Mid Latitude TEC Variations before and during the Balkan Peninsula Seismic Activity of 24th May 2009

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Abstract: In this paper the Total Electron Content (TEC) data of 8 Global Positioning System (GPS) stations of the EUREF network, 4 close and 4 remote stations to EQ epicentre, which are being provided by IONOLAB (Turkey), were analysed using Fast Fourier Transform Analysis in order to investigate the TEC variations over North-western Balkan Peninsula before and during the seismic activity of 24^{th} of May, 2009. The main conclusions of this analysis are the following. (a)Morning and evening extension of the day time TEC values are manifested over the EUREF stations with epicentral distances< 1200km during the pre-, co- and post- main earthquake period i.e. from 13/05 to 26/05/2009,(b) exalting of 2-6 TECU in the morning an evening TEC values from 18/05 to 26/05/2009 is observed from all the stations of the program, (c) TEC oscillations in a broad range of frequencies occur randomly over a broad area of several hundred km from the earthquake and (d) 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 i.e. the higher Fractal Brownian frequency the closer to the epicentre site. We conclude that the LAIC mechanism through acoustic or gravity wave could explain this phenomenology.

Key words: GPS network, ionospheric total electron content, Fast Fourier Transform Analysis, Lithosphere Atmosphere Ionosphere Coupling

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. 2012). 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 North-western Balkan Peninsula before and during the seismic activity of 24th of May, 2009. It should be noticed that the case study of this paper meets all the requirements set by Afraimovich (2004) for promising identification of TEC variations possibly related with tectonic activity i.e. Quiescent Geomagnetic conditions and insignificant solar activity.

2. The data

2.1 TEC values

In this paper we are interesting in the variation of TEC over the North-western Balkan Peninsula before and during the seismic activity of 24th of May 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 from150km to 2200 for the time period between 01/05/2009 and 30/05/2009.

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 displays the 8 EUREF stations while Figure 1 displays the locus of the eight GPS stations and of 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.

Table 1 The 8 EUREF stations

No	GPS Station	Distance (km)	Longitude (deg)	Latitude (deg)	Location
1	YEBES	2181.6	-3.0886	40.5200	Yebes(Spain)
2	TLSE	1728.1	1.4812	43.5607	Toulouse(France)
3	MATE	511.0	16.7045	40.6491	Matera(Italy)
4	OHRI	160.3	20.8019	41.1172	Ohrid(FYROM)
5	SOFI	150.3	23.3947	42.5561	Sofia(Bulgaria)
6	BUCU	444.6	26.1257	44.4639	Bucuresti(Romania)
7	POLV	1256.9	31.5400	49.6000	Poltava(Ukraine)
8	ZECK	1543.9	41.5700	43.2900	Zelenchukskaya(Russia)

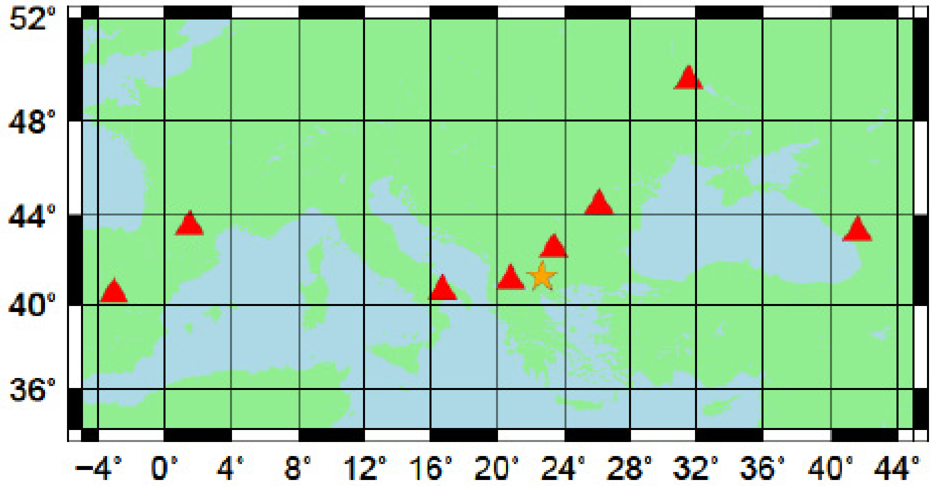

***Figure 1.** The stations of the network (in red) and the earthquake of May 24, 2009 (in orange)*

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. However in time periods of uneven variations of TEC the provider change the sampling gap (resolution) to 2.0 or 1.0 or even 0.5 minute in an unpredictable way, a fact which hardens the FFT elaboration of the Time Series. So, special attention was given in order to analyze segments of data with the same sampling gap. Figure 2 displays the variations of TEC over the 8 EUREF stations data during the time period of 01/05/ 2009 to 30/05/2009.

