



# Local changes in the total electron content immediately before the 2009 Abruzzo earthquake

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## Abstract

Ionospheric TEC (total electron content) variations derived from GPS measurements recorded at 7 GPS stations in Northern, Central and Southern Italy before and after the 2009 Abruzzo earthquake (EQ) of magnitude  $M_w 6.3$  were processed and analyzed. The analysis included interpolated and non-interpolated TEC data. Variations in the TEC of both regional and local characteristics were revealed. Several regional changes were observed in the studied period: 1 January–21 April 2009. After analyzing non-interpolated TEC data of 5 GPS stations in Central Italy (*Unpg* (Perugia), *Untr* (Terni), *Aqui* (Aquila), *M0se* (Rome) and *Paca* (Palma Campania, (Naples))), a local disturbance of TEC was also found. This local TEC disturbance arises preparatory to the EQ main shock occurred at 01:32 UT on 06 April 2009, maximizes its amplitude of  $\sim 0.8$  TECu after the shock moment and disappears after it. The local TEC disturbance was confined at heights below 160 km, i.e. in the lower ionosphere.

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## 1. Introduction

Electromagnetic perturbations due to seismic activity have been known for a long time (Milne, 1890). Variations in ionospheric parameters above seismically active regions are one of the most actual aspects of these perturbations. Since the pioneering investigations devoted to the ionospheric effects caused by the powerful Alaska earthquake occurred on March 28, 1964 ( $M = 9.2$ ), extensive research of seismic-related anomalous effects in different ionospheric parameters has been carried out for a few decades (Davies and Baker 1965; Leonard and Barnes 1965; Datchenko et al. 1972; Larkina et al. 1983; Gokhberg et al. 1983;

Parrot and Mogilevsky 1989; Hayakawa 1999; Hayakawa and Molchanov 2002; Strakhov and Liperovsky 1999; Pulinets and Boyarchuk 2004). Among all the ionospheric parameters being sensitive to strong earthquakes (EQs) the ones of the F2 region and the total electron content (TEC) are those for which the earthquake induced variations are studied the most. Variations in the F2 region parameters have been frequently revealed a few days before strong EQs by means of ground-based vertical sounding (Gokhberg et al. 1988; Gaivoronskaya and Zelenova 1991; Pulinets 1998; Ondoh 1998, 2000; Liu et al. 2000; Silina et al. 2001; Rios et al. 2004). A decrease of the critical frequency of the F2 layer ( $f_oF2$ ) from its monthly median at single ionosonde station Wakkanai was observed within  $\pm 3$  days around the strong EQ with  $M = 7.8$  in Japan (Ondoh, 1998, 2000). Decreases of  $f_oF2$  observed one,

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three, and four days before the main shock of the powerful Chi–Chi EQ at single ionospheric station in Taiwan ( $M = 8.2$ ) also have been recorded by Liu et al. (2000). They have found that the corresponding electron density decrease is about 51% from its normal value obtained from 15-day median process. Very close similarities in most parameters describing the precursory anomalies (leading time, sign of  $f_oF2$  and value of electron density depletion, duration of each anomaly, and time period in LT) have been considered by Hobara and Parrot (2005). Simultaneous records from 60 different ionospheric stations have enabled Hobara and Parrot (2005) to separate the global events from the local ones, and to find that the Hachinohe EQ event ( $M = 8.3$ ) was characterized by an  $f_oF2$  decrease of 3 MHz 4 days before and 2 days after the EQ. This  $f_oF2$  decrease maximizes in the afternoon (15:00 LT) hours. Statistical analyses have been also conducted by Liu et al., 2006 on possible relationships between the  $f_oF2$  effects and 184 EQs with  $M > 5.0$  occurring during years 1994–1999 in the Taiwan area. They have revealed that the effect of  $f_oF2$  decrease (more than 25% lower than the median reference curve) takes place in the afternoon time and within 5 days before the EQ. Moreover, they have also found that this effect increases with the EQ magnitude, decreases with the distance of the ionospheric station from the epicenter (only stations within a distance of 150 km from the epicenter can show this EQ induced variations), and that only the  $M > 5.4$  EQs have a significant chance to cause such an  $f_oF2$  decrease.

Statistical analyses on ionospheric changes prior to strong EQs show that abnormal TEC disturbances occur around the epicentral area (of hundreds and even thousand km) several days before the occurrence of EQs (Liu et al., 2000, 2001, 2004). It is not surprising that the vertical TEC obtained using GPS (dual frequency measurements) is also very sensitive to changes in the  $f_oF2$  electron density measured by ionosondes. According to Houminer and Soicher (1996) the correlation between TEC and  $f_oF2$  can reach the value of 0.9. In that way, the anomalous ionosphere modification before some strong EQs has been found using GPS TEC measurements in the recent years (Calais and Minster 1995; Liu et al. 2002, 2004; Plotkin 2003; Pulinets et al. 2005; Krankowski et al. 2006; Zakharenkova et al. 2006, 2007a,b; Ouzounov et al. (2011)). Results from TEC measurement around Chi–Chi earthquake by Liu et al. (2001) showed severe depletion of TEC around the epicenter (with a radius of 100–200 km) some days before the EQ. A 15-day running median of the TEC and the associated inter-quartile range have been utilized as a reference for identifying abnormal TEC signals during 20  $M \geq 6.0$  EQs in the Taiwan area from September 1999 to December 2002 (Liu et al., 2000, 2004). Their results show that the pre-earthquake TEC anomalies appear during 18:00–22:00 LT within 5 days prior to 16 of all the 20  $M \geq 6.0$  considered EQs. The study performed by Pulinets et al. (2001) for several seismic events located at various latitudes show instead either a

localized enhancement or a decrease of electron density with a spatial extent of about  $20^\circ$  in latitude and longitude. One day before the Kythira (Southern Greece) EQ occurred on 8 January 2006, a significant increase of TEC at the nearest stations, up to values 50% greater than the background condition, in the time interval between 10:00 and 22:00 UT has been recorded. The area of this significant TEC enhancement had a size of about 4000 km in longitude and 1500 km in latitude (Zakharenkova et al., 2007a). Seismo-ionospheric anomalies in GPS TEC over European and Japan regions have been analyzed by Zakharenkova et al. (2007b) and let them conclude that the occurrence of such variations may be registered in Europe 1–2 days before the EQs, while for very strong Japanese EQs this temporal interval can reach 5 days.

Recent analyses of ionosonde and/or TEC observations around strong earthquakes that have recently occurred at Wenchuan (12.05.2008), Haiti (12.01.2010) and Tohoku (11.03.2011) confirmed the appearance of large-scale TEC variations centered close to the earthquake epicenters (Zhao et al., 2008; Liu et al., 2009, 2011; Xu et al., 2010, 2011; Akhoondzadeh and Saradjian, 2011; He et al., 2012; Le et al., 2013).

On 9 May, 2008 (a geomagnetic quiet day,  $K_p \leq 2$ ), 3 days prior to the Wenchuan earthquake the averaged value of the maximum ionospheric electron density at F2 peak ( $N_mF2$ ), measured by two Chinese ionosondes close to the EQ epicenter, was about 2 times higher than the median value (Zhao et al., 2008). This finding (positive increase of F2 region electron density on 9 May) was verified later by Xu et al. (2010) using hourly values of  $f_oF2$  from ten ionosondes' measurements. Furthermore, using Global Ionospheric Map (GIM), Liu et al. (2009) have found that TEC above the Wenchuan EQ epicenter anomalously decreased in the afternoon of days 6–4 and in the late evening of day 3 before the earthquake, but increased in the afternoon of day 3 before the earthquake. These results were supplemented by F3/C satellite data that showed that the ionospheric F2 peak electron density  $N_mF2$ , and height  $h_mF2$ , decreased approximately 40% and descended about 50–80 km, respectively (Liu et al., 2009). These findings indicate a sequence of TEC reductions (lasting several days) and an enhancement of TEC (in the afternoon hours of day 3) prior to the Wenchuan earthquake. Xu et al. (2011) have tried to model analytically the quasistatic electric field, one of the most reasonable mechanism of generation of seismo-ionospheric variations. Based on five out of ten ionosonde measurements, the authors succeeded in quantifying the quasistatic electric field magnitude as 2 mV/m, that is one order higher than the background electric field values.

TEC enhancements over the epicenter were also observed on 11 January 2010, a day prior to the Haiti earthquake (Liu et al., 2011). Applying three methods (interquartile method, wavelet transformation and Kalman filter), Akhoondzadeh and Saradjian (2011) have detected a considerable number of anomalous TEC occurrences with

a time resolution of two hours during the 15 days prior to the earthquakes occurred at Samoa (2009) and Haiti (2010) in a period of low geomagnetic activity. The authors underlined how the TEC anomalies were highly related to impending earthquakes.

