TEC variations over Mediterranean before and during the strong earthquake (M=6.2) of 12th October 2013 in Crete, Greece

M.E. Contadakis, D.N. Arabelos, G. Vergos, S.D. Spatalas

Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Greece

Abstract

In this paper the Total Electron Content (TEC) data of 8 Global Positioning System (GPS) stations of the EUREF network, which are being provided by IONOLAB (Turkey), were analysed using Discrete Fourier Analysis in order to investigate the TEC variations over Mediterranean before and during the strong earthquake of 12th of October 2013, which occur in western of Crete, Greece. In accordance to the results of similar analysis on the occasion of earthquakes in the area (Contadakis et al 2008; 2012a; 2012b) the main conclusions of this analysis are the following. (a) TEC oscillations in a broad range of frequencies occur randomly over a broad area of several hundred km from the earthquake and (b) high frequency oscillations ($f \geq 0.0003$Hz, periods $T \leq 60$m) seems to point to the location of the earthquake with a questionable accuracy but the fractal characteristics of the frequencies distribution, points to the locus of the earthquake with a rather higher accuracy. We conclude that the LAIC mechanism through acoustic or gravity wave could explain this phenomenology.

Key words: GPS network, ionospheric total electron content, wavelet analysis

1. Introduction

It is generally accepted by the scientific community that tectonic activity resulting to earthquakes induces variations in earth ionosphere by means of the so called Lithosphere -Atmosphere- Ionosphere mechanism (Molchanov et al. 2004; Molchanov et al. 2008; Korepanov et al 2009). This strong opinion emerged from the results of a great amount of research done by means of ground- based experiments (Molchanov et al. 2004; Molchanov et al. 2005; Roznoi et al. 2004; Roznoi et al. 2009; Biagi et al. 2009; Hayakawa 2013), Space-born studies (Parrot 2006; Hayakawa et al. 2000) and combined space- born and ground- based studies (Roznoi et al. 2007; Muto et al. 2008, Boudjada et al. 2013) as well. Finally The development of GPS and GLONASS satellite systems provide a perfect opportunity for a simultaneous inspection of TEC variations over a great number of locations around the earth and furthermore to investigate any interrelation of these variations or isolate variations of TEC which may occur over a particular site with enhanced tectonic activity. A lot of work has also be done in this direction (see for instance Afraimovich et al. 2001; Afraimovich et al. 2002; Akhoondzadeh et al. 2010; Akhoondzadeh 2012; Contadakis et al. 2008; Contadakis et al. 2012a; 2012b). These studies indicated that over a broader area over the site where a strong earthquake occur (magnitude >5.5) uneven variations of TEC are observed. Recently some researchers criticize the conception on ionospheric precursors to earthquakes as it is deduced from Observational Data of low accuracy and resolution in conditions of Moderate Geomagnetic activity (Afraimovich et al., 2004, Dautermann et al., 2007; Astafyeva et al., 2011; Thomas et al., 2012; Masci 2012)

In this paper the Total Electron Content (TEC) data of 8 Global Positioning System (GPS) stations of the EUREF network (http://www.epncb.oma.be) which are being provided by IONOLAB (http://www.ionolab.org) were analysed using Fast Fourier Transform Analysis in order to investigate the TEC variations over the Mediterranean before and during the seismic activity of 12 of October, 2013 westward of Chanea of Crete, Greece.

2. The seismic activity west of Chanea in October of 2013

The Hellenic Arc, been the margin along which the collision between the Eurasian and the Mediterranean plates takes place, is dominated by low-angle thrust faults. Such a thrust-faulting zone, following the Hellenic trench, is located at the south-western part of this margin (Papazachos and Delibasis, 1969). The faults of this zone, exhibiting NW-SE direction and dipping towards NE, that is, towards the concave side of the arc (Aegean), are responsible for the generation of strong, mostly shallow, earthquakes. Figure 1, quoted from Papazachos et al. (1998) displays the main morphotectonic characteristics and Figure 2, quoted from Papazachos et al. (1999) displays the main faulting zones and faulting type in the area of Greece. The earthquake of the October 12, 2013, M=6.5 (Figure 3) was generated by a thrust fault striking NW-SE with right-lateral component (az=340^0, Dip=3^0, Rake=130^0 according to GCMT). The seismic fault is located at a relatively small depth at the early stage of the formation of the Wadati-Benioff zone (Papazachos and Comninakis, 1970, 1971; Papazachos et al., 2000; Scordilis 2013 (private comunication) which is propagating at bigger depths to the NE. Table 1 displays the seismic sequence of this earthquake as it is quoted from the Geodynamic Institute of NOA (http://www.gein.noa.gr/services/cat.html).

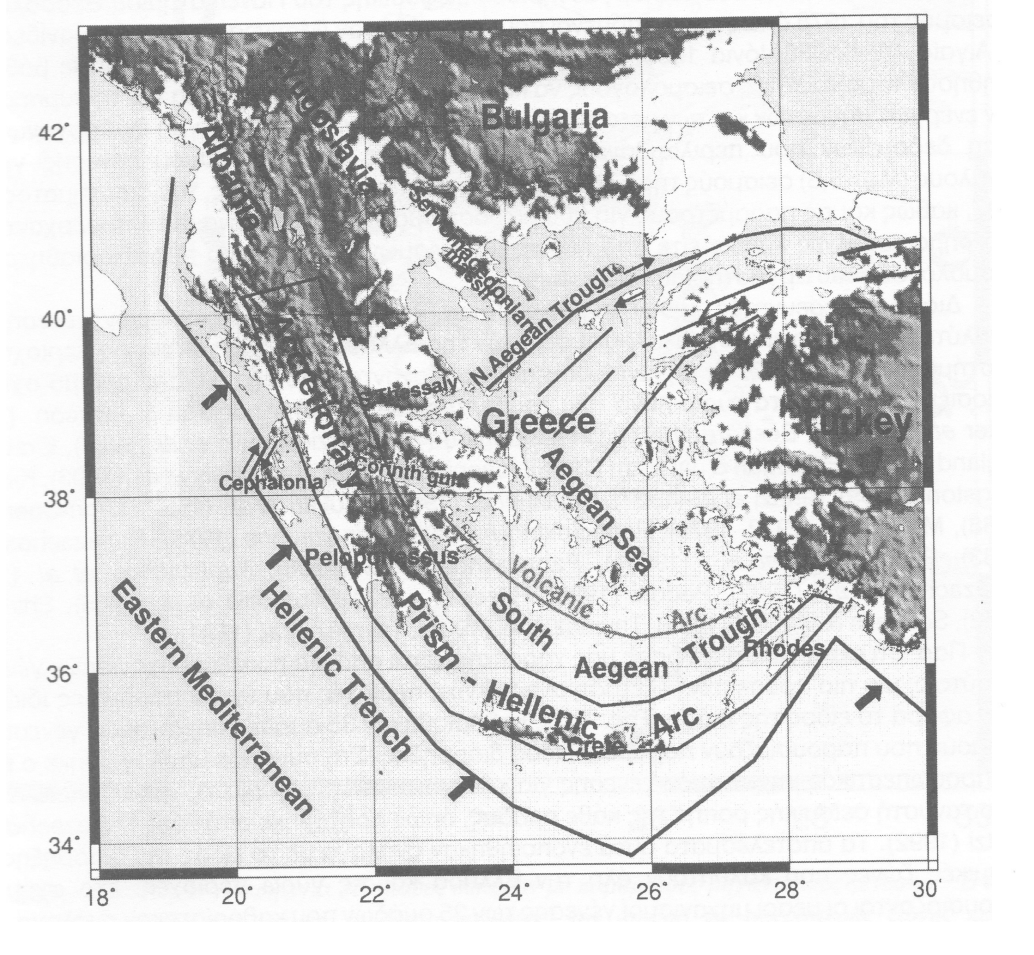

Figure 1. The main morphotectonic characteristics of the broader area of Greece. (Papazacos et al. 1998)

