LOCAL CHANGES IN THE TOTAL ELECTRON CONTENT IMMEDIATELY BEFORE THE 2009 ABRUZZO EARTHQUAKE

by

P. I. Nenovski[1], M. Pezzopane[2], L. Ciraolo[3], M. Vellante[4], U.Villante[4], M. DeLauretis[4]

[1]University Center for Space Research and Technologies, SofiaUniversity, Sofia, Bulgaria
[2]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
[3] ICTP,Trieste, Italy
[4]Dipartimento di Scienze Fisichee Chimichedell'Università dell'Aquila, L'Aquila, Italy

Abstract. Ionospheric TEC (Total Electron Content) variations derived from GPS measurements recorded at 7 GPS stationsin Northern, Centraland Southern Italy before and after the 2009Abruzzo earthquake (EQ) of magnitude M_w6.3 were processed and analyzed. The analysis included interpolated and non-interpolated TEC data. Variationsin the TEC of both regional andlocal characteristics were revealed. Several regional changes were observed in the studied period: 1 January-21 April 2009. After analyzing non-interpolated TEC data of5GPS 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 disturbancearisespreparatory to the EQ main shockoccurred at 01:32 UT on 06 April 2009, maximizes its amplitudeof ~ 0.8 TECu after the shock moment and disappears after it. The localTEC disturbance was confined at heights below 160 km, i.e. in the lower ionosphere.

***Keywords*:**GPS measurements, total electron content (TEC), TEC disturbance, lower ionosphere, earthquakeshock

Corresponding author:

Dr Petko Nenovski, petko.nenovski@abv.bg

1. Introduction

Electromagnetic perturbations due to seismic activityhave been known for a long time (Milne, 1890). Variations in ionospheric parameters above seismically active regionsare one of the most actual aspects of these perturbations. Since the pioneering investigations devoted to the ionospheric effects caused bythe powerful Alaska earthquake occurredon 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 theTotal Electron Content (TEC) are those for which the earthquake induced variations are studied the most.VariationsintheF2 regionparametershavebeenfrequently revealed a few days before strong EQsby 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 medianat single ionosonde station Wakkanai wasobserved within ±3 days around the strongEQwith M=7.8 in Japan (Ondoh, 1998, 2000). Decreases of f_oF2observed one, three, and fourdays before the main shock of the powerfulChi–Chi EQat single ionospheric station in Taiwan (M=8.2) also have been recordedby Liu et al. (2000).They have found that thecorresponding electron density decrease is about 51%from its normal value obtained from 15-day medianprocess. Very close similarities in most parameters describingthe precursory anomalies (leading time, sign of f_oF2 andvalue of electron density depletion, duration of eachanomaly, 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 thelocalones, and to find that theHachinohe EQevent (M=8.3)was characterized byanf_oF2 decrease of 3MHz 4 days beforeand 2 days after the EQ, this decrease maximizing.This in the afternoon (15:00 LT) hours.Statistical analyses have been also conducted by Liu et al., 2006on possible relationships between the f_oF2 effects and 184 EQswith M>5.0 occurring during years 1994÷1999 in the Taiwan area. They have revealed that the effect of f_oF2 decrease (more than25% 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 EQmagnitude, decreaseswith the distance of the ionospheric station from the epicenter (only stations within a distance of 150 km from the epicenter can show this EQinduced variations), and thatonly the M>5.4 EQshave a significantchance to cause such an f_oF2 decrease.

Statistical analyses on ionosphericchanges prior to strongEQsshow that abnormal TEC disturbances occur aroundthe 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 TECobtained using GPS (dual frequency measurements) is also very sensitive to changes in the f_oF2electron density measured by ionosondes. According to Houminer and Soicher (1996) the correlation between TECand foF2can reach the value of 0.9. In that way, the anomalous ionosphere modification before some strong EQshas been found using GPS TECmeasurements 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 earthquakeby Liu et al. (2001) showedsevere depletion of TEC around the epicenter (with a radius of100–200 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 20M≥6.0 EQsin 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 18:00–22:00LT within 5 days prior to 16 of all the 20M≥6.0 considered EQs. The study performedby Pulinets et al. (2001) for several seismic eventslocated at various latitudes show instead either a localizedenhancement or a decrease of electron density witha spatial extent of about 20° in latitude and longitude.One day before the Kythira (Southern Greece) EQoccurred on 8 January 2006, a significant increase of TECat the nearest stations, up to values 50% greater than the background condition, in the time interval between 10:00 and22:00 UT has been recorded.The area of this significant TECenhancement had a size of about 4000 km in longitude and 1500 km in latitude (Zakharenkova et al, 2007a). Seismo-ionospheric anomalies in GPS TECover European andJapan regionshavebeenanalyzedby Zakharenkova et al.(2007b) and letthem conclude that the occurrence of such variations may be registered in Europe 1-2 days before theEQs, while for very strong Japanese EQsthis temporal interval can reach 5 days.

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

On 9 May, 2008(a geomagnetic quiet day, Kp ≤ 2), 3 days prior to the Wenchuan earthquakethe 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 foundthat TECabove 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 increasedin 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 densityN_mF2, and heighth_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 inquantifying 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 theHaiti 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 underlinedhow 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.

Anotherform of enhancement of ionospheric TEC immediately before the 2011 Tohoku-oki earthquake (M_w9) has been reported by Heki (2011). The TEC enhancement emerges ~ 40 minutes before the main shock. Heki and Enomoto (2013) have scrutinized the nature of characteristics of the TEC change preceding the 2011 M_w9 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 occured before all the M≥8.5 earthquakes happened in this century, suggesting their seismic origin (Heki and Enomoto, 2013).

In this paper using data from 5 GPS stationsin Central Italy and some other stations in Northern and SouthernItaly we thoroughly analyzeboth 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 destructiveAbruzzo earthquakeoccurred close to L'Aquila on April06, 2009, at 01:32 UT;the latitude and longitudeof the epicenter were 42.33N and 13.33E, respectively,and the correspondingmagnitude 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 $M_L > 3$wereregistered 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, distributedin 6 orbits around the Earth at an altitude of ~ 20000 km.Each satellite transmits dual very high frequencies of signals, 1575.42and 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 propagatesthrough ionosphere. The slant TEC (STEC), i.e. the integral of the electron density over a line ofsight from a ground receiver to a satellite on the signalpropagation 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 pathsL_1 and L_2) relative to the two carriers. Properly combining the code and phase differential delaysone getsthe STECbetween a GPS satelliteand a groundbased dual-frequency receiver, which can be written as

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

where a = 1/40.3,β_r +$\beta_s$are the differential hardware biasesfor receiver and satellite, respectively and μ_{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 μ 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 STECcan be convertedto vertical TEC (VTEC), which is the projectionof oblique TEC on the thin-shell, using an elevationmapping 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 ionospheremodeledas a thin shell at a height of 400 km. Thisintercept is named as: ionospheric piercepoint (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 TECGPS station. Further in the text, only VTEC is analyzed and hence, the standardacronym TEC is used for VTEC.

