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# Brief communication: Co-seismic displacement on 26 and 30 October 2016 ($M_w = 5.9$ and 6.5) – earthquakes in central Italy from the analysis of a local GNSS network

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**Abstract.** On 24 August 2016 a strong earthquake ($M_w = 6.0$) affected central Italy and an intense seismic sequence started. Field observations, DInSAR (Differential INterferometry Synthetic-Aperture Radar) analyses and preliminary focal mechanisms, as well as the distribution of aftershocks, suggested the reactivation of the northern sector of the Laga fault, the southern part of which was already rebooted during the 2009 L'Aquila sequence, and of the southern segment of the Mt Vettore fault system (MVFS). Based on this preliminary information and following the stress-triggering concept (Stein, 1999; Steacy et al., 2005), we tentatively identified a potential fault zone that is very vulnerable to future seismic events just north of the earlier epicentral area. Accordingly, we planned a local geodetic network consisting of five new GNSS (Global Navigation Satellite System) stations located a few kilometres away from both sides of the MVFS. This network was devoted to working out, at least partially but in some detail, the possible northward propagation of the crustal network ruptures. The building of the stations and a first set of measurements were carried out during a first campaign (30 September and 2 October 2016). On 26 October 2016, immediately north of the epicentral area of the 24 August event, another earthquake ($M_w = 5.9$) occurred, followed 4 days later (30 October) by the main shock ($M_w = 6.5$) of the whole 2016 summer–autumn seismic sequence. Our local geodetic network was fully affected by the new events and therefore we performed a second campaign soon after (11–13 November 2016). In this brief note, we provide the results of our geodetic measurements that registered the co-seismic and immediately post-seismic deformation of the two major October shocks, documenting in some detail the surface deformation close to the fault trace. We also compare our results with the available surface deformation field of the broader area, obtained on the basis of the DInSAR technique, and show an overall good fit.

## 1 Geological framework

The central Apennines are characterized by north-east-verging thrust-propagation folds, involving Mesozoic–Tertiary sedimentary successions. During the 2016 sequence, coseismic deformation was recorded at the rear of the Sibillini thrust, which separates the homonymous mountain chain from the Marche–Abruzzi foothills (Fig. 1). According to many studies in the area, the main thrust-related anticlines and associated reverse faults 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 (NFS) (Calamita and Pizzi, 1992; Calamita et al., 1982, 1995, 1999, 2000; Blumetti et al., 1990; Blumetti,