When earthquakes occurred during periods of high solar activity and/or geomagnetic activity (e.g. Tohoku EQ), ionospheric anomalies were also detected (Ouzounov et al., 2011; He et al., 2012; Le et al., 2013). After removing the influence of solar radiation origin in GIM TEC, the analysis results showed that TEC around the Tohoku epicenter increased in the afternoon on 8 March 2011, 3 days before the earthquake (He et al., 2012). Le et al. (2013) have also shown that only the solar radiation enhancement is not enough to produce the observed TEC enhancement on 8 March, i.e. the observed TEC enhancement might be related to a combined effect of the earthquake preparation process and geomagnetic activity occurred on 7 March 2011.

Another form of enhancement of ionospheric TEC immediately before the 2011 Tohoku-oki earthquake ( $M_w$ 9) has been reported by Heki (2011). The TEC enhancement emerges  $\sim 40$  min before the main shock. Heki and Enomoto (2013) have scrutinized the nature of characteristics of the TEC change preceding the 2011  $M_w$ 9 Tohoku earthquake. The authors first have confirmed the reality of the enhancement using also ionosonde and magnetometer data. The amplitude of the preseismic TEC enhancement is within the natural variability, and its snapshot resembles to large-scale traveling ionospheric disturbances. The authors have shown that similar TEC anomalies occurred before all the  $M \geq 8.5$  earthquakes happened in this century, suggesting their seismic origin (Heki and Enomoto, 2013).

In this paper using data from 5 GPS stations in Central Italy and some other stations in Northern and Southern Italy we thoroughly analyze both temporal and spatial characteristics of ionospheric TEC variations in association with the 2009 Abruzzo earthquake. We pay attention on TEC changes around the main EQ shock occurred on 6 April 2009. We will differentiate regional changes from local ones and then compare the observed local TEC changes with the recent Heki's findings.

## 2. Data and analysis

The very destructive Abruzzo earthquake occurred close to L'Aquila on April 06, 2009, at 01:32 UT; the latitude and longitude of the epicenter were 42.33N and 13.33E, respectively, and the corresponding magnitude equal to  $M_w = 6.3$  ( $M_L = 5.8$ ). This earthquake was classified by the Istituto Nazionale di Geofisica e Vulcanologia as an  $M_L = 5.8$  event, with a depth of 8.8 km. It was preceded by a persistent seismic activity for approximately three months: namely, between January 16 and April 5, 2009, 34 seismic events with  $2 < M_L < 3$ , and 9 with  $M_L > 3$  were registered in the territory (Fig. 1). The strongest event was

followed by a large numbers of aftershocks with remarkable events on April 7, 17:47 UT ( $M_L = 5.3$ ) and on April 9, 00:52 UT ( $M_L = 5.1$ ) (Fig. 2).

GPS system consists of more than 24 satellites, distributed in 6 orbits around the Earth at an altitude of  $\sim 20,000$  km. Each satellite transmits dual very high frequencies of signals, 1575.42 and 1227.60 MHz. Ionospheric TEC can be computed on the basis of phase delay between Global Positioning System (GPS) station's dual frequencies while electromagnetic wave propagates through ionosphere. The slant TEC (STEC), i.e. the integral of the electron density over a line of sight from a ground receiver to a satellite on the signal propagation path, can be estimated from the standard GPS observations (pseudo-range and phase), relative to the two available carriers  $f_1$  (1575.42 MHz) and  $f_2$  (1227.60 MHz). This is done forming the differential delays of the pseudo-ranges (directly) and phases (transformed into optical paths  $L_1$  and  $L_2$ ) relative to the two carriers. Properly combining the code and phase differential delays one gets the STEC between a GPS satellite and a ground based dual-frequency receiver, which can be written as

$$\text{STEC} = a[f_1^2 f_2^2 / (f_1^2 - f_2^2)] [(L_1 - L_2) - (\beta_r + \beta_s) - \mu_{Arc}] \quad (1)$$

where  $a = 1/40.3$ ,  $\beta_r + \beta_s$  are the differential hardware biases for receiver and satellite, respectively and  $\mu_{Arc}$  an additional term, variable from arc to arc, depending on the way the receiver processes the pseudo-range. For the data used in present work, a calibration technique estimated, cumulatively, the hardware biases plus the term  $\mu$  for each arc. It is worth noting that the presence of gaps in the data may severely affect the calibration. Unfortunately, recording of TEC data from the *Aqui* (L'Aquila) station (the closest to the earthquake epicenter) was interrupted around the EQ shock, and this unfortunately constrained us to neglect these data. Another caution comes from the fact that each satellite-receiver pair has a different measurement bias, therefore only their temporal changes are meaningful and analyzed further.

The STEC can be converted to vertical TEC (VTEC), which is the projection of oblique TEC on the thin-shell, using an elevation mapping function (Dautermann et al., 2007). The location of a recorded VTEC is defined as the intercept of the ray path of the GPS signal and the ionosphere modeled as a thin shell at a height of 400 km. This intercept is named as: ionospheric pierce point (IPP). The VTECs can be interpolated in order to estimate the vertical TEC in locations different from the IPP's, in particular along the vertical over the TEC GPS station. Further in the text, only VTEC is analyzed and hence, the standard acronym TEC is used for VTEC.

Time resolution of the set of interpolated TEC data we use is 5 min, i.e. 288 values per day for each TEC station. GPS data from January 1 to April 21, 2009 are processed and then corresponding TEC time series are obtained. These time series are given in TEC units (TECu), where  $1 \text{ TECu} = 10^{16}$  electrons/m<sup>2</sup>. Because of satellite and

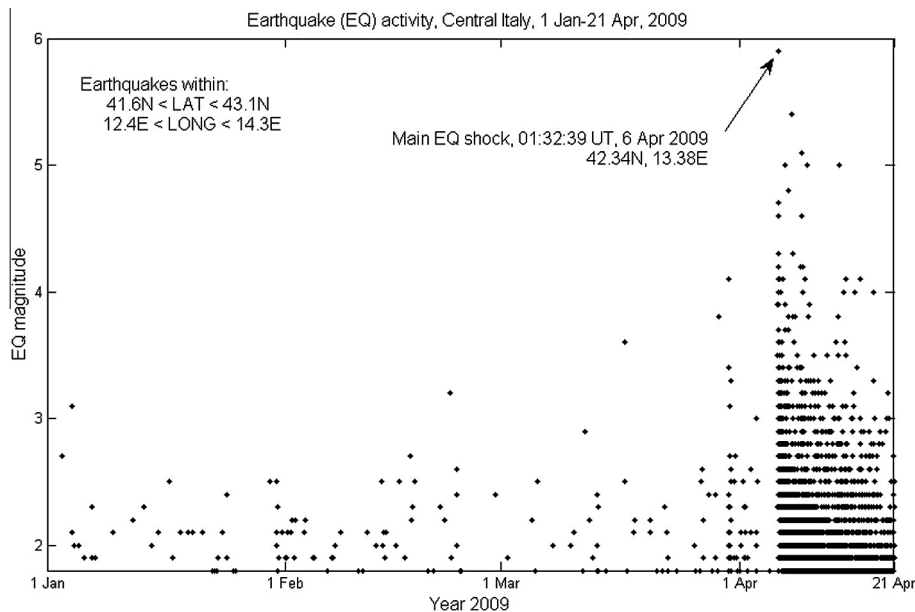


Fig. 1. Earthquake activity in Central Italy during the period 1 January–21 April 2009. 34 seismic events with  $2 < M_L < 3$  (and 9 with  $M_L > 3$ ) were registered in the territory.

### 2.1. Interpolated TEC data

In statistics, envelope method is mostly used to identify possible significance of disturbances. Under the assumption of normal distribution with mean  $\mu$  and standard deviation  $\sigma$  of TECs and if an inter-quartile range is assumed (e.g. Liu et al., 2004), the expected values of upper bound and lower bound of envelope are  $\mu \pm 1.34\sigma$ . If the observed TEC falls out of either the associated lower or upper bounds of such an envelope, it is declared at confidence level of about 82% that a lower or upper abnormal signal is detected. Li et al. (2009) have used bounds  $\mu \pm 2\sigma$ , and for that case the confidence level is equal to 95%. Thus, upper and lower bounds of TEC variations can be determined at different confidence levels. The mean for a sliding window, which is 4 days long, is assumed as background TEC. Interpolated TEC variations and corresponding upper and lower bounds fixed at  $\mu \pm 1.34\sigma$  were inspected for 5 TEC stations, *Unpg* (43.1N, 12.4E), *Untr* (42.6N, 12.7E), *Aqui* (42.4N, 13.4E), *M0se* (41.9N, 12.5E) and *Paca* (40.9N, 14.6E). For convenience only the interval 1 April–7 April 2009 is illustrated (Fig. 3). The four TEC stations: *Unpg*, *Untr*, *M0se* and *Paca*, are the closest ones to the EQ epicenter, with distances respectively of  $\sim 110$ ,  $\sim 60$ ,  $\sim 90$  and  $\sim 180$  km from L’Aquila (Fig. 2). The actual TEC variations (in TECu) of each TEC GPS station are in blue, while the upper and lower bounds are marked respectively with red and green lines. From Fig. 3 it is possible to see that there are two moments when the TEC value is below the  $\mu - 1.34\sigma$  value (on 1–2 April) or exceeds  $\mu + 1.34\sigma$  (on 5–6 April). Inspecting the TEC variations (not shown) for the whole interval, 04 January–21 April 2009, one can see that there are a lot of time intervals on which the TEC values are definitely above the upper bound of  $\mu + 1.34\sigma$  for all 5 stations (such events are noticed on



Fig. 2. Map of GPS stations (black triangles) located in Italy. Encircled are stations *Unpg*, *Untr*, *Aqui*, *M0se* and *Paca*. Red circles highlight the epicenters of earthquakes (EQs) of magnitude  $M > 4$  occurred in Central Italy for the period 01 January–30 April 2009. Green circle denotes the epicenter of the main EQ shock occurred on 6 April 2009. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

receiver biases,  $\beta_s$  and  $\beta_r$ , and  $\mu$ , the calculated interpolated TEC data from different satellites can differ and the TEC difference can reach 1–2 TECu. For non-interpolated TEC data only temporal changes are meaningful and hence taken into account.



