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The Pollino 2011-2012 seismic swarm (southern Italy): first results of the M_L=3.6 aftershock recorded by co-located electromagnetic and seismic stations

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ABSTRACT In the framework of S3 project "Short term earthquake forecasting" supported by Department of Civil Protection (DPC) and National Institute of Geophysics and Volcanology (INGV), a magnetotelluric (MT) station was installed in the Pollino area (southern Italy) during September 2012 by the Institute of Methodologies for Environmental Analysis (IMAA-CNR, Italy) in order to investigate possible correlation between electromagnetic signals and seismicity. For the last two years Pollino area has been characterized by swarm-type seismicity, culminating with the earthquake occurred on October 25, 2012 of magnitude M_W=5.0. After the mainshock, the INGV installed a seismic station close to the MT station. In this paper, we focus the analysis on the largest event (M_L=3.6) recorded during the co-located electromagnetic and seismic experiment. We applied time-frequency misfit criteria based on the continuous Morlet wavelet transform to compare the electric and seismic homologous components: this analysis confirms an overall good waveform similarity between the signals, but also some interesting differences in amplitude for frequencies above 1 Hz in correspondence of the arrival of particular seismic phases that need further investigations.

Key words: electric and magnetic field, electrokinetic effects, earthquakes, time-frequency analysis.

1. Introduction

Over the last two decades, the existence of electromagnetic (EM) signals associated to earthquakes has been worldwide reported (Matsushima *et al.*, 2002; Johnston *et al.*, 2006; Zlotnicki *et al.*, 2006). The connection between the propagating mechanical perturbation within the subsoil and the EM signal is generally complex and, although the increasing number of experimental pieces of evidence, the generating physical mechanism is still unclear. It is generally believed that these signals are due to electrokinetic effects associated with the seismic wave passage in a porous media (with fluids) and/or to the seismic wave crossing the discontinuity induced by subsoil electrical properties (electrical double layer) (Thompson and Gist, 1993; Pride, 1994; Garambois and Dietrich, 2001; Gao and Hu, 2010).

Most of the experimental studies already published on this topic are based on the description of seismo-related EM anomalies related to highly energetic earthquakes occasionally