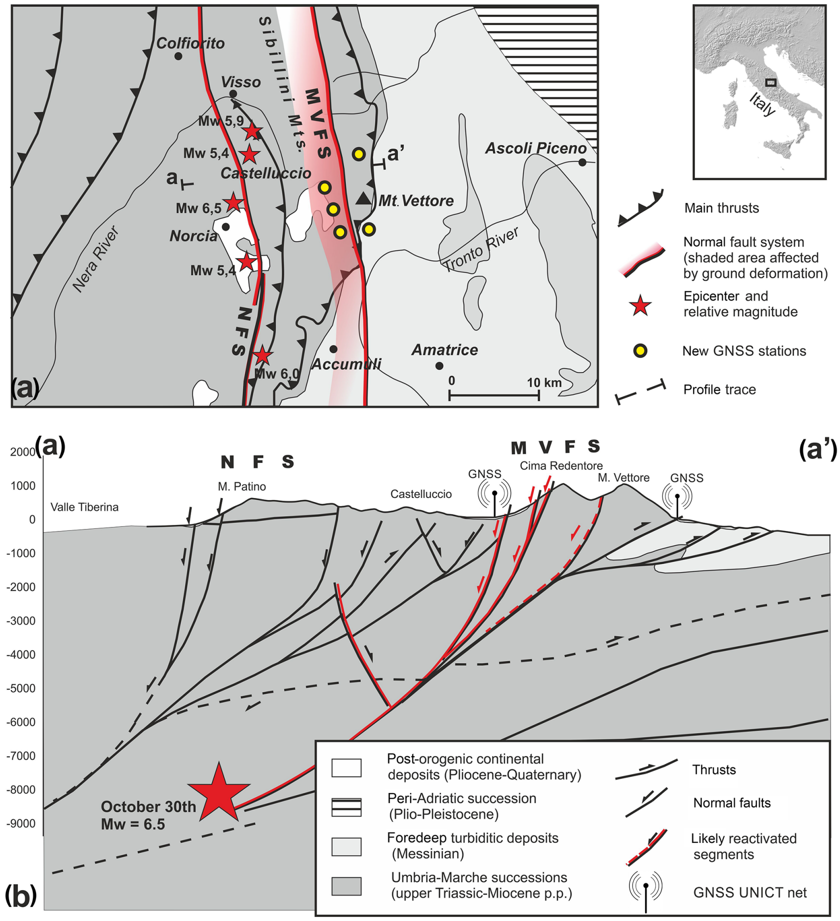


**Figure 1.** Simplified seismotectonic map of the central Apennines **(a)** and geological profile across the epicentral area **(b)**. The location of the major event (30 October) is from GdL INGV (2016), while the main geostructural features from Pierantoni et al. (2013) and Mantovani et al. (2011) have been modified.

1995; Brozzetti and Lavecchia, 1994; Cello et al., 1998; Galadini and Galli, 2000; Pizzi and Scisciani, 2000; Pizzi et al., 2002; Boncio et al., 2004; Galadini, 2006; Gori et al., 2007) and the Mt Vettore fault system (MVFS) (Calamita and Pizzi, 1992; 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 been yet 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.

Within a distance of few tens of kilometres, significant evidence of ground deformation has been provided by several recent earthquakes, like the 1979 Norcia event ($M_w = 5.9$, reactivating the Norcia fault; e.g. Deschamps et al., 2000), the 1984 Gubbio event ($M_w = 5.6$, Gubbio fault; e.g. Boncio et al., 2004), the 1997 Colfiorito shakes ($M_w = 5.7$, 6.0 and 5.6, Calfiorito–Cesi–Costa fault system; e.g. Cello et al., 1997), the 2009 L'Aquila main shock and the Campotosto aftershock ($M_w = 6.3$ and 5.4, Upper Aterno Valley – Paganica fault system and Gorzano fault; Blumetti et al., 2013) The same occurred with the 2016 seismic sequence.

Surface evidence of 24 August (e.g. EMERGEO WG, 2016; Livio et al., 2016; Aringoli et al., 2016) was mainly observed in the area of the Laga basin (Gorzano fault), which corresponds to the footwall block of the Sibillini thrust, while debated ground ruptures (e.g. Valensise et al., 2016) also occurred in the southern sector of the MVFS, which belongs to the hanging-wall block of the orogenic structure. In contrast, as a consequence of the main shock of 30 October, the entire western flank of Mt Vettore was affected by impressive geological effects and clear coseismic ruptures mapped for a minimum length of 15 km between Castelluccio, Norcia and Ùssita (EMERGEO WG, 2016) (Fig. 2). The surface ruptures occurred along distinct fault splays of the fracture system. For example, along the western slope of Mt Vettore, three main west-dipping splays were activated together with two antithetic branches (Figs. 1 and 2). The observed vertical offset reached 2 m along the main west-dipping fault segment,