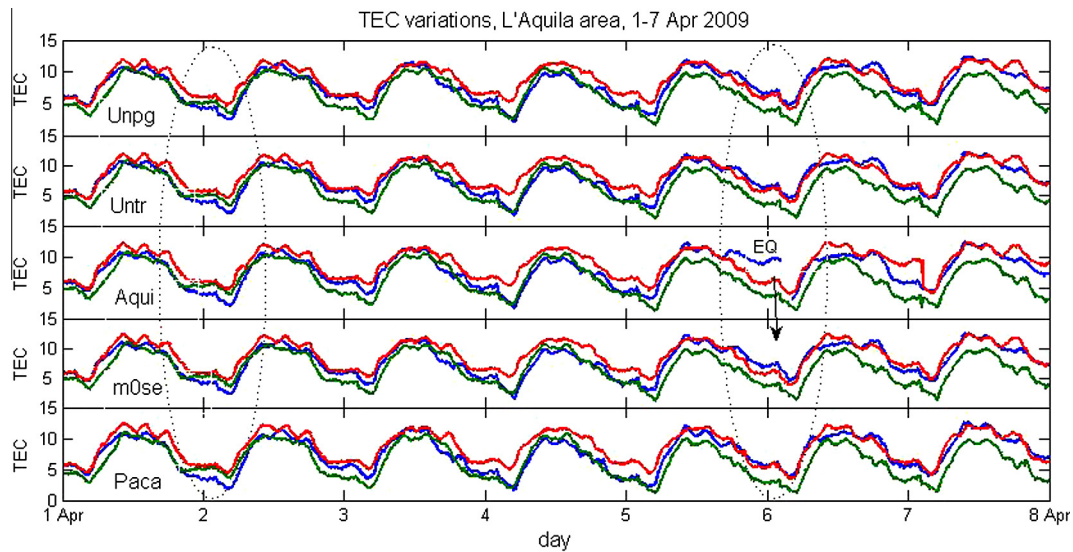


Fig. 3. Interpolated TEC variations (blue) and corresponding upper (red) and lower (green) bounds fixed at  $\mu \pm 1.34\sigma$  are depicted for 5 TEC stations: *Unpg* (43.1N, 12.4E), *Untr* (42.6N, 12.7E), *Aqui* (42.4N, 13.4E), *M0se* (41.9N, 12.5E) and *Paca* (40.9N, 14.6E). The arrow marks the EQ shock moment (01:32 UT) of the Abruzzo earthquake (EQ) occurred on 6 April 2009. The dashed oval on the left indicates the nighttime TEC decrease (well below  $\mu - 1.34\sigma$ ) on 1–2 April 2009 at all five stations. The dashed oval on the right (around the EQ shock moment) indicates: (i) an artificial deviation of interpolated TEC values around the EQ shock moment at station *Aqui* due to data gap; (ii) an anomalous increase of interpolated TEC values at *Unpg*, *Untr*, *M0se* and *Paca* above the upper bounds. It is visible that the data gap at *Aqui* starts on late 5 April and continues on early 6 April and therefore the TEC data at station *Aqui* on days 5–6 April are considered as not reliable and omitted in our analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

24 January; 1–2, 14, 21–22 and 27 February; 8–9, 21 and 24 March; and 9 April 2009 implying that positive anomaly variations occurred in these time intervals). Variations at one TEC station only have also been observed: (i) on 9 January at station *M0se* (close to Rome), (ii) on 12 January at *Unpg*, and (iii) on 5 April at L'Aquila. TEC spikes on 09 and 12 January are false signals due to data gaps. An extreme anomalous TEC disturbance of 3 TECu is recorded on 5 April only at L'Aquila. Its duration is at least 11–12 h.

Looking at these TEC interpolated data (Fig. 3) two kinds of TEC disturbances were discriminated: (i) TEC disturbances of regional character that appear simultaneously at all TEC GPS stations in the L'Aquila area; and (ii) disturbances of local character that emerge at only one TEC GPS station. The causes of disturbances of the first class need to be sought in various regional and/or global factors, such as solar/geomagnetic activity meteorological/lightning activity, which can significantly contribute to ionosphere TEC variations. For the 1 January–21 April 2009 the geomagnetic conditions were pretty quiet with values of the geomagnetic index  $K_p$  lower than 2 but, nonetheless, TEC variations due to global and/or regional factors are however present.

Fig. 4 illustrates interpolated TEC data from 31 March to 10 April 2009 at L'Aquila area and shows that regional TEC data are by and large coincident except for an interval of increased dispersion on 3–6 April 2009. The geomagnetic activity for the whole period was extremely low ( $K_p < 3$ ); hence, this unusual scattering is not associated with the geomagnetic activity.

An operation failure of the GPS receiver at L'Aquila (*Aqui* station) however occurred at 02:25 UT on the EQ day (6 April 2009) – 53 min after the EQ shock moment. Because of TEC data interruption around the EQ shock moment and subsequent data calibration problems, changes of TEC recorded at L'Aquila station (42.4N, 13.4E) were clearly detached from the TEC trends observed at the other TEC GPS stations in the L'Aquila area; thus TEC changes from *Aqui* around the EQ shock were considered as fictitious and hence, will not be considered further.

In order to find local meaningful changes of TEC in time, regular changes in the TEC (diurnal ones) should be removed. The following quantity is then introduced:

$$DTEC = (\text{TEC}(i, j) - \mu(\text{TEC}(k, j))) / \sigma(\text{TEC}(k, j)), \quad (2)$$

$$i - 5 \leq k \leq i - 1$$

where  $\text{TEC}(i, j)$  represents the TEC value function of the day ( $i$ ) and minute ( $j = 1$  to 288);  $\mu(\text{TEC})$  and  $\sigma(\text{TEC})$  denote respectively the mean value and the standard variation calculated over the previous 5 days,  $i - 5$  to  $i - 1$ . Our choice corresponds to a 5-day running mean, which is enough to remove the variations larger than 5 days. It is worth noting that such a choice is dictated by the 5 min resolution of TEC data. The diurnal TEC variations are strongly dependent on and move forth/back with the sunrise/sunset time. The difference  $\text{TEC}(i, j) - \mu(\text{TEC}(k, j))$  thus represents the TEC signal to be investigated for its possible relationship with earthquake activity. In (2) it is evaluated by comparison with the corresponding natural/observational TEC noises represented by  $\sigma(\text{TEC}(k, j))$ ,

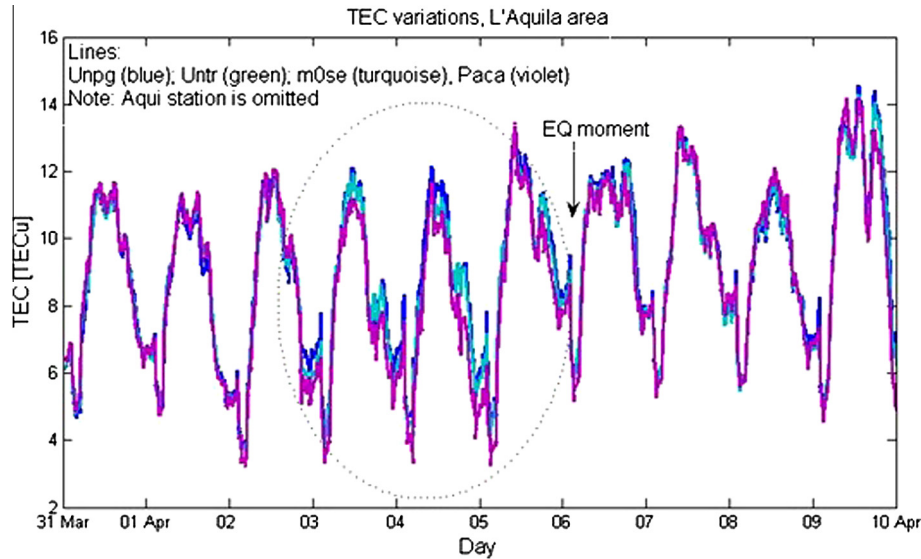


Fig. 4. TEC daily curves in Central Italy for 31 March–10 April 2009. Note a good coincidence of all TEC trends for two intervals, before 3 April and after 6 April. A scattering of TEC data starts on late 2 April and continues on 3–6 April both in night and day hours. This scattering effect is highlighted by the dashed oval.

which describes the overall (local) variability of the signal including all sources of its variability, observed at daytime moment  $j$  in similar observational conditions occurred on previous  $k$  days. In this way, the measured TEC signal can be quantified in terms of signal to noise (S/N) ratio. DTEC (2) is henceforth called *TEC index* (or TECi). Calculation of DTEC variations according to (2) means that we consider the TEC variations as signals of Gaussian distribution. For standard Gaussian distributions of signal the mean of DTEC should be zero. If an anomalous signal however exists in the time series, it is expected to emerge clearly detached from the Gaussian distribution. Consequently the mean of such a signal should be away from zero. For theoretical foundation of signal detection problems we refer to the Neyman–Pearson test of statistical hypotheses (see Neyman and Pearson, 1933).