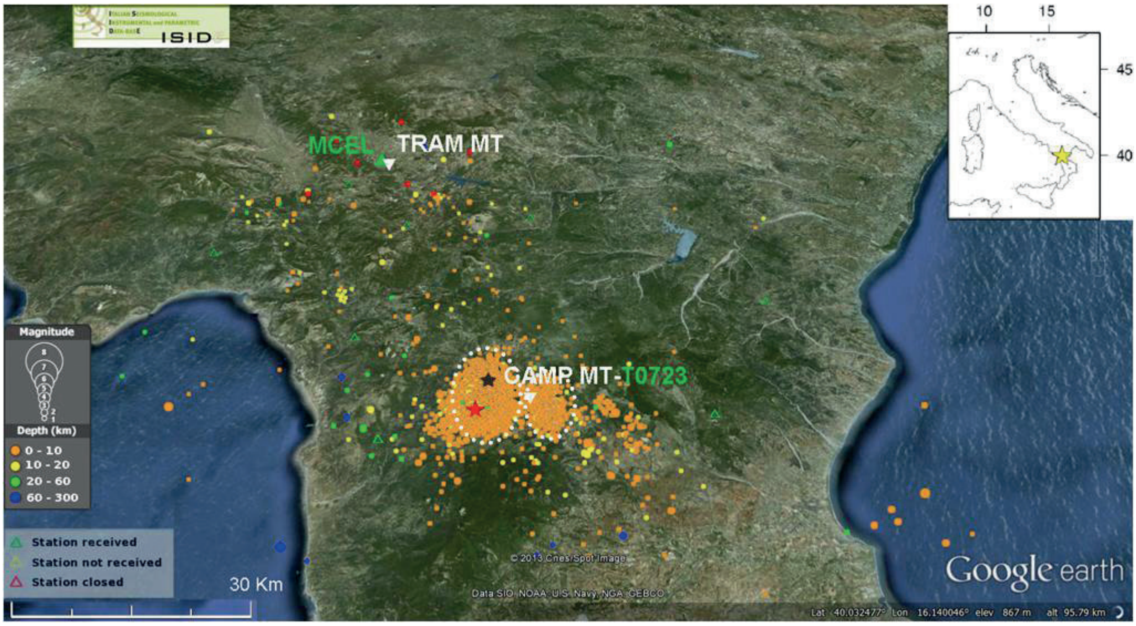

Fig. 1 - Locations of the MT stations (CAMP MT and TRAM MT), of the seismic stations (MCEL and T0723) and distribution of earthquake epicentres (M_L≥0.1) in the Pollino area (southern Italy, Calabro-Lucanian Apennines) from January 2012 to January 2013 within a radius of 50 km around CAMP MT station. Two spatial earthquake clusters are indicated with white dot circles. The red star indicates the epicentre of the mainshock (M_W=5.0, October 25, 2012 at 23:05:24 UTC) while the black star indicates the M_L=3.6 events studied in this work. MCEL and T0723 are the seismic stations managed by INGV, nearest to MT stations.

recorded during magnetotelluric (MT) surveys. There is, hence, a lack of a sufficiently large observational database of co-located EM and seismic data.

In 2011 the seismic swarm occurred in the Pollino area (more than 3600 events in the last two years with local magnitude M_L≥0.1) has given a rare opportunity to study, with a robust observational base, the earthquake-related temporal patterns of EM signals. In Balasco *et al.* (2014), the first results of a continuous EM monitoring are showed. The analysis of the EM time series highlighted the presence of seismo-related anomalies even in correspondence of moderate/small seismic events (M_L≥2.0), well distinguishable from the background signal. The comparison of the features in the anomalies recorded at two different monitoring stations (Fig. 1), the first installed in the focal area (Campotenese, CAMP MT: lat. 39.894° N, lon. 16.085° E, elevation 1487 m) and the second at about 50 km away from it (Tramutola, TRAM MT: lat. 40.297° N, lon. 15.805° E, elevation 890 m), allowed the authors to heuristically define the relationship among earthquake magnitude, hypocentral distance and seismo-related anomaly amplitude. A comparative analysis between the EM time series and the seismogram is necessary for a better understanding of the physical mechanism governing the coupling between seismic and EM phenomena. When the largest seismic event occurred on October 25, 2012 at 23:05:24 UTC, the seismic station closest to CAMP MT station reached saturation; therefore we compared the EM data acquired only by TRAM MT station with the seismic data recorded at the Monticello station (MCEL: lat. 40.3249° N, lon. 15.8019° E, elevation 960 m), which is the nearest seismic station of the National Institute of Geophysics and Volcanology (INGV) to TRAM MT (Balasco *et al.*, 2014).

Despite good similarity exists between the two signals, some questions regarding the existence of possible site effects could not be completely addressed due to the not exact co-location of the TRAM MT and MCEL seismic stations, placed at about 3 km from each other.

During 2012, due to the increase of seismicity, the INGV installed a further temporary seismic network to integrate the permanent one in the Pollino area, and, a few days after the mainshock of M_W=5.0, a temporary seismic station was installed just at the site where the CAMP MT station was operating (T0723: lat. 39.89360° N, lon. 16.08646° E, elevation 1484 m).

In this paper, then, we present the preliminary results of the comparative analysis of co-located seismic and co-seismic EM signals.

2. Investigated area

The investigated area is located in a very complex seismogeological framework represented by the transition zone from the southern Apennines and Calabria, characterized by different tectonic regimes, subduction and extension, respectively.