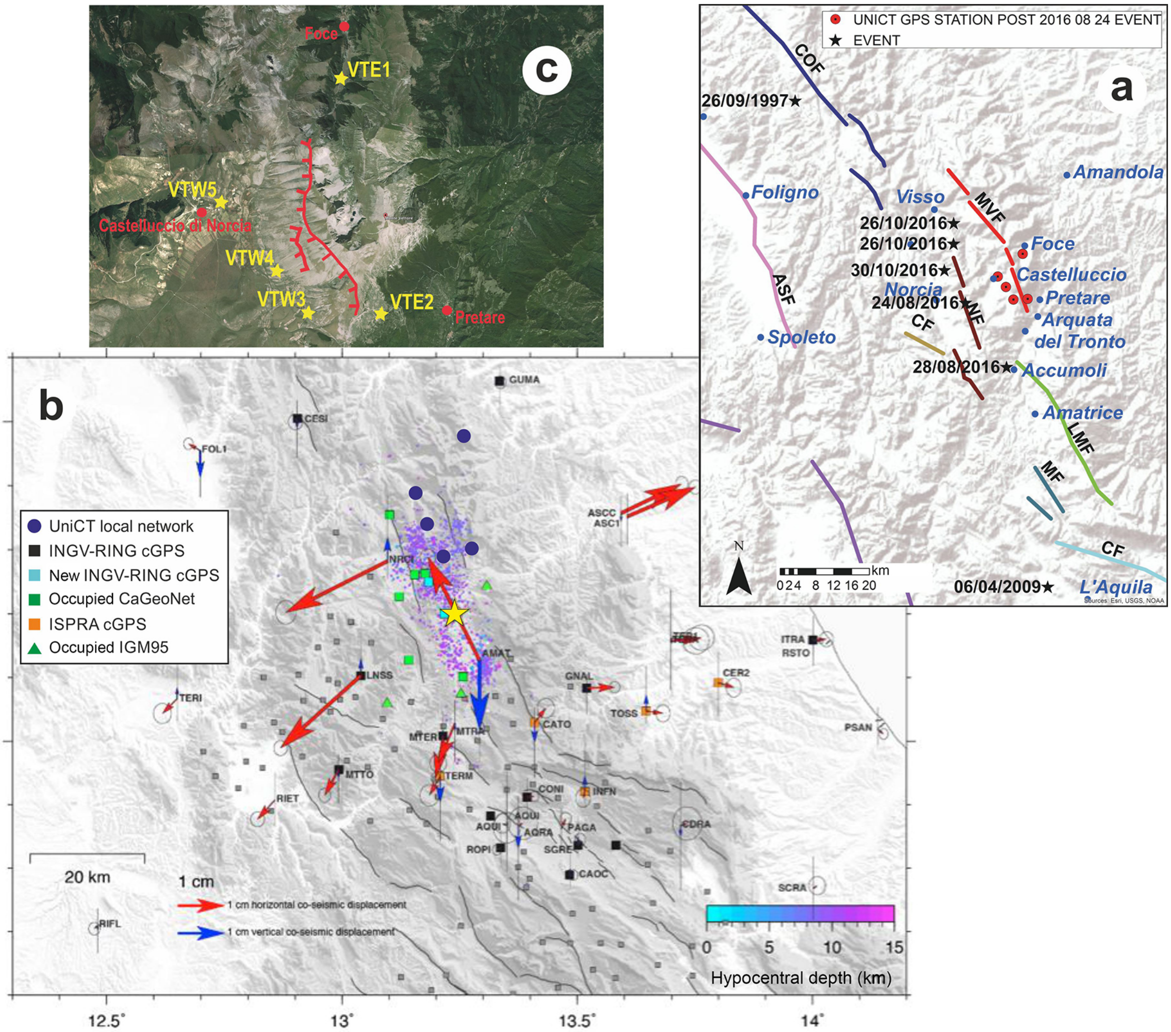


**Figure 2.** **(a)** Digital elevation model with shaded relief of the central Apennines showing the active fault system and the major events since 1997 (ASF: Assisi fault; COF: Colfiorito fault; CF: Cascia fault; MVF: Mt Vettore fault; NF: Norcia fault; LMF: Laga mountain range fault; MF: faults of the Montereale basin). **(b)** Horizontal (red arrows) and vertical (blue arrows) consensus co-seismic displacements (with 68 % confidence errors), and the local UniCT GPS network. The aftershocks of 24 August, $M_w = 6.0$ main event (yellow star) are coloured as a function of depth (from http://iside.rm.ingv.it). **(c)** Google Earth map showing the new five GNSS stations (yellow stars) located in the near field (and surrounding) of the 30 October coseismic ground ruptures (red lines).

where the slickensides show a prevalent dip-slip component of motion. Vertical displacements of a few centimetres were also recorded along an antithetic surface rupture bordering the west of the Castelluccio plain, about 6–7 km from the main ground rupture, possibly connected to a secondary fault (Figs. 1b and 2).