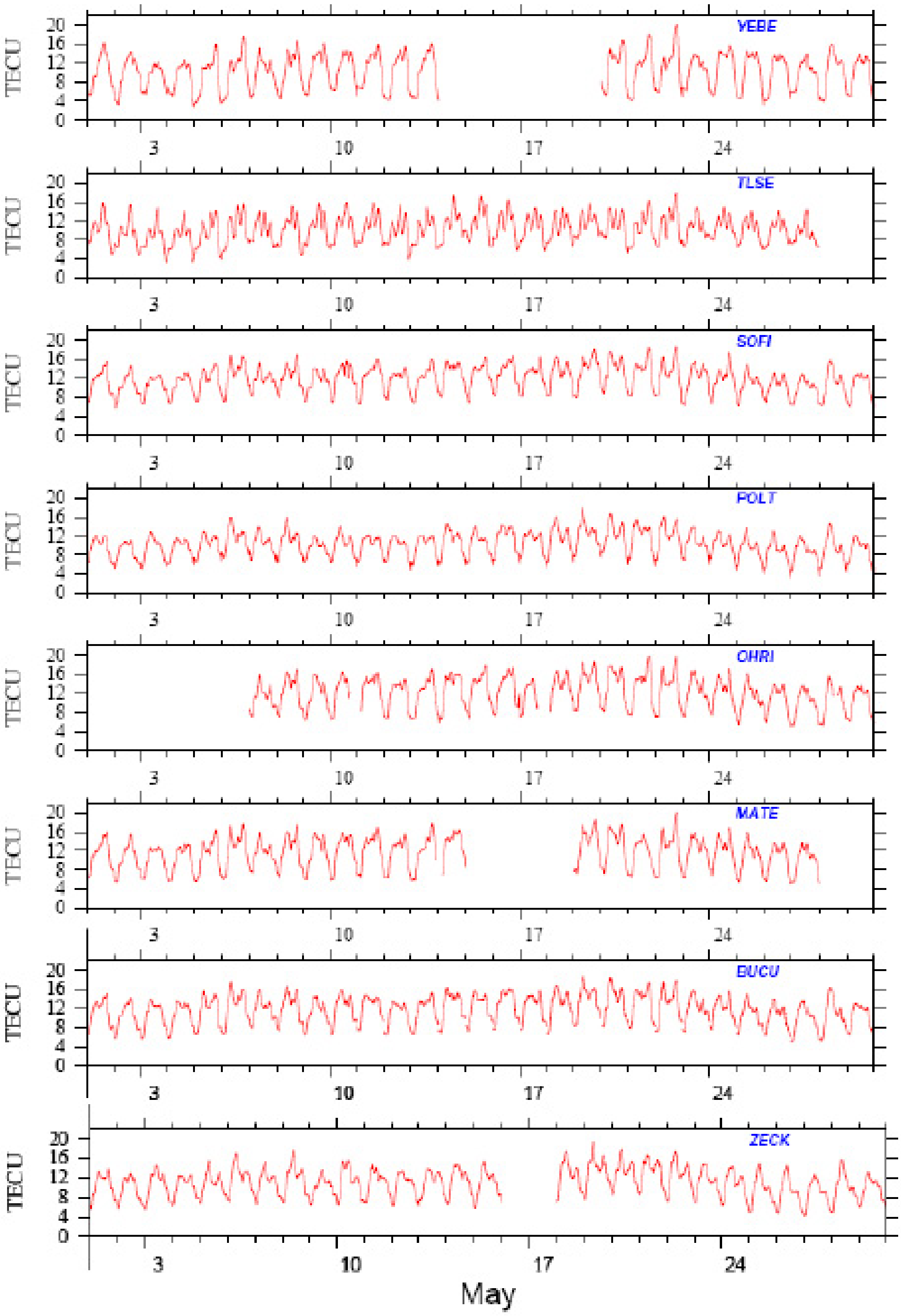

Figure 2. *TEC variations in the time period between 01/05/2009 and 30/05/2009 for the EUREF stations.*

2.2 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 3 displays the Dst-index variations on May of 2009. From Figure 3 it is seen that Dst index is mostly 0 and only on 8 ,10,19/05/2009 some weak disturbances with |Dst|<10 nT are present. From Figure 4 it is seen that the kp index is mostly 0-2 , 3 on 4 , 6/05 and 4 on 8/05. This meens that during May of 2009 dominate Quiescent Geomagnetic conditions. Also Auroral Electrojets were quite rare and weak in this month. Only on 8 and 22 of May some weak substorms were observed (Space Magnetism Faculty of Science, Kyoto University (http://swdcwww.kugi.kyoto-u.ac.jp/index.html)).It is also known that the earthquake epoch fall in the Minimum of the solar activity cycle. The Solar Spot Number is mostly 0 and only in some days up to 10. In concluding, it is seen that in general the planetary conditions are quite favourable for the identification of possible TEC variations of non planetary origin.