The Pollino area has been considered as a seismic gap for a long time due to incompleteness of historical catalogues (Rovida *et al*., 2011), although the major faults in this area such as the Castrovillari Fault (Cinti *et al.,* 1997), the Pollino Fault (Michetti *et al.,* 1997), and the Mercure Fault (Papanikolaou and Roberts, 2007) represent a significant seismogenic potential (M=6.5-7.0). Over the last years, the seismic activity in the Pollino area has been very weak. In 2011, the seismicity in the area gradually intensified and a seismic swarm took place. The 2011-2012 earthquake hypocentre depths range between 2 and 10 km approximately (http://iside.rm.ingv.it). Two spatial earthquake clusters are clearly defined: the western and the eastern cluster (Fig. 1). In particular, the former, which comprises most of the seismicity, delineates a NNW-SSE fracture; for the eastern cluster the trend of the seismogenic source is more doubtful. The major event occurred on May 28, 2012 (M_W=4.3) in the eastern cluster and on October 25, 2012 (M_W=5.0) in the western one. The focal mechanisms evaluated for most of the seismic sequence (Totaro *et al*., 2013) show an extensional process with an anti-Apennine trend associated to a normal fault (NW-SE or NNW-SSE).

3. Acquisition setup and data

During September 2012 the CAMP MT station was installed in the Pollino area, where the seismic swarm started in 2010 was very dense. The station is equipped with a receiver MT24LF (Magnetotelluric 24-bit A/D Low Frequency system), two orthogonal induction coils (EMI Schlumberger BF-4) that measure the time-varying magnetic field ($H_{x,NS}$ and $H_{y,EW}$), and two 50 m electrical dipoles to measure the electric field in the surface plane ($E_{x,NS}$ and $E_{y,EW}$). The horizontal coils are buried in 0.5-m deep trenches, while the vertical coil and the Pb-PbCl2 electrodes are placed in 0.5-m deep drilled holes. The frequency of electric and magnetic data recording is set to 6.25 Hz.

The data are recorded in continuous mode and, at the time of writing of this paper, the

CAMP MT station was operative. Through a visual inspection, the EM data measured during earthquake occurrences show a very similar variation to that of the seismograms. These particular features, always well evident in the electric field also for very low magnitude events (M<2.0), led us to investigate in more detail these observations with the contribute of the analogue seismic signals.

In the days following the mainshock occurred on October 25, 2012, the INGV installed 5 seismic stations in stand-alone configuration with 6 channels (a tri-axial short-period velocimeter and an accelerometer). Moreover, the GeoForschungsZentrum (GFZ, Potsdam) also installed in the area of the seismic swarm a temporary seismic network with 10 seismic stations: 3 broad-band (STS2.5 Streckeisen), 5 short-period (Mark L4C-3D), and 2 accelerometric stations. In particular, one of the INGV seismic stations (T0723 station) was installed in the same site of our CAMP MT station. The T0723 station is still operating and is equipped with a LE 3D Lite Lennartz velocimeter, an Episensor FBA-ES-T Kinemetrics accelerometer, and a REF TEK 130-1 data logger. The sampling frequency of the seismic receiver is 125 Hz; solar panels and batteries provide power supply. At the present time only the velocimeter data are available to us.

4. Results and discussion

After the installation of the seismic station T0723 (on October 26, 2012) in the same site of CAMP MT, on November 25, 2012 at 08:28:39UTC the event of magnitude M_L=3.6 occurred (lat. 39.921°N, lon. 16.027°E, depth 7.5 km). This circumstance was a unique opportunity to check on similarities and/or differences between seismic and EM signals. In fact, the distance between the MT and the seismic station was only 9.6 km and, furthermore, the recordings of the event at both stations were clearly visible.