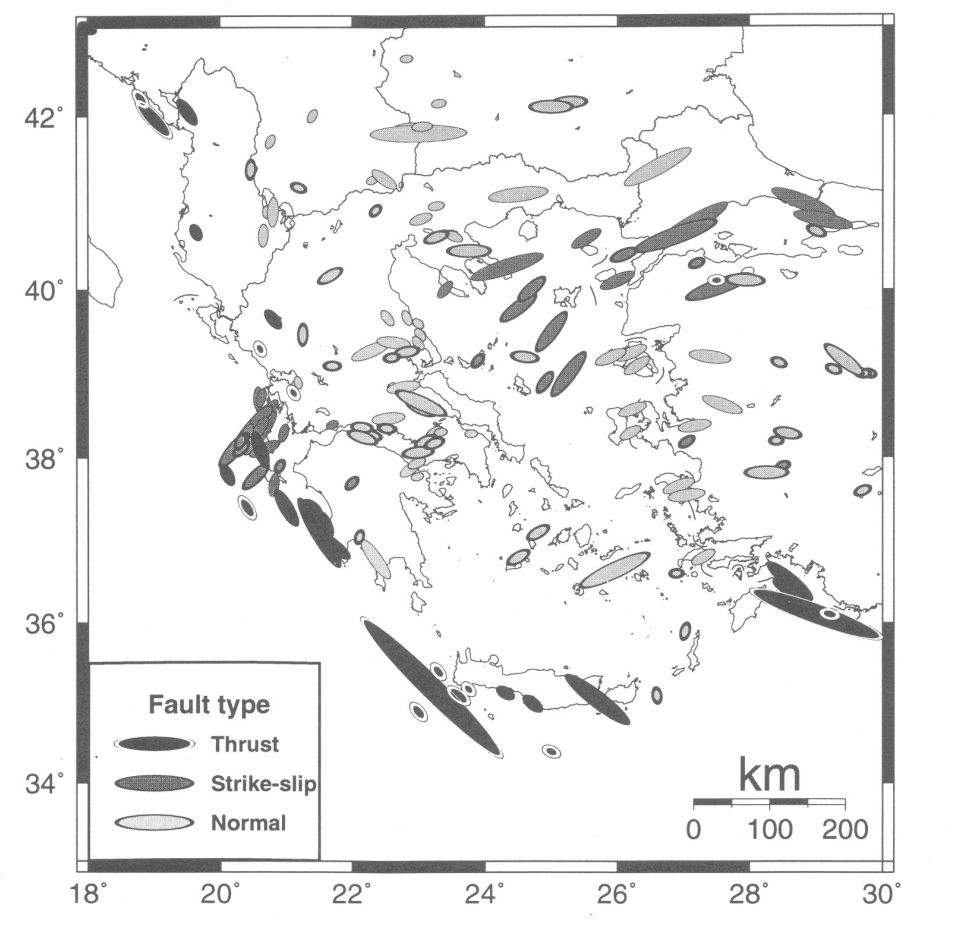

Figure 2. Rapture zones in the area of Greece (Papazachos et al. 1999)

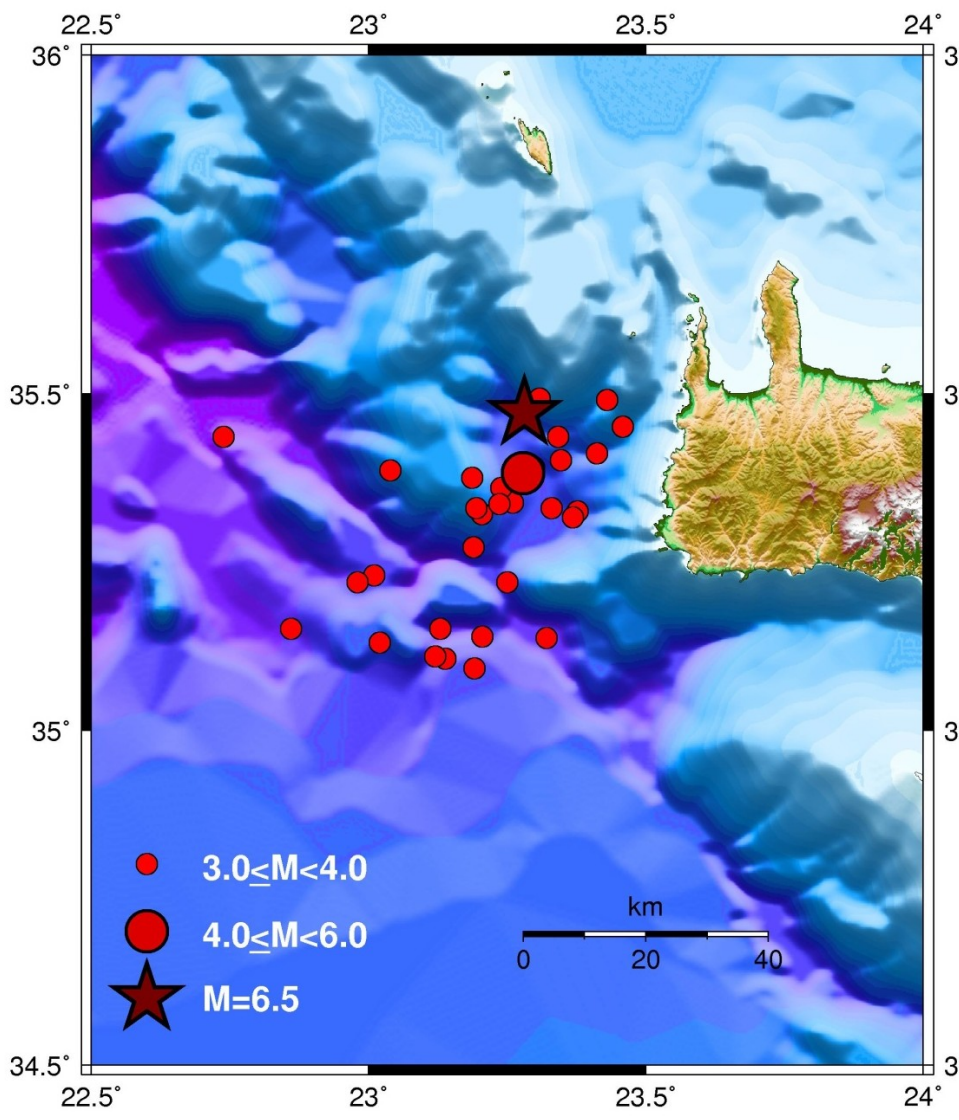

Figure 3. Geographical distribution of the aftershocks (which were recorded up to the end of November 2013, red circles) of the October 12, 2013, M=6.5 mainshock (denoted by a star) which occurred in the SW part of the Hellenic arc, ~20km off the west coast of Crete