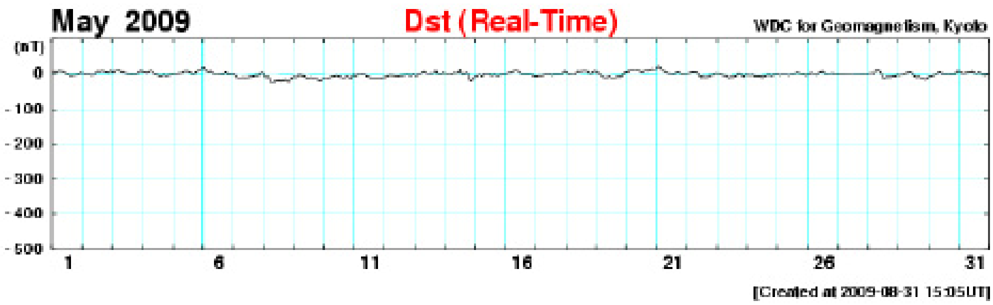

Figure 3. *Dst variations in May, 2009*

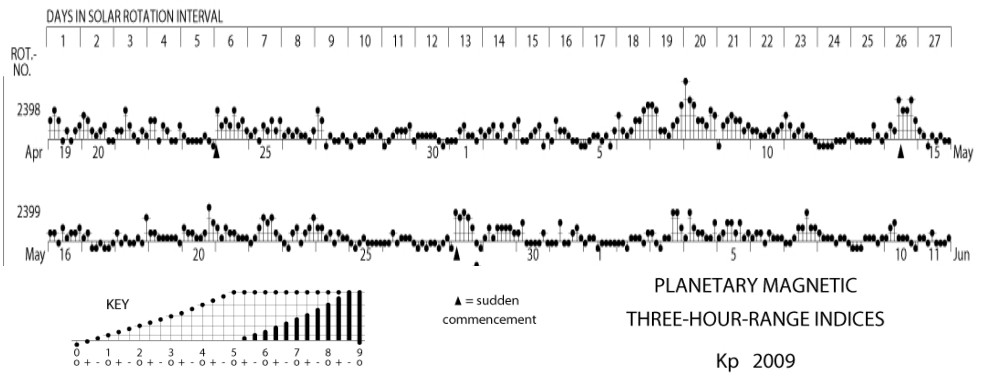

Figure 4.*Three-hour kp index in Bartel presentation for May 2009*

2.3 Seismic activity in the broader area of the Balkan Peninsula

Table 2 displays the seismic activity in the broader area of North-western Balkan Peninsula which follows that of the Central Italy one month later, quoted from the web site Orfeus Wilbert II,
http://www.orfeus-eu.org/cgi-bin/wilberII/wilberII_page2.pl.

Table 2. Seismic activity in a broader area of NorthwesternBalkanPeninsula

Date	Time	Mag	Lat	Lon	Depth	Description
2009-06-22	20:58:40	4.7	42.5	13.4	2.0	CentralItaly
2009-06-21	11:20:04	4.6	43.5	17.3	10.0	NorthwesternBalkanPeninsula
2009-06-07	09:00:06	4.7	38.3	22.1	2.0	Greece
2009-06-01	08:03:39	4.5	41.2	22.7	2.0	NorthwesternBalkanPeninsula
2009-05-30	02:55:25	4.8	43.3	13.2	60.0	CentralItaly
2009-05-28	08:43:33	4.6	41.2	20.2	2.0	Albania
2009-05-24	19:37:05	5.0	41.3	22.7	2.0	NorthwesternBalkanPeninsula
2009-05-24	16:23:09	4.6	41.3	22.7	2.0	NorthwesternBalkanPeninsula
2009-05-24	16:17:50	5.4	41.3	22.7	2.0	NorthwesternBalkanPeninsula
2009-05-17	22:39:26	4.5	38.1	22.7	2.0	Greece
2009-05-17	11:59:04	4.7	38.1	22.8	10.0	Greece
2009-05-02	15:44:20	4.5	37.6	22.8	60.0	SouthernGreece

3. Data analysis

The data consist of TEC values sampled every 2.5 minutes for each station and for the time interval between 01/05/2009 and 30/05/2009. 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 North-western Balkan Peninsula we first compare the variations over all the EUREF stations for this time period. Then we analyze the data time series using Fast Fourier Transform Analysis for a finer investigation.