At a first sight, the MT electric and magnetic fields showed variations very similar to that of the seismic waveform. Fig. 2 shows the comparison along the N-S and E-W directions among the seismic waveform (Vel NS, Vel EW) measured by the T0723 station, and the electric (E_x, E_y) and magnetic (H_x, H_y) fields measured by the CAMP MT station. The seismic traces were deconvolved by the instrumental response and re-sampled with the same sampling rate of the MT station (6.25 Hz). In Fig. 2, it is possible to observe that the duration of the EM signals is consistent with the duration of the seismic wavefield. Like for the other earthquakes of the Pollino swarm with M_L≥2.0 (Balasco *et al.*, 2014), the components of the electric field appear more sensitive to the passage of the seismic wave than those of the magnetic field. The first S-wave arrival of the seismic wavefield is well evident also in the EM signals; however, the electric field signal (E_x, E_y) seems to precede the first P-wave arrival. Following Balasco *et al*. (2014), we quantitatively compared the seismic and EM recordings by using the globally-normalized time-frequency misfit criteria based on the continuous Morlet wavelet transform, which was developed by Kristekova *et al*. (2009). In particular, the misfit is expressed in percentage values and the goodness of fit is discretized with an increasing level of agreement from 0 (poor) to 10 (excellent). Before applying the time-frequency misfit and goodness-of-fit criteria we normalized the series.

The results of our analysis confirm the overall similarity among signals both in time and