It is worth noting that the August–October earthquakes occurred in a sector of the central Apennines characterized by high geodetic strain rates (e.g. Devoti et al., 2011; D'Agostino, 2014), where several continuous GNSS stations are operating.

## 2 Implementation and analysis of UNICT discrete GPS stations

Following the 24 August $M_w = 6.0$ earthquake, the GEOmatic Working Group of the Catania University (UNICT), in collaboration with the SpinOff EcoStat s.r.l. and research from Ferrara University, started a detailed monitoring of ground deformation in the epicentral area using the Global Navigation Satellite System (GNSS) technique. GNSS measurements have been conducted in static mode, set to a time of 6 h and in a post-processing position in order to reduce tropospheric error, and using IGS precise products for orbits. The IGS station coordinates were kept fixed in order to align the final velocity field with the WGS84 reference frame. The

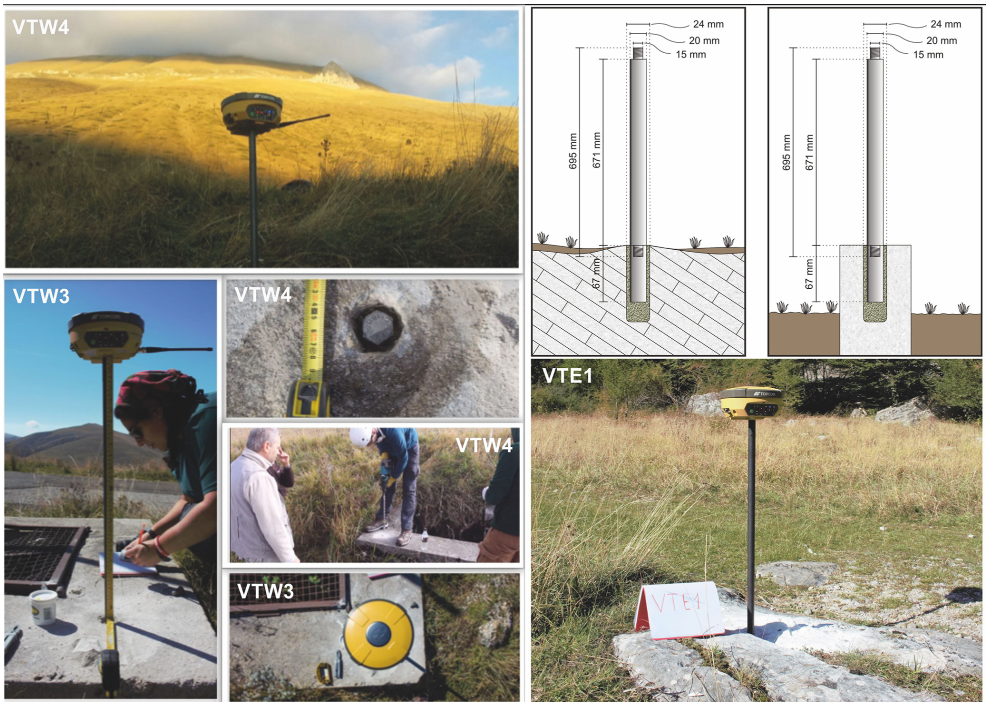


**Figure 3.** Synoptic picture showing installation of the new GNSS stations, measurement and processing phases.

measurement mode, adopted for receiver–satellite range determination, is performed with a double frequency receiver, allowing phase and code measurements on the signal carrier (L1, L2, C1, P1, P2, S1, S2). The coordinates estimation is based on the principle of minimum squares.

To this end, five GNSS stations have been installed on new benchmarks purposely built by the working group and here referred to as a UNICT 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 the tectonic setting (Fig. 1b);

iv. the lack of possible gravitational instabilities in both static and dynamic conditions at sites where the new benchmarks are built.