4. Results

4.1 The overall variation of TEC

The variation of TEC over the 8 EUREF stations for the time period from 01/05/2009 to 30/05/2009 is shown in Figure. 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 1200km and for the time period from 14/05/2009 to 26/05/2009, the day time TEC values are morning and evening extended by 30 to 250 minutes, comparing with the mean day time TEC duration for each station. This is not the case for the stations with epicentral distance greater than 1200km. Figures 5, 6 , 7, 8 and 9 display the morning and evening extensions

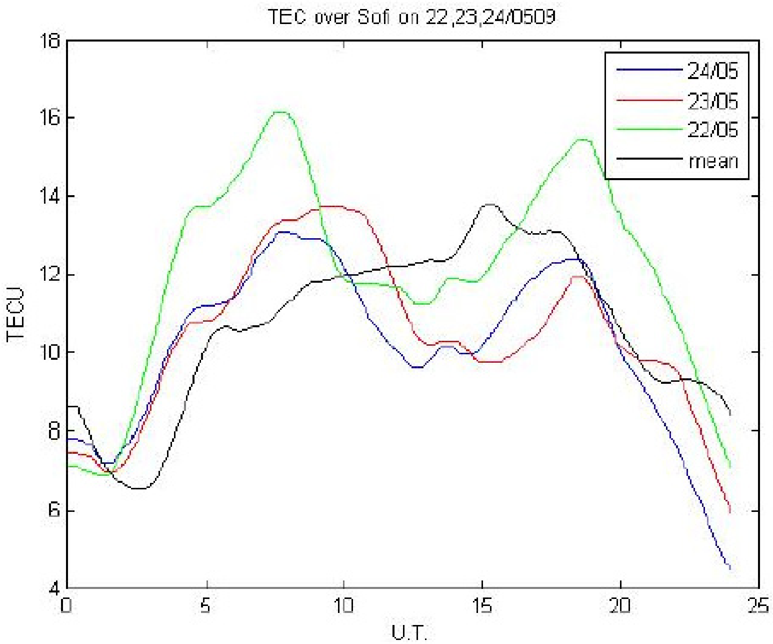

***Figure 5**. Daily TEC variations over the Station of Sofia on 22, 23,24/05/2009. (Epicentral distance=150.3 km)*

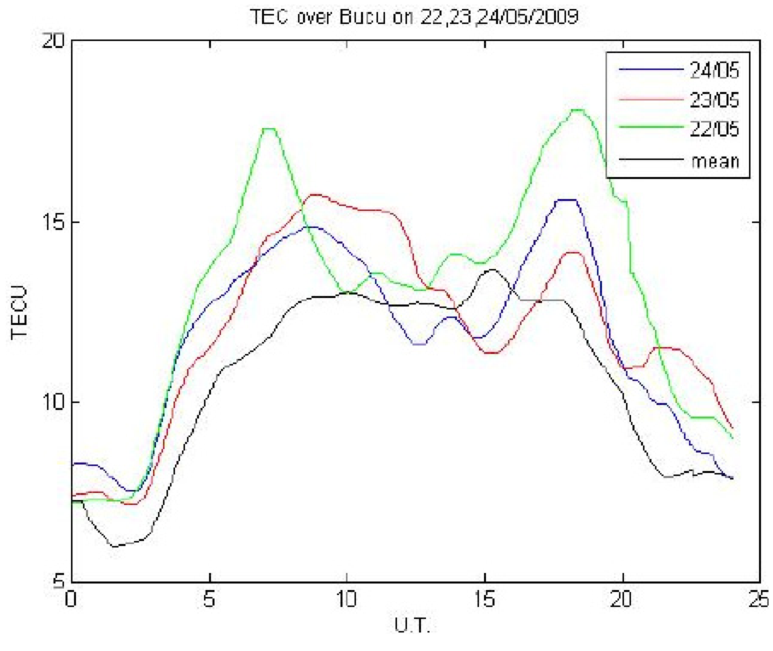

***Figure 6.** Daily TEC variations over the Station of Bucuresti (Romania) on 22, 23,24/05/2009 .(Epicentral distance=444.6km)*