3. The data

3.1 TEC values

In this paper we are interesting in the variation of TEC over the Mediterranean before and during the seismic activity of 12th of October so we use the TEC estimates provided by IONOLAB (http://www.ionolab.org) (Arikan et al. 2009) for 8 mid latitude GPS stations of EUREF which cover epicentral distances from the active area ranging from 650km to 2500km for the time period between 28/09/2013 and 15/10/2013. The selected GPS stations have about the same latitude and are expected to be affected equally from the Equatorial Anomaly as well as from the Auroral storms.

Table 1: Earthquake activity in October of 2013 west of Chanea of Creta, Greece

Date and time (GMT)	Epicenter	λ (deg)	φ (deg)	Depth (km)	ML
2013/10/20 04:49:48	47.4 km W of Chanea	35.44	23.50	48	3.4
2013/10/19 03:39:58	57.5 km W of Chanea	35.50	23.38	47	3.1
2013/10/19 02:19:20	64.8 km W of Chanea	35.50	23.30	57	3.6
2013/10/16 13:47:59	53.1 km W of Chanea	35.42	23.44	44	3.5
2013/10/13 17:43:50	73.4 km WSW of Chanea	35.35	23.23	41	3.9
2013/10/13 13:12:24	66.9 km WSW of Chanea	35.18	23.40	21	3.0
2013/10/13 03:43:12	63.1 km W of Chanea	35.47	23.32	54	3.1
2013/10/13 00:01:23	56.5 km W of Chanea	35.43	23.40	56	3.4
2013/10/12 19:39:29	73.0 km W of Chanea	35.49	23.21	34	3.1
2013/10/12 19:36:25	66.7 km W of Chanea	35.41	23.29	55	3.5
2013/10/12 15:27:04	66.0 km W of Chanea	35.40	23.30	44	3.4
2013/10/12 14:57:06	74.3 km WSW of Chanea	35.35	23.22	33	3.1
2013/10/12 14:05:50	57.5 km W of Chanea	35.50	23.38	50	3.8
2013/10/12 13:55:28	62.4 km WSW of Chanea	35.34	23.36	29	3.2
2013/10/12 13:40:36	61.5 km WSW of Chanea	35.34	23.37	30	3.0
2013/10/12 13:33:09	68.2 km WSW of Chanea	35.38	23.28	30	3.0
2013/10/12 13:11:53	66.6 km W of Chanea	35.50	23.28	65	6.2
2013/10/05 17:42:32	75.5 km SW of Chanea	35.00	23.47	34	3.2
2013/10/02 03:28:12	60.5 km W of Chanea	35.56	23.35	43	3.0

Table 2 displays the 8 EUREF stations while Figure 4 displays the locus of the eight GPS stations and the main shock. The IONOLAB TEC estimation system uses a single station receiver bias estimation algorithm, IONOLAB-BIAS, to obtain daily and monthly averages of receiver bias and is successfully applied to both quiet and disturbed days of the ionosphere for station position at any latitude. In addition, TEC estimations with high resolution are also possible (Arikan et al. 2008). IONOLAB system provides comparison graphs of its TEC estimations with the estimations of the other TEC providers of IGS in its site.. In this work only TEC estimations in perfect accordance among all providers were used. The TEC values are given in the form of a Time Series with a sampling gap (resolution) of 2.5 minutes.

Table 2: The Euref stations

No	GPS Station	Distance (km)	Longitude (deg)	Latitude (deg)	Location
1	MAD	2506.9469	-3.7143	40.4180	Madrit(Spain)
2	EBRE	1879.4657	2.6000	36.7667	Yebes(Spain)
3	NOT1	766.7702	14.9898	36.8759	Sicily(Italy)
4	MATE	826.8452	16.7045	40.6491	Matera(Italy)
5	ORID	664.4125	20.8019	41.1172	Ohrid(FYROM)
6	ANKR	988.1607	32.7586	39.8875	Ankara(Turkey)
7	NICO	914.8816	33.3667	35.1667	Nicosia(Cyprus)
8	ZECK	1870.7057	41.5700	43.2900	Zelenchukskaya(Russia)

3.2 Geomagnetic and Solar activity indices

The variations of the geomagnetic field were followed by the Dst-index and the planetary kp three hour indices quoted from the site of the Space Magnetism Faculty of Science, Kyoto University (http://swdcwww.kugi.kyoto-u.ac.jp/index.html) for the time period of our data. Figure 5 displays the Dst-index variations on October of 2013. From this figure it is seen that Dst index is mostly 0 and only on 2 and 9/10/2013 significant disturbances with |Dst|<60nT are present. Also Auroral Electrojets were rare and. only on 2 and 9 of October substorms with magnitude of 1500nT and 1000nT respectively.were observed. The earthquake epoch fall in the midle of the solar activity cycle. The daily Solar Spot Number as it quoted from Boudler NOA range from 35 to 45 untill 08/10 and rased to 90 from 09/10 and later on. It can be seen that the planetary conditions are not favourable for the identification of possible TEC variations of non planetary origin for the days of 02/10/and 09/10/2013. These days were excluded.