Time resolution of the set of interpolated TECdata we useis5 min, i.e.288 values per day for each TEC station. GPS datafrom January 1 to April20, 2009 of 17 stations(in Italy mainly and Greece)are processed and then corresponding TEC time series obtained. These time series are given in TEC units (TECu), where 1 TECu $=10^{16}$ electrons/m^2.Because of satellite and receiver biases, β_s and β_r, and μ, the calculated interpolated TEC data from different satellitescan differ and the TEC difference can reach 1-2 TECu. For non-interpolated TEC dataonly temporal changes are meaningful and hence taken into account.

2.1. Interpolated TEC data

In statistics,envelope method is mostly used toidentify possible significance of disturbances. Under the assumption ofnormal distribution with mean μ and standard deviationσ of TECsandif 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 TECfalls out of either the associated lower or upper bounds of such an envelope,it is declared at confidence level of about 82% that alower or upper abnormal signal is detected. Li et al (2009) have used bounds$\mu \pm 2\ \sigma$, and for that casethe confidencelevel is equal to95%.Thus, upper andlower bounds of TEC variations can be determined atdifferent confidence levels. The meanfor a sliding window, which is 4 days long, is assumedas background TEC.Interpolated TEC variationsand corresponding upper and lower bounds fixed at $\mu \pm 1.34\sigma$wereinspectedfor 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 Apr–7 Apr 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 ~110, ~60, ~90 and ~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 Figure3 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 Jan-21 Apr 2009, one can see that there area lot of time intervals on which the TEC values are definitely above the upper bound of $\mu+1.34\sigma$ for all5 stations (such events are noticed on 24 January; 1-2, 14, 21-22 and 27 February; 8-9, 21 and 24March; and 9 April 2009 implying thatpositive 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 Aprilat L'Aquila. TEC spikes on 09 and 12 January are false signals due to data gaps. Anextremeanomalous TECdisturbance of 3 TECuis recorded on 5 April only at L'Aquila. Its duration is at least 11-12 hours.

Looking at these TEC interpolated data (Fig.3)two kinds ofTEC disturbances were discriminated: i) TECdisturbances of regional character that appear simultaneously at all TEC GPS stations in the L'Aquila area; and ii) disturbances of localcharacter 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 activitymeteorological/lightning activity, which can significantly contribute to ionosphereTEC variations. For the 1 January-21 April 2009 the geomagnetic conditions were pretty quiet with values ofthe geomagnetic index Kp lowerthan 2 but, nonetheless, TEC variations due to global and/or regional factors are however present.

Figure 4 illustrates interpolated TECdata from 31 March to 10 April 2009at L'Aquila area and shows that regional TEC dataare 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 (Kp < 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 minutes 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)wereclearly 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 shockwere considered as fictiousand hence, will not be considered further.

In order to find local meaningfulchanges of TEC in time, regular changes in the TEC (diurnal ones) should be removed. Thefollowing quantityisthen introduced:

$$DTEC = (TEC(i,j) - \mu(TEC(k,j)))/\sigma(TEC(k,j)), \quad i\text{-}5 \le k \le i\text{-}1 \qquad (2)$$

where TEC(i,j)represents the TEC value function of the day (i) and minute (j = 1 to 288);μ(TEC) and σ(TEC) denote respectively the mean value and the standard variation calculated over the previous 5 days, i-5÷i-1. Our choice corresponds to a 5-day running mean, which is enough to remove the variationslarger than 5 days.It is worth noting that such a choice is dictated by the 5 minutes resolution of TEC data. The diurnal TEC variations are strongly dependent on and move forth/back with the sunrise/sunset time. The difference TEC(i,j)–μ(TEC(k,j)) thus represents the TEC signal to be investigated for its possiblerelationship with earthquake activity. In (2) it is evaluatedby comparison with the corresponding natural/observational TEC noises represented by σ(TEC(k,j)), which describes the overall(local) variability of the signal including all sources of its variability, observed at daytime moment *j*in similar observationalconditions 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 clearlydetached 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 Jan–21 April 2009 (Figure5).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(mean(TECi)+2*max(std(TECi))),and inversely, to be lower thanmin(mean(TECi)–2*max(std(TECi))).This condition appears more restrictive ifcompared to one station measurements.One sees that the daily TEC indices behave similarly and presentseveral 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 degrees in latitude) (Figure 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 intermixed with the IPPs of other GPS stations. Therefore actual (non-interpolated) GPS TEC data with sampling frequency of 30 seconds 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 EL ≥67°. 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 EL ≥ 67° are of short duration (several tens of minutes and less). Figure 7 sketches sample elevation angle, azimuth angle and TECchanges over ~6 hours period observed at Aqui station with the satellite #8 on 5 April 2009.In addition, TEC data from satellite #8 at *Untr* are overlappedon those recordedat *Aqui*. The TEC shows gentle curvatures due to satellite elevation changes.The TEC trends at *Aqui* and *Untr* (≈55 km distance between them) are practically coincident.

Figure 8 represents pierce points (IPPs) of GPS satellites referred to *Untr* (in black) and *Aqui* (in blue) stations.The EQ epicenter is markedby a red star. The pierce points on 6 April are calculated for elevation angles exceeding 83 degrees, so pieces of GPS satellite trajectories projected/mapped as pierce points at 400 km height, are sketched. A crossing of 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 *Aqui* (an assumption).In order to avoid possible intersection of IPPs of the two GPS stations (Figure 8), say *Aqui* and *Untr*, elevation angle (EL) should be increased,e.g. EL ≥ 86°. Then IPPs of given GPS station would lie within a circle of radius less than 30 km centered aroundthe 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 epicentre.As can be seen(Figures9a and 9b), the non-interpolated TEC data are 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.

Figures 8a and 8bshowTEC(non-interpolated data, all satellite data) as recorded at *Untr* and *Aqui* 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 TECuwere detected around midnight(compare TEC at midnight on 5 vs 6 April (of ~3 TECu) andat the beginning 00:00 UT on5 April(of ~ 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, #29are considered doubtful.*Untr*TEC data arethen used as indicative of possible local TEC variations expected over*Untr* and *Aqui*stations separated by a distance of ~55 km. On the other hand,the two *Untr* and *Aqui* GPS stations are at distances of ~ 80 and90 km from the *M0se*GPS station. Thus TECdifferences (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 substracted 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 variationbetween different satellites is ranged between ±0.2 TECu for much of the time(Figures10a and 10b). The absolute error of TEC measurements is 0.01 TECu (10^{14} electrons/m^2). 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° were absent around the EQ shock momentbetween 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°.Then, TEC differences from satellites with EL ≥ 67° revealeddefinitely different behavior – a hump-like distribution of the DTEC difference of a ~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(Figures10a and 10b).