Further, daily TEC indices can be calculated. It is performed by averaging over the all 288 TEC index values per day. Applying daily TEC index (mean of (2)) we are thus able to discriminate possible anomalous signal from TEC data series. The determined daily TEC index (TECi) variations for the four stations in the L'Aquila (*Unpg*, *Untr*, *M0se*, *Paca*) area are disposed for the period 01 January–21 April 2009 (Fig. 5). The mean (MEAN) and standard deviation (STD) are determined and, of course, different for each station (*Unpg*, *Untr*, *M0se* and *Paca*). In seeking anomalous signals it is assumed that such signals should exceed the MAX value of all 4 MEANs + 2 \* MAX of all 4 STDs, i.e.  $\max(\text{mean}(\text{TECi})) + 2 * \max(\text{std}(\text{TECi}))$ , and inversely, to be lower than  $\min(\text{mean}(\text{TECi})) - 2 * \max(\text{std}(\text{TECi}))$ . This condition appears more restrictive if compared to one station measurements. One sees that the daily TEC indices behave similarly and present several coinciding extremes for all 4 TEC GPS stations indicating TEC anomalies of

regional type. In the studied period such events appear at least on 1–2 February, 19–20 March and 5–6 April 2009.

In particular, on 5 April 2009 a distinct (regional) increase of TEC density covers all latitudes from *Tori* (Torino) to *Cagl* (Cagliari) at least (over 5° in latitude) (Fig. 6).

## 2.2. Non-interpolated data

Interpolated TEC data do not help to identify TEC disturbance of local extent. The main reason is that the IPPs from one GPS station are widely distributed and are inter-mixed with the IPPs of other GPS stations. Therefore actual (non-interpolated) GPS TEC data with sampling frequency of 30 s from each GPS satellite are also examined. Non-interpolated TEC data are obtained from all satellites with a minimum elevation angle EL of around 10°. In our analysis we exploit TEC data of satellites with  $\text{EL} \geq 67^\circ$ . Of course, during the course of the day different satellites appear at a given GPS receiver and corresponding TEC data collected from each satellite with  $\text{EL} \geq 67^\circ$  are of short duration (several tens of minutes and less). Fig. 7 sketches sample elevation angle, azimuth angle and TEC changes over ~6 h period observed at *Aqui* station with the satellite #8 on 5 April 2009. In addition, TEC data from satellite #8 at *Untr* are overlapped on those recorded at *Aqui*. The TEC shows gentle curvatures due to satellite elevation changes. The TEC trends at *Aqui* and *Untr* ( $\approx 55$  km distance between them) are practically coincident.

Fig. 8 represents pierce points (IPP) of GPS satellites referred to *Untr* (in black) and *Aqui* (in blue) stations. The EQ epicenter is marked by a red star. The pierce points on 6 April are calculated for elevation angles exceeding 83°, so pieces of GPS satellite trajectories projected/mapped as pierce points at 400 km height, are sketched. A crossing of

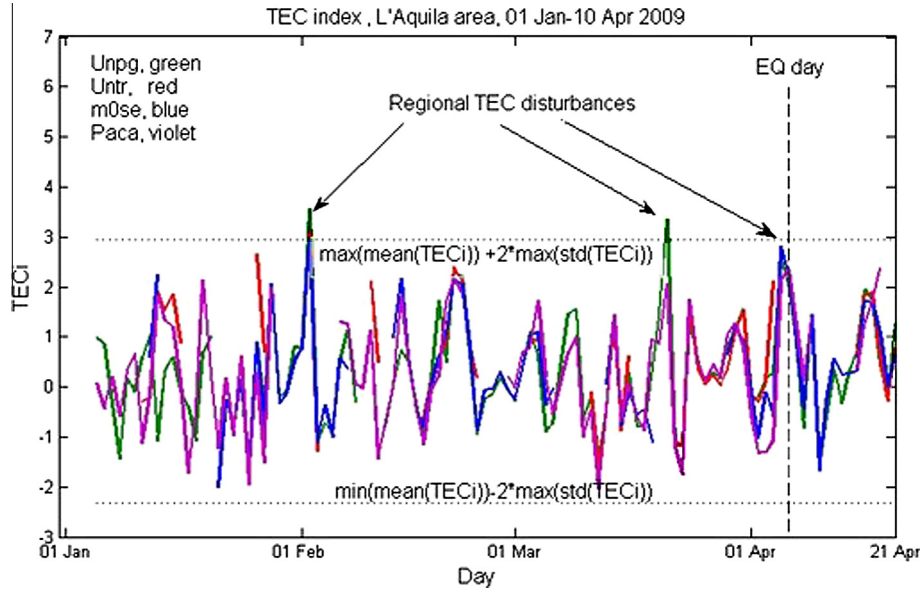


Fig. 5. Daily TECi variations for L'Aquila and the four stations (*Unpg*, *Untr*, *M0se*, and *Paca*) in the L'Aquila area for the period 01 January–21 April 2009. TECi is calculated by averaging over the all 288 TEC index values per day. TECi behaves similarly at all stations and presents several coinciding extremes. The daily TEC index of each station regularly bounds between  $\text{mean}(\text{TECi}) \pm 2 * \text{std}(\text{TECi})$ . In seeking anomalous signals it is assumed that such signals should exceed the maximum (MAX) value of all 4 MEANs + 2 \* MAX of all 4 STDs, i.e.  $\text{max}(\text{mean}(\text{TECi})) + 2 * \text{max}(\text{std}(\text{TECi}))$ , and inversely, to be lower than  $\text{min}(\text{mean}(\text{TECi})) - 2 * \text{max}(\text{std}(\text{TECi}))$ . There are peaks of regional increase in TEC on 1–2 Feb, 19–20 March and 5 April 2009.

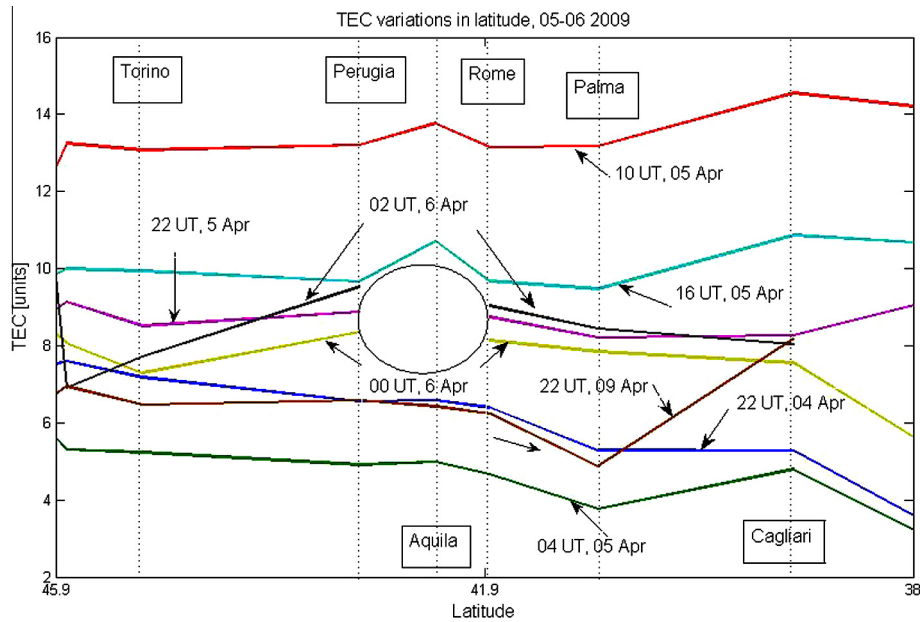


Fig. 6. TEC data from GPS stations spanning North (one station, Torino), Central (5 stations) and South (Cagliari) Italy are displayed. The latitude position of each GPS stations is named and indicated by vertical dashed lines. TEC distributions in latitude at every 6 h on 5 April, are shown. TEC trends in latitude at 22 UT on 4 and 9 April (see brown and blue thick lines) are also drawn being used as reference trends. At 22 UT on 5 April a regional increase of TEC of amplitude  $\sim 2 \text{ TECu}$  (see violet line) with respect to the 22 UT TEC data on 4 and 9 April was clearly observed. At 10 and 16 UT on 5 April only slight increases of TEC at Aquila station were registered. These TEC increases were recorded only at *Aquila* station and might be questioned because of the GPS data interruption occurred around the EQ shock. It seems that a TEC maximum is really present between Perugia (*Unpg*) and Palma (*Paca*). This is also inferred by the TEC increase from Torino to Perugia and the TEC decrease from Rome to Palma at 00 and 02 UT, which suggests a possible TEC maximum between Perugia and Rome latitudes. Note that the *Aquila* TEC data for the time interval: 22 UT, 5 April–02 UT, 6 April are consciously/tentatively canceled (see ellipse), because considered as fictitious. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