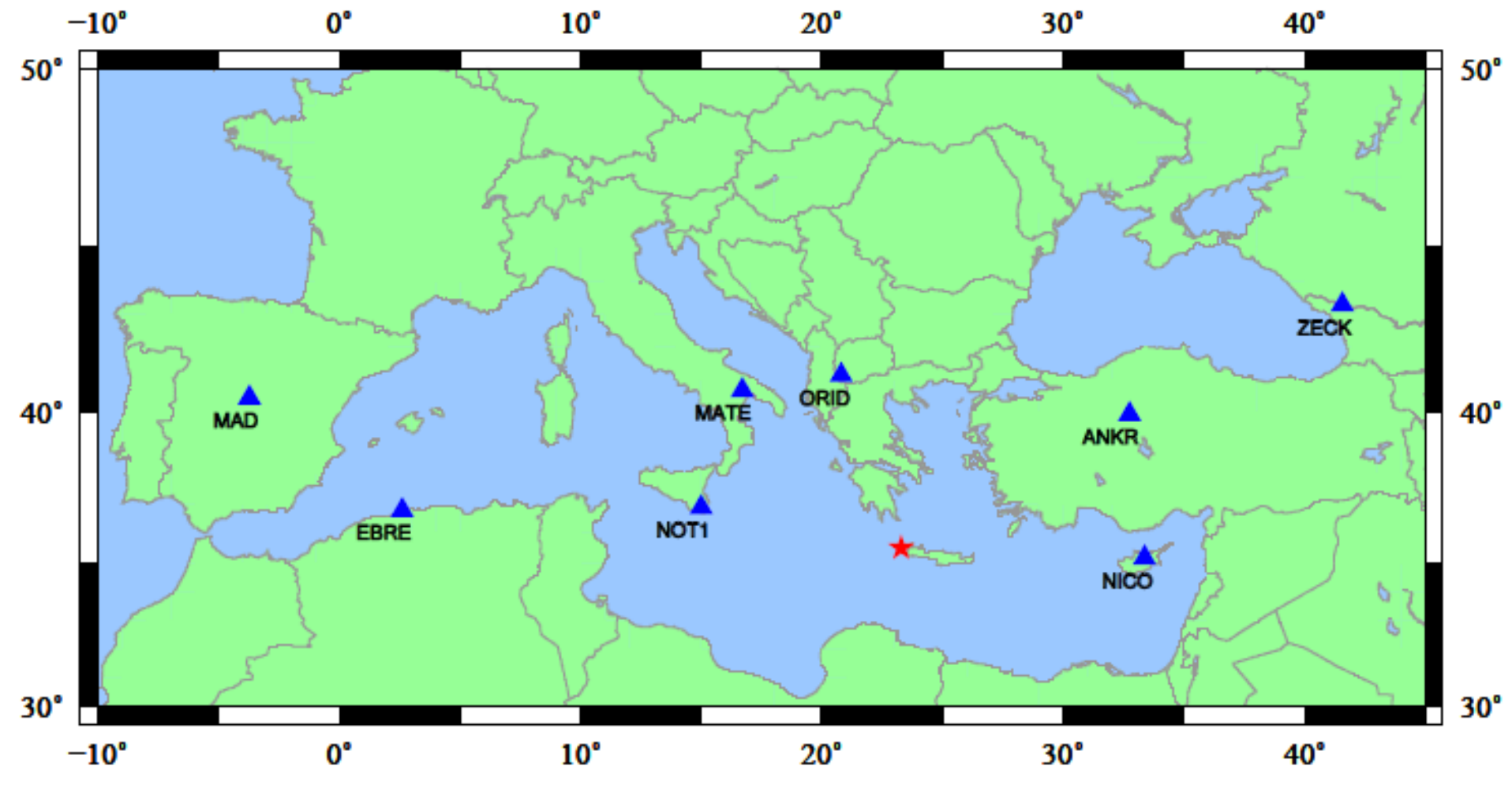

Figure 4. The locations of GPS stations (blue triagles) and the epicenter of the main shok (red star)

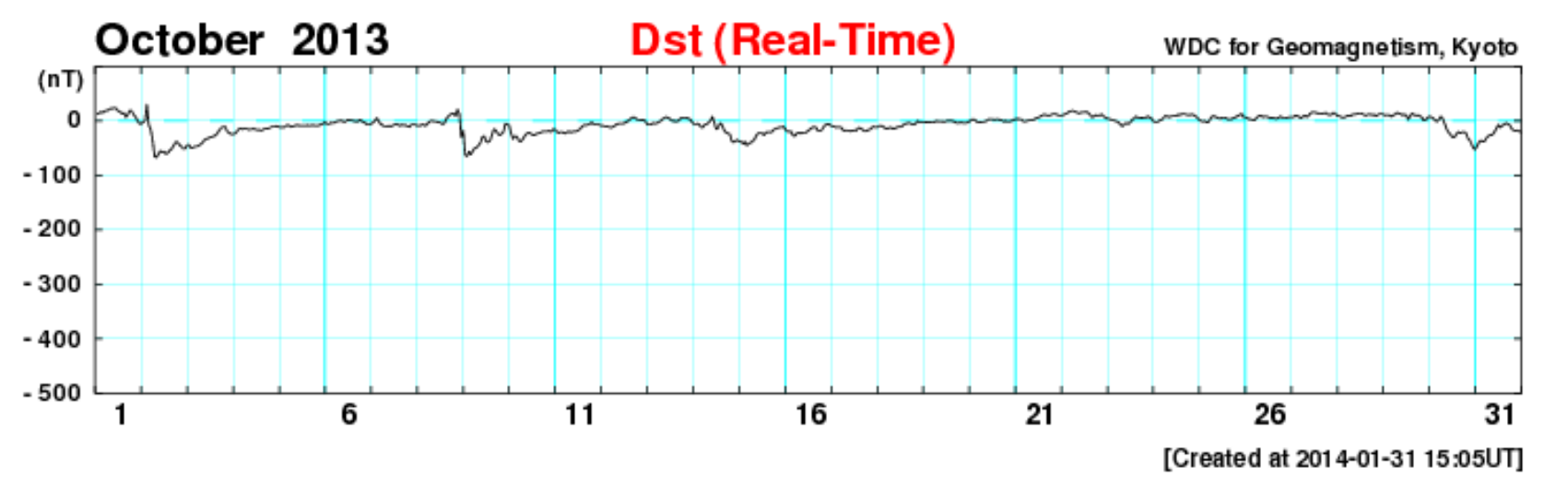

Figure 5. Dst-index variations on October of 2013

4. Data analysis

The data consist of TEC values sampled every 2.5 minutes for each station and for the time interval between 28/09/2013 and 15/10/2013. In order to find any peculiar variation of TEC over the stations of this study, which may potentially be connected with the tectonic activity of the Mediterranean we first compare the variations over all the EUREF stations for this time period. To facilitate this procedure the residuals of the TEC's from the 16days mean for all the stations and for the 16 days of our program were computed (we remind that two days were excluded from the analysis).Then we analyze the data time series using Fast Fourier Transform Analysis for a finer investigation.

5. Results

5.1 The overall variation of TEC

The variation of TEC over the 8 EUREF stations for the time period from 28/09/2013 to 15/10/2013 is shown in Figure 6. Inspecting the day-night TEC variations of each station during the above time period we realize that for the stations with epicentral distance smaller than 900km and for the time period from 08/10/2013 to 15/10/2010, the day time TEC values are increased while no morning or evening extensions comparing with the mean day time TEC duration for each station were observed. As an example Figure 7 displays the daily TEC variation over Mate station for the days 10,11 and 12/10/2013 and the mean daily variation for all 16 days. It is seen that the exalting range from 2 to 6 TECU and are higher on 11/10/2013. This exalting decreases with epicentral distance. This is shown in Figure 8 where the daily mean TEC residuals from the 16 days mean daily TEC for 10,11,12/10/2013 and for the nearest (Orid) and remote (Mad)GPS station are being displayed. Figure 9 displays the decrease of the mean residuals for the same days.