It is important to have in mind thatTEC observations strictly provide electron content along the ray satellite–receiver. Due tothe proximity ofthe two stations (*M0se* and *Untr*) the corresponding rays from a satellite are nearly parallel (forming a pairof IPPs). At the same time, the ray pair from another satellite will intersect the ionosphere somewhere else, forming another paired IPPs. Assatellites move, their IPPs will form intersecting traces overthe two close stations area.Usually, the TEC difference between two close stations practicallyapproximatesthe 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 maybe really different from noise. Furthermore, one-polarizedstructure (above the noisy level) can appear in the situation where the paired IPP traces become detached, below some height as itcanbe inferred from Figure 11a), and TEC disturbance of local extent (over either station)may appear (Figure 11a). Under the chosen elevation angle EL ≥ 67°, the IPPs of *Untr*and*M0se* stations become detached at heights below 160 km (Figure 11a and 11b). Therefore, given that the positive perturbation ΔTEC was recorded at *Untr* but not at *M0se*, and taking into account Figures 11 and the related considerations, the perturbation ΔTEC 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 a jump increase immediately after the EQ shock of ~ 0.8 TECu (Figure 10b). This jump might be caused by the EQ shock itself and was located at *Untr*station. TEC difference between the two close stations *Untr* and *Unpg* (of distance ~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 relativeincrease of TEC between *Untr* (*Unpg*) and *M0se* stations starts at the end of 5 April(~2 hours before the EQ shock) and persists around the EQ 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 ≥67°) reveal an existence of positive TEC disturbance localizedat the *Untr* area placed atdistance ~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 thatthe*Untr*(*Unpg*)–*Aqui*line liesapproximately parallel to the Appenine's fault system.

3. Discussion

Using GPS TEC data from TEC GPS stationswe investigated ionospheric anomalies for the period 1 January-21 April 2009, including the M_w6.3 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 periodpositive TEC increases of regional characterwere 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 ~ 16 hours 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 3April 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 reductionduringnighttime hours on 2 Apr 2009.

TEC changes *of local character* centered in time at the EQ shock moment was also recorded. This local TEC disturbance was of shorter time duration (~ 3 hours) and localized in the EQ area. More specifically, the observed TEC disturbance presents aspatial scale which is shorterthan 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 ~ 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 ~ 40 minutes 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.

Asopposed to the Heki's finding of positive TEC anomaly (Heki, 2011; Keki 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 ~ 3 hours. The relative amplitude (between *Untr* and. *m0se*) reaches a value of ~0.5 TECu before the EQ shock and 0.8 TECu after the EQ shock. The local TEC disturbance around the L'Aquila EQ 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 ~60 km from L'Aquila);

iii) it is likely located at low ionospheric heights, that isat E layer 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 (Figure 11a and 11b).

Note the Heki's finding refers to positive TEC changes extended over wide region (hundreds km) and occurred at ionospheric F2 layer 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 aredetected 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-region (Es activity) before earthquakes often manifested by the excess of f_oEs over the f_oF2 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 agreementwith 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 itis 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.

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, 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 duringnighttime hours for low geomagnetic activity conditions (Kp< 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_w6.3 2009 Abruzzo earthquake have been reported.Tsolis and Xenos (2010) have analyzedf_oF2 signals collected from Rome,San Vito and Athens ionospheric stations, and have verifiedan existence of seismo-ionospheric precursors prior toM_w6.3 L'Aquila earthquake.By applyinga 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 correspondingcorrelation 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 Figure 4).The short-time TEC disturbance describedin 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 thef_oF2 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 EQepicenter between 30 March and 1 April 2009. The authors' findings are that TIR anomalies are indicative for seismic events of medium and low magnitudeas foreshock with M_L=4.1 occurred on 30 March 2009(Lisi et al, 2010). Radon emission starting to be intensified on 30 March2009 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 explainobserved ionospheric variations associated withearthquakes. For example, quasi-electrostatic (QE) fields (Pierce, 1976)and electromagnetic fields (Molchanov et al., 1995) penetration mechanisms have beenproposed. Gravity waves (GW) asan agent of ionospheric variations (mainly in the low ionosphere) areexamined by Molchanov and Hayakawa(1998), as well. Ionospheric variations are also considered to be initiated by gas (radon) release from thecrust above earthquake preparation region (Pulinets etal., 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 therocks, electric charges at the Earth'ssurface and electric currents in the atmosphere-ionospheresystem 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 andHashimoto 1990, 1992; Freund 2000; Freund et al., 2004;Takeuchi et al., 2006).Then electric field/current inthe ionosphere and Joule heatingcould 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 worthnoting that sporadic E layers and their dynamics successfully were studied recently by TEC measurements (Maeda and Heki, 2014).

A promising hypothesisto explain the observed anomalous disturbances in TEC(even if they occur at E heights) maythusbe related to a seismogenic electric fields/currents action. More efforts however would be desirable both inmodeling and in monitoring preparatory and seismogenic processes in the Lithosphere-Atmosphere-Ionosphere (L-A-I) systemand 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 inanomalous 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_w6.3 Abruzzo earthquake, andthe analyses described in the papersuggest an admissible connection between theEQ shock process and the generation of local TEC disturbances at lower ionosphere heights.

