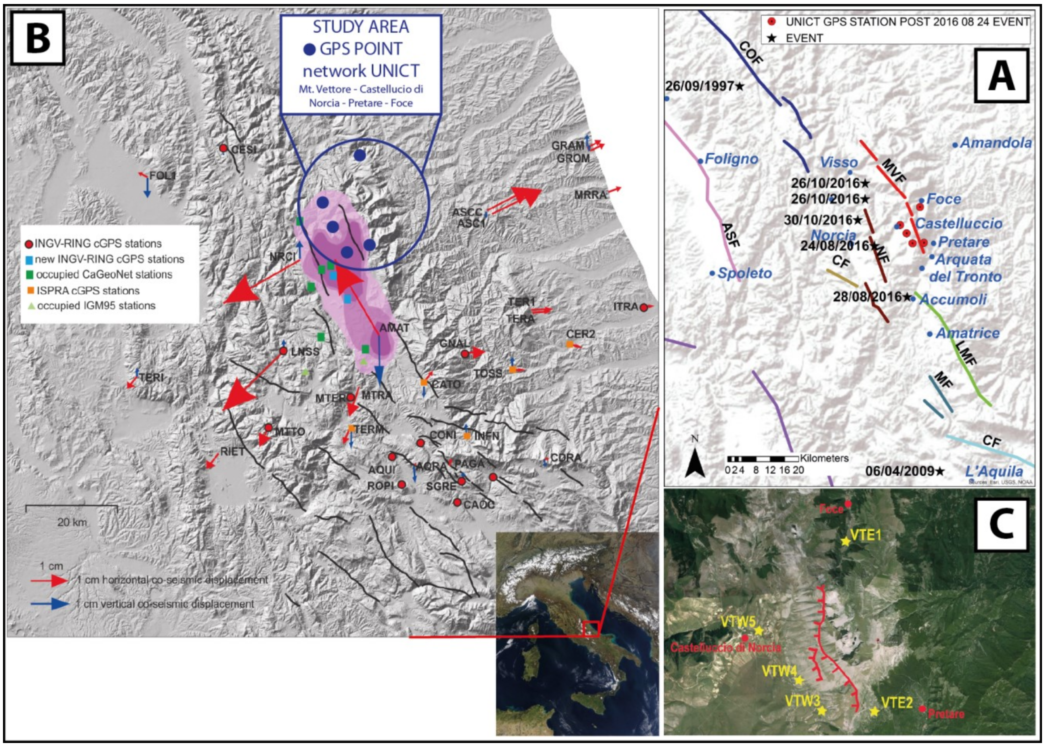


Fig. 2 – *A) Digital Elevation Model with shaded relief of central Apennines showing the active fault system. ASF: Assisi Fault; COF: Colfiorito Fault; CF: Cascia Fault; MVF: Mt. Vettore Fault; NF: Norcia Fault; LMF: Laga Mts. Fault; MF:faults of the Montereale basin and mains events since 1997. B) The figure shows the horizontal (red arrows) and vertical (blue arrows) consensus co-seismic displacements (with 68% confidence errors), together with the August 24$^{th}$, Mw 6,0 mainshock (yellow star) and aftershocks (colored as a function of depth) from http://iside.rm.ingv.it; and the position of UNICT_NET GPS C). Red coloured segments represent the October 30$^{th}$, coseismic deformation.*

After the August 24$^{th}$, 2016 mainshock, field observations (EMERGEO W.G., 2016) showed that only the southern segment of the Monte Vettore Fault system was reactivated in the northern sector of the epicentral area (Fig. 2C). So, a continuous alignment of newly formed coseismic ruptures was mapped for more than 5.2 km; conversely, in the southern sector, only few sparse observations of discontinuous (maximum 300 m-long) unclear ground ruptures with small displacements have been observed (EMERGEO W.G., 2016).