Similar phenomena have been reported by many scientists in the case of strong earthquakes (see for instance Akhoondzadeh 2012). These phenomena may be explained by the transmission of the lithospheric perturbations through a LAIC mechanism in the ionosphere which influences the turbidity and ionization of all ionospheric layers. According to Liperovski et al. (2005) thermal, pressure and ionic variations generated at the ground level as a result of the tectonic stresses in an earthquake preparation period, propagate upward through the atmosphere as acoustic or standing gravity waves and produces modification of the turbulization of the lower ionosphere.

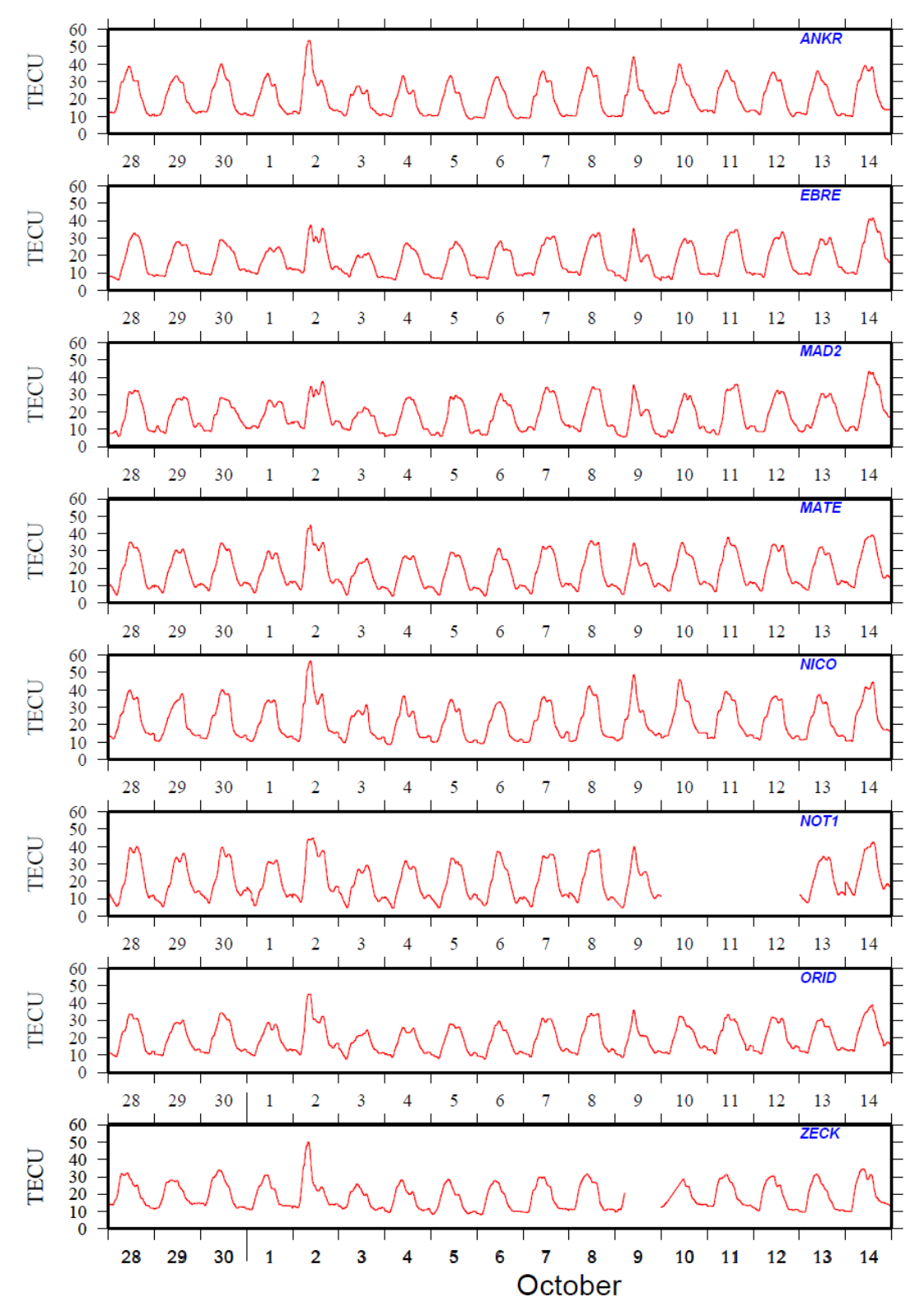

Figure 6 . TEC variations over the eight stations in the period 28/09/2013 to

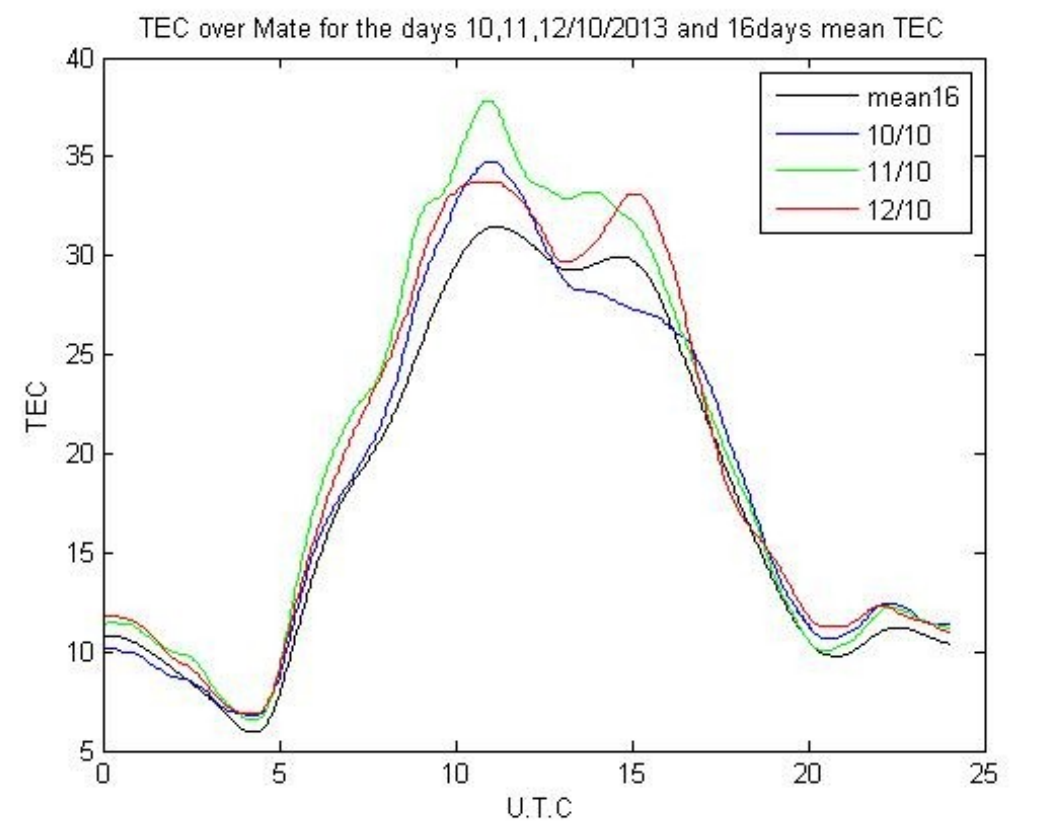

Figure 7. Daily TEC variation over Mate for the days 10,11,12/10/2013 and the Mean TEC variation for the 16 days of the program.