Based on the above criteria, the working group installed the benchmarks at the bottom of both the 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 reconstructing the principal deformation zone which developed as a consequence of the 24 August event (Fig. 2) and was

i. much closer to the epicentral area than the 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.

Building the GNSS monument on the UNICT benchmarks consists of the following steps (Fig. 3):

i. the selection of a suitable site, 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 the GPS signal reception with short-term exams and controlling parameters set through the quality check carried out by the software TEQC (http://www.unavco.org/software/data-processing/teqc/teqc.html);

iii. the 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 re-

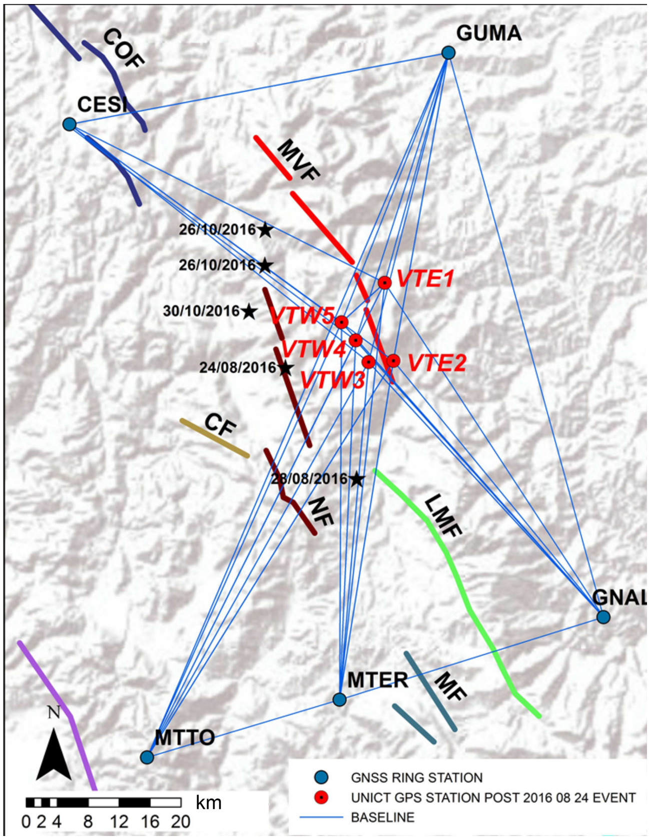


**Figure 4.** Baselines obtained by combining the new GPS UNICT stations with selected GNSS ones from the RING network.

alized through small-sized battery-powered equipment (Makita DHR243 hammer drill);

iv. fixing and anchoring the knurled steel bushing (length 67 mm and diameter 20 mm), with bicomponent resins or quick-setting cements;

v. following the cementation to the artefact or to rocky outcrop; a male–male threaded bar can be screwed in until the end of the stroke; the height could be variable and this fact is considered in the data processing. We have used a threaded bar 670 mm high.

The GPS monument is thus completed with a GNSS receiver TOPCON, mounted with 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 6 h in static mode.

Following the 24 August event, at the end of September 2016 the working group carried out the first survey campaign with the installation of five UNICT benchmarks: two stations were located east of the Mt Vettore fault (VTE1, VTE2) and the other three (VTW3, VTW4, VTW5) were west of the fault (Figs. 4 and 5). During November 2016 (i.e. after the 30 October event), a second field campaign was carried out following the same procedure and using the same instrumentation. The second set of measurements allowed us to record the co-seismic displacement caused by both the $M_w = 5.9$ and $M_w = 6.5$ events of 26 and 30 October, respectively (DOY, day of year, 2016/274 and DOY 2016/318).

The data from survey-mode GNSS stations have been downloaded and processed using TOPCON magnet analysis software, evaluating co-seismic solutions (Table 1) and comparing them with AUSPOS web-based online services for GPS data processing (Ocalan et al., 2013). Its engine is based on Bernese 5.2 software. In the software TOPCON, the baseline is automatically created for any pair of static occupations, where we set minimum duration to 6 h, the maximum baseline length to 50 km and the cut-off angle to 15°. The troposphere model is Goad–Goodman and the meteorological model is NRLMSISE-00 (neutral temperature and densities in Earth's atmosphere).