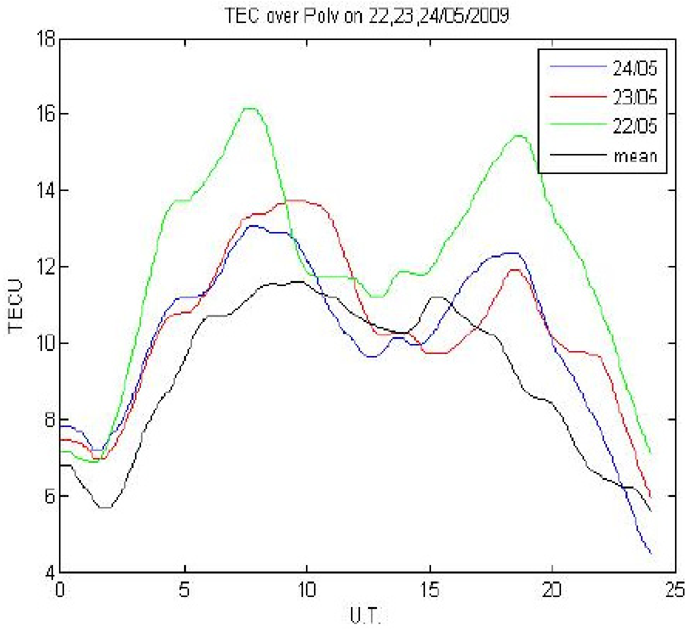

Figure 7. *Daily TEC variations over the Station of Poltava (Ukraine) on 22,23,24/05/2009. (Epicentral distance=1256.9)*

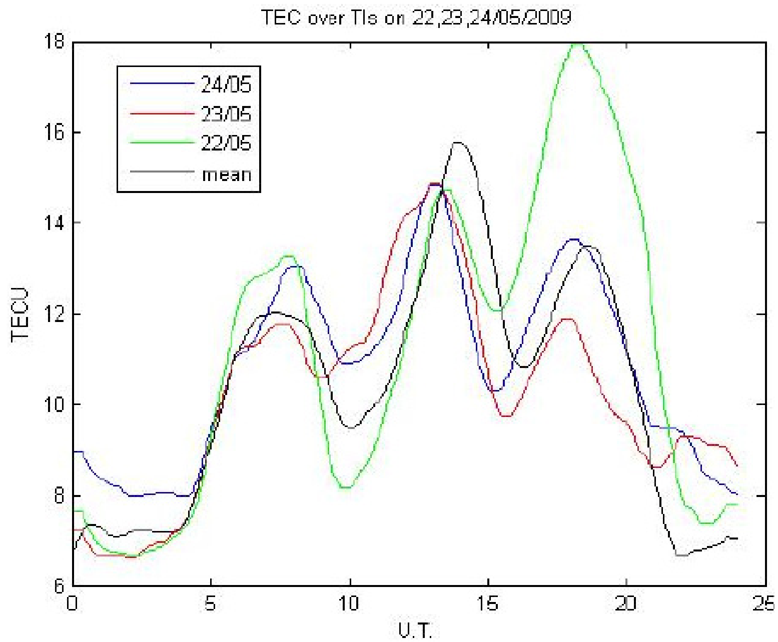

Figure 8. *Daily TEC variations over the Station of Toulouse (France) on 22, 23,24/05/2009. (Epicentral distance=1728.1km)*

for a sample of stations with varying epicentral distances for the days 22,23,24/05/2009 as an example. In these figures the mean TEC variation for the days 11,12,13/05/2009, which we considered as reference TEC daily variation is display in black color line.We have used the mean value of the days 11,12 and 13 for which all the indices indicate that no planetary disturbance exist, as it is seen from figures 3,4, as comparison TECs.

The same phenomenon has been observed in the case of the L'Aquila earthquake (Contadakis et al. 2012) and was considered a counterpart phenomenon of the anomalous evening terminator time in VLF/LF transmission (Yoshida et. al 2008) and was observed in the time interval 2 - 8 days before L'Aquila earthquake, as it was reported by Rozhnoi et al. (2009). In addition exalting in the morning and evening TEC values are observed in the time interval from 18/05 to 25/05/2009 for all the stations. These exalting range from 2 to 6 TECU and are higher on 22/05/2012. This phenomenon has been reported by many scientists in the case of strong earthquakes (see for instance Akhoondzadeh 2012).

The possibility that the observed exaltings are of planetary casualty is very limited since the geomagnetic field conditions and the solar activity are very quiet in this time period, as it is seen from figures 3,4. In addition the possibility that the weak geomagnetic substorm of 22/05/2009 is responsible for the TEC exalting of 22/05/2009 is also quite limited. In an extensive study of Ding et al (2008), they found that 135 strong geomagnetic storms produce up to 3.5TECU variation. For instance the strong geomagnetic storms of 21 and 22/01/2004 (AE index ~800nT) produced 1.5 and 1.0 TECU in mid ltitudes. So it is hard one to believe that the weak substorm of 22/05/2009 (AE index<200nT) produce the observed exalting.