After the second mainshock (October 30), brittle deformation reached the surface producing evident ground ruptures along the Mt. Vettore – Mt. Bove Fault systems. A continuous rupture was mapped for a minimum length of 15 km between the Castelluccio di Norcia and Ussita (EMERGEO W.G., 2016) (Fig. 2). The coseismic rupture occured along distinct fault splays of the fracture system. For example, along the western slope of Mt. Vettore three main west dipping branches were activated together with two antithetic structures (Figs. 1 and 2). The vertical offset reaches 2 m along the main west dipping fault splay, where the slickensides show a prevalent vertical component of motion. Vertical displacements of few centimetres were also recorded along the antithetic tectonic structure bordering to the west the Castelluccio plain, about 6-7 km far from the main ground rupture (Fig. 2).

**Implementation and Analysis of UNICT discrete GPS stations**

Following the August, 24$^{th}$, $M_W$ 6.0 earthquake, the GEOmatic Working Group of the Catania University (UNICT) in collaboration with the SpinOff EcoStat s.r.l. and researches of the Ferrara University, started a detailed monitoring of ground deformation in the epicentral area using the Global Navigation Satellite System (GNSS) technique. For this aim, five GNSS stations have been installed on benchmarks built by the working group and here referred to as UNICT_NET network (Fig. 3). These new stations have been realized taking into account the following criteria:

I. the distribution of the existing permanent and discrete measurement benchmarks belonging to different networks that were active before the event of 24 August (IGM; RING; CAGEONET; DPC; ISPRA) (Fig. 2B).
II. the seismotectonic setting of the area in relation to the macroseismic data and to the reactivated structures (Figs. 1 and 2);
III. surface and deep geometry of the major faults related to tectonic setting (Fig. 1B).
IV. the non-occurrence of possible instabilities in both static and dynamic conditions in sites where the new benchmarks are built.

Based on the above criteria, the working group installed the benchmarks at the bottom of both western and eastern slopes of Mt. Vettore, within an area about 8 km-long and 5 km-wide in the N-S and E-W directions, respectively. The distribution of the benchmarks was planned for depicting the principal deformation zone developed as a consequence of the August 24$^{th}$, event (Fig 2 and 3) and particularly with points:

I. much closer to the epicentral area than the already existing ones belonging to other networks (Fig. 2B);
II. characterized by equivalent distances from the reactivated Mt. Vettore Fault segments (Fig. 2);
III. within a distance of 30 km from the closest permanent network points that have been not affected by deformation, therefore allowing a rigorous elaboration during the post processing phases (Fig. 3).

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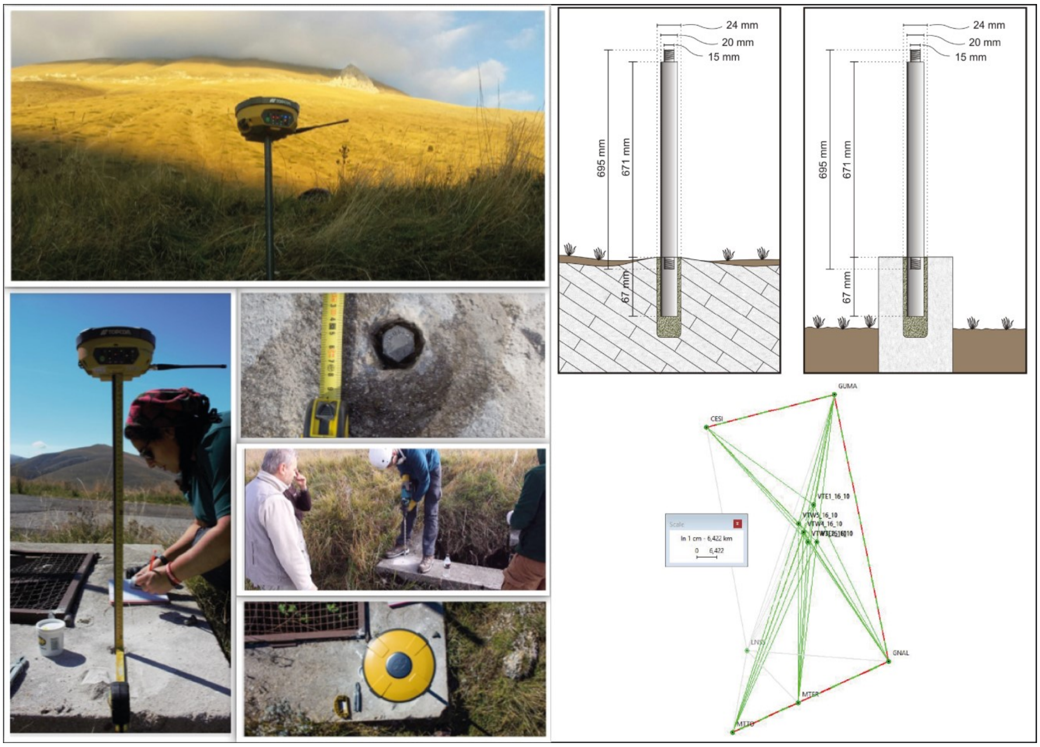