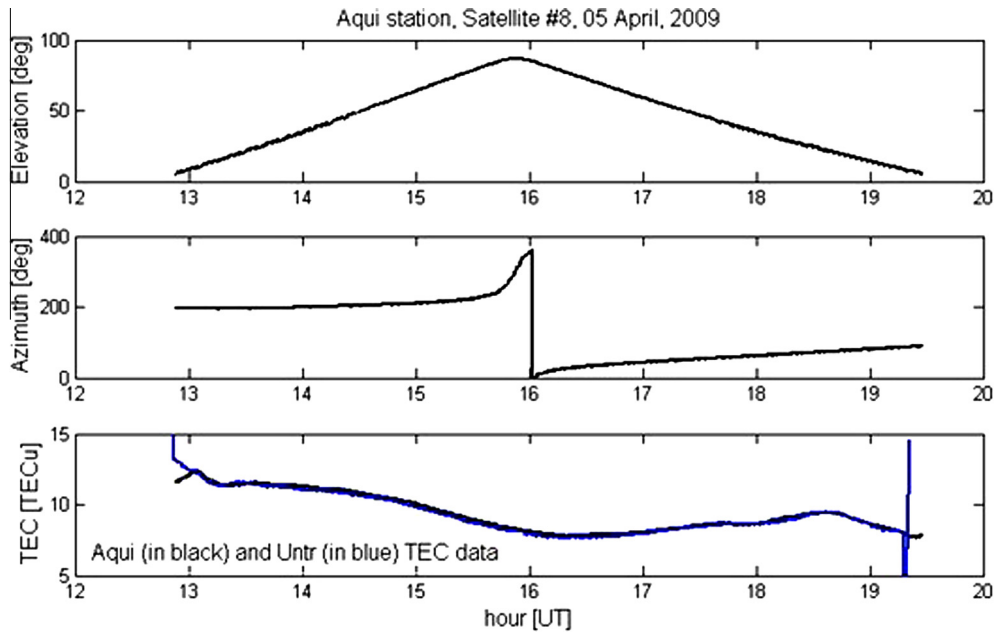


Fig. 7. Elevation angle, azimuth angle and TEC data taken from satellite #8 at Aquí station on 5 April 2009. For comparison TEC data from satellite #8 at *Untr* are overlapped on those recorded at *Aquí*. The TEC trends at *Aquí* and *Untr* GPS stations ( $\sim 55$  km distance between them) are practically coincident.

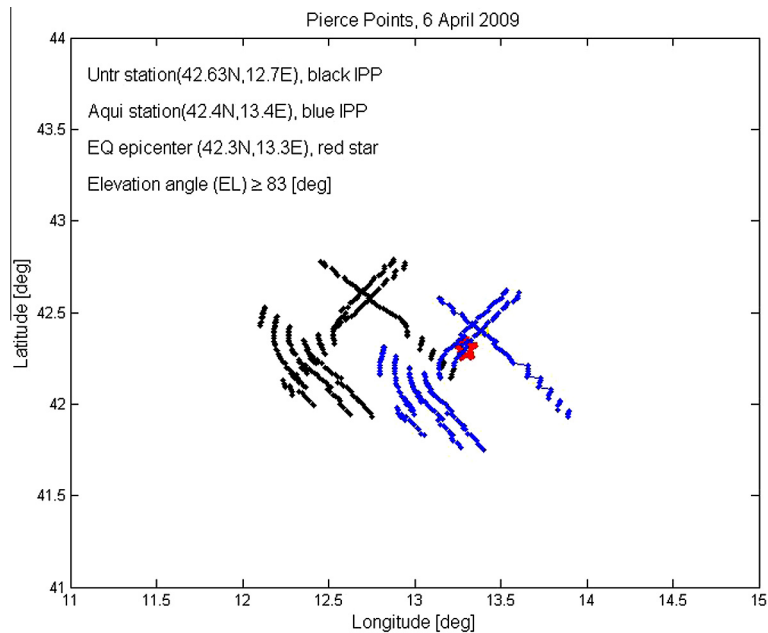


Fig. 8. GPS satellite trajectories projected/mapped as pierce points at 400 km height on 6 April 2009 are sketched. Pierce points of *Untr* and *Aquí*—satellite line-of-sight trajectories are given in black and blue, respectively. The EQ epicenter is marked by a red star. Note that pierce points refer to elevation angles, EL, greater than  $83^\circ$ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pierce points of the two stations is observed. The TEC variations at the two stations might be identical provided that the spatial scales of TEC exceed considerably the distance between *Untr* and *Aquí* (an assumption). In order to avoid possible intersection of IPPs of the two GPS stations (Fig. 8), say *Aquí* and *Untr*, elevation angle (EL) should be increased, e.g.  $EL \geq 86^\circ$ . Then IPPs of given GPS station would lie within a circle of radius less than 30 km

centered around the GPS receiver. Choosing much higher elevation angles imply that non-interpolated TEC data will not provide continuous set of data points. Under this circumstance numerous data gaps are expected. Such TEC data gaps do not allow to record uninterruptedly the whole evolution of the disturbance process occurred around the earthquake moment above the epicenter. As can be seen (Figs. 9a and 9b), the non-interpolated TEC data are



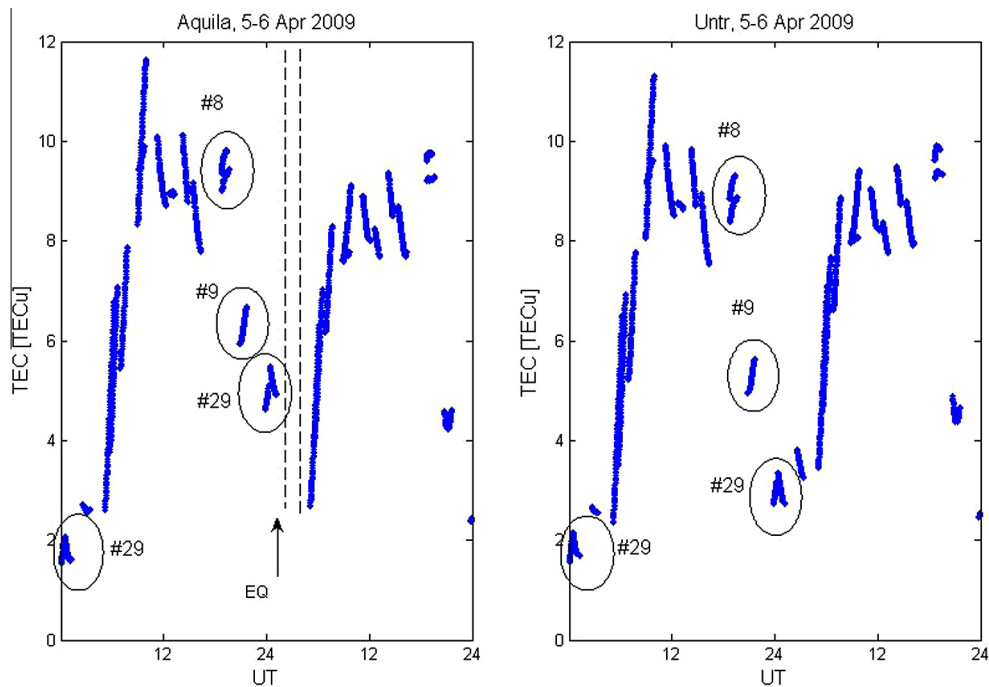


Fig. 9a. All satellite TEC data on 5 and 6 April at *Aquila* and *Untr* stations. The two dashed vertical lines (left panel) indicate data gap (no satellites with elevation angle greater than 84°). Note that at *Untr* on 6 April at 00:00 UT there is an increase of TEC till ~3 TECu (see satellite #29, right panel), while the TEC value recorded on 5 April 00:00 UT was of ~2 TECu. TEC increase at *Aquila* (satellites #8, #9, #29) is considered doubtful and therefore, is not used in our analysis. It is worth noting that TEC data are practically coincident at *Aquila* and *Untr* except for satellites #8, #9 and #29.