Both phenomena may be explained by the generation of Es-layers. More specifically we suggest that lithospheric perturbations transmitted through a LAIC mechanism in the ionosphere, influence the turbidity and ionization of all ionospheric layers and may generate Spread-Es phenomena too. 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 Es-layers. The generation of Spread-Es phenomena was verified by the ionograms of Rome (epicendral distance 459km) and Athens (epicentral distance 422km) Ionosondes. Finally we have to stress that apart of these major timely persistent TEC variations, TEC variations are also observed and in isolated days, spreaded in all the month of May. As an example the evening daily TEC extention which is observed on 06/05/2009 , has no planetary reason, as it is deduced from figures 3,4. On the other hand the inspection of ionograms from Rome and Athens Ionosondes show Es spared presence and enhanced E-level ionization for the day TEC extension time. These facts together with the high frequency disturbances attenuation as the epicentral distance

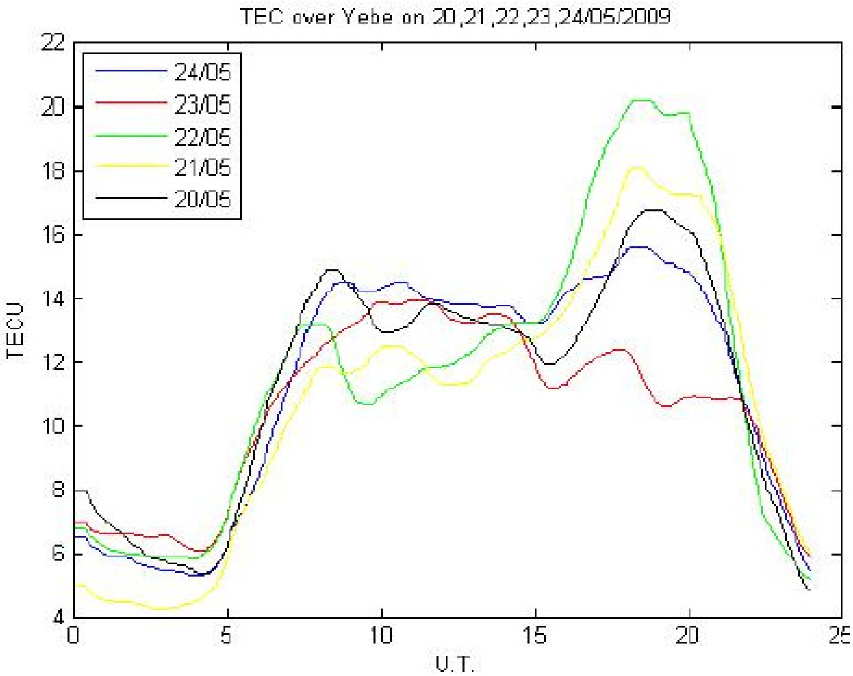

Figure 9. *Daily TEC variations over the Station of Yebes(Spain) on 22, 23,24/05/2009. (Epicentral distance=2181.6km)*

increase, which was found for the major TEC variations (see Table 3), favor the suggestion that the observed TEC variation of 6/05/2009 are of tectonic casualty. Finally we have to stress that apart of these major timely persistent TEC variations, TEC variations are also observed and in isolated days spread in all the month of May. As an example the evening daily TEC extention which is observed on 06/05/2009 , has no planetary reason, as it is deduced from figures 4,5 an6. On the other hand the inspection of ionograms from Rome and Athens Ionosondes show Es spared presence and enhanced E-level ionization for the day TEC extension time. These facts together with the high frequency disturbances attenuation as the epicentral distance increase, which was found for the major TEC variations (see Table 3), favor the suggestion that the observed TEC variation of 6/05/2009 are of tectonic casualty

4.3 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. 2012). As an example Figure 10 displays the logarithmic power spectrum of TEC over Yebes (Spain) on the 30/03/2009. It is realized that the spectrum of TEC variations over Yebes contain random variations in the high frequency part ($f > 0.0003983$ Hz, period < 50.215 minutes) and periodical variations in the low frequency part ($f < 0.0003983$ Hz, period > 50.215 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.

Table 3 displays the daily limited periods of TEC variations over the EUREF-stations of our program during May of 2009. 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 Sofia, the closest Station to the epicentre 3 days before the earthquake occurrence i.e. on 21/05/2009. (To be compared with that of a remote station i.e. Figure 10).