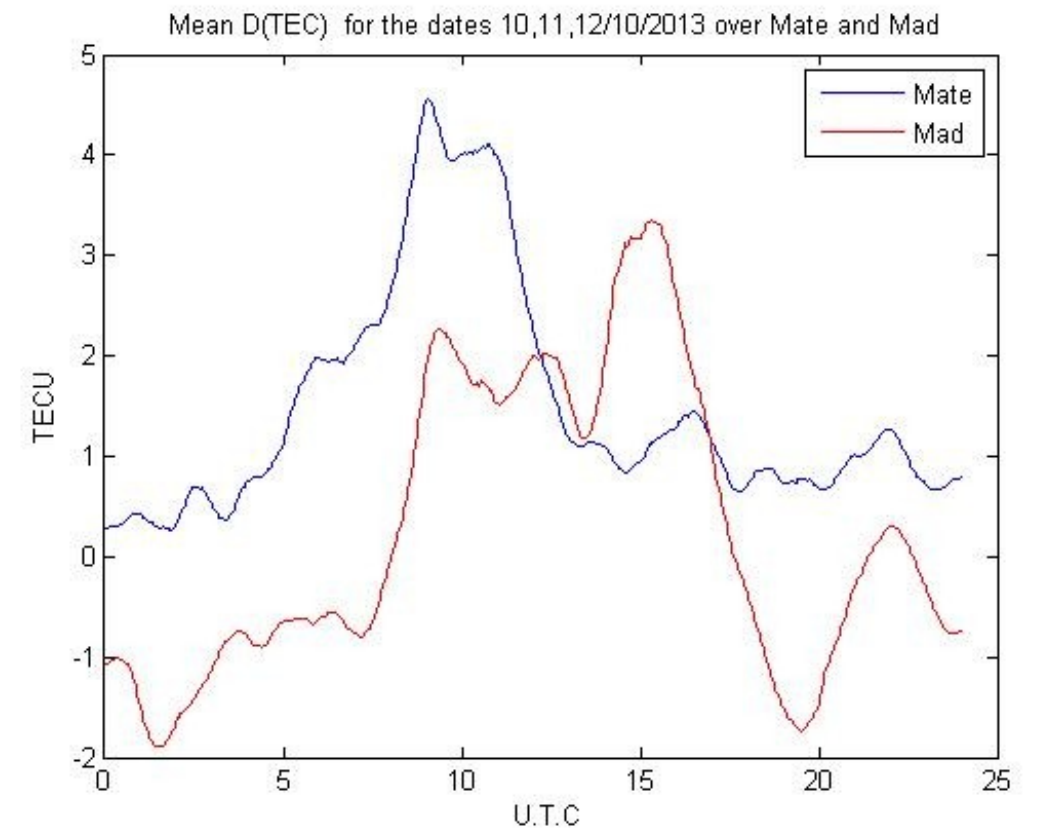

Figure 8. Mean TEC residuals for the dates 10,11,12/10/2013 over the stations Mate and Mad

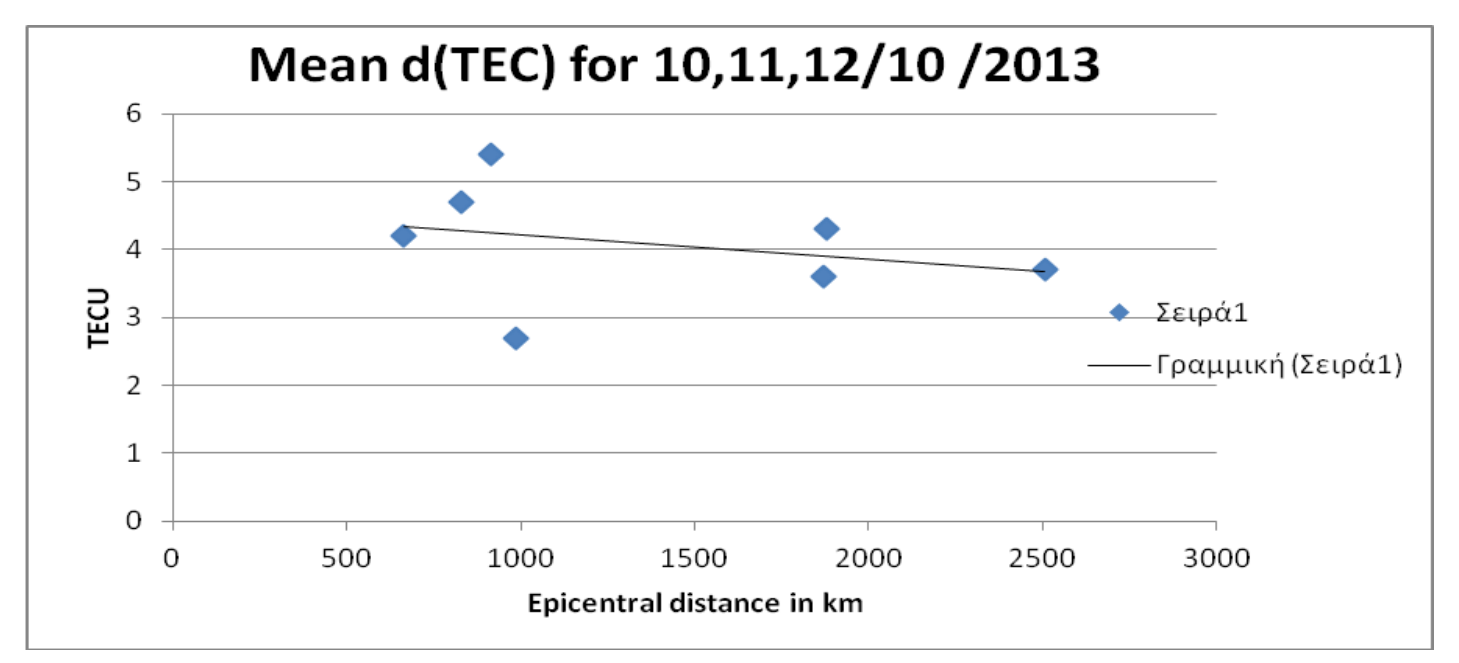

Figure 9. Variation of mean TEC residuals with epicentral distance.