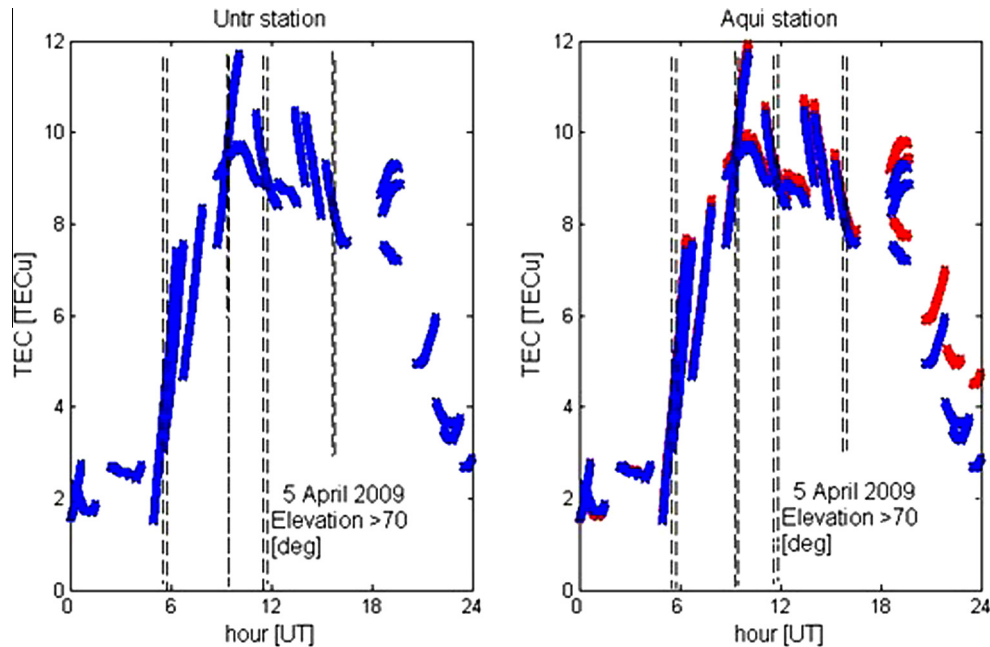


Fig. 9b. All satellite TEC data recorded on 5 April 2009 at *Aquila* and *Untr* stations. Twin dashed vertical lines indicate data gap (no satellites with elevation angle exceeding 70°) at the GPS station. TEC data are practically coincident except the time interval 18–24 UT. The corresponding TEC increases at *Aquila* (in red) are however considered doubtful. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

grouped and each group (spot centered, or located in time) contains data (30 points in average) only from one satellite being over the questioned GPS stations.

Figs. 9a and 9b show TEC (non-interpolated data, all satellite data) as recorded at *Untr* and *Aquila* on 5, 6 April 2009. TEC data are practically coincident except for the

satellites #8, #9 and #29 for which differences of up to several TECu were detected around midnight (compare TEC at midnight on 5 vs 6 April (of  $\sim 3$  TECu) and at the beginning 00:00 UT on 5 April (of  $\sim 2$  TECu)). The differences at *Aqui* however were not considered reliable because of the data interruption occurred on 6 April. Therefore, TEC increases at *Aqui* as recorded by satellites #8, #9, #29 are considered doubtful. *Untr* TEC data are then used as indicative of possible local TEC variations expected over *Untr* and *Aqui* stations separated by a distance of  $\sim 55$  km. On the other hand, the two *Untr* and *Aqui* GPS stations are at distances of  $\sim 80$  and 90 km from the *M0se* GPS station. Thus TEC differences (of local character) occurred between two GPS stations in the L'Aquila area – *M0se* and *Untr* are further analyzed.

A TEC difference method is suggested here based on consecutive satellite TEC data of two close GPS stations. Differences  $DTEC = TEC_{Aqui} - TEC_{Untr}$  and  $DTEC = TEC_{Untr} - TEC_{M0se}$  of non-interpolated TEC data on days 28 March–07 April 2009 are constructed for stations *Aqui* and *Untr* (not presented here) and for stations *Untr* and *M0se*. These TEC data (for each satellite) at given time  $t$  with elevation angle exceeding a certain value EL simultaneously at the two stations are subtracted to each other. This method, in principle, will allow variations of TEC along quasi-parallel line-of-sights (due to the closeness of the two stations) to be excluded. Except variations whose scales are comparable and/or less than the distance between close stations. One sees that with one exception (to be examined later) the DTEC variation between different satellites is ranged between  $\pm 0.2$  TECu for much of the time (Figs. 10a and 10b). The absolute error of TEC measurements is 0.01 TECu ( $10^{14}$  electrons/m<sup>2</sup>). The standard deviation varies from case

to case and in fact lies between 0.050 and 0.145. Note that this becomes possible for close GPS stations (of distance less than 100 km). Unfortunately, GPS satellites with elevation angle  $EL > 86^\circ$  were absent around the EQ shock moment between 16:00 UT (on 5 April) and 04:50 UT (on 6 April) for the Aquila area. In seeking non-interpolated TEC data that would cover the EQ shock moment the elevation angles EL was reduced to  $67^\circ$ . Then, TEC differences from satellites with  $EL \geq 67^\circ$  revealed definitely different behavior – a hump-like distribution of the DTEC difference of a  $\sim 0.4$ – $0.5$  TECu, well above the noise level and standard deviation that were already determined, also emerges centered close to the EQ shock moment (Figs. 10a and 10b).

It is important to have in mind that TEC observations strictly provide electron content along the ray satellite-receiver. Due to the proximity of the two stations (*M0se* and *Untr*) the corresponding rays from a satellite are nearly parallel (forming a pair of IPPs). At the same time, the ray pair from another satellite will intersect the ionosphere somewhere else, forming another paired IPPs. As satellites move, their IPPs will form intersecting traces over the two close stations area. Usually, the TEC difference between two close stations practically approximates the noisy level provided that the STEC distribution in the area of intersecting traces is uniform. On the contrary, under non-uniform STEC conditions, TEC difference between two close stations may be really different from noise. Furthermore, one-polarized structure (above the noisy level) can appear in the situation where the paired IPP traces become detached, below some height as it can be inferred from Fig. 11a), and TEC disturbance of local extent (over either station) may appear (Fig. 11a). Under the chosen elevation angle  $EL \geq 67^\circ$ , the IPPs of

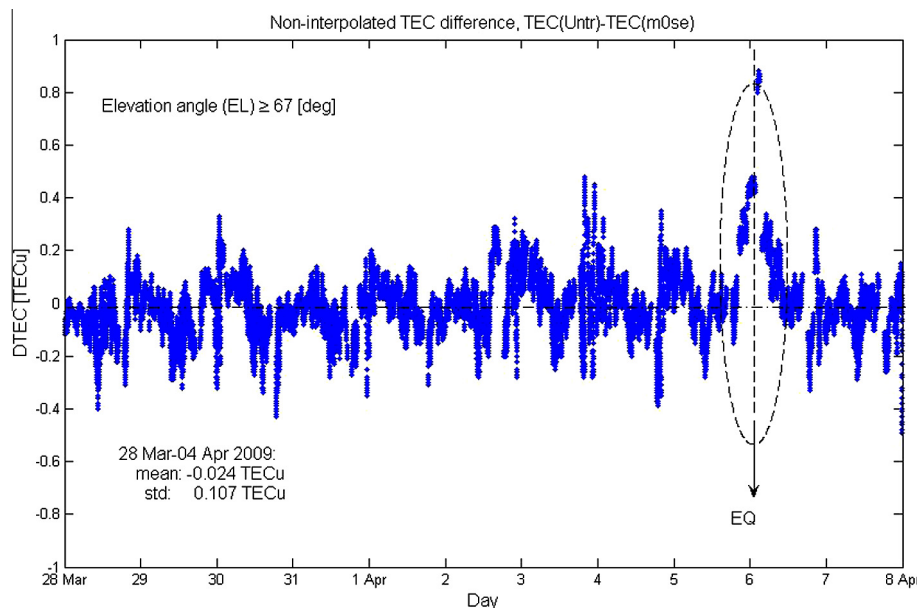


Fig. 10a. Non-interpolated vertical TEC difference  $TEC(Untr) - TEC(M0se)$  for 28 March–7 April 2009 taken from all satellites crossing GPS stations in Central Italy with elevation angle greater than  $67^\circ$  at the two stations. This difference is close to 0, with a mean value of 0.024 TECu. The only exception is a time interval (of several hours) around the EQ shock moment (highlighted by a dashed ellipse). In that time interval, the TEC difference becomes positive and reaches amplitude of  $\sim 0.8$  TECu just after the EQ shock moment.