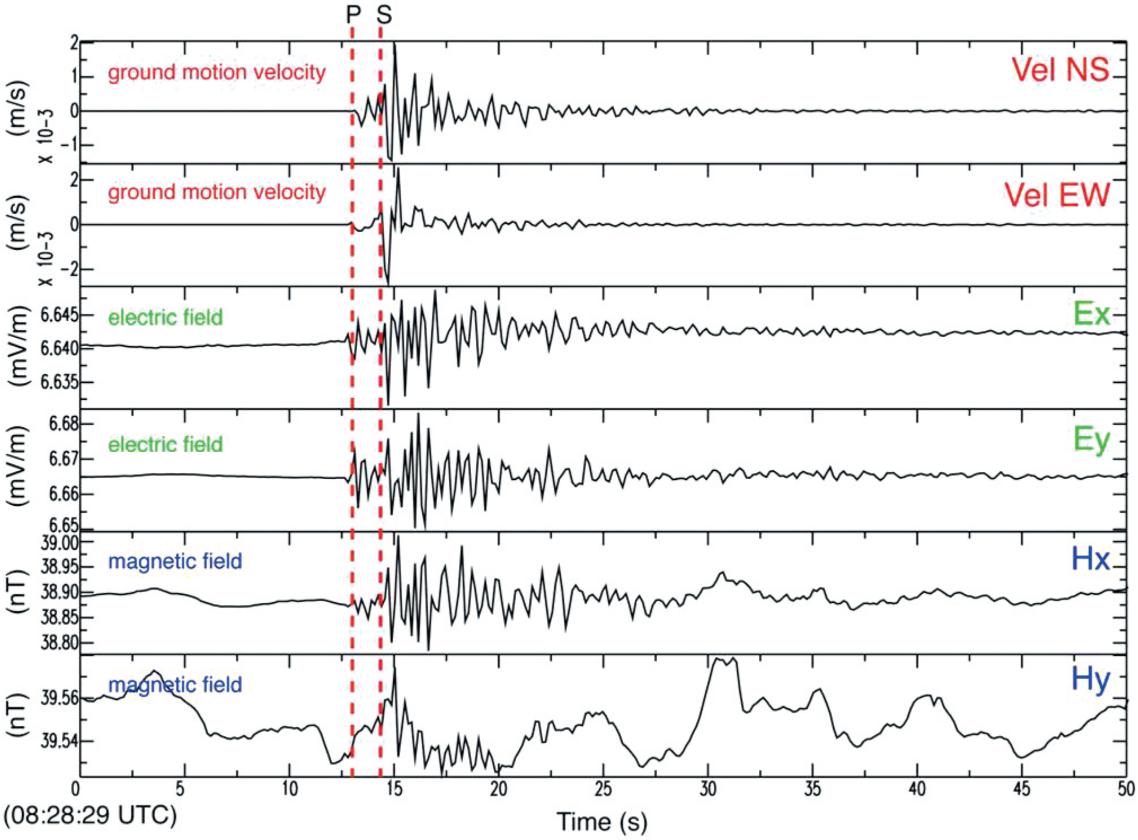

Fig. 2 - Comparison between the N-S and E-W components of the ground motion velocity, recorded by the seismic station T0723, and the electric (E_x, E_y) and magnetic (H_x, H_y) fields, recorded by the CAMP MT station. P- and S-wave arrival times of the seismic wavefield are indicated with vertical red dashed lines.

frequency. Fig. 3 shows the time-frequency envelope misfit (TFEM) and the time-frequency envelope goodness of fit (TFEG) evaluated: i) between E_x and the N-S component of the seismogram (left panels), ii) and between E_y and the E-W component of the seismogram (right panels). It is possible to observe that along both directions the discrete goodness-of-fit values (for details, see Kristekova *et al.*, 2009) are generally excellent or good, with misfits below 60%.

The main differences are observed just after the time of the first S-wave arrival (T1 of Fig. 3), where the largest amplitudes of the seismic wavefield occur. In particular, between T1 and T2 (where T2 is about 2.5 s after T1) the amplitude of the seismic wavefield is larger than the electric fields above 1 Hz (Fig. 3), determining the consequent negative envelope misfit (blue colours in the TFEM panels). On the other hand, in the same frequency range, the largest amplitudes of the electric field are distributed over a larger period of time with respect to the seismic wavefield, and then positive envelope misfit is observed after T2 (red colours in the TFEM panels). Furthermore, it should be noted that the TFEM of the N-S signals is characterized by a better goodness of fit than the E-W ones, whose TFEM indicates that the spectral content of E_y in correspondence of S-wave is shifted to higher frequency regard to the ground motion.