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FIGURE CAPTIONS

Fig. 1. Earthquake activity in Central Italy during the period 1 January–6 April 2009.34 seismic events with 2 < M_L< 3 (and 9 with M_L> 3) were registered in the territory.
Fig. 2. Map of GPS stations (black triangles) located in Italy. Encircled arestations *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.
Fig. 3. Interpolated TEC variations (blue) and corresponding upper (red) and lower (green) bounds fixed at $\mu \pm 1.34\sigma$ are depictedfor 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 ovalon 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 andomitted in our analysis.
Fig.4.TEC daily curvesin 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 highlightedby the dashed oval.
Fig. 5. Daily TECivariations for L'Aquila and the four stations (*Unpg*, *Untr*, *m0se*, and *Paca*) in the L'Aquila area for the period 01 Jan–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 regularly bounds between mean(TECi)±2*std(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 dashedlines.TEC distributions in latitudeatevery 6hours 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 ~2 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 slightincreases of TEC at Aqui station were registered.These TEC increases were recorded only at Aqui station and might be questioned because of the GPS data interuption occurred around the EQ shock. It seems that a TEC maximum is really present between Unpg (Perugia) and Palma (Paca). The same seems to happen also at 00 and 02 UT on 6 April;this is inferred by theTEC 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 Aqui TEC data for the time interval: 22 UT, 5 Apr–02 UT, 6 Apr are consciously/tentatively cancelled (see ellipse), because considered as fictious.
Fig.7. Elevation angle, azimuth angle and TEC data taken from satellite #8 at Aqui station on 5 April 2009. For comparison TEC data from satellite #8 at Untr are overlappedon those recordedat Aqui. The TEC trends at Aqui and Untr GPS stations (~55 km distance between them) are practically coincident.
Fig. 8.GPS satellite trajectories projected/mapped as pierce points at 400 km heighton 6 April 2009 are sketched. Pierce points of Untr and Aqui–satellite line-of-sighttrajectories are given

in black and blue, respectively. The EQ epicenter is markedby a red star. Note that pierce points refer to elevation angles, EL,greater than83 degrees.

Fig. 9a. All satellite TEC data on 5 and 6 April at Aqui and Untr stations. The two dashedvertical lines (left panel) indicate data gap (no satellites with elevation angle greater than84 degrees). 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 theTECvalue recorded on 5 April 00:00 UT was of ~ 2 TECu.TEC increase at Aqui (satellites #8, #9, #29) isconsidered doubtful and therefore, isnot used in our analysis.It is worth noting that TEC data are practically coincident at Aqui and Untr except for satellites #8, #9 and #29.

Fig. 9b. All satellite TEC data recorded on 5 April 2009 at Aqui and Untr stations. Twin dashedvertical lines indicate data gap (no satellites with elevation angle exceeding 70 degrees) at the GPS station. TEC data are practically coincident except the time interval 18-24 UT. The corresponding TEC increases at Aqui (in red) are however considered doubtful.

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 degrees 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 ~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(blue) and 86 (red) degrees. Note that around the EQ shock moment there were no satellites with elevation angles greater than 86 degrees. The TEC anomaly is ‘caught’ by satellites of less elevation angles (between 67 and 86 degrees).In a time intervalof 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 ~0.8 TECu just after the EQ shock moment.

Fig. 11a. Cones ofline-of-sights trajectories centered at two TEC GPS stations: *M0se* and *Untr*, EQ epicenter (marked with a star) and concentric fronts of seismogenic 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.PPs of *Untr* and *M0se* stations are detached to each other. Note that few satellites of elevation angles exceeding 67 degrees are visible at *Untr* and *M0se* stations for the time span of 6 hours centered at the EQ shock moment.Note that the area of *Untr* is closer than the area of *M0se* to the EQ epicenter.

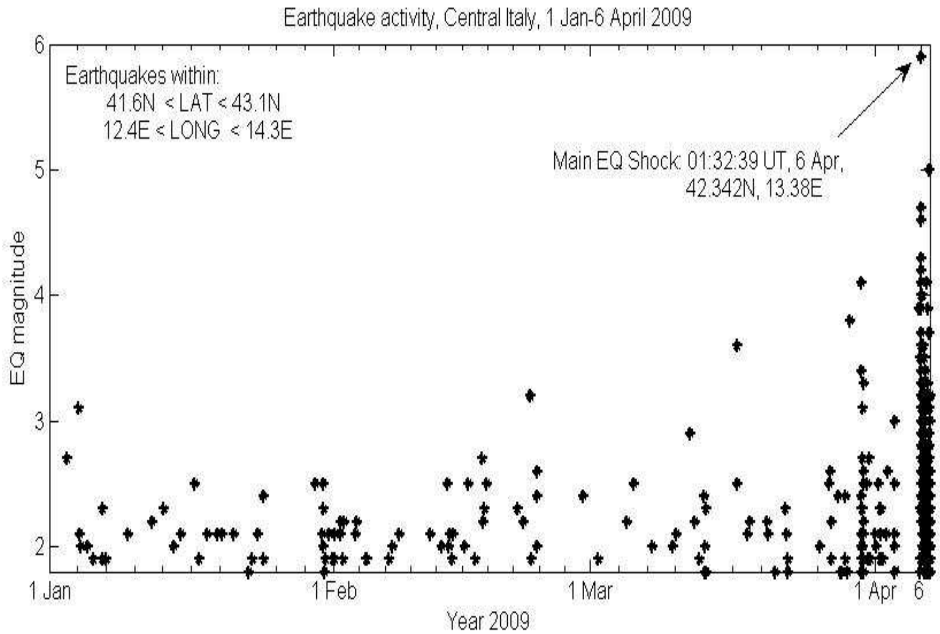

Earthquake activity, Central Italy, 1 Jan-6 April 2009
Earthquakes within:
41.6N < LAT < 43.1N
12.4E < LONG < 14.3E
Main EQ Shock: 01:32:39 UT, 6 Apr,
42.342N, 13.38E
EQ magnitude
Year 2009
1 Jan
1 Feb
1 Mar
1 Apr
6

Fig. 1.


zouf
bzrg
rove
brix
biel
nova
pavi
pado
unfe
medi
geno
prat
44°N
unpg
elba
untr
aqui
m0se
paca
mate
vluc
40°N
cagl
milo
36°N
8°E
12°E
16°E
20°E

Fig. 2.

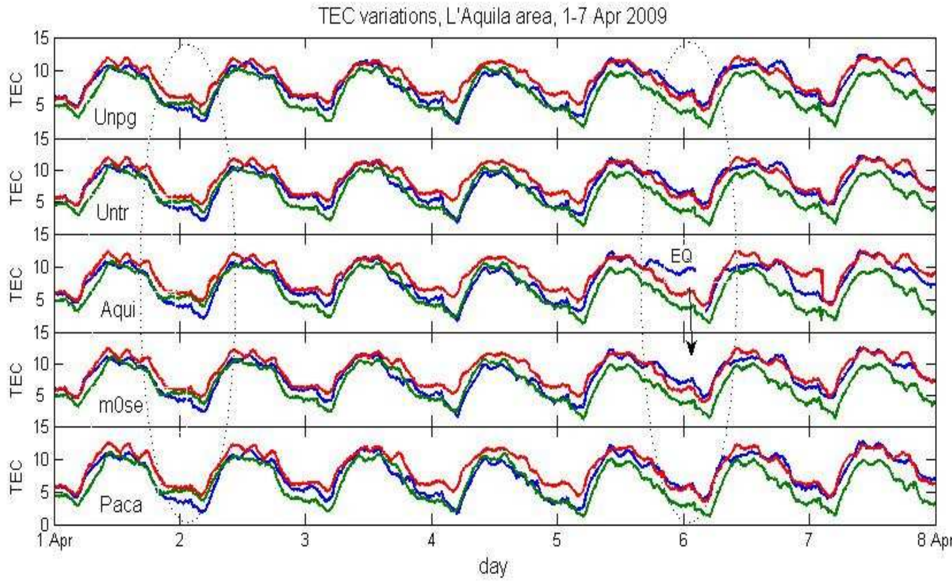

TEC variations, L'Aquila area, 1-7 Apr 2009
TEC
Unpg
Untr
Aqui
m0se
Paca
EQ
day
1 Apr
2
3
4
5
6
7
8 Apr
0
5
10
15

Fig. 3.