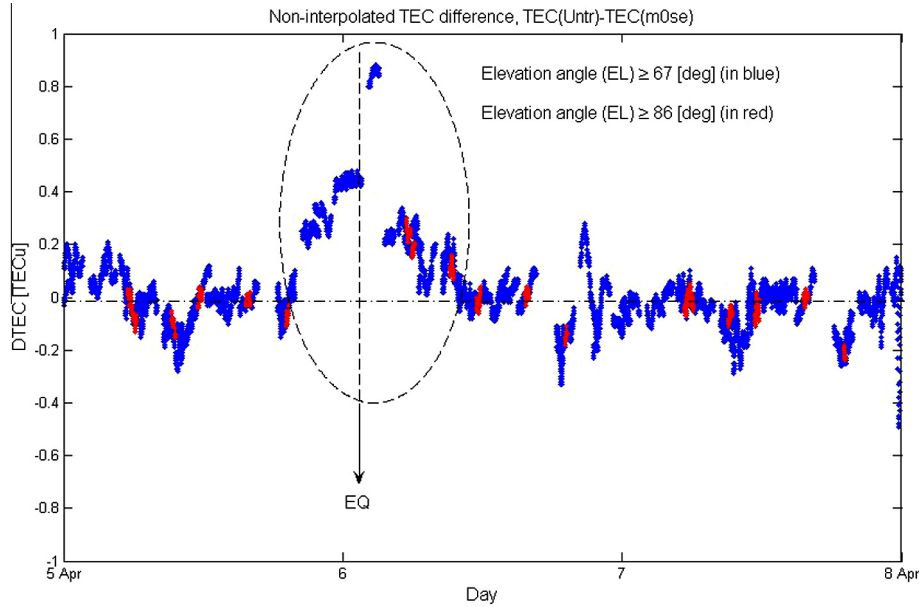


Fig. 10b. Non-interpolated TEC difference  $TEC(Untr) - TEC(M0se)$  for 5–8 April 2009 taken from all satellites crossing GPS stations in Central Italy with elevation angles greater than  $67^\circ$  (blue) and  $86^\circ$  (red). Note that around the EQ shock moment there were no satellites with elevation angles greater than  $86^\circ$ . The TEC anomaly is ‘caught’ by satellites of less elevation angles (between  $67^\circ$  and  $86^\circ$ ). In a time interval of several hours (highlighted by a dashed ellipse), the TEC difference represents a hump-shaped distribution and reaches amplitude of 0.4–0.5 TECu centered at the EQ shock moment, except an outlier of  $\sim 0.8$  TECu just after the EQ shock moment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

*Untr* and *M0se* stations become detached at heights below 160 km (Figs. 11a and 11b). Therefore, given that the positive perturbation  $\Delta TEC$  was recorded at *Untr* but not at *M0se*, and taking into account Fig. 11 and the related considerations, the perturbation  $DTEC$  can be thought to be likely initiated in the lower part of the ionosphere, that is below 160 km.

The hump-like distribution is of amplitude 0.4–0.5 TECu prior to the EQ shock, followed by an outlier

of  $\sim 0.8$  TECu immediately after the EQ shock (Fig. 10b). This outlier might be caused by the EQ shock itself. TEC difference between the two close stations *Untr* and *Unpg* (of distance  $\sim 60$  km) also was tested and did not reveal similar anomaly (figure not shown here). This suggests that the TEC disturbance is extended up to *Unpg* station, but not to *M0se*. The relative increase of TEC between *Untr* (*Unpg*) and *M0se* stations starts at the end of 5 April ( $\sim 2$  h before the EQ shock) and persists around the EQ

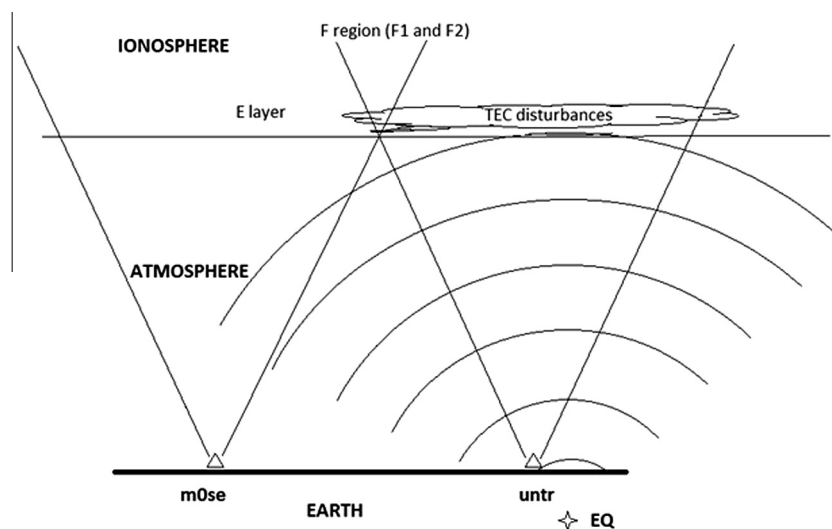


Fig. 11a. Cones of line-of-sights trajectories centered at two TEC GPS stations: *M0se* and *Untr*, EQ epicenter (marked with a star) and concentric fronts of seismicogenic disturbances above the EQ epicenter are illustrated. Disturbances in the ionosphere within the cones become detached to each other only for heights less than 160 km. Above these heights the cones and associated disturbances become overlapping and hence cannot be easily separated.

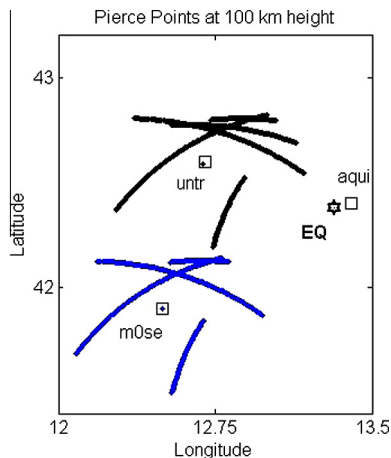


Fig. 11b. Pierce points of *Untr* and *M0se* satellites line-of-sight at 100 km height around the EQ shock moment are illustrated. IPPs of *Untr* and *M0se* stations are detached to each other. Note that few satellites of elevation angles exceeding  $67^\circ$  are visible at *Untr* and *M0se* stations for the time span of 6 h centered at the EQ shock moment. Note that the area of *Untr* is closer than the area of *M0se* to the EQ epicenter.

shock. Thus, the observed TEC difference can be considered as a positive TEC disturbance (of 0.4–0.5 TECu) centered at the EQ shock over the *Untr* station.

The examined non-interpolated TEC data (with elevation angle  $EL \geq 67^\circ$ ) reveal an existence of positive TEC disturbance localized at the *Untr* area placed at distance  $\sim 80$  km from *M0se*. It is worth noting that the *Aqui* area is placed also itself approximately at the distance of 90 km from *M0se*, and that the *Untr*(*Unpg*) – *Aqui* line lies approximately parallel to the Apennine's fault system.

### 3. Discussion

Using GPS TEC data from TEC GPS stations we investigated ionospheric anomalies for the period 1 January–21 April 2009, including the  $M_w 6.3$  Abruzzo earthquake on 6 April 2009. In our analysis the TEC data from the TEC station *Aqui* (the closest to the EQ epicenter) were not considered because of GPS data interruption causing calibration errors. For the mentioned period positive TEC increases of regional character were observed on 1–2 February, 19–20 March, 2009. Positive TEC increase was also recorded on 5 April with an amplitude peak close to the EQ epicenter (between Perugia (*Unpg*) and Palma (*Paca*)). This regional TEC increase starts  $\sim 16$  h before the EQ shock moment and covers a zone from Torino (at North) to Cagliari (at South). Regional TEC data were by and large coincident except for an interval of increased dispersion starting on 3 April and ending on 6 April, 2009. It is worth noting that the regional TEC increase recorded on 5 April was preceded by a regional TEC reduction during nighttime hours on 1–2 April 2009.

TEC changes of local character centered in time at the EQ shock moment were also recorded. This local TEC disturbance was of shorter time duration ( $\sim 3$  h) and localized in the EQ area. More specifically, the observed TEC

disturbance presents a spatial scale which is shorter than the distance between *M0se* and *Untr* stations. Usually, local TEC increase and subsequent density gradient mechanism would produce density expansion with sufficiently low velocity and should result in TEC difference between two close TEC stations. The TEC difference in our case disappears  $\sim$  one hour after the EQ shock. Further, the latitudinal/longitudinal position of the *Untr* station (42.6N, 12.7E) (where the positive TEC anomaly was observed) is in NW direction from the EQ epicenter and approximately overlaps with the local faults (including the ruptured one) oriented in NW–SE direction.