*Fig. 3 Synoptic picture showing installation, measurement and processing phases of the UNICT_NET.*

The realization of GPS monument on the UNICT benchmarks consists of the following steps:

I. selection of a suitable point, corresponding to a massive rocky outcrop or a man-made monument with foundation; these sites must be also free of structures or other natural elements in the surroundings that may constitute a perturbation during recording;
II. testing of GPS signal reception by short-term exams, and control of parameters set by the quality check carried out by software TEQC (http://www.unavco.org/software/data-processing/teqc/teqc.html);
III. implementation of the hole for housing the bushing and check of its verticality; the hole has a diameter of 35 mm and a depth of 100 mm, it is realized through small-sized battery-powered equipment (Makita DHR243 hammer drill) (Fig. 3);
IV. fixing and anchoring of the knurled steel bushing (length 67 mm and diameter 20 mm), with bi-component resins or quick-setting cements (Fig. 3);
V. following the cementation to the artefact or to rocky outcrop, a male-male threaded bar can be screwed in until end of stroke; the height could be variable and this fact will be considered in the data processing. We have used a threaded bar 670 mm-high. (Fig. 3).

The GPS monument is thus completed with a GNSS receiver TOPCON, mounting a HiPer V antenna, characterized by 226 channels and position accuracy with band L1+L2 in Static mode of 3 mm + 0,1 ppm (horizontal) and 3,5 mm + 0,4 ppm (vertical). All registrations last six hours in static mode.

Following the August 24th, event, at the end of September 2016 the working group have started the first survey campaign with the installation of five UNICT benchmarks: two stations have been located east of the Mt. Vettore fault (VTE1,VTE2), the other three (VTW3,VTW4, VTW5) west of the fault (Figs. 3 and 4). During November 2016 (*i.e.* after the October 30th event), a second field campaign was carried out following the same procedure and using the same instrumentation. The second set of measurements allowed to record the co-seismic displacement caused by both the $M_w$ 5.9 and $M_w$ 6.5 events of October 26th and 30th, respectively.

The data from survey-mode GNSS stations have been downloaded and processed using TOPCON Magnet analysis software evaluating co-seismic solution.

For the analyses we referred to the measurement of a stable reference frame of five GNSS stations belonging to the RING (Rete Integrata Nazionale GPS) network, with a maximum baseline length of 30 km using stations CESI, GNAL, GUMA, MTER and MTTO (Figs. 3 and 4). Data processing has been carried out with adjustment by Least Squares and a TAU Criterion.