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 50 km, using stations CESI, GNAL, GUMA, MTER and MTTO (Figs. 4 and 5). Data processing has been carried out with adjustment using least squares and a TAU criterion.

## 3 Concluding remarks

Using the GNSS technique, we investigated the ground deformation that occurred in the surroundings of the Mt Vettore fault system during the 2016 central Italy seismic sequence. This foresight allowed us to record the co-seismic deformation and part of the post-seismic deformation of the second and third (strongest) events ($M_w = 5.9$ and $M_w = 6.5$) on 26 and 30 October 2016, respectively. Taking into account the geometry of the fault system in the broader epicentral area and following the stress-triggering concept (Stein et al., 1999; Steacy et al., 2005), we identified a potential fault zone that is vulnerable to future seismic events just north of the fault segment that was reactivated during the 24 August earthquake (Figs. 2b and 5). With this in mind, in order to measure the post-seismic deformation and to possibly record the potential migration of the co-seismic process, we selected some sites and built five new GNSS benchmarks, distributed east and west of the northern–central segment of the Mt Vettore fault system. For site selection we also considered the presence and distribution of other benchmarks placed before the second seismic event by other research groups (IGM; RING; CAGEONET; DPC; ISPRA). The epicentral location of the October events confirmed our guess and then we performed a second campaign of measurements (10–13 November) in this area to quantify the relative motion of the stations.

The measured deformation (with 95 % confidence errors) is characterised by both horizontal and vertical movements

**Table 1.** Three-component co-seismic displacements and relative uncertainties estimated for the GNSS stations of the UNICT network. Coordinates are WGS84 east and north, respectively. All displacement and uncertainty values are in millimetres. For all stations, the cut-off angle is 15°, the troposphere model is the Goad–Goodman and the meteorological model used is NRLMSISE-00. The table can be download as an ASCII file on the INGVRING web page (http://ring.gm.ingv.it).

| ID | Station | Longitude | Latitude | $disp_{N-S}$ | $disp_{E-W}$ | $disp_{UP}$ | $unc_{N-S}$ | $unc_{E-W}$ | $unc_{UP}$ |
|---|---|---|---|---|---|---|---|---|---|
| VTE1 | FOCE_SENTIERO | 13°15′57.45166″ | 42°51′57.04340″ | 141 | 312 | 29 | 15.5 | 16.5 | 44.0 |
| VTE2 | PRETARE | 13°16′33.20959″ | 42°47′56.56780″ | 60 | 282 | 67 | 19.0 | 16.5 | 46.0 |
| VTW3 | QUARTUCCIOLO | 13°14′46.41153″ | 42°47′56.57032″ | 198 | 26 | −349 | 15.5 | 14.5 | 36.0 |
| VTW4 | COLLE_CURINA | 13°13′55.01245″ | 42°48′59.62491″ | 102 | 288 | −769 | 15.5 | 15.0 | 36.0 |
| VTW5 | CASTELLUCCIO_VALLE | 13°12′56.20423″ | 42°49′54.89014″ | 353 | 418 | −707 | 15.0 | 13.5 | 37.5 |