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 morning/evening extension of the day time TEC values and the respective TEC exalting for the eight 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 0.003Hz (period 5min) and 0.0002Hz (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 iono-

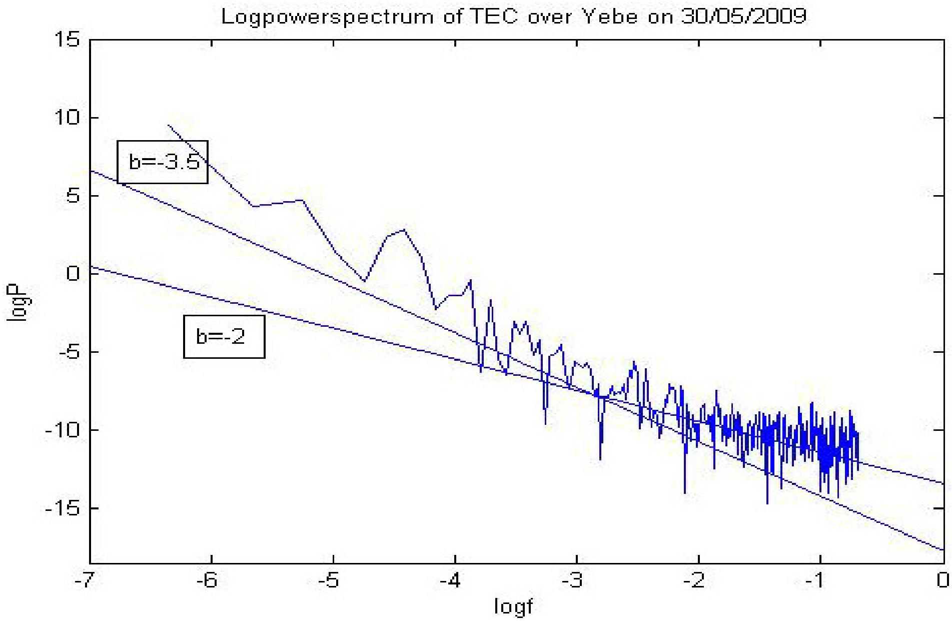

Figure 10. *The logarithmic power spectrum of TEC over Yebes (Spain) on the 30/05/2009.*

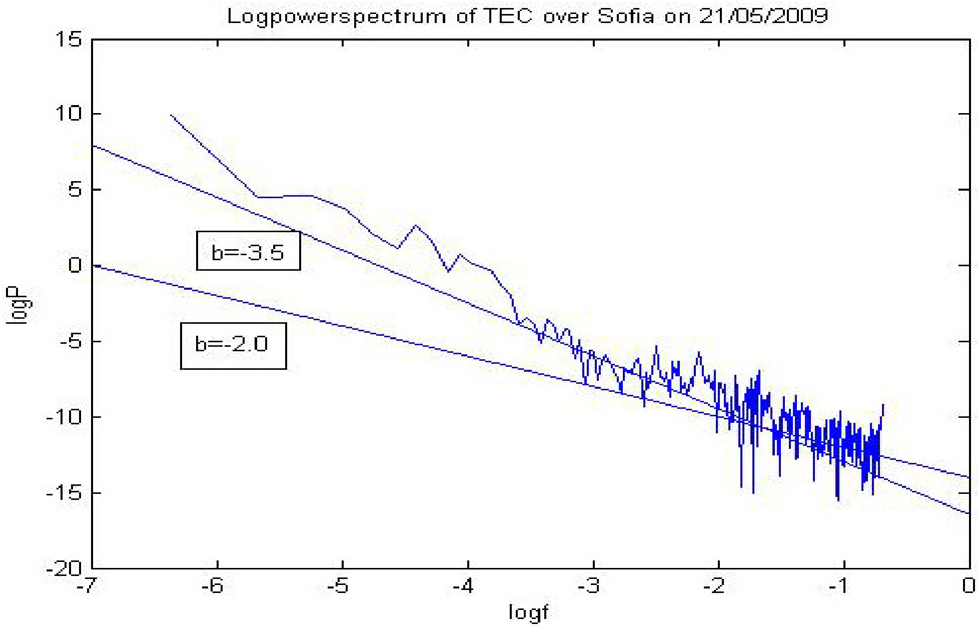

Figure 11. *The logarithmic power spectrum of TEC over Sofia (Bulgaria) on the 21/05/2009.*

Table 3. displays the daily limited periods of TEC variations over the EUREF-stations of our program during the May of 2009