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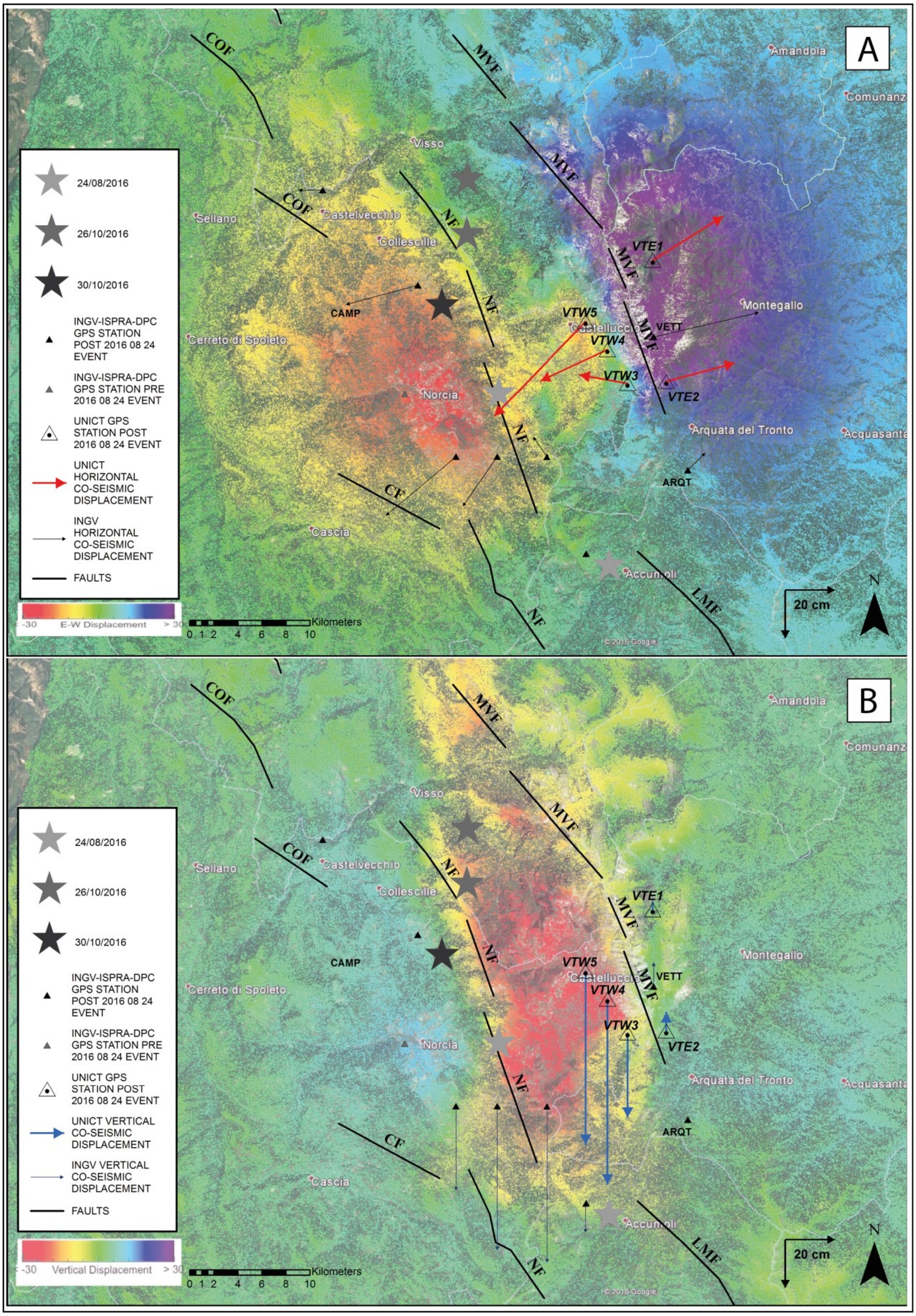


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*Fig. 4 The two color-coded maps show the E-W (a) and VERTICAL (b) displacement distribution obtained by the DInSAR technique (http://www.irea.cnr.it/index.php?option=com_k2&view=item&id=761:nuovi-risultati-sul-terremoto-del-30-ottobre-2016-ottenuti-dai-radar-dei-satelliti-sentinel-1), while the red and blu arrows represent the consensus pre-, co-, and post-seismic displacements (with 95% confidence errors) on the basis of the GNSS UNICT network. Epicenters of the October, 26th and 30th $M_w$ 5.9 - 6.5 and of the August, 24th, $M_w$ 6 events are also shown (http://ring.gm.ingv.it) as well as the position and relative measured vector of the CaGeoNet stations (Anzidei et al. 2008; Galvani et al., 2012), the IGM95 benchmarks (http://www.igmi.org/geodetica/) re-occupied by ISPRA (www.isprambiente.gov.it) after the mainshock and the continuous GPS stations managed by ISPRA and the Civil Protection Department (DPC).*