5.3 Fast Fourier Transform Analysis

The Power Spectrum of TEC variations will provide information on the frequency content of them. Apart of the well known and well expressed tidal variations, for which the reliability of their identification can be easily inferred by statistical tests, small amplitude space-temporal transient variations cannot have any reliable identification by means of a statistical test. Nevertheless looking at the logarithmic power spectrum we can recognize from the slop of the diagram whether the contributed variations to the spectrum are random or periodical. If they are random the slop will be 0, which correspond to the white noise, or -2 which correspond to the Brownian walk, otherwise the slop will be different the so called Fractal Brownian walk (Turcotte, 1997). This means that we can trace the presence of periodical variations in the logarithmic power spectrum of TEC. This method was successfully applied in a previous work (Contadakis et al. 2008, Contadakis et al. 2012a, Contadakis et al. 2012b). As an example Figure 10 displays the logarithmic power spectrum of TEC over Mad (Spain) on the 10/10/2013. It is realized that the spectrum of TEC variations over Mad contain random variations in the high frequency part ($f > 0.0003033$ Hz, period < 50.50 minutes) and periodical variations in the low frequency part ($f < 0.0003033$ Hz, period > 50.50 minutes).

This is a typical logarithmic power spectrum of TEC, and we have seen that we can trace the presence of periodical variations. The breaking point on the diagram indicates the limited frequency below of which (or correspondently the limited period above of which) periodical variations of TEC exist.

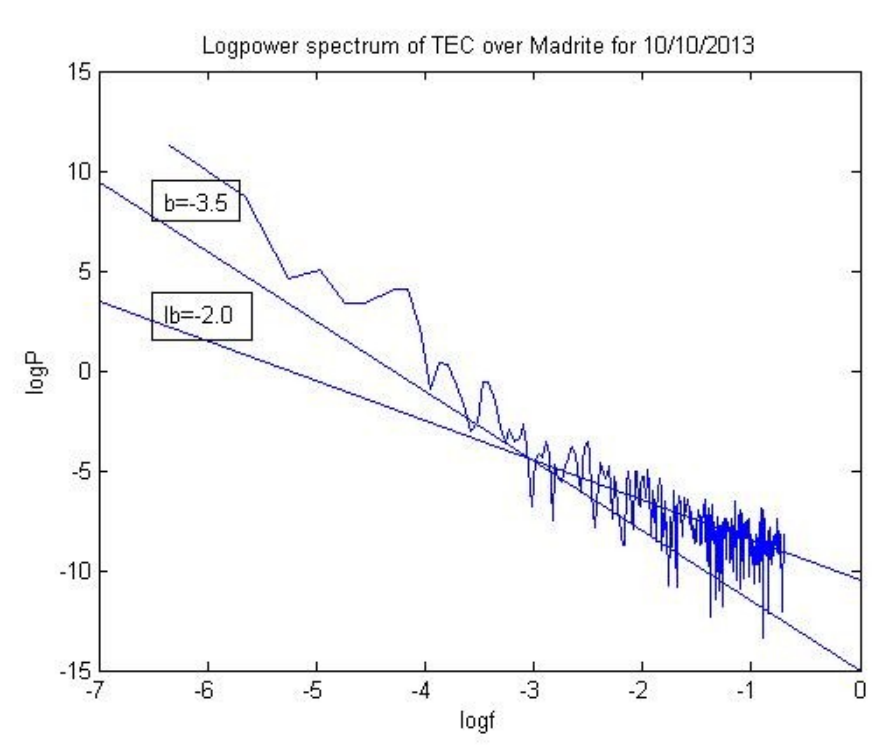

Figure 10. Logarithmic power spectrum of TEC over Mad on 10/10/2013

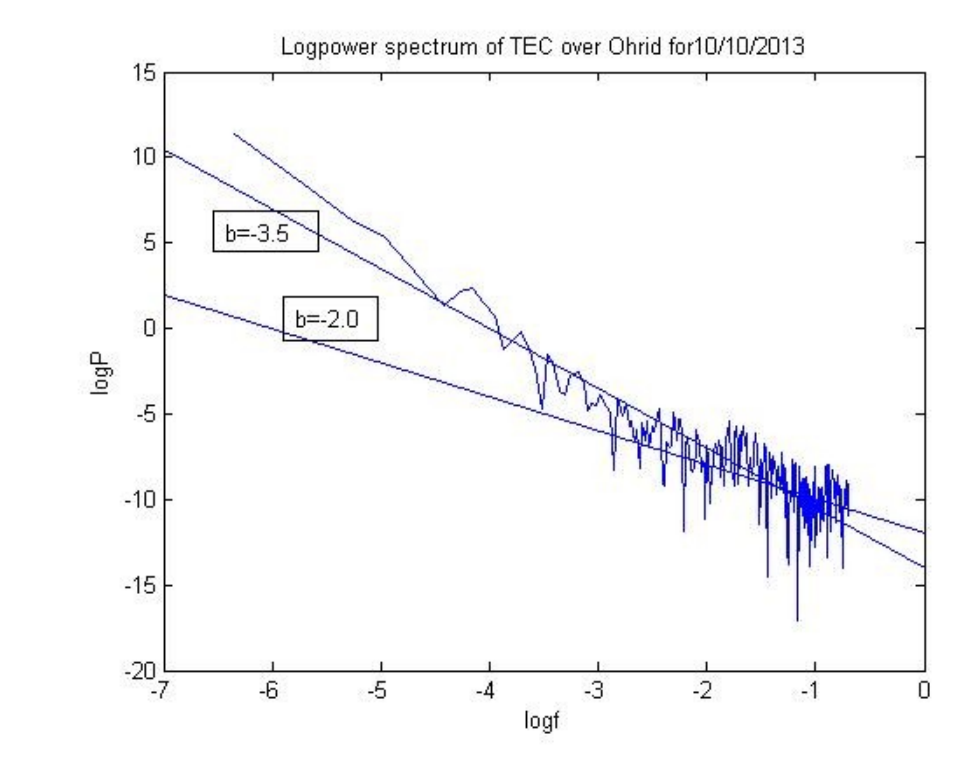

Figure 11. Logarithmic power spectrum of TEC over Orid on 10/10/2013

As it is shown in previous studies (Contadakis et al 2012a,b) It is realized that the limited period of TEC variations become smaller and smaller as long as we approach the earthquake epicentre. This means that the frequency content of TEC variation is extended to higher frequencies (i.e shorter wavelengths) as we approach the epicentre. This is shown in Figure 11, which display for a comparison the logarithmic power spectrum of TEC variations over Ohrid, the closest Station to the epicentre on 10/10/2013.(limited frequency f = 0.0018 Hz, period =9.17 minutes, to be compared with that of a remote station i.e. Figure 10).This is shown also in Figure 12,which displays the mean limited period variation with epicentral distance.