May/2009	Zel	Polv	Bucu	Sofi	Ohri	Mate	Tls	Yebe
1	37.199	27.558	30.456	9.173	41.112	27.558	18.473	37.199
2	37.199	24.935	33.659	24.935	20.415	37.199	41.112	41.112
3	11.204	27.558	37.199	10.138	41.112	37.199	41.112	37.199
4	27.558	27.558	37.199	27.558	8.300	37.119	30.456	37.199
5	33.659	27.558	37.199	27.558	49.673	30.456	41.112	37.199
6	37.199	37.119	18.473	12.383	30.456	30.456	41.112	37.199
7	41.112	15.124	18.473	27.558	4.482	60.750	45.436	18.473
8	41.112	15.124	27.558	18.473	41.112	27.558	50.214	13.372
9	37.199	37.199	27.558	11.204	33.659	30.456	50.214	18.473
10	41.112	41.112	11.204	13.685	3.004	22.563	61.331	37.199
11	27.558	27.558		16.715	27.558	37.199	55.495	41.112
12	37.199	33.659	20.415	45.435	24.935	33.659	55.495	37.199
13	27.558	33.659	18.475	8.300	24.935	27.558	37.199	37.199
14	27.558	41.112	9.173	13.685	4.482	50.214	22.563	
15	22.563	27.558	24.935	11.204	24.935		61.331	
16	16.535	33.659	27.558	11.204	50.214		61.331	
17	30.563	37.199	24.935	10.138	9.000		50.214	
18	41.112	41.112	22.563	22.563	50.214		50.214	
19	41.112	30.456	20.415	18.473	50.214	37.199	50.214	
20	45.435	27.558	20.415	18.473	30.456	37.199	41.112	
21	41.112	27.558	37.199	12.383	27.558	13.685	33.659	41.112
22	41.112	33.659	37.199	18.473	8.300	30.456	41.112	41.112
23	45.435	37.199	22.563	18.473	16.715	30.456	41.112	37.199
24	37.199	30.456	27.558	20.415	27.558	24.935	55.495	37.199
25	50.214	24.935	41.112	20.415	18.473	27.558	41.112	41.112
26	41.112	24.935	16.445	18.473	24.935	33.659	18.473	37.199
27	27.558		41.112	18.473	33.659	33.659	30.456	41.112
28	24.936	27.558	41.112	20.415	6.796	41.112	18.473	37.199
29	41.112	30.456	27.558	27.558	8.300		18.473	67.782
30	41.112	37.199	37.199	30.456	11.204		27.558	50.214

sphere). 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 Table 3 and is presented in the Figures 12 by means of the variation of the mean daily limited period with the epicentral distance.

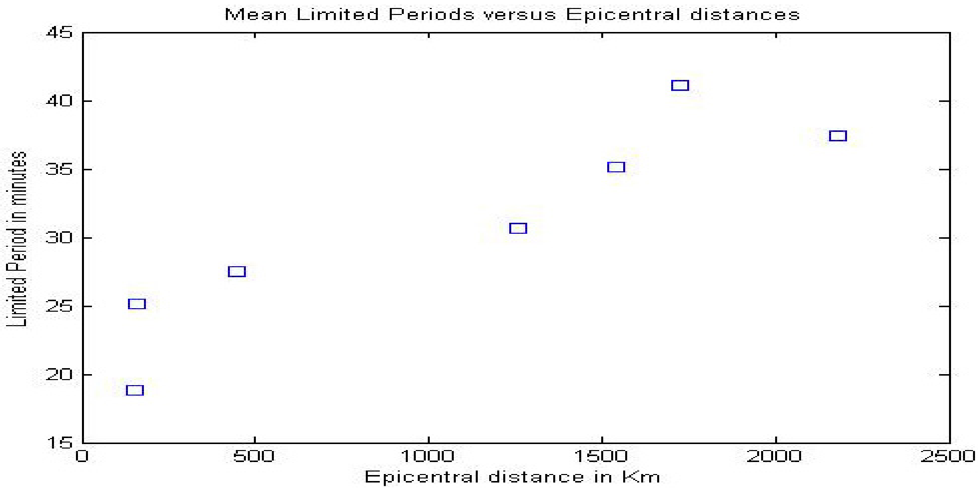

Figure 12. *Daily limited periods for TEC variations versus Epicentral Distance*

5. Concluding Remarks

The Analysis of TEC variations over 8 mean latitude EUREF GPS stations during the month of the seismic activity of the North-western Balkan Peninsula indicate that TEC oscillations in a broad range of frequencies occur randomly over a broad area of several hundred km from the earthquake. Morning and evening extension of the day time TEC values are manifested over the EUREF stations with epicentral distances< 1200km during the pre-, co- and post- main earthquake period i.e. from 13/05 to 26/05/2009, while exalting of 2-6 TECU in the morning an evening TEC values from 18/05 to 26/05/2009 is also observed from all the stations of the program. The attenuation of the high frequency oscillations ($f \geq 0.0003$Hz, periods $T \leq$ 60min) 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.

Acknowledgements: The authors are grateful to Professors F. Arikan and U. Sezer, the persons in charge of IONOLAB, for their willingness to provide any useful information about the data of IONOLAB.

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