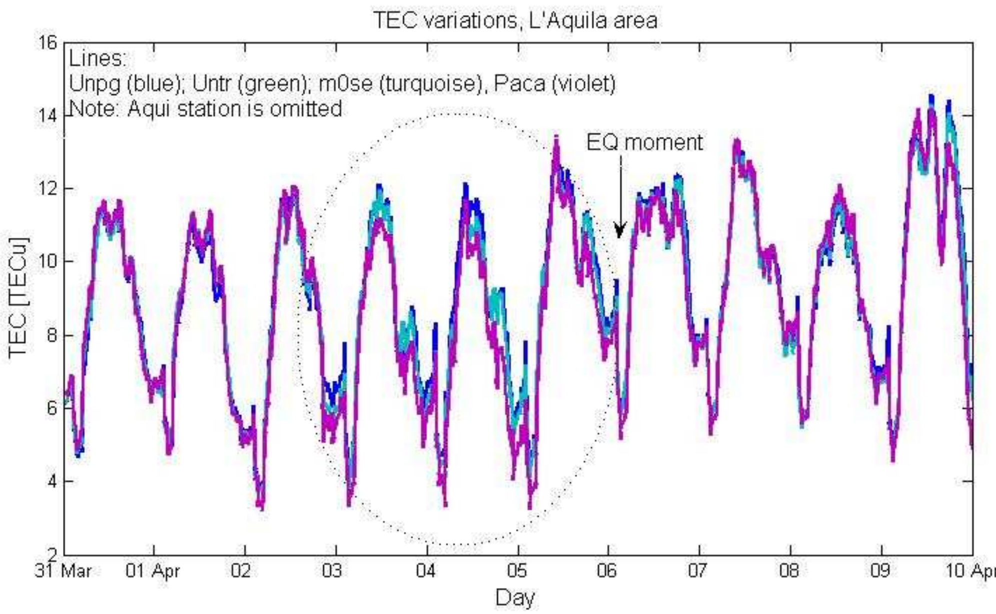
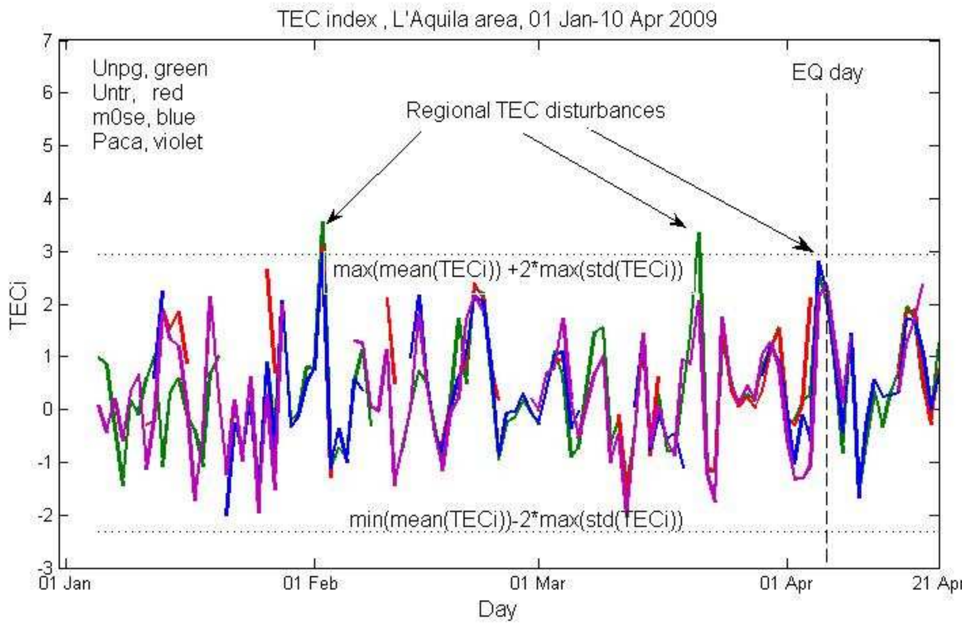

TEC variations, L'Aquila area
Lines:
Unpg (blue); Untr (green); m0se (turquoise), Paca (violet)
Note: Aqui station is omitted
EQ moment
TEC [TECu]
16
14
12
10
8
6
4
2
31 Mar
01 Apr
02
03
04
05
06
07
08
09
10 Apr
Day

Fig. 4.



TEC index , L'Aquila area, 01 Jan-10 Apr 2009
Unpg, green
Untr, red
m0se, blue
Paca, violet
EQ day
Regional TEC disturbances
max(mean(TECi)) +2*max(std(TECi))
min(mean(TECi))-2*max(std(TECi))
TECi
7
6
5
4
3
2
1
0
-1
-2
-3
01 Jan
01 Feb
01 Mar
01 Apr
21 Apr
Day

Fig. 5.