| SITE ID | MARKER NUMBER | lon °E | lat °N | Hei (m) | Ground Distance (m) | Delta Ell. (m) | Network |
|---|---|---|---|---|---|---|---|
| VTE1 | FOCE_SENTIERO | 13° 15' 58,16654'' | 42° 51' 55,80640'' | 1091,690 | 0,344 | 0,034 | UNICT |
| VTE2 | PRETARE | 13° 16' 33,92314'' | 42° 47' 55,33158'' | 1049,532 | 0,294 | 0,077 | UNICT |
| VTW3 | QUARTUCCIOLO | 13° 14' 47,12569'' | 42° 47' 55,33427'' | 1475,886 | 0,203 | -0,352 | UNICT |
| VTW4 | COLLE CURINA | 13° 13' 55,72696'' | 42° 48' 58,38892'' | 1371,543 | 0,308 | -0,771 | UNICT |
| VTW5 | CASTELLUCCIO_VALLE | 13° 12' 56,91921'' | 42° 49' 53,65362'' | 1375,999 | 0,547 | -0,722 | UNICT |

*Tab 1 - Co-seismic displacements (in m) estimated for the GNSS stations of the UNICT network on both sides of the principal deformation zone of the Monte Vettore Fault characterized by a mean distance lower than 4 km from the PDZ). The table can be download as ASCII file on the INGVRING web page (http://ring.gm.ingv.it). The first column indicates the GNSS station name ; lon: longitude (°E), lat: latitude (°N), Hei: station height (in meters). Ground distance and vertical co-seismic displacements and corresponding uncertainties, in m. The last column indicates the GNSS/GPS network.*

**Concluding remarks**

Based on the GNSS technique, a detailed monitoring of the ground deformation occurred in the surroundings of the Mt. Vettore Fault segment, partially reactivated by the August 24th ($M_W$ 6.0), has been carried out. This foresight action allowed us to record the second (strongest) event ($M_W$ 6.5) of October 30th, 2016. On the basis of the laws and models on stress-triggering theory (Stein et al., 1999; Steacy et al., 2005), we have identified the specific fault zone most vulnerable to future seismic events just north of the fault segment reactivated on 24th August (Figs. 2B and 4). Consequently in order to measure the post seismic deformation and to record a potential migration of the coseismic process, we have placed the GNSS benchmarks, both east and west of the northern-central segment of the Mt. Vettore Fault system, close to other benchmarks located before the second seismic event by other research groups (IGM; RING; CAGEONET; DPC; ISPRA). The measured deformation (with 95% confidence errors) is characterised by horizontal and vertical movement. From north to south, the east benchmarks indicated 344 mm eastward horizontal displacement and 34 mm upward (VTE1), 294 mm eastward horizontal displacement and 77 mm upward component of motion (VTE2); on the contrary, all the three western benchmarks have recorded westward horizontal displacement and downthrown component of motion: 547 mm and -722 mm (VTW5); 308 mm and -771 mm (VTW4); 203 mm and -352 mm (VTW3). So, the maximum horizontal displacement was 891 mm in correspondence of the northen sector of the Mt. Vettore fault segment, while the maximum vertical displacement was 848 mm.

In conclusion, the comparison between our results and the displacement distribution obtained with DInSAR techniques, and other GNSS stations, active before the second seismic event (Fig. 4), indicate the consistency of the data.

Moreover, the semi-quantitative analysis along the west-east deformation transect (Fig. 5), indicate an anomalous variation of both horizontal and vertical deformation, suggesting a possible "seismic efficiency" of the Norcia fault system, located to the west of the Mt. Vettore fault system. We have placed new benchmarks in strategic positions for monitoring pre, inter and post-seismic deformation.

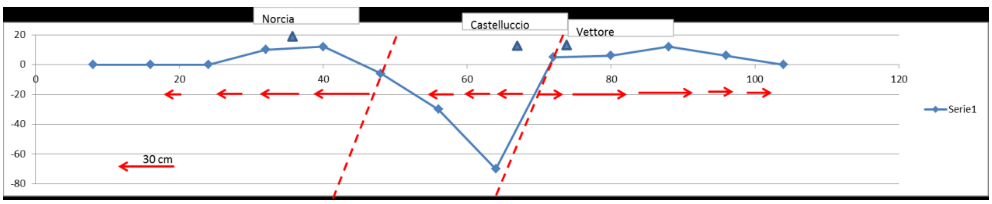


*Fig. 5 Semi-quantitative comparison between west-east deformation transects obtained by DInSAR techniques and our GNSS measurements (see fig 4)*

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