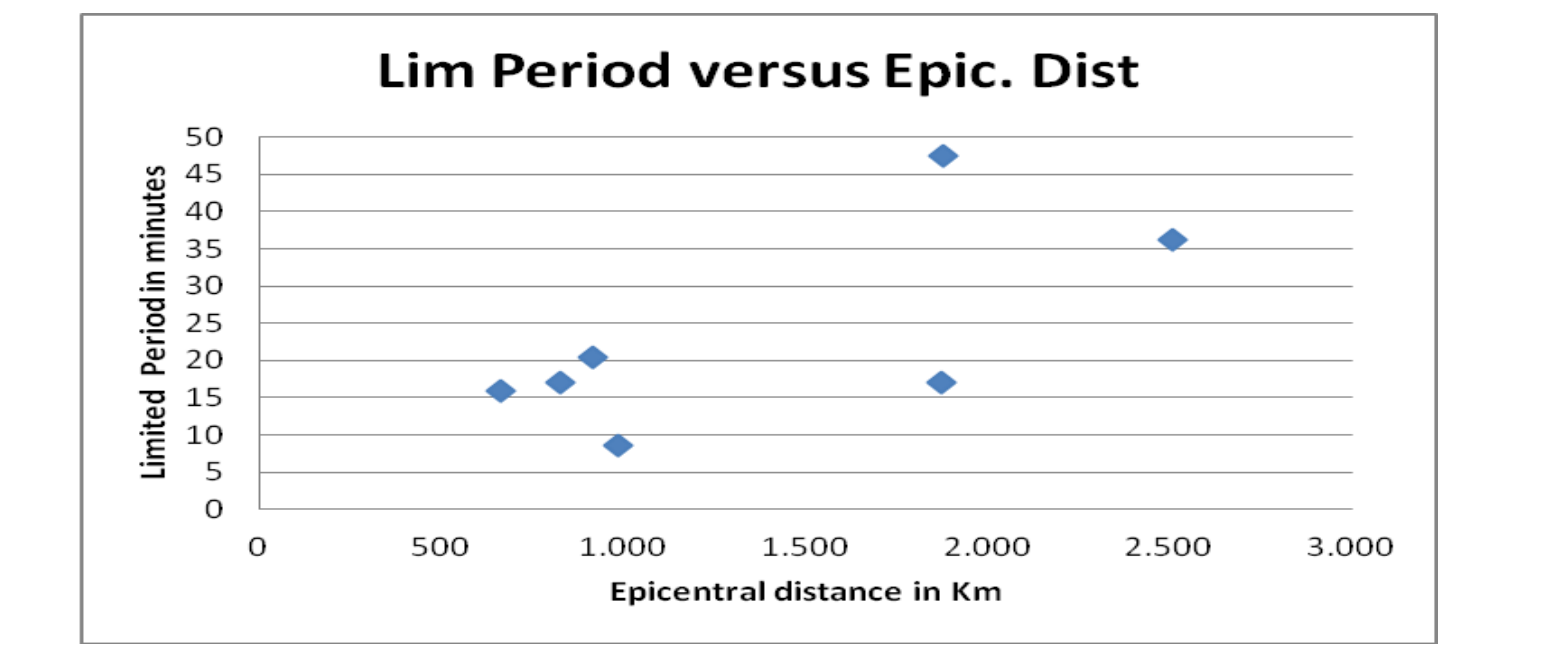

Figure 12. Variation of mean limited period for 10,11,12/10/2013 with the Epicentral distance

The qualitative explanation of this phenomenology can be offered on the basis of the LAIC model which we have used in order to explain the respective TEC exalting for the 3 last days before the earthquake: Tectonic activity during the earthquake preparation period produces anomalies at the ground level which propagate upwards in the troposphere as Acoustic or Standing gravity waves (Hayakawa et al. 2011, Hayakawa 2011). These Acoustic or Gravity waves affect the turbidity of the lower ionosphere, where sporadic Es-layers may appear too, and the turbidity of the F layer, where complete disorganization of the gravity waves at the point of the arrival of the standing wave occurred. Therefore the logarithmic power spectrum of TEC variations shows a random pattern over all the frequencies. Subsequently the produced disturbance starts to propagate in the ionosphere's waveguide as gravity wave and the inherent frequencies of the acoustic or gravity wave can be traced on TEC variations (i.e. the frequencies between 0.0003Hz (period 5min) and 0.002Hz (period 100min)), which according to Molchanov et al. (2004, 2006) correspond to the frequencies of the turbulent induced by the LAIC coupling process to the ionosphere). As we move far from the disturbed point, in time or in space, the shorter wavelength variation is progressively attenuated. This fact is clear from Figure 12.

6. Concluding Remarks

The Analysis of TEC variations over 8 mean latitude EUREF GPS stations during the month of the seismic activity of the Creta, Greece, indicate that TEC oscillations in a broad range of frequencies occur randomly over a broad area of several hundred km from the earthquake while exalting of 2-6 TECU in TEC values from 10/10 to 15/10/2013 is also observed from all the stations of the program. The attenuation of the high frequency oscillations ($f \geq 0.0003$Hz, periods $T \leq 60$min) seems to point to the location of the earthquake. That is the more distant the station the higher frequency (i.e. shorter period) constituent are missing from the TEC disturbances. We conclude that the LAIC mechanism through acoustic or gravity waves could explain this phenomenology.

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3 Method of analysis

In order to check the possible correlation between Earth tides and earthquake occurrence we check the time of occurrence of each earthquake in relation to the sinusoidal variation of Earth tides and investigate the possible correlation of the time distribution of the earthquake events with Earth tides variation. Since the periods of the Earth tides component are very well known and quite accurately predictable in the local coordination system we assign a unique phase angle within the period of variation of a particular tidal component, for which the effect of earthquake triggering is under ivestigation, with the simple relation:

, (1)

where f_i = the phase angle of the time occurrence of the i earthquake in degrees,
t_i = the time of occurrence of the i earthquake in Modified Julian Days (MJD),
t_o = the epoch we have chosen in MJD,
T_d = the period of the particular tidal component in Julian Days.

We choose as epoch t_o, i.e. as reference date, the time of the upper culmination in Thessaloniki of the new moon of January 7, 1989 which has MJD = 47533.8947453704. Thus the calculated phase angle for all the periods under study has 0 phase angle at the maximum of the corresponding tidal component (of course M2 and S2 has an upper culmination maximum every two cycles). As far as the monthly anomalistic moon concern the corresponding epoch t_o is January 14, 1989 which has MJD = 47541.28492.

We separate the whole period in 12 bins of 30° and stack every event according to its phase angle in the proper bin. Thus we construct a Cumulative Histogram of earthquake events for the tidal period under study.

A crucial point of this analysis is the use of a proper statistical test which will give us arguments to decide if such a result is correct or not i.e. will provide us a proper confidence level to our decision. To this purpose we use the well known Shuster's test (Shuster 1897, see also Tanaka et al. 2002; 2006 and Cadicheanu et al. 2007). In Shuster's test, each earthquake is represented by a unit length vector in the direction of the assigned phase angle α_i. The vectorial sum D is defined as:

, (2)

where N is the number of earthquakes. When α_i is distributed randomly, the probability to be the length of a vectorial sum equal or larger than D is given by the equation:

, (3)

Thus, $p < 5\%$ represents the significance level at which the null hypothesis that the earthquakes occurred randomly with respect to the tidal phase is rejected. This means that the smaller the p is the greater the confidence level of the results of the Cumulative Histograms is.

4. Results