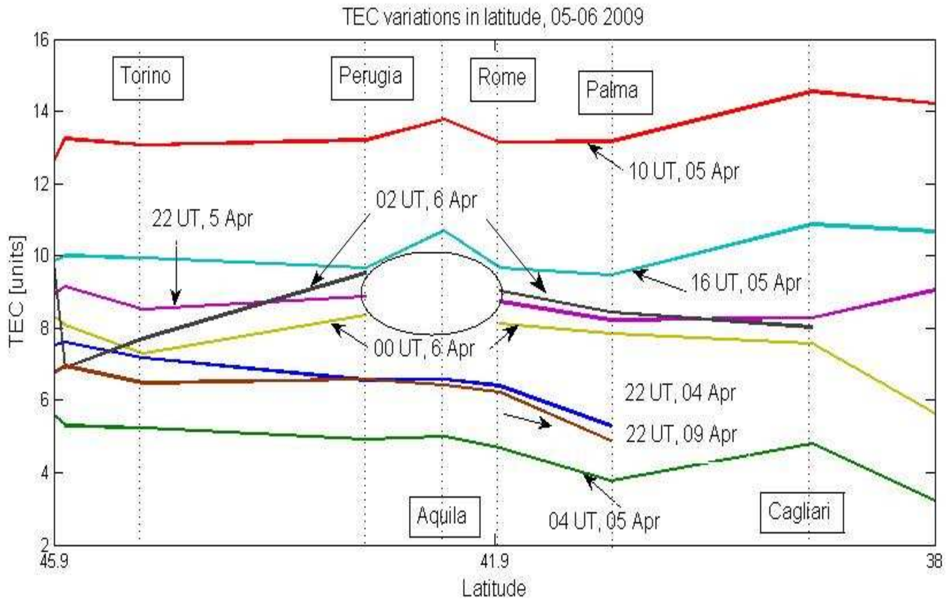

TEC variations in latitude, 05-06 2009
Torino
Perugia
Rome
Palma
10 UT, 05 Apr
02 UT, 6 Apr
22 UT, 5 Apr
16 UT, 05 Apr
00 UT, 6 Apr
22 UT, 04 Apr
22 UT, 09 Apr
Aquila
04 UT, 05 Apr
Cagliari
TEC [units]
Latitude
16
14
12
10
8
6
4
2
45.9
41.9
38

Fig. 6.

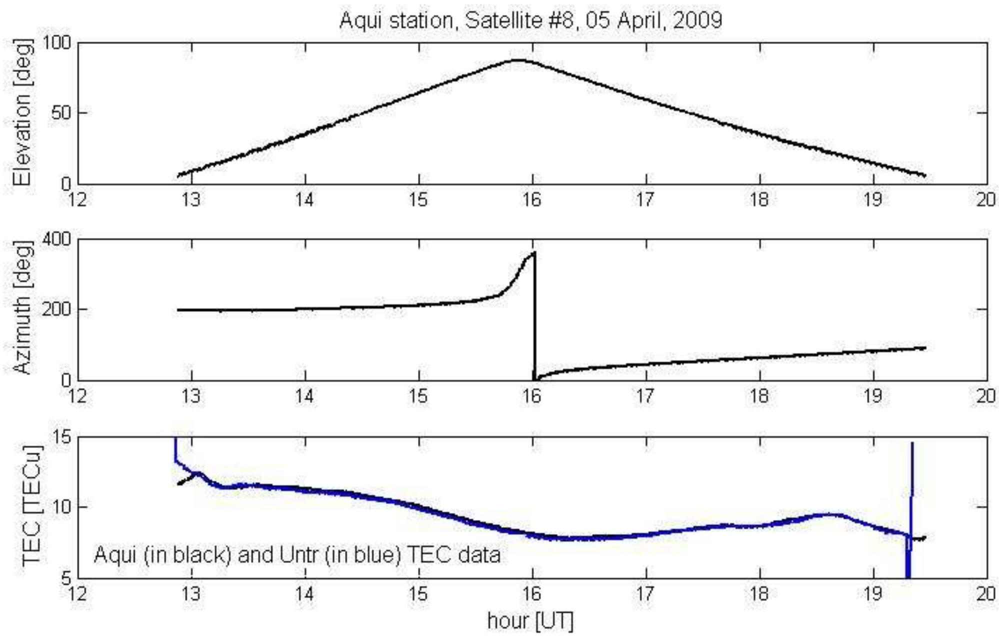

Aqui station, Satellite #8, 05 April, 2009
Elevation [deg]
Azimuth [deg]
TEC [TECu]
Aqui (in black) and Untr (in blue) TEC data
hour [UT]

Fig. 7.

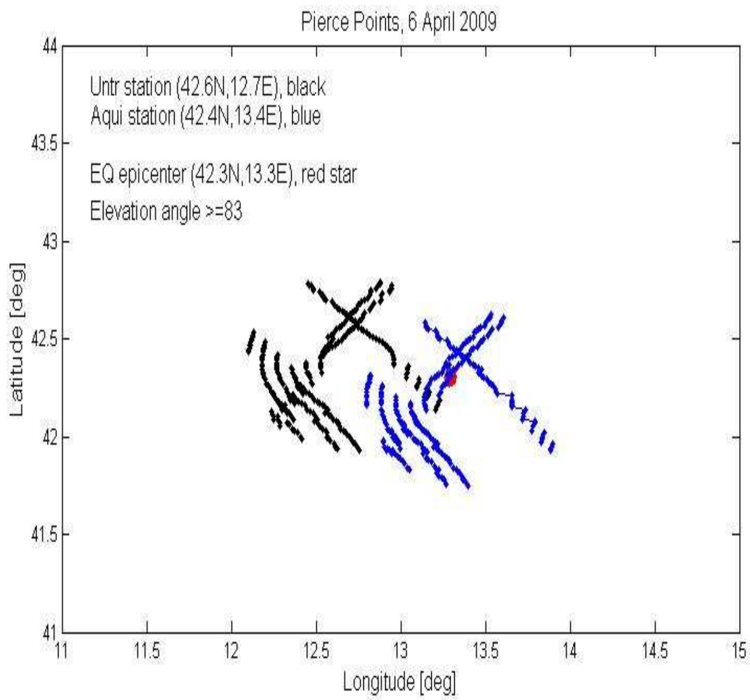

Pierce Points, 6 April 2009
Untr station (42.6N,12.7E), black
Aqui station (42.4N,13.4E), blue
EQ epicenter (42.3N,13.3E), red star
Elevation angle >=83
Latitude [deg]
Longitude [deg]
44
43.5
43
42.5
42
41.5
41
11
11.5
12
12.5
13
13.5
14
14.5
15

Fig. 8.