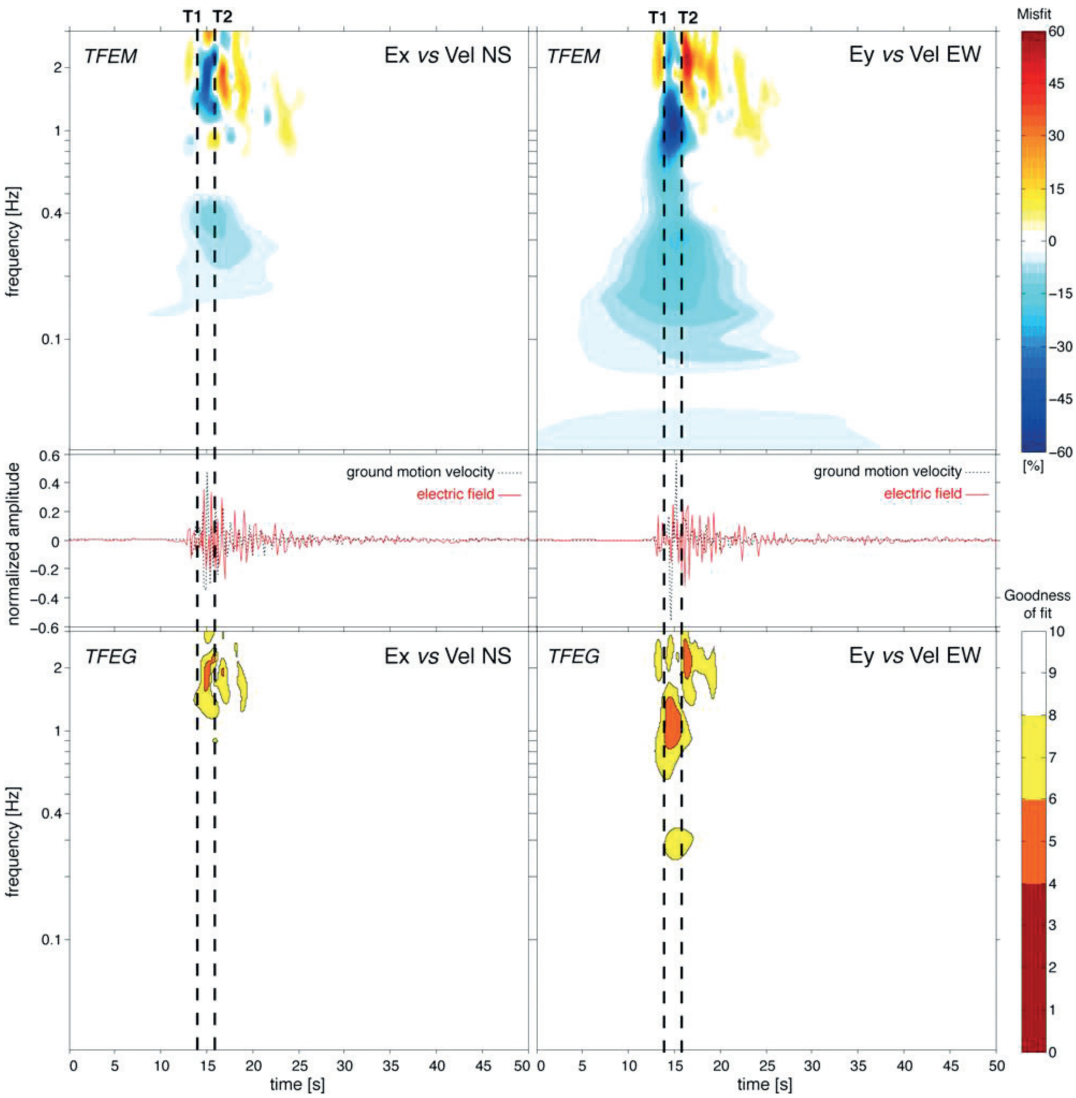

Fig. 3 - Time-frequency envelope misfit (TFEM, top panels) and time-frequency envelope goodness-of-fit (TFEG, bottom panels) between the electric field (E_x, E_y) and the ground motion velocity (Vel NS, Vel EW) recorded at the same site by the MT station and the seismic station, respectively. EM and seismic traces are also synchronized and the begin time corresponds to 08:28:29 UTC of November 25, 2012. The period of time between T1 and T2 is the window inside which negative misfit at frequencies above 1 Hz is observed.

5. Conclusion

Few days after the mainshock of M_W=5.0 (October 25, 2012), a temporary seismic station was installed in the same site of the CAMP MT station. The possibility of comparing co-located seismic and EM time series allowed to address some of the still open questions related to the nature and the characteristics of the EM seismo-related signals. The study presented in this paper analyse in details the findings of Balasco *et al*. (2014) where the mainshock was analyzed.

Several peculiar characteristic features are observed in the analysis of the mainshock M_W=5.0 and of the M_L=3.6 event occurred on November 25, 2012. In both these events, using the globally-normalized time-frequency misfit criteria to search for similarities between the seismic traces and the related seismo-electro anomalies, the main differences between the electric and the seismic response are visible after the arrival of the first S-wave, when the EM signal has generally a higher frequency content than that of the seismic signal for frequencies above 1 Hz, with exception for the period between T1 and T2 of Fig. 3. Considering the co-location of the seismic and MT stations such differences cannot be ascribed to local site effects and thus confirm the hypothesis of the proportionality of the electrical field with the acceleration of the seismic wave, as it is expected during coseismic effects (Mahardika *et al.,* 2012).

Regarding the arrival time, it seems to be confirmed the earlier arrival of the EM fluctuation respect to the seismic signal (the first P-wave arrival). This last point requires a deeper investigation based on the analysis of all the collected events of the swarm using a higher sampling frequency of EM field. Furthermore, it would be desirable the installation of a multi-parametric network (seismic and electromagnetic) also to investigate the propagation-related phenomena (i.e., attenuation).

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