The only previous finding of positive TEC anomaly which appears immediately before the EQ shock, is by Heki (2011), Heki and Enomoto (2013). The positive TEC anomaly appears  $\sim 40$  min before the great (M9) Tohoku earthquake on 11 March 2011. This transient anomaly emerges and disappears simultaneously at several TEC GPS stations placed at different distances from the EQ epicenter. Another wave-like TEC disturbances of smaller amplitude appears some time earlier and propagates with a speed close to the acoustic one far away from the epicenter (Heki and Enomoto, 2013). Heki (2011) however has found similar positive TEC anomalies anticipating other strong EQs around the world.

As opposed to the Heki's finding of positive TEC anomaly (Heki, 2011; Heki and Enomoto, 2013), the positive TEC difference recorded around the L'Aquila EQ shock presents the following characteristics:

- (i) it retains its positive value for  $\sim 3$  h. The relative amplitude (between *Untr* and *M0se*) reaches a value of  $\sim 0.5$  TECu before the EQ shock. The local TEC disturbance around the L'Aquila EQ moment presented a hump-like distribution and returned to the background level within an hour after its maximum;
- (ii) it appears in a localized area close to the EQ epicenter (*Untr* station is placed at  $\sim 55$  km from L'Aquila);
- (iii) it is likely located at low ionospheric heights, that is at E-region heights. This finding follows from a requirement of non-overlapping IPPs related to the *Untr* and *M0se* stations. Non-overlapping IPPs occur for heights  $< 160$  km (Figs. 11a and 11b).

Note the Heki's finding refers to positive TEC changes extended over wide region (hundreds km) and occurred at ionospheric F2 region heights.

Previous results on ionospheric variations (precursors) indicate that there are both positive and negative deviations from undisturbed level and what was revealed recently is that they are not sporadic, on the contrary they are related to the day of earthquake. The specific day when the precursory variations are detected is also not random and happens during the same interval of the local time (LT), specific for different seismic zones. Further, (i) ionospheric precursors may last from 4 to 12 h, and can repeat the same variations several consecutive days



prior the EQ; (ii) the leading time of ionospheric precursors emerging before the seismic shock is shorter for smaller and deeper earthquakes, even though the limiting time for them statistically confident remains 5 days; (iii) the ionospheric TEC anomaly does not necessary characterize all the area of earthquake (Pulinets and Davidenko, 2014). Concerning precursors phenomena in different layers of the ionosphere there are: (i) seismic related D-region variability detected by anomalous effects in the VLF radio propagation; (ii) intensification of sporadic E layer (Es activity) before earthquakes often manifested by the excess of  $f_oE_s$  over the  $f_oF_2$  during earthquake preparation period; (iii) in addition to TEC variations itself, the scale height and ion composition are also important factors to identify the ionospheric precursors because their morphology is quite different from the same parameters variations during the geomagnetic storms (Pulinets and Boyarchuk, 2004).

The observed features of TEC enhancements observed in Central Italy (Abruzzo) on 5 April, 2009 are in good agreement with the statistical characteristics of the seismic related TEC variations cited above: first, the TEC enhancement lasts for about half a day up to the EQ shock, second, its leading time is one day, how it is expected for earthquakes of magnitude around 6, and third, its spatial scale occupies a region of radius 150–200 km which is within the earthquake preparation zone given by the Dobrovolsky's formula (Dobrovolsky et al., 1979).

Our findings of the height of the observed hump-like TEC changes (below 160 km) might be related to an enhancement of electron content in the E-region heights, similar to those previously observed by other authors (e.g. Liperovsky et al., 2005; Nenovski et al., 2010), which is in agreement with the following two circumstances: it appears during nighttime hours for low geomagnetic activity conditions ( $K_p < 2$ ). Hence, as a most probable source of such a localized structure of electron density enhancement, an emergence of quasistatic electric field over the epicenter is suggested. Of course, acoustic-gravity waves generated over the epicenter by some mechanism (e.g. density/temperature variations at the Earth surface preceding the EQ shock) might be another source of the observed local TEC enhancement at the E-region heights.

Other geophysical evidences of the  $M_w 6.3$  2009 Abruzzo earthquake have been reported. Tsolis and Xenos (2010) have analyzed  $f_oF_2$  signals collected from Rome, San Vito and Athens ionospheric stations, and have verified an existence of seismo-ionospheric precursors prior to  $M_w 6.3$  L'Aquila earthquake. By applying a cross correlation analysis method they have found that the ionosphere over Rome was disturbed by a strictly local event, suggested by the fact that the corresponding correlation coefficient was very similar to those characterizing the other two stations, with the exception of distinguishable drops on 16 March and 4 and 5 April, 2009. An existence of ionospheric disturbances in F2 region over Rome on 4 and 5 April (Tsolis and Xenos, 2010) might be considered in accordance with the TEC data dispersion which is observed on

3–6 April (see Fig. 4). The short-time TEC disturbance described in this work around the EQ shock moment however is a local event placed at heights lower than 160 km and moreover, it was recorded at *Untr* and *Unpg* stations and not at *M0se* station (Rome); hence, it could have been accidentally omitted by the  $f_oF_2$  analyses performed by Tsolis and Xenos (2010).

Thermal infra-red (TIR) emissions near tectonic boundaries of Central Italy have been also identified in space-time correlation with Abruzzo EQ epicenter between 30 March and 1 April 2009. The authors' findings are that TIR anomalies are indicative for seismic events of medium and low magnitude as foreshock with  $M_L = 4.1$  occurred on 30 March 2009 (Lisi et al., 2010). Radon emission starting to be intensified on 30 March 2009 as well as TEC (regional) increase (on 5 April 2009) has been already reported by Ouzounov et al. (2009). The spatial and temporal characteristics of both TIR anomalies and radon emission however seem not to be in compliance with local and temporal scales of the transient TEC disturbances recorded immediately before the Abruzzo earthquake.

Various physical mechanisms have been suggested so far to explain observed ionospheric variations associated with earthquakes. For example, quasi-electrostatic (QE) fields (Pierce, 1976) and electromagnetic fields (Molchanov et al., 1995) penetration mechanisms have been proposed. Gravity waves (GW) as an agent of ionospheric variations (mainly in the low ionosphere) are examined by Molchanov and Hayakawa (1998), as well. Ionospheric variations are also considered to be initiated by gas (radon) release from the crust above earthquake preparation region (Pulinets et al., 1994). Alpha decay of radon gas released from the crust can also ionize the atmosphere. They may change the electric resistivity of the lower atmosphere, which could disturb the global electric circuit and redistribute ionospheric electrons (Pulinets and Ouzounov, 2011; Pulinets and Davidenko, 2014). Due to the stress of the rocks, electric charges at the Earth's surface and electric currents in the atmosphere-ionosphere system could appear (Freund, 2003, 2008; Freund et al., 2004; Pulinets et al., 2003). It is worth noting that such electric charges and currents under stress in laboratory conditions already have been measured (Enomoto and Hashimoto 1990, 1992; Freund 2000; Freund et al., 2004; Takeuchi et al., 2006). Then electric field/current in the ionosphere and Joule heating could modify and/or redistribute the electron concentration/temperature in height. A model of ionospheric variations based on the effect of atmospheric electric current flowing into the ionosphere was proposed by Sorokin et al. (2006). As a result plasma density in the lower ionosphere increases and formation of an anomalous, sporadic E layer is possible (Sorokin and Chmyrev, 2010). A sporadic E layer may be generated by discharge processes (Ondoh and Hayakawa, 2002), as well. It is worth noting that sporadic E layers and their dynamics successfully were studied recently by TEC measurements (Maeda and Heki, 2014).

A promising hypothesis to explain the observed anomalous disturbances in TEC (even if they occur at E-region heights) may thus be related to a seismogenic electric fields/currents action. More efforts however would be desirable both in modeling and in monitoring preparatory and seismogenic processes in the Lithosphere–Atmosphere–Ionosphere (L–A–I) system and their effects not only in the ionospheric F2 region but also in the lower ionosphere in order to highlight and quantify the chain of processes resulting in anomalous TEC events.

#### 4. Conclusion

In this paper we have examined temporal and spatial extent of TEC changes around the destructive Abruzzo earthquake occurred on 6 April 2009. The observed changes in TEC were of regional and local character. The former appeared repeatedly on the EQ day and before it. The regional TEC changes observed on 5 April was characterized by an amplitude maximum in the EQ area and an enhanced dispersion persisting on 4–6 April. A possible association of these TEC changes of regional character with the EQ preparation mechanism could not be excluded.

The paper was however mainly focused on the temporal TEC changes of local character. A growth of positive TEC disturbance approaching the EQ shock moment attaining its maximum value close or after the EQ moment was recorded. A TEC difference method is suggested, based on consecutive satellite TEC data at two close TEC stations and requiring that the corresponding pierce points are detached. The local TEC disturbance was found to lie likely at E layer heights (less than 160 km).

In conclusion, a preparatory nature of local TEC changes preceding and accompanying the EQ shock moment is evidenced for the  $M_w$ 6.3 Abruzzo earthquake, and the analyses described in the paper suggest an admissible connection between the EQ shock process and the generation of local TEC disturbances at lower ionosphere heights.

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