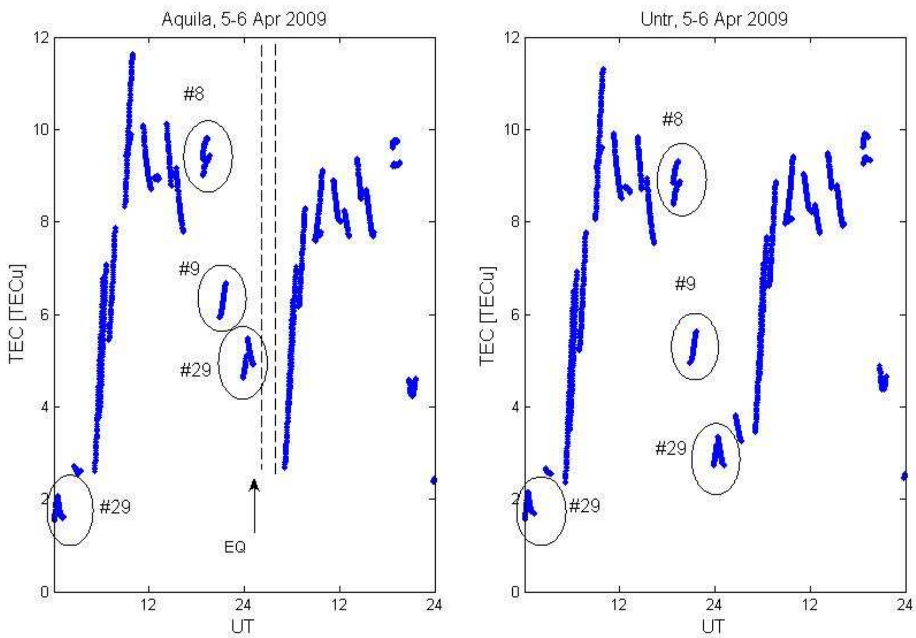

Aquila, 5-6 Apr 2009
Untr, 5-6 Apr 2009
TEC [TECu]
UT
#8
#9
#29
EQ
0
2
4
6
8
10
12
24

Fig. 9a.

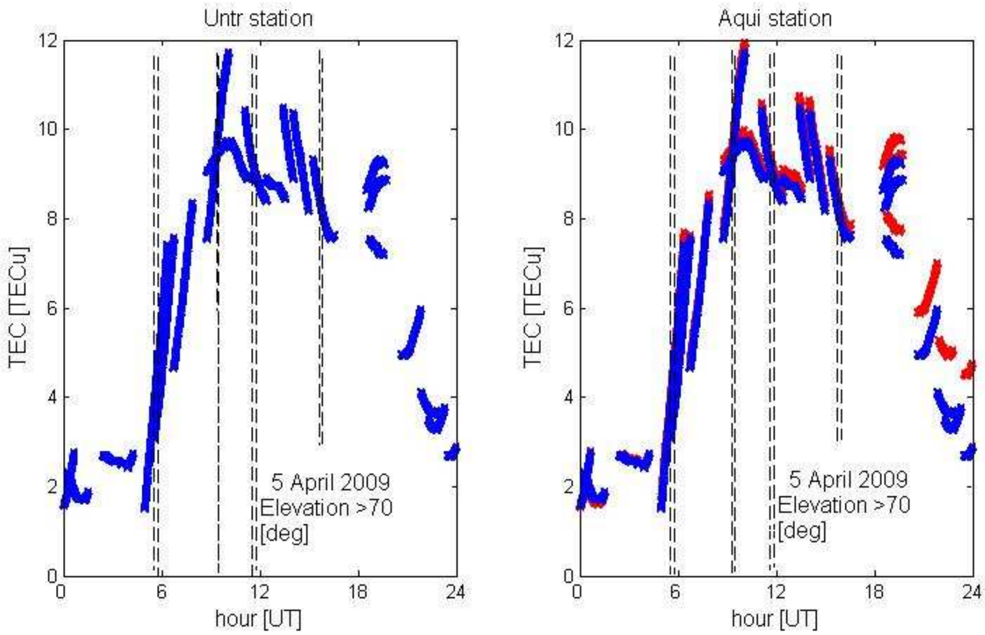

Untr station
Aqui station
TEC [TECu]
hour [UT]
5 April 2009
Elevation >70
[deg]
0
2
4
6
8
10
12
0
6
12
18
24

Fig. 9b.

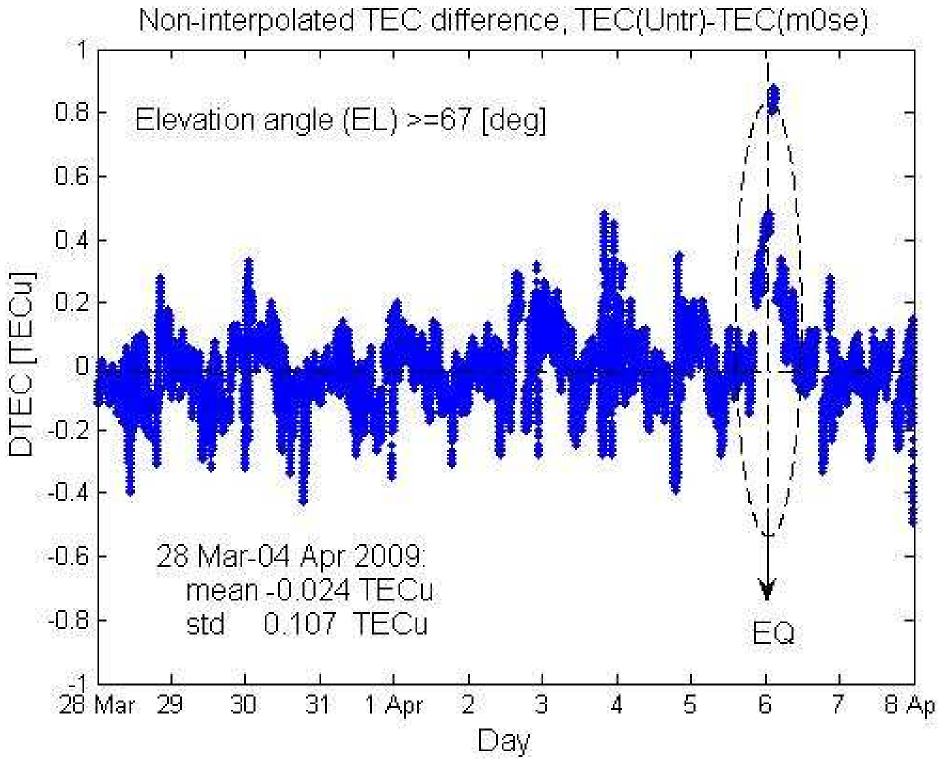

Non-interpolated TEC difference, TEC(Untr)-TEC(m0se)
Elevation angle (EL) >=67 [deg]
28 Mar-04 Apr 2009:
mean -0.024 TECu
std 0.107 TECu
EQ
DTEC [TECu]
Day
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
28 Mar
29
30
31
1 Apr
2
3
4
5
6
7
8 Apr

Fig. 10a.

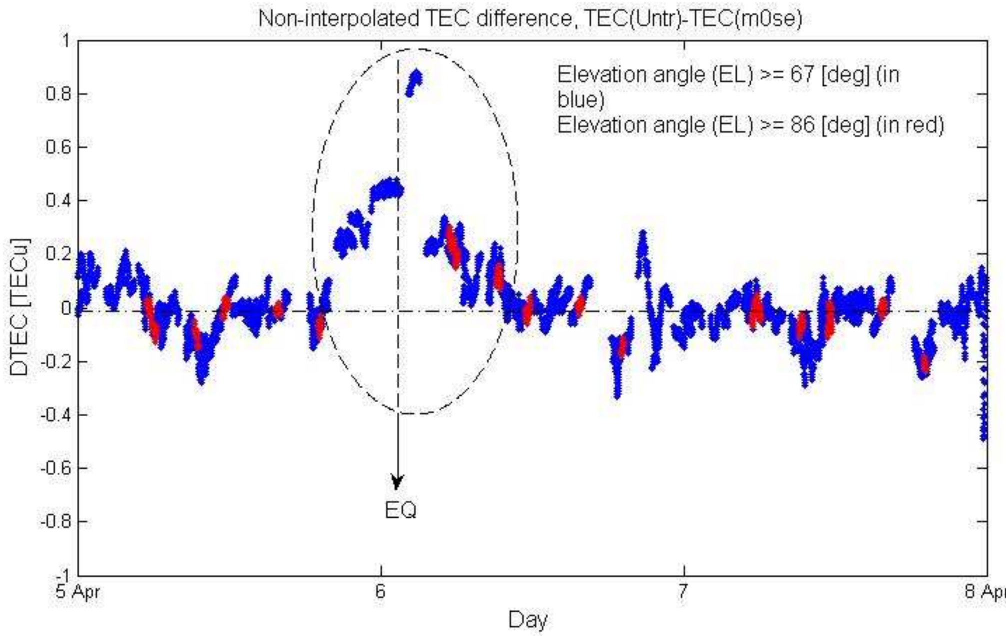

Non-interpolated TEC difference, TEC(Untr)-TEC(m0se)
Elevation angle (EL) >= 67 [deg] (in blue)
Elevation angle (EL) >= 86 [deg] (in red)
EQ
DTEC [TECu]
Day
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
5 Apr
6
7
8 Apr

Fig. 10b.

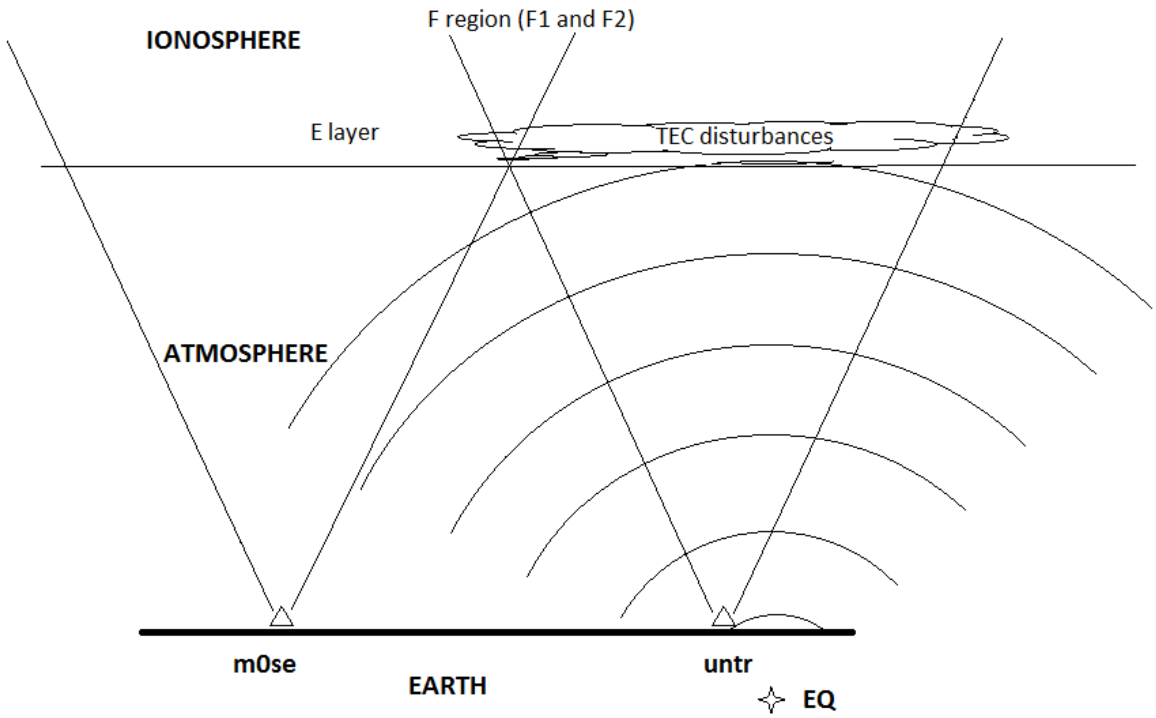

F region (F1 and F2)
IONOSPHERE
E layer
TEC disturbances
ATMOSPHERE
m0se
EARTH
untr
EQ

Fig. 11a.

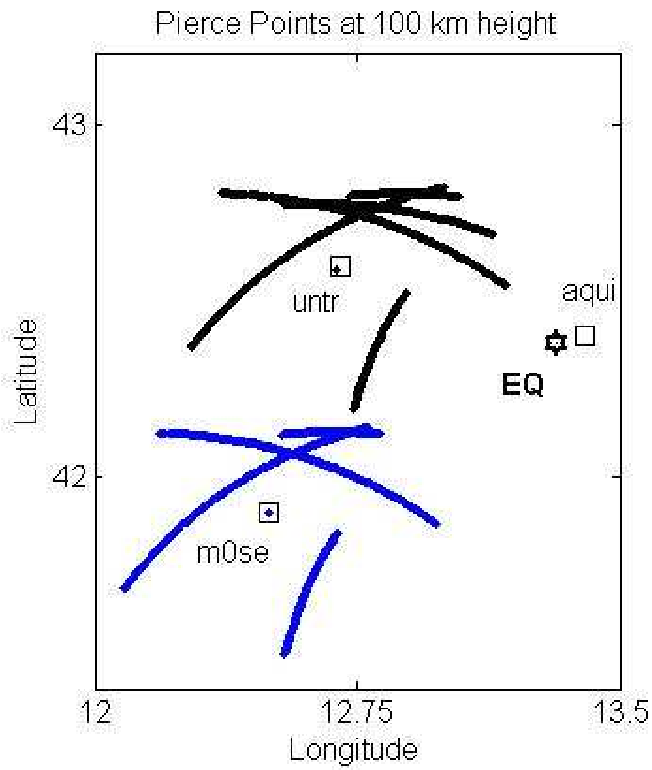

Pierce Points at 100 km height
43
42
Latitude
untr
aqui
EQ
m0se
12
12.75
13.5
Longitude

Fig. 11b.