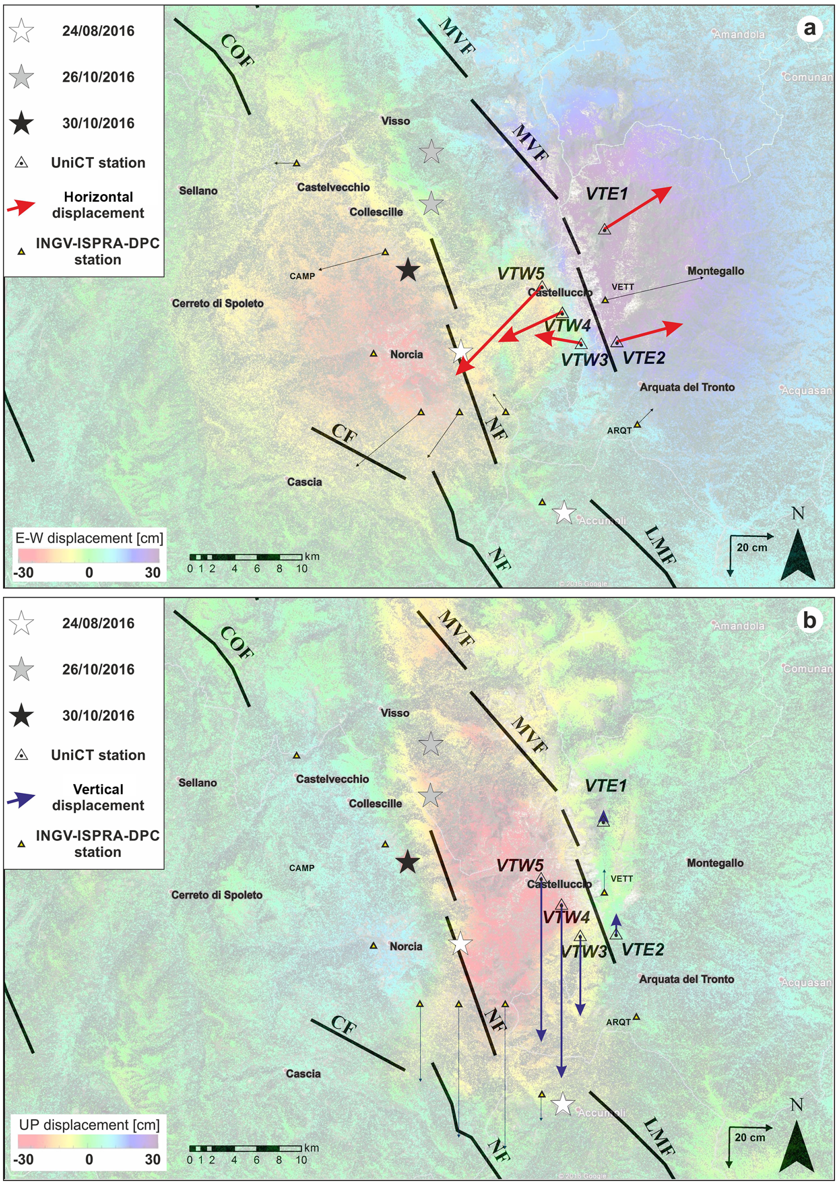


**Figure 5.** Colour-coded maps showing the E–W **(a)** and vertical **(b)** displacement distribution obtained by the DInSAR technique (http://www.irea.cnr.it/index.php?option=com) recorded on 26 October 2016 (pre-event images) and on 1 November 2016 (post-event images). The red and blue arrows represent the consensus pre-, co-, and post-seismic displacements (with 95 % confidence errors) on the basis of the GNSS UNICT network. Epicentres of major shocks are from http://ring.gm.ingv.it.

(Table 1). In particular, the east benchmark VTE1 recorded 312 mm of eastward horizontal displacement and 29 mm of upward motion, while the VTE2 recorded 282 mm of eastward horizontal displacement and 67 mm of upward component of motion. On the contrary, all three western benchmarks recorded westward horizontal displacements (419, 288 and 26 mm) and subsidence (707, 288 and 769 mm) for stations VTW5, VTW4 and VTW3, respectively. In conclusion, we documented ca. 730 mm of ENE–WSW lengthening over a distance of 7 km corresponding to the northern sector of the Mt Vettore fault segment, while the off-fault vertical displacement between the footwall and hanging-wall blocks was 736 mm.

We also compared our results with the displacement distribution obtained by other research groups using DInSAR techniques recorded between 26 October 2016 (pre-event images) and 1 November 2016 (post-event images), and with other GNSS stations that were active before the second seismic event. In Fig. 5 we may observe the overall consistency of the different approaches and data sets.

*Data availability.* The data will not be made available until the completion of the project.

*Competing interests.* The authors declare that they have no conflict